Modeling, simulation and optimization of the detection of Gamma-Ray Burst with GLAST

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Introduction

The Gamma-ray Large Area Space Telescope (GLAST) is an international space mission that will study the cosmos in the energy range 10 keV-300 GeV, the upper end of which is one of the last poorly observed region of the celestial electromagnetic spectrum. The ancestor of the GLAST/LAT was the Energetic Gamma Ray Experiment Telescope (EGRET) detector, which flew onboard the Compton Gamma Ray Observatory (CGRO). The amount of information and the step forward that the high energy astrophysics made thanks to its 9 years of observations are impressive. EGRET showed the high-energy gamma-ray sky to be surprisingly dynamic and diverse, with sources ranging from the Sun and Moon to massive black holes at large redshifts. Most of the gamma-ray sources detected by EGRET remain unidentified. EGRET uncovered the tip of the iceberg, raising many questions, and it is in the light of EGRET’s results that the great potential of the next generation gamma-ray telescope can be appreciated. GLAST will have an imaging gamma-ray telescope vastly more capable than instruments flown previously, as well as a secondary instrument to augment the study of gamma-ray bursts. The main instrument, the Large Area Telescope (LAT), will have superior area, angular resolution, field of view, and dead time that together will provide a factor of 30 or more advance in sensitivity, and capability for study of transient phenomena. The GLAST Burst Monitor (GBM) has a field of view several times larger than the LAT and will provide spectral coverage of gamma-ray bursts (GRB), transient phenomena that extend from the few keV up to LAT energies. With the LAT and GBM, GLAST will be a flexible observatory for investigating the great range of astrophysical phenomena best studied in high energy gamma rays. They are among the central subjects of NASA’s Structure and Evolution of the Universe (SEU) research theme planned for study of black holes and dark matter. The anticipated advances in astronomy and high energy physics with GLAST are described briefly in the first chapter of this thesis. NASA plans to launch GLAST in early 2007.

The GLAST mission includes physics and astrophysics programs in the partner countries of France, Germany, Italy, Japan, and Sweden, and the mission will be supported by a vigorous, multidisciplinary guest investigator program to maximize its discovery potential. A crucial role is played by the Italian collaboration, which is basically responsible for the construction of the silicon strip tracker, by far the most complex among the GLAST sub-detectors (with \( \sim 80 \text{ m}^2 \) of active silicon surface and a number of electronics channels approaching \( 10^6 \)). The actual flight hardware production is ongoing; two engineering models have been constructed, as a final validation of the instrument design both in terms of the mechanical structure and in terms of sensors technology and readout electronics performance. One non-fly tower has been assembled and tested and two of the eighteen flight tower have been already built, successfully tested and delivered to the collaboration. A big efforts has also been devoted from the Italian collaboration to the software development. The LAT community has set up a full simulator of the detector based on Geant 4, a Montecarlo toolkit developed at Cern. In the first part
of this thesis the Montecarlo of the LAT instrument will be presented and will be used for studying the performance of the instrument. The LAT detector will be described in terms of Instrument Response Functions (IRF), a series of matrices derived from the Montecarlo data analysis that describe the instrument performance in terms of detection efficiency, angular and energy resolution. The processed events need to be filtered by a selection cut, whose goal is to maximize the energy and the angular resolution by discarding the events that have been wrong reconstructed. The price to pay is, of course, the efficiency or, in other words, the effective area. The “good event” selection is a selection cut which reach the compromise between good resolution and good efficiency. It is important to underline that the knowledge of the IRF is needed for the calibration of the instrument during astronomical observations: the raw data are the result of the convolution between the real flux and the Instrument Response Function: thus, in order to obtain an estimation of the astronomical flux, raw data need to be de-convolved with the IRF.

The LAT simulator software starts from the simulation of the gamma ray sky. The detailed description of the sky, including diffuse emissions and point sources, such as the complete EGRET catalogue or transients, allows the detector to be studied in a realistic astrophysical environment. Part of my work during this thesis deals with the simulation of Gamma Ray Bursts (GRBs), an astrophysical source that emits flashes of high energy radiation. The GRB are indeed one of the most exciting phenomena in the high energy sky. Fascinating for their transient behavior and for their mysterious origin, they provide information from the furthest region of the universe. They represents a key study for the GLAST mission due both to the GLAST Burst Monitor, which is dedicated to the observation of Bursts, and to the LAT detector, which will shed light onto the features of their high energy emission, first observed by the EGRET satellite. Two different simulators have been developed. The first one is based on the observations made by the ancestors of GLAST. The Burst And Transient Source Experiment (BATSE) onboard the CGRO, was a detector dedicated to the science of GRB in a range of energy between 20 keV and almost 1 MeV. In this region GRBs are bright and many of them was detected by this experiment. The phenomenological model idea is to extrapolate the results of BATSE to the LAT energies. The spectral shape and the pulse shape are in this case parameterized functions whose parameters are obtained from the BATSE catalogue. There is no physical motivation in such a model, but the observables are well reproduced. A different approach has been followed within the development of the second simulator: the physical model. This model starts from physical considerations, from the study and the comprehension of the physics inside a GRB. It does not support merely extrapolations as in the case of the GRB phenomenological model, but it builds the spectrum and the temporal profile from what we know about this sources and what we know, in general, about high energy astrophysics. Two typical aspects of this branch of astrophysics are encountered and studied during this thesis. The first is the acceleration of particles to high energy. Observed photons come from accelerated particles. Gamma-rays can be thought as the final stage of a process of energy transformation, which begins, probably from an explosion of a massive star characterized by the emission of material into the surrounding environment. This material is moving at high speed carrying out most of the initial energy of the star as kinetic energy. This kinetic energy has to be converted somehow into kinetic energy of accelerated particles and, finally, to radiation. Shock’s mechanism plays a crucial role in particles acceleration, and their presence has been confirmed by several observations. Even though shocks in GRB have not been directly observed, they may share the same problematic of the shocks which have been observed in other sources. In supernova remnant (SNR) shocks heat
the surrounding medium accelerating particles, and the jet of some AGN shows unique feature of internal shocks. Another important subject relate to GRB is the study of the emission processes. The observed spectrum is typically non thermal (this means that is not a black body). The main emission process involved in the GRB science is synchrotron radiation from relativistic moving particles. Nevertheless synchrotron radiation depends on the initial distribution of particles: study on this subject will be presented in the appendix and the results are used in the development of the physical model. The high energy emission from GRB has been studied and, in particular, two aspects of interest have been investigated. The first is a suppression of the synchrotron spectrum due to the finite maximum energy for accelerating particles. Electrons, which are radiating their energy via synchrotron emission, cool rapidly due to the intense magnetic field. The energy losses balance the acceleration mechanism and a maximum energy can be reached by the electrons. On the other hand, another aspect related to the high energy range has been studied: the Inverse Compton scattering between the high energy electrons and the synchrotron photons. Since the electrons that scatter are the same that are producing the photons, this emission process is also known as Self Synchrotron Compton (SSC). The studies I have done in this field and the simulation software I have developed for the GLAST community are presented in this thesis. The GRB simulator is part of the official GLAST/LAT software and it has been used for studying the detector performance in the observation of these transient sources. The simulators can be used for sampling photons accordingly with the flux and the temporal evolution of the bursts as previewed by each model. These photons are then processed by the full GLAST/LAT simulator and the response of the detector can be analyzed and studied. The simulated data are identical (in terms of data structure) to the real scientific data that will be available when GLAST will be operative. Some tools dedicated to the analysis and to the visualization of GRB are presented: I will describe the typical analysis that can be done using LAT data, and, finally, I will apply the available tools on the simulated bursts. I had the opportunity to join the Data Challenge One (DC1), Montecarlo data taken with the goal of simulating of one day of gamma-ray sky, for studying in detail the response of the detector, for testing the developed software and for having the first experience of doing science with GLAST. In the simulated sky of the DC1, several simulated Gamma-ray bursts were shining. The number of simulated bursts was extremely high, much bigger than the observed one. This allows to have enough statistic in order to test and exercise algorithms and performs analysis. Nevertheless, one of the goal of the DC1 was to implement bursts trigger algorithms in order to detect transient signals. Some of these algorithms will be described. The rate trigger is a simple algorithm based on the rapid increasing of the counts rate when a burst occurs. Better results are obtained if also the spatial information are used and the trigger rate is applied separately on different part of the sky, reducing in this way the background rate. The strawman LAT GRB alert is the alert system that probably will be adopted by the LAT team for triggering transient signal. It makes use of the spatial and temporal informations looking for clustering events in time and space. The algorithm has been developed by members of the GRB and Solar Flair science team as IDL routines. A modified version edited in C++ has been here developed.
Chapter 1

The scientific case for the GLAST experiment

The development of the gamma-ray astrophysics up to the tens of GeV is completely related to the development of balloons and satellites since the Earth atmosphere absorbs gamma rays from the cosmos. The first satellite was Explorer X1, that, in 1961 detected tens of photons isotropically distributed in the sky. In the 1967 OSO III (Orbiting Space Observatory) detected a diffuse emission spatially connected to the Galactic Plane. Both extragalactic diffuse radiation and galactic emission were in this way observed. In 1969 and 1970 an array of military satellites (VELA) able to detect X-ray and gamma-ray was launched by the United States. Even if these satellites were made to monitor the eventuality of nuclear russian experiment in the Earth atmosphere or on the Moon, they serendipitously discover transient flashes of radiation named Gamma-Ray Bursts. The first satellite entirely dedicated to gamma-ray astrophysics was SAS-2, launched in 1972 that was able to detect with more accuracy the diffuse emission and was also able to resolve the first point sources (like the Vela pulsar and the Crab pulsar). In 1975 the European Space Agency (ESA) launched COS-B whose discoveries are contained in the first gamma-ray catalog of point sources, including the well known extragalactic source 3C 273. A big step forward has been done in 1991 with the launch of the NASA satellite Compton Gamma Ray Observatory (CGRO). The Burst And Transient Source Experiment (BATSE) and the Energetic Gamma Ray Experiment Telescope (EGRET) were the two main instrument onboard the CGRO. The first was dedicated to the science of the bursts and transients, while the second was dedicated to the highest energetic astrophysics ever done in space, reaching the upper limit of observation of 30 GeV. GLAST will enter in the panorama of the high energy astrophysics making a big step forward in the science and in the technological development, carrying in space the knowledge of the solid state detectors, devices used, up to now, only in the high energy laboratory on ground. The universe is largely transparent to gamma rays in the energy range of GLAST. Energetic sources near the edge of the visible universe can be detected by the light of their gamma rays. There is good reasons to expect that GLAST will see known classes of sources to redshifts of 5, or even greater if the sources existed at earlier times. The small interaction cross section for gamma rays also means that gamma rays can provide a direct view into natures highest-energy acceleration processes. Gamma rays point back to their sources, unlike high-energy cosmic rays, which are deflected by magnetic fields. Galactic gamma ray sources are related to compact objects, such as neutron stars or accreting black holes. Supernova remnants are an astrophysical object which may contain the secret of cosmic ray acceleration. Structures
like shells that interact with the Inter Stellar Medium (ISM) have been observed with
the high resolution telescopes in X-Ray wavelength, and this site have been associated
with shocks. The main sources of extragalactic radiation are the Active Galactic Nuclei
(AGN), and in particular Blazars, a particular class of AGN whose jet is aligned with
the line of sight. In the extragalactic universe also transient sources, like GRB are shing-
ing flashes of radiation. The diffuse galactic component is thought to be related to the
interaction of photons with cosmic rays, while the extragalactic component is probably
the results of the contribution of thousands of unresolved point sources. Part of the
extragalactic diffuse component could be related with the decay of exotic particles in
the Primordial Universe.

1.1 Blazars and Active Galactic Nuclei

In the universe there are billions of Galaxies, which differs basically from their mor-
phology in the Hubble diagram. The luminous contribution of their luminosity is given
by the contribution of all the stars in the galaxy \(10^{12}\). In the forties, the american
astronomer C. Seyfert discovered a new class of galaxies, particularly intense in their
nuclei and with a broad band emission line. This kind of objects, called Seyfert galax-
ies, were associated to a new class of galaxies named Active Galactic Nuclei. Other
examples of AGN, are the Quasars and BL Lac. Their luminosity is extremely high
\((\sim 2 \times 10^{46}\text{erg/s} \text{ which corresponds to more then twenty Milky Way galaxies})\). The
first observation at high energy came from COS-B, which observed the brightest quasar:
3C 273 \[1\]. In Fig. 1.1 the Spectral Energy Distribution of two Quasars are shown. In
the figure, 3C279 contains also the EGRET observation \[2\].

EGRET detected high energy radiation from Blazars \[3\], very powerful objects char-
acterized by the fact that the collimated jet is pointing towards the observer. The
radiation is boosted by the bulk Lorentz Factor and photons have been observed up to
the TeV energies. Blazars are also characterized by high degree of polarization, and by
variability on the order of a day. The emission above 100 MeV is a significant fraction of
the total luminosity, and in flaring state the gamma-ray luminosity can exceed the lumini-
osity in all other bands by a factor of \(\sim 10\) or more. The spectral energy distribution is
characterized by a double component, one peaked at almost x-ray energy, probably
caused by synchrotron emission in the jet (Fig. 1.2). The high energy component is
peaked at GeV energies, and it is probably related to the Inverse Compton reprocess-
ment of the synchrotron spectrum, also called *Self Synchrotron Compton (SSC)*. The emission is believed to be powered by accretion onto supermassive black holes at the cores of distant galaxies.

Blazar AGNs now compose the largest fraction of identified gamma-ray sources in the EGRET range, with 66 high-confidence and 27 lower-confidence identifications [4].

Directly comparing the point source sensitivity reach by EGRET in one year of observation for high latitude sources (|b| > 30), and the estimated one for GLAST, and extrapolating the LogN – LogS distribution for blazars, the discovery space is enormous. Fig. 1.3 shows the logNLogS distribution from [5, 6]. GLAST will increase the number of known AGN gamma-ray sources from about 70 to thousands. Moreover, it will effectively be an all-sky monitor for AGN flares, scanning the full sky every three hours. It will greatly decrease the minimum time scale for detection of variability, and will offer near-real-time alerts for spacecraft and ground-based observatories operating at other wavelengths. Using EGRET, AGN flares were measured to vary on the shortest time scales - eight hours - that were able to be determined with statistical significance.

### 1.2 Unidentified Sources

More than 60% of the sources observed by EGRET [4] have no counterpart at other wavelengths. The difficulties in the identification is both related to the nature of these sources and due to the experimental limits of the EGRET telescope. These sources should have an high value of the ratio \( L_\gamma / L_\lambda \), where \( L_\gamma \) is the luminosity of the source in \( \gamma \)-rays and \( L_\lambda \) is the luminosity of the source at lower energies. This makes them possible powerful accelerators of particles. Nevertheless they are also clustered along the Galactic Plane, making their detection more difficult. Less than one third of these are extragalactic (probably blazar AGNs), with the rest most likely within the Milky Way. Recent work suggests that many of these unidentified sources are associated with the nearby Gould Belt of star-forming regions that surrounds the solar neighborhood [7], while apparently-steady sources are likely to be radio-quiet pulsars [8].

The poor angular resolution of the EGRET detector (\( \sim 5.8^\circ \)) and its relatively small effective area, which can be converted in poor sensitivity to faint sources, represent the main reason of the unidentification of these sources. (see also: [9, 10, 11])
Figure 1.3: Predicted number of observed high latitude Blazars in one year of observation. The comparison is between the EGRET point source sensitivity for sources at high latitude, and the estimated one for GLAST. The LogN LogS distribution is from [5, 6].

Figure 1.4: The Third EGRET Catalog (3EG). The sources, collected by class, are shown in galactic $l$ and $b$ coordinates.
GLAST will be the first telescope with an appropriate combination of angular resolution (\(\sim 3.5^\circ\) at 100 MeV and \(\sim 0.15^\circ\) above 10 GeV) and sensitivity to faint objects, enabling the identification of the EGRET sources. GLAST will be able to directly search for periods in sources at least down to EGRET’s flux limit. Transient sources within the Milky Way are poorly understood, and may represent interactions of individual pulsars or neutron star binaries with the ambient interstellar medium. Some of the unidentified EGRET sources may be associated with recently discovered Galactic microquasars. GLAST will be able to explore these source classes in detail.

1.3 Extragalactic Background Light

An apparently isotropic, presumably extragalactic, component of the diffuse gamma-ray flux was discovered by the SAS-2 satellite and confirmed with EGRET. The low sensitivity and the poor angular resolution of EGRET did not allow a identification of this light as the contribution of many point sources. The hypothesis on the origin of the Extragalactic Background Light (EBL) are various, from the most conservative, such as the summed contribution of thousands of AGN, to more exotic, such as the contribution of the annihilation from exciting particles which came from some unknown process that took place in the primordial universe, or from some particles deriving from the extension of the standard model to supersymmetric particles (SUSY), which can contribute substantially to the Dark Matter content of the universe and that can be found in the Galactic halos (see next section). The EBL is a spectrum well described by a power law with index 2.1\(\pm\)0.3 over EGRET energies and it is consistent with the average index for blazars that EGRET detected, which lends some support to the hypothesis that the isotropic flux is from unresolved AGN sources [12]. The improved angular resolution of GLAST will allow the separation and the identification of possible point-like sources to the EBL. The sensitivity of GLAST at high energies will also permit the study of the extragalactic background light by measurement of the attenuation of AGN spectra at high energies. This attenuation is from pair production with photons in the background light primarily produced by young stars at visible to ultraviolet wavelengths. Owing to the large size of the AGN catalog that GLAST will amass, intrinsic spectra of AGNs will be distinguishable from the effects of attenuation. The measured attenuation as a function of AGN redshift will relate directly to the star formation history of the universe.

1.4 New Particle Physics

The flux limit of GLAST at higher latitudes, thanks to the large effective area, is a factor of \(\sim 30\) or more lower than EGRET’s. As discussed in section 1.1, whereas EGRET identified about 70 AGNs, GLAST should see thousands, resolving a big component of the extragalactic diffuse emission. Any remaining diffuse emission would be of great interest. It is thought that diffuse extragalactic gamma-ray emission could originate from the decay of exotic particles in the primordial universe. The energy spectrum of this component should be different from the AGN contributions. The left panel of figure 1.5 shows the diffuse contribution of the relics particles, and the measured fluxes for EGRET and GLAST. The large effective area of GLAST, especially at high energies, may permit a statistically significant detection of this spectral difference. This improvement is expected due to the much larger energy range and sensitivity of GLAST as compared to EGRET, as well as the ability of GLAST to resolve contributions of point sources to the extragalactic background.
A different contribution is the possible decay of supersymmetric particles. Assuming the existence of the dark matter in the halo of our Galaxy, hypothesis also sustained by the comparison between the rotational curves of the galaxies and the baryonic visible matter, GLAST would be capable to detect the gamma-rays as result from its annihilation (for a review on galactic Dark Matter, see [13]).

The lightest supersymmetric particle (LSP), $\chi$, is perhaps the most promising candidate for the dark matter of the universe [14, 15]. It is neutral (hence the name neutralino), and stable if R parity is not violated. Supersymmetry seems to be a necessity in superstring theory (and M-theory) which potentially unifies all the fundamental forces of nature, including gravity. If the scale of supersymmetry breaking is related to that of electroweak breaking, then this density $\Omega_\chi$ may be the right order of magnitude to explain the nonbaryonic dark matter. Although the highest-energy accelerators have begun to probe regions of SUSY parameter space, the limits set at this time are not very restrictive. The mass of the neutralino particle can be constrained, in order to make up the overall Dark Matter in the universe. The required mass is in the range $30 \, \text{GeV} < M_\chi < 10 \, \text{TeV}$, depending on the model chosen. If neutralinos make up the dark matter of the Milky Way, they have nonrelativistic velocities. Hence, the neutralino annihilation into the $\gamma\gamma$ and $\gamma Z$ final states would give rise to gamma rays with unique energies, that is, gamma-ray lines with:

$$E_\gamma = M_\chi$$

or,

$$E_\gamma = M_\chi (1 - (m_Z/4M^2)),$$

depending on the preferred channel. The signature would be spatially diffuse, narrow line emission peaked toward the Galactic center. Figure 1.5 shows the predicted signal from neutralino annihilation into $\gamma\gamma$, with an assumed mass of $\sim 47 \, \text{GeV}$.
1.5 Gamma-Ray Bursts

Gamma-Ray burst are one of the most powerful sources of gamma-ray emission. The brightest GRB at GeV energy is $10^4$ times brighter than the brightest AGN. GRB are intense flashes of gamma-ray, lasting from some milliseconds up to hundreds of seconds. GLAST will continue the recent revolution of gamma-ray burst understanding by measuring spectra from keV to GeV energies and by tracking afterglows. With its high-energy response and very short deadtime, GLAST will offer unique capabilities for the high-energy study of bursts that will not be superseded by any planned mission. GLAST will make definitive measurements of the high-energy behavior of bursts that EGRET could not. The spectral variation with time is an open question, as the spectral shape above 30 MeV. Time-resolved spectral measurements with GLAST, combining data from LAT and GBM, will permit determination of the minimum Lorentz factors for the acceleration of particles, and the possibility of an Inverse Compton emission at high energies. Particularly interesting for cosmology is the determination of the distances using the GRB as standard candles [16, 17]. Another interesting use of GRBs as standard candles at cosmological distances has been suggested by [18], which suggest that the fine-scale time structure and hard spectra of GRB emissions are very sensitive to the possible dispersion of electromagnetic waves in vacuo with velocity differences $\delta v \sim E/E_{\text{QG}}$, as suggested in some approaches to quantum gravity. Measurements of the delay between the arrival time of high energy photons and low energy photons might be sensitive to a dispersion scale $E_{\text{QG}}$ comparable to the Planck energy scale $E_P \sim 10^{19}$ GeV, sufficient to test some of these theories. GLAST, thanks to the big lever arm made by comparing low energy photons measured by the GBM and the high energy photons collected by the LAT together with its very short deadtime ($\sim 100\mu s$), is certainly the most suitable observatory for these studies (see, for reference, [19]).

The LAT and the GBM will detect more than 200 bursts per year and provide near-realtime location information to other observatories for afterglow searches. GLAST will have the capability to slew autonomously toward bursts to monitor for delayed emission with the LAT. Gamma-Ray Burst will be presented with more details in chapter 5, where the main observations will be presented. An empirical model for GRBs, which describes the phenomenology of GRB phenomena using the available observations will be presented in chapter 6, while a GRB model based on physics consideration and on the theory of the fireballs will be presented in chapter 7. Both the models have been developed during this work of thesis and have been used for GRB simulation within the GLAST/LAT software.

1.6 Pulsars

From observations made with gamma ray experiments through the EGRET era, seven gamma-ray pulsars are known. GLAST will be able to directly search for periodicities in all EGRET unidentified sources. Because the gamma-ray beams of pulsars are apparently broader than their radio beams, many radio-quiet, Geminga-like pulsars likely remain to be discovered. GLAST will discover many gamma-ray pulsars, potentially 250 or more, and will provide definitive spectral measurements that will distinguish between the two primary models proposed to explain particle acceleration and gamma-ray generation: the outer gap and polar cap models [20]. No steady pulsed TeV component has been observed at the moment, an high energy cut-off is supposed to drop the spectrum. In some cases the spectrum is steeper than an exponential, which is consistent with the magnetic pair production above the polar cap region. On the other hand, there is no
Figure 1.6: Comparison between the two emission models theoretically developed for explain the Pulsar spectrum. From the figure is evident that the error box of EGRET do not allow the discrimination between the Polar Cap Model and the Outer Gap Model, while simulations show the GLAST will be the potentiality of disentangling the two models.

enough statistic in the EGRET data for distinguish with significantly precision the different emission at high energies as predicted by the two models (see Figure 1.6). GLAST will be able to collect the statistics needed for significantly validate the predicted emission and to distinguish between the two different predictions for the high energy cut-off of the pulsar spectrum.

1.7 Cosmic Rays and Interstellar Emission

Cosmic Rays (CR), relativistic cosmic particle from the space, are studied since early in the twentieth century. Even so, the question of the origin of cosmic rays (CR) nuclei remains only partially answered, with widely accepted theoretical expectations but incomplete observational confirmation. Theoretical models and indirect observations support the idea that CR are produced in the Galaxy by Supernovae Remnants (SNR). The main mechanism which is believed to be at the base of the CR production is the shock acceleration, happening when the Supernovae shell shocks with the Inter Stellar Medium (ISM). The shock mechanism is an efficient particle accelerator up to TeV energies, and, in the case of SN, on time scales of $10^3 - 10^4$ years. The accelerated CR escape from the SNR remaining trapped in the Galactic magnetic field. Observing charged particles, there are no possibility to directly observe the sites of their production, due to magnetic deviation. CRs interact with the interstellar gas and photons, producing gammas (for examples, via Bremsstrahlung, or $\pi_0$ decay, or via Compton Scattering). Photons are not deviated by the galactic magnetic field and a direct observation of the accelerator sites is then possible. GLAST will spatially resolve remnants and precisely measure their spectra, and may determine whether supernova remnants are sources of cosmic-ray nuclei. The high resolution radio catalog at 21 cm (1.4 GHz) will be the trace route for detailed searches for Supernovae Remnants (Figure 1.7). GLAST will also be able to detect the diffuse emission from a number of local group and starburst galaxies, and to map the emission within the largest of these for the first time. Spatial
and spectral studies of the gamma-ray emission will permit the distributions of cosmic-ray protons and electrons to be measured separately and will test cosmic-ray production and diffusion theories.

### 1.8 The Galactic Center

A very interesting case of gamma-ray observation is the center of our own Galaxy, 8.5 kpc far. A strong excess of emission was observed by EGRET in the Galactic Center (GC) region [23], peaking at energies > 500 MeV. The close coincidence of this excess with the GC (within an error box of 0.2°) and the fact that it is the strongest emission maximum within 15 degrees from the GC was taken as evidence for the source’s location in the GC region. The emission intensity, observed over 5 years, did not provide evidence of time variation. The angular dependence of the excess appeared only marginally compatible with the signature expected for a single compact object, and it was more likely associated with the contribution of many compact objects with diffuse interactions within 85 pc from the center of the Galaxy. Finally, the spatial distribution of the emission did not correlate with the detailed CO-line surveys. The observed spectrum was peculiar and different from the large scale galactic gamma-ray emission. Recently the High Energy Stereoscopic System (H.E.S.S.) array of Cherenkov telescopes, detected very high energy emission from the galactic center [24]. They associate the excess to a source, coincident within 1' of Sag A+. For explaining the excess in the GC different scenarios has been proposed. The excess can be related to the diffuse emission from accelerated electrons confined in the ”Radio Arc”[25, 26, 27], or to the high energy emission from protons interacting with the with the ambient matter[28, 29]. Source models comprehend the emission from an accumulation of many middle-age pulsars[30] or the Advection Dominated Accretion Flow (ADAF) [31, 32, 33] into a black hole, possibly combined with a jet extracting energy from the accretion disk [34]. Finally, an obvious candidate for the proton accelerator could be the young (10^4 yr) and unusually powerful (total explosion
energy $\simeq 4 \times 10^{52}$ erg) supernova remnant Sgr A East [28]. Alternatively, scenarios which the neutralino annihilation is responsible of the excess have also been tested, but no “smoking-gun” was found. Particularly interest for the prospects for GLAST, the H.E.S.S. team cannot support the hypothesis that the excess observed by EGRET is the result of a continuum emission resulting from the supersymmetric particle annihilation. In particular, they conclude that, assuming that the observed $\gamma$-ray present a continuum annihilation spectrum, the lower limit of 4 TeV on the cut-off implies $M_\chi > 12$ TeV. Above such energy, from particle physics and cosmology arguments [35, 36], the $M_\chi$ is disfavored. The possible annihilation channel of supersymmetric particles, cannot, anyway, be excluded; nevertheless the discovery space for direct evidence of dark matter annihilation is naturally reduced below the H.E.S.S. energy threshold ($\sim 100$ GeV), in the GLAST energy range.

1.9 Solar Flares

The star of our planetary system has been known to produce gamma rays with energies greater than several MeV during its flaring period. Accelerated charged particles interact with the ambient solar atmosphere, radiating via Bremsstrahlung high energy gamma-rays (see, e.g.,[37, 38]). Secondaries produced $\pi^\pm$ by nuclear interaction yield gamma-rays with a spectrum that extends to the energies of the primary particles. Proton and heavy ion interactions also produce gamma rays through $\pi^0$ decay, resulting in a spectrum that has a maximum at 68 MeV and is distinctly different from the bremsstrahlung spectrum. The processes that accelerate the primary particles are not well known, but stochastic acceleration through Magnetize Hydrodynamic (MHD) turbulence or shocks ([39, 40]) are thought to be the most credible mechanisms. Particle are accelerated in large magnetic loops that are energized by flares, and they get trapped due to magnetic field, generating gamma rays ([41, 42]). Figure 1.9 shows the extraordinary flare of June 11, 1991 detected by the EGRET telescope. The contribution from electron bremsstrahlung and from pion decay are separately shown.

GLAST will have unique high-energy capability for study of solar flares. EGRET discovered that the sun is a source of GeV gamma rays. GLAST will be able to determine
where the acceleration takes place, and whether protons are accelerated along with the electrons. The large effective area and small deadtime of GLAST will enable the required detailed studies of spectral evolution and localization of flares. GLAST will be the only mission observing high-energy photons from solar flares during Cycle 24.

1.10 Complementarity with Ground-Based Telescopes

GLAST in orbit will complement the capabilities of the next-generation atmospheric Cherenkov (ACT) and shower gamma-ray telescopes that are planned, under construction, or beginning operation, such as CELESTE, HESS, MAGIC, MILAGRO, STACEE, VERITAS, ARGO, WIPPLE and the Italian satellite AGILE. The ground-based telescopes detect the Cherenkov light or air-shower particles from cascading interactions of very high-energy gamma rays in the upper atmosphere. Since that high energy cosmic rays convert in the atmosphere, they have very large effective collecting areas (> $10^8$ cm$^2$), but small fields of view ($\sim 1^\circ$)$^1$, and limited duty cycles relative to satellites. The next-generation Cherenkov telescopes will have sensitivities extending down to 50 GeV and below, as in the case of MAGIC telescope for which the threshold is supposed to reach 10 GeV, providing a broad useful range of overlap with GLAST. Figure 1.10 shows the predicted sensitivity of a number of operational and proposed ground-based Cherenkov telescopes. The sensitivity for CELESTE, STACEE, VERITAS, Whipple is for a 50 hour exposure on a single source. For the EGRET, GLAST, and AGILE satellites, and for MILAGRO and ARGO the computed sensitivity is for one year of all sky survey. The level of the diffuse background assumed is $2 \times 10^{-5}$ $ph/(cm^2 s sr)$ $(100$ $MeV/E)^{1.1}$, in agreement with the background measured

$^1$with the exception of MILAGRO
Figure 1.10: Different sensitivity curves and energy range for planned ACT and space telescopes. The sensitivity are computed considering the effective area of the various experiments and the observational time (50 hours), requiring a significance of at least 5 $\sigma$ above the background level. The crab flux (dashed line) is also represented on the plot for direct comparison [43, 44].

by EGRET at high galactic latitudes. In the figure a Crab-like flux is also shown (with power law index equal 2), requiring that the number of source photons detected is at least 5 $\sigma$ above the background [43]. For a detailed description of the figure, see also [44].
Chapter 2

GLAST: The Gamma-Ray Large Area Space Telescope

One of the last bands of the electromagnetic spectrum to be explored for astronomy is the range above 20 MeV. The principal reason for the late start was technological: for energies up to tens of GeV, detectors must be placed in orbit, and even from orbit detection of the low fluxes of celestial gamma rays is difficult.

2.1 EGRET

First came EGRET (Energetic Gamma Ray Experiment Telescope), launched in 1991 on board the Compton Gamma Ray Observatory (CGRO); it made the first complete survey of the sky in the 30 MeV-10 GeV range. The telescope is shown schematically in Fig. 2.1. A gamma-ray entering the telescope within the acceptance angle converts into an electron-positron pair in one of the thin plates between the spark chambers in the upper portion of the telescope. If at least one particle of the pair is detected by the directional time-of-flight coincidence system as a downward moving particle, and if there is no signal in the large anticoincidence scintillator surrounding the upper portion of the telescope, the track imaging system is triggered, providing a digital picture of the gamma-ray event, and the analysis of the energy signal from the NaI(Tl) detector is initiated. Incident charged particles are rejected by the anticoincidence dome. Low energy backward-moving charged particles which do not reach the anticoincidence dome are rejected by the time-of-flight measurement. The directional telescope consists of two levels of a four by four scintillator array with selected elements of each array in a time-of-flight coincidence. The upper spark chamber assembly consists of 28 spark chamber modules interleaved with twenty-seven 0.02 radiation length plates in which the gamma ray may convert into an electron pair. The initial direction is usually determined from the upper spark chamber data. The lower spark chamber assembly, between the two time-of-flight scintillator planes, allows the electron trajectories to be followed, provides further information on the division of energy between the electrons, permits seeing the separation of the two electrons for very high energy gamma rays, and shows the entry points of the electrons into the NaI detector. The energy of the gamma ray is determined in large part from measurements made in an eight radiation-length thick, 76 cm x 76 cm square NaI(Tl) scintillator crystal below the lower time-of-flight scintillator plane. Spark chamber measurements of Coulomb scattering in the thin plates and position information in the spark chamber system also aid in the energy determination. The energy resolution of the experiment is about 20% (FWHM) over the central part of
the energy range. The resolution is degraded to about 25% above several GeV due to incomplete absorption in the NaI calorimeter, and at energies below about 100 MeV where ionization losses in the spark chamber plates comprise an appreciable portion of the total energy. EGRET raised many interesting issues and questions which can be addressed by a NASA mid-class mission (Delta II rocket) like GLAST.

2.2 The GLAST observatory

The GLAST mission was conceived to address important outstanding questions in high-energy astrophysics, many of which were raised but not answered by results from EGRET. The main instrument on board the GLAST detector is the LAT (Large Area Telescope) that is a pair conversion telescope, like EGRET, but the detectors will be based on solid-state technology, obviating the need for consumables and greatly decreasing instrument dead-time. Aside from the main instrument LAT, a gamma-ray telescope for the energy range between 20 MeV and 300 GeV, a secondary instrument, the GLAST Burst Monitor (GBM), is foreseen. With this monitor one of the key scientific objectives of the mission, the determination of the high-energy behavior of gamma-ray bursts and transients can be ensured. Its task is to increase the detection rate of gamma-ray bursts for the LAT and to extend the energy range to lower energies (from $\sim 10$ keV to $\sim 30$ MeV). It will provide real-time burst locations over a wide FoV with sufficient accuracy to allow re-pointing the GLAST spacecraft. GLAST is planned to be launched early in 2007 from the Kennedy Space Center on board a Delta 2920 vehicle. It will have a 550 km altitude circular orbit, with an inclination of 28.5°.
2.2.1 The scientific driven requirements

The basic instrumental requirements for the GLAST experiment are: a short dead time for transient studies, a good energy resolution over a broad energy band, a large field of view and effective area with excellent angular resolution in order to achieve high sensitivity with great localization power. Below, for each science topic, an estimate of the basic telescope properties that are more relevant to reaching the science goals are listed.

- Blazars and Active Galactic Nuclei (AGN):
  - Broad energy response from 20 MeV to 300 GeV to explore the low energy spectrum where many AGN have peak emission, to measure high energy cutoff and to overlap with ground based telescopes.
  - Energy resolution better than 10% between 100 MeV and 10 GeV to facilitate the study of spectral breaks at both low and high energies.
  - Peak effective area greater than 8000 cm\(^2\) to allow for variability studies of bright sources down in the sub-day timescales.
  - FOV at least 2 sr for significant sky coverage.
  - Flux sensitivity better than \(6 \times 10^{-9} \text{ cm}^{-2}\text{s}^{-1}\) for the 1 year sky survey to measure the AGN logN-logS function.
  - Mission life of at least 5 years.

- Unidentified sources:
  - Source localization power to less than 5 arcmin for sources of strength \(> 10^{-8} \text{ cm}^{-2}\text{s}^{-1}\) and 0.5 arcmin for strong sources \((> 10^{-7} \text{ cm}^{-2}\text{s}^{-1})\) to facilitate counterpart searches at other energies.
  - Broad energy range to extrapolate spectra into the hard x-ray and TeV regimes to facilitate studies at other wavelengths.
  - Peak effective area greater than 8000 cm\(^2\) to allow for variability studies of bright sources down in the sub-day timescales.
  - Short dead time for short term variability studies.
  - Wide \((> 2 \text{ sr})\) FOV to allow high duty cycle monitoring of unidentified sources for time variability.
- Mission life of at least 5 years.

- Gamma-ray diffuse background:
  - Background rejection capability such that the contamination of the observed high latitude diffuse flux (assumed to be $1.5 \times 10^{-5} \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$) is less than 10% for $E > 100 \text{ MeV}$.
  - Broad energy response from 20 MeV to 300 GeV to extend the measurement of the diffuse background to unexplored energy ranges.
  - Broad field of view (more than 2 sr) for sensitive full sky maps.

- Dark matter:
  - Broad energy range with response up to 300 GeV to constrain dark matter candidates.
  - Spectral resolution of 6% above 10 GeV for side-incident events to identify relatively narrow spectral lines.
  - Mission life of at least 5 years, for reaching high statistical significance

- Gamma Ray Bursts (GRBs):
  - Quick (less than 5 s) localization of GRBs.
  - Broad field of view (more than 2 sr) to monitor a substantial fraction of the sky at any time.
  - Energy resolution better than 20% above 1 GeV to allow searching for breaks in the spectra.
  - Less than 100 $\mu$s dead time for identifying correlation between low energy and high energy time structures in the bursts.
  - Single photon angular resolution better than 10 arcmin at high energy for good localization.

- Solar flares:
  - Long mission lifetime (more than 5 years) to provide solar flares observations over a range of solar cycle activity.
  - Broad energy band (20 MeV - 300 GeV) to observe high energy emission.
  - Less than 100 $\mu$s dead time to ensure good time resolution during flares.

- Pulsars:
  - Energy resolution better than 10% in the 100 MeV - 10 GeV energy range, where pulsars breaks occur.
  - Less than 100 $\mu$s dead time for resolving pulsation in the light curve.
  - Large effective area for improving the statistics.
  - Large FOV to allow high duty cycle monitoring of pulsars.

- Interstellar clouds, SNRs, Galactic Center and Cosmic Rays production:
  - Single photon angular resolution better than 3.5° at MeV for normal incidence, improving to better than 0.1° at 1 GeV for mapping extended sources.
– Point source localization better than 1 arcmin for identifying Supernovae remnants.
– Energy resolution better than 10% above 100 MeV for studying the spectral shape in proximity of SNR and of the GC.
– Broad energy band (up to 300 GeV) for correlating the observations with ground-base telescopes, especially in the observation of the high energy emission from SNR and GC.

Moreover, the direct detection of gamma-ray implies that the observatory has to be placed in orbit, in order to avoid the atmospheric absorption. This necessity is strictly linked with the Space Craft requirements in terms of mass, dimensions and power consumption. The following table summarize “mission requirements” set by the Space Craft interaction.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Mission requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass</td>
<td>3000 kg</td>
</tr>
<tr>
<td>Center of gravity</td>
<td>&lt;0.246 m from the LAT/SC interface</td>
</tr>
<tr>
<td>Overall dimensions</td>
<td>Maximum x-y dimension &lt;1.8 m</td>
</tr>
<tr>
<td></td>
<td>Maximum z dimension &lt;3.15 m</td>
</tr>
<tr>
<td>Power consumption</td>
<td>Average power (1 orbit) &lt;650 W</td>
</tr>
<tr>
<td></td>
<td>Peak power &lt;1000 W</td>
</tr>
<tr>
<td></td>
<td>Peak power duration &lt;10 min</td>
</tr>
</tbody>
</table>

### 2.3 The Large Area Telescope

The total photon cross section above 10 eV is shown in figure 2.3, with the contribution of the main processes. Below 1 MeV the photon is absorbed by the atom, ejecting an electron (photoelectric effect). Above ~10 MeV the main interaction process is the pair production mechanism with the conversion of a photon in a electron-positron pair. The cross section remains flat beyond two decades over the energy range shown (from [45]). Pair conversion telescopes use this cross section for converting high energy photons to produce an $e^+ - e^-$ pair. The pair conversion process permits the determination of the incident photon direction via the reconstruction of the trajectories of the resulting $e^+e^-$ pairs. This technique is illustrated in Fig. 2.4 in which the incident radiation first passes through an anticoincidence shield, which is sensitive to charged particles, then through thin layers of high-Z (tungsten) material called conversion foils. The photon converts in these layers producing an electron-positron pair, forming the basis for the underlying measurement principle by providing an unique signature for gamma rays, which distinguish them from charged particles. The trajectories of these charged particles are measured by the tracking detectors and their energies are then measured by a calorimeter. The characteristic signature of a gamma event for GLAST will be:

- No signal from the anticoincidence shield.
- Two tracks in the tracker that starts from the same position within the tracker volume, identifying a “conversion vertex”.
- An electromagnetic shower in the calorimeter.
Figure 2.3: Photon total cross sections as a function of energy in lead: The different contributions are for the following processes (from [45]): $\sigma_{\text{p.e.}}$: Atomic photoelectric effect (electron ejection, photon absorption), $\sigma_{\text{Rayleigh}}$: Rayleigh scattering (the atom is neither ionized nor excited), $\sigma_{\text{Compton}}$: Incoherent Compton scattering (scattering off an electron), $\kappa_{\text{nuc}}$: Pair production in the nuclear field, $\kappa_{\text{e}}$: Pair production in the electron field.
The field of view (FOV) of a such detector, depends essentially on the angular acceptance. GLAST/LAT reaches an opening angle of $\sim 70^\circ$, corresponding to a solid angle greater than 2 sr.

![Diagram of Anti-Coincidence Detector](Figure 2.4: Principle of photon detection in a pair conversion telescope. The instrument is basically made of an anti-coincidence detector (ACD), a tracker/converter module and a calorimeter for the measure of the energy.)

The Large Area Telescope (LAT) comprises an array of 16 identical “tower” modules (see Fig. 2.5), each with a tracker (Si strips), a calorimeter (CsI with PIN diode readout) and a Data Acquisition (DAQ) module. The towers are surrounded by a finely segmented anti-coincidence detector (ACD), made by plastic scintillator with PMT readout, while the support structure is an aluminum strong-back “Grid” with heat pipes for transport of heat to the instrument sides.

### 2.3.1 Anticoincidence Detector

The purpose of the ACD is to detect incident charged cosmic ray particles that outnumber cosmic gamma rays by more than 5 orders of magnitude. In the case of the EGRET telescope, due to the presence of the gas in the spark chamber that suffered deterioration if exposed to high amounts of radiation, and due to the long dead time, the ACD was monolithic and its signal was used in the level 1 trigger. The use of ACD in the first level trigger implied less efficiency, especially at high energy where self-vetoed events were automatically discarded. In the case of backsplash, for instance, the scattered charged particles can cross the ACD, releasing energy (the self-veto reduced the EGRET efficiency by more than 50%).

The Anticoincidence Detector (ACD) of GLAST has a segmented plastic scintillator to minimize self-veto at high energy and to enhance the background rejection: the estimated Montecarlo efficiency is greater then 0.9997. Signals from the ACD can be
Figure 2.5: The LAT instrument components: The ACD is the anti-coincidence detector, for the background rejection. CAL is the calorimeter which provides measurements on the energy. The Tracker is the complex tracker system based in Si Strips Detectors. The Grid has the structural function of hinging the towers. The DAQ electronic is mounted below. The thermal blanket covers the full instrument providing heat insulation.

used as a veto trigger or can be used later in the data analysis [46]. One advantage of the LAT detector is the short dead time and the consequent high trigger rate. This allows the ACD trigger signal to be processed in Level 2. At this stage all the information coming from all the detector in the tower can be used for saving self-veto events. Typically, the reconstructed track in the tracker is extrapolated back to the ACD, if there is no signal in the closest ACD tile the event is not discarded.

2.3.2 The Tracker

The tracker is, by far, the most challenging detector onboard the GLAST satellite.

Silicon Strip Detectors

The advent of the 6” wafers technology, dating to few years ago, has allowed to reduce the number of Silicon Strip Detectors (SSDs) to be procured by one half (if compared with the “traditional” 4” technology), with considerable cost and time savings in the tracker assembly. This choice has also limited the list of potential manufacturer to few companies with whom an intense prototyping program has started; simplicity and robustness of design, high quality, predictability and uniformity of performance, ease of testing have been the leading criteria of this activity.

GLAST tracker sensors are obtained from high resistivity (> 5kΩ/cm) wafers; they are single sided, AC coupled, and passivated with glass; 384 p+ strips (56 μm wide) are implanted on a 400 μm thick n-type substrate and biased through poly-silicon resistors, for a total active area of 87.5 mm × 87.5 mm. For each strips there are two AC pads for wire bonding (on the Al decoupling electrode) and one DC pad (contacting the implant) for testing purposes. The choice of the substrate thickness results from the optimization
Figure 2.6: The LAT ACD detector. Principal dimensions are shown in the figure together with the position of the Grid.

of different and somehow conflicting requirements, such as good signal to noise and vertexing capabilities, low multiple scattering, low bias voltage. A 228 µm strip pitch (it used to be 201 µm in the previous design, successfully tested in two engineering models) has been chosen as the ideal compromise between tracking resolution, reduction of the necessary electronics read out channels, power consumption and reliability.

Trays

A tray is the mechanical module which supports the silicon sensors and the conversion foils, and, once staked with other trays, builds a tower structure. The structure of the tray is complex and, for ensuring the perfect alinement of the tower, tight requirements on the dimension of each components are necessary.

Each tray, as depicted in figure 2.7, is made by a honeycomb core (Hex cel), covered on each faces with carbon fiber sheets. Depending on the tray’s position in the stack (see below), tungsten foils of different thickness are glued on the bottom face of the tray. A kapton bias circuit is then glued on the surface of the trays and finally, on both sides the silicon strip detectors are glued on the kapton foil. The SSD are bonded together in strip of 4 tiles, building a ladder. Thus, four ladders together build the silicon surface of the tray. The strips of the silicon detectors run parallel in both the surfaces of the tray.

Towers

Each of the 16 Tracker tower modules consists of a stack of 19 tray structures. The first 12 trays ("medium trays") count 0.025 radiation length of converter material, the
Figure 2.7: An “exploded” view of a tray. The internal structure of a tray is made by an honeycomb core, covered by a carbon fiber face sheet. On the bottom face of the tray tungsten foil are glued. Silicon strip detectors are glued, through the Kapton bias circuit, on the tray. The SSD, previously bonded forming ladders, are than bounded to the electronics, located at two sides of the detector.

following 4 trays (“heavy trays”) are equipped with 0.25 radiation length of tungsten, for maximizing the conversion efficiency, while the last two trays have no tungsten on them (“light trays”). Since the silicon detector wafers cover both sides of a tray with the strips on each side running in the same direction, when a tray is staked into a tower it is rotated by 90° with respect to the adjacent trays. In this way each W foil is followed immediately by an x, y plane of detectors with a 2mm gap between x and y layers\(^1\). The detectors are located close to the conversion foils to minimize multiple-scattering errors. The bottom tray is mounted on the support grid, and for this reason it has an extra flange which require a slightly different production chain.

The electronics preamplifier hybrids are glued vertically to the tray sides to minimize the gap between towers, and the strips are connected to them thanks a 90° bond. Each silicon plane on a tray has a 37 cm×37 cm active cross section, giving a total silicon area of 83 m² (comparable with the ATLAS detector planned for the CERN LHC project). In all there are 11500 silicon strip detectors and a total of 1 million channels (the strip pitch is 200µm).

This technique has been successfully applied in particle physics experiment in accelerators, and perfectly matches the requirements for a gamma-ray telescope. In particular provides with:

- High detection efficiency (99%),
- High spatial resolution (60µm RMS),
- Low electronic noise: the measured occupancy noise per strip is less than 10\(^{-6}\),
- Negligible cross-talk,
- Ease trigger and read-out.

\(^1\)Accordingly with the GLAST nomenclature, a (logical) plane is made by two x, y layers, while the (physical) tray is done by two x or two y layers.
2.3.3 The Calorimeter

The calorimeter is made of 96 CsI crystals (thallium doped) per tower arranged into a hodoscopic imaging configuration and with PIN diode read-out on each end. The electronics chain for each PIN diode is composed of a preamplifier which feeds two shaping amplifiers. Discriminators divide the energy domain into four energy ranges, two peak-detecting track and holds. A third faster shaping amplifier, peaking at 0.5\(\mu\)s is used for fast trigger discrimination. The main features of the calorimeter detector are the large dynamic range \((5 \times 10^9)\), low nonlinearity (less than 2%), low power consumption, and minimal dead time (less than 20\(\mu\)s per event).

Figure 2.8: The Calorimeter tower module of the LAT detector.

2.4 The LAT trigger

The LAT trigger is a 3-level system. Primary requirements are high efficiency for all measurable gamma rays, and background reduction to fit with telemetry capacity. Two separate conditions may initiate a hardware trigger for a given tower (LT1). The first request is for the tracker to have three planes hit in a row. The second involves the calorimeter, considering the number of hits in the module. Tower triggers are OR’d in the central Tower Electronic Module (TEM) and fanned out to each tower. At this level the expected average trigger rate is expected to be of the order of few kHz, to be compared with the few Hz representing the average \(\gamma\) trigger rate. Upon a LT1 all the towers are read out within 20 \(\mu\)s and the full instrument information is available to the onboard filter, which is basically responsible for reducing the data volume and fit it into the telemetry constraints. The ACD information is optionally used to reduce LT1 rate ("controlled mode"). The second trigger level (LT2) is a tower-based trigger, in parallel for all towers. It uses a fast track finding algorithm and extrapolates track candidates to the ACD tiles to search for vetoes. The veto is not applied to events with large energy deposition in CAL. As the final step a "full" onboard event reconstruction (including the extrapolation to the ACD tiles) is performed; the L3T rate is expected to be of the order of 25-30 Hz. Albedo photon events are removed by comparing the reconstructed photon direction with the Earth’s horizon. The cosmic ray event rate is reduced to less than 15 Hz.

The main features of the three levels trigger are summarized in Table 2.9.
The main advantages of the LAT detector will be the wide field of view (2sr) and the extremely short dead time per event (<100μs). These performances, together with the excellent background rejection (better than $2.5 \times 10^5 : 1$), will allow GLAST to detect both faint sources and transient signals in the gamma-ray sky. The capabilities of the GLAST LAT detector compared to those of EGRET are summarized in table 2.1. Several performances of the LAT detector, such as the angular and energy resolution, the field of view and the effective area are plotted in figure 2.10, compared to those of EGRET.

<table>
<thead>
<tr>
<th>Quantity</th>
<th>EGRET</th>
<th>LAT (Minimum Spec.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy Range</td>
<td>20 MeV-30 GeV</td>
<td>20 MeV-300 GeV</td>
</tr>
<tr>
<td>Peak Area</td>
<td>1500 cm$^2$</td>
<td>8000 cm$^2$</td>
</tr>
<tr>
<td>Field of View</td>
<td>0.5 sr</td>
<td>&gt; 2sr</td>
</tr>
<tr>
<td>Angular Resolution</td>
<td>5.8°</td>
<td>&lt; 3.5° (100 MeV)</td>
</tr>
<tr>
<td>Energy resolution</td>
<td>10%</td>
<td>&lt; 10%</td>
</tr>
<tr>
<td>Deadtime per event</td>
<td>100 ms</td>
<td>&lt; 100μs</td>
</tr>
<tr>
<td>Source Location Det.</td>
<td>15°</td>
<td>&lt; 0.5°</td>
</tr>
<tr>
<td>Point Source Sensitivity</td>
<td>$1 \times 10^{-7}$ cm$^{-2}$s$^{-1}$</td>
<td>$&lt; 6 \times 10^{-9}$ cm$^{-2}$s$^{-1}$</td>
</tr>
</tbody>
</table>

Table 2.1: GLAST LAT specification and performance compared with EGRET
Figure 2.10: LAT detector performance compared with EGRET for a point source observation.
2.5 The GLAST Burst Monitor

The GBM instrument has been designed for helping the LAT in the discovery of GRBs. GBM consists of 12 thin NaI(Tl)-plates, which are sensitive in the energy range between $\sim 10$ keV and $\sim 1$ MeV. Two additional BGO detectors, which are able to detect gamma-rays in the energy range between 150 keV and 30 MeV, are responsible for the overlap in energy with the LAT main instrument.

The 12 NaI(Tl) and 2 BGO scintillation detectors are mounted on the spacecraft as shown in Fig. 2.2. The normals to the crystal discs of the 12 NaI(Tl) detectors are oriented in the following manner: six crystals in the equatorial plane (hexagonal), four crystals at 45° (on a square) and two crystals at 20° (on opposite sides). This arrangement results in a large field of view for the GBM of > 8 sr and provides the opportunity for locating the origin of the burst by comparing the count rates of different NaI's (same method as used by BATSE). The two BGO detectors will be mounted on opposite sides of the spacecraft, providing nearly a $4\pi$ sr field of view.

![GBM Burst Monitor](image)

Figure 2.11: Side view and cross-section of one of the 12 NaI(Tl)-detector modules.

Fig. 2.11 presents the design of the NaI(Tl) detector unit. These detectors consist of circular crystal disks made from NaI(Tl) having a diameter of 127 mm (5 inch) and a thickness of 12.7 mm (0.5 inch). For light tightness and for scaling the crystals against atmospheric moisture (NaI(Tl) is very hygroscopic) each crystal is packed light-tight and in a hermetically sealed Al-housing (with the exception of the glass window to which the Photomultiplier Tube (PMT) is attached). In order to allow the measurement of X-rays down to 5 keV, the radiation entrance window is made of a 0.2 mm thick Beryllium sheet. Opposite to the Be sheet a circular glass plate covers and seals the crystals. The inner sides of the packing material have a reflective white cover in order to increase the light output of the crystals.

The two bismuth germanate (BGO) scintillators, are cylindrical in shape, with a diameter of 127 mm (5 inch) and a length of 127 mm (5 inch). The BGO cover shown in Fig. 2.5 is made of CFRP (Carbon Fibre Reinforced Plastic) with interface parts made of titanium. The expected response of the NaI(Tl)- and BGO-detectors, expressed in effective area and energy resolution, is summarized in Fig. 2.13.

2.5.1 GBM burst trigger

The trigger scheme for the GBM will be similar to that used with CGRO/BATSE. The trigger requirement will be an excess in count rate above a threshold, specified in standard deviations above background, simultaneously for two of the NaI(Tl)-detector modules. The standard setting of the GBM threshold will be $4.5\sigma$ above background
Figure 2.12: Side-view of the BGO detector unit. A bismuth germanate (BGO) scintillator-crystal, cylindrical in shape with a diameter of 127 mm (5 inch) and a length of 127 mm (5 inch), is viewed from both ends by a 5 inch PMT.

Figure 2.13: Effective area of a NaI(Tl)- and BGO-detector in dependence on the photon energy, with Θ as angle of incidence. The double arrow shows the energy range of the NaI(Tl) (left graph) and BGO (middle graph) detectors. The right graph shows the energy resolution of the NaI(Tl)- and BGO-detectors in dependence on the photon energy.

(energy interval: 50 keV to 300 keV, time interval for sensitivity calculations: 1.024 s). The requirement on the absolute on-board trigger sensitivity is < 1.0 photons cm⁻²s⁻¹, with < 0.75 photons cm⁻²s⁻¹ as a goal (BATSE at 5.5σ threshold: ~ 0.2 photons cm⁻²s⁻¹). It is also planned to search on ground for fainter bursts using more sophisticated algorithms. One method is the summing of rates of closely pointing detectors and the inclusion of the BGO detector count rates. The current estimated sensitivity on ground is ~ 0.35 photons cm⁻²s⁻¹ (5 σ excess).

Based on the log N – log P burst intensity distribution determined by BATSE [47] and considering the actual detector geometry, including the blockage by the LAT and spacecraft, the GBM will trigger on about 150-200 bursts per year. The estimated background level is based on BATSE rates and includes the effects of the variations due to altitude, latitude and longitude, and accounts for dead time due to transits through the South-Atlantic Anomaly (SAA). The simulation does not include the increased trigger rate one can expect by having additional triggering schemes that BATSE did not have, particularly the capability to trigger at lower energies.

2.5.2 GBM burst localization

The GBM determines locations of γ-ray burst by comparing count rates of NaI(Tl)-detectors, which are facing the sky in different directions. It is planned to increase the location accuracy in three stages: on board, automatic on ground and on ground
manually. The burst location will be calculated on board in real time, yielding an accuracy of about $< 15^\circ$ (1 $\sigma$ radius) within 1.8 s, which can be used as LAT trigger. If the burst occurred in the LAT field of view, data-reduction modes (reducing the LAT background by isolating the area of the GBM burst direction in the LAT dataspace) can be initiated in the LAT, which will increase the LAT sensitivity for weak bursts. If the burst occurred outside the LAT field of view (FoV), a rough localization within $\sim 20^\circ$ is enough to ensure the coverage after the LAT repointing (in few minutes). In this way the delayed high-energy $\gamma$-ray emission can be observed, (as in the case of GRB940217). This is possible because the GBM FoV with $> 8$ sr is significantly larger than the LAT FoV with approximately 3 sr.

After the transmission of the detector count rates to ground, the burst location can be computed with improved accuracy of better than $5^\circ$ within 5 s. This will happen in near-real time (several seconds). This information can be used for the search of afterglow emission at other wavelengths, as input for the Gamma-ray burst Coordinates Network (GCN) and as input for the Interplanetary Network (IPN).

The ground manual algorithms, which means a detailed analysis of the data with human interaction, will yield an improved burst location $< 3^\circ$ after one day.

### 2.5.3 GBM burst spectra and light curves

The burst monitor will provide time-resolved spectra and energy-resolved lightcurves in the energy range between 10 keV and 30 MeV, overlapping with the LAT lowest energy range (low-energy threshold at $\sim 20$ MeV). In order to fulfill the scientific goals the burst monitor will have four main data types. Two continuous data types are designed for burst analysis, for extremely long-lasting bursts, search for non-triggered events and for the detection of bright sources via the Earth-occultation technique. The first continuous data type accumulates 128 energy channels with 8.2 s time resolution for each detector and the second continuous data type 8 energy channels every 0.256 s. In response to a burst trigger, the GBM will produce a third datatype with high temporal resolution (2 $\mu$s) and 128 channel spectral resolution. The fourth data type provides information on the burst location and spectral estimates determined on board.
Chapter 3

GLAST LAT Full Simulation

During the development of the instrument, a parallel activity is also taking place: the software development. Two different types of software have been developed by the LAT team, one for the detailed simulation of the instrument, finalized to its comprehension and to drive, whenever it is possible, the technical decision. The other is the scientific software, which comprehends all the series of algorithms mainly devoted to the analysis of the scientific data. In this thesis I will describe both types of software, and I will focus the attention on the software which I have personally developed. This chapter is mainly an introduction to the LAT simulation framework, which consists, basically, in a detail simulation of the instruments, allowing to study the response of the instrument to simulated astrophysical sources. A consistent part of the work made during the thesis has been done on this topic, it will be described in Chapter 6,7, and 8. Chapter 9 is dedicated to the discussion of the scientific software.

The LAT simulation package, written in C++, is based on the Geant4 [48] Monte-carlo toolkit, and it is integrated into a general framework used to process events. The simulation starts from the incoming particle generators. The sources can be both particle beams, mainly used for testing the Montecarlo propagator, or particles extracted from the cosmic rays distribution on Earth surface (very useful for comparing the data taken in the laboratory using CR), or even astrophysical sources, which are useful for study the investigation capability of GLAST once in orbit. The particles are then propagated into the detector and a full Montecarlo simulation is performed. A detailed simulation of the electronic signals inside silicon detectors has been provided, in order to reconstruct the digitized signal (strip ID and Time Over Treshold). The simulated data are at this point identical to the real “raw data” coming from the detector hardware. A unique repository for the geometrical description of the detector has been realized using the XML language and a C++ library to access this information has been designed and implemented.

3.1 Data flow, storage and partnership between the packages

GLAST is a complex system, and detailed computer simulations are required to design the instrument, to construct the response function and to predict the background in orbit. To accomplish these tasks an object-oriented C++ application called Gleam (GLAST LAT Event Analysis Machine) was developed and implemented by the GLAST LAT collaboration. The GLAST off-line software is based mainly on Gaudi, a C++
framework, originally developed at CERN\(^1\). In the GLAST framework, Gaudi manages the loop of particles to be simulated, then a series of algorithms are applied such as the digitization the reconstruction and the filtering of data, for the final Level 1 data production.

![Diagram of GLAST simulation and reconstruction](image)

**Figure 3.1:** General scheme for simulation and reconstruction within the GLAST off-line software framework.

The structure of the GLAST off-line software is graphically described in figure 3.1. The first step of the simulation is represented by the *Flux* generation, a set of classes which describe a generic source of particles/photons. The flux package, described in detail later in this chapter, allows the computation of the position and of the inclination of the satellite. The main brick of the LAT full simulation is the Montecarlo propagation tool. The LAT team has inherited its set of classes from the standard *Geant4* toolkit. The Gaudi interface to *Geant4* manages the Geant4 event loop, so that the particles produced by the *Flux* package are processed by the Geant4 propagator. The geometry of the detector has been completely described via *xml* files, particularly indicated for modular geometries. The choice is to use a single geometry file for both propagation, digitization and reconstruction. The charge released in active volumes are processed by a digitization algorithm, that computes the digital information of the volume hit. These information are clones of the real "raw" data. From this point up to the final product represented by Level 1 data, there are no more differences between real data and simulated data. The next step is done by the reconstruction algorithms, which reconstruct the tracks of the charged particles, trying to find the intersection of the electron-positron produced in the pair production. The vertex is then used to find the incoming direction of the gamma. Tracker reconstruction and calorimeter reconstruction

\(^1\)http://proj-gaudi.web.cern.ch/
work together in the attempt to reconstruct the energy of the incoming particle. The information coming from the tracker, the calorimeter and the anticoincidence system are used for rejecting charged particles.

The data flow of the information in the GLAST software is represented schematically in figure 3.2. All the main packages interact with a data structure called “Transient Data Store” or just TDS. The TDS is a temporally storage of objects, which contains the data structure of the GLAST event. The TDS allows that all data structure are well defined and the implementation of algorithms that manage the data will not affect the whale simulation chain. Every algorithm retrieves (or fill) a defined data structure contained in the TDS, so that its act cannot affect the behaves of other algorithms. The TDS is then refreshed every Montecarlo events, and no more than a single event is stored. In the figure both the flows of the simulated data (anti-clockwise) and of the real data (from “Level 0” to “Level 1”) are represented. The dashed arrows correspond to the flow of the logical information, the solid arrows are instead the real dataflow, where all the interactions with the TDS are enhanced.

Figure 3.2: Scheme for simulation and reconstruction within the GLAST off-line software framework. The relationship between the different packages and the Transient Data Store (TDS) are underlined with solid lines. Dashed lines are the logical sequence of the different operations. Dotted and dashed-dotted lines are the flaw of the mission data, from Level 0 to Level 1 data.

3.2 The Source Generation package

The Source Generation is the first algorithm called within the particle loop. It takes care of the orbital position of the instrument, and provide the correct illumination of the detector. The orbit is saved in a text file, which contain the position of the satellite and its inclination every given amount of time (usually 30 seconds). The Algorithm retrieves the information about the position of the satellite and keeps track of the elapsed time. It creates the source spectrum to be used to feed the Montecarlo simulation. The relative
position of the satellite with respect to the Earth or to a galactic coordinate frame is in this way computed and the correct illumination of the satellite with the particles generated from the source is correctly computed.

The main object containing the description of a “Spectrum” class, which is the class that describe a generic source is schematically represented in the figure 3.3.

![Diagram](image)

Figure 3.3: Layout of the Spectrum interface for the development of generic sources.

The basic concept is that the “external word”, represented in particular by the Montecarlo simulation, asks to the spectrum object for processing a photon (or, in general, a particle). The spectrum object has to return an energy and a time interval to wait before the next iteration. Given the nature of the spectrum source (point like, diffuse, beam, test particle, uniform,...) and its position with respect to GLAST, the correct incoming direction is computed and passed to the Montecarlo propagator. Eventually the rate and the flux can be computed by the Spectrum object class. By default, for a point like static source with rate $R$ the interval is computed from the Poisson distribution, as:

$$\Delta t = -\log(1 - \zeta)/R;$$  \hspace{1cm} (3.1)

where $\zeta$ is a random number extracted from a uniform distribution between 0 and 1. Any further implementation of this spectrum class has to take care of the redefinition of the “Interval” and of the “energy” method. The simulator of Gamma Ray Burst developed during this thesis fully implements the case of a rapid transient source, where the eq.3.1 no longer holds. The GRB simulator description and the extractor method are described in Chapter 6,7, and 8. Many different sources are available in the LAT simulator. Many of those sources are commonly described with a simple power law where the normalization and the power index are the parameters. Other sources are monochromatic, beam-like sources are also considered. Extended sources are also allowed as the diffuse galactic and extragalactic simulated gamma-ray emission. The parameters are defined in an xml file which is parsed passing the parameters to the simulator. More then one
source can certainly be created and a particular class of source, namely a “composite” source manages the contributions from different sources. Basically, at each source computes the time interval to wait for the next photon, and the source with the shortest interval is selected. All the time intervals computed by the other sources are rescaled at the new iteration time. With this simple way to concatenate different sources a detailed description of the sky has been possible.

3.3 The Simulation package

The algorithm which is responsible for generating the interactions of particles with the detector is based on the Geant4 Montecarlo toolkit [48] which is an Object Oriented (OO) simulator of the passage of particles through matter. Its application areas include high energy physics and nuclear experiments, medical science, accelerator and space physics.

Geant4 (G4) provides a complete set of tools for all the domains of detector simulation: Geometry, Tracking, Detector Response, Run, Event and Track management, Visualisation and User Interface. A large set of Physics Processes handle the diverse interactions of particles with matter across a wide energy range, as required by G4 multi-disciplinary nature; for many physics processes a choice of different models is available. In addition a large set of utilities, including a powerful set of random number generators, physics units and constants, a management of particles compliant with the Particle Data Group, as well as interfaces to event generators and to object persistency solutions, complete the toolkit. G4 exploits advanced Software Engineering techniques and OO technology to achieve the transparency of the physics implementation and hence provide the possibility of validating the physics results. The OO design allows the user to understand, customise or extend the toolkit in all the domains. At the same time, the modular architecture of G4 allows the user to load and use only the components needed. To build a specific application the user-physicist chooses among these options and implements code in user action classes supplied by the toolkit2.

Within the Gleam framework the simulation is managed by the Gaudi algorithm G4Generator 3. The main simulation is controlled by a customized version of the G4 standard RunManager. Since the GLAST main event loop is driven by Gaudi and it will not use any graphics or data persistency features of Geant4, we have included in the RunManager only the real necessary parts for setup and run the generator. RunManager itself uses the following classes:

- DetectorConstruction: this class provides the list of materials and the geometry of the detector. In our case this information is stored in XML files; to access them the DetectorConstruction class uses methods of a Gaudi service. The Geometry class implements methods to traverse the geometry of GLAST and build a concrete Geant4 representation of it; the Material class does the same for the materials definitions.

- PhysicsList: this class is the access point to the physics processes selection and customization. It uses other classes (GeneralPhysics, EMPhysics, HadronPhysics, MuonPhysics, IonPhysics) to set up particular physics processes. Since the Geant4 toolkit is open to new physics processes (along with new description of already

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2http://cern.ch/geant4
3http://www-glast.stanford.edu/cgi-bin/viewevs/G4Generator/
present processes), this will be the access point for further development in the physics selection.

- **PrimaryGeneratorAction**: this class is in charge of production and injection of primary particles in the detector simulation. In our cases it is linked to the Gaudi algorithm that is responsible to generate the incoming fluxes of particles.

- **DetectorManager**: this class manages the setup and working of the sensitive detectors of the simulation and their interaction with the GAUDI Data Store. It is concretely implemented in the two subclasses PosDetectorManager and IntDetectorManager; the first one is associated with detector that saves hits information in the Si planes of the LAT tracker (TRK), while the second one is used for Anti-coincidence (ACD) tiles and Calorimeter (CAL) cells.

Figure 3.4 shows an event generated using Geant4 within the GLAST LAT experiment.

A validation procedure of the electromagnetic and the hadronic physical processes relevant to GLAST is being designed. Such procedure could help in validating the data produced with the full chain of simulation, digitization, reconstruction and analysis.

### 3.4 The Digitization package

The main goal of the digitization package is to compute the identifiers of active volumes assigning an digital id conforming to the physical hardware address. In such a way the digital information of the simulation is of the same type as the real “raw data”. In the case of the tracker, not only the list of the hit strip is returned, but also the Time Over Threshold of the signal in each single strip. This information, not available in the case of the real hardware, is used for computing the ToT of the read out controller (there are two read out controller for each tray, each one reads half of the strip on the tray,

![Figure 3.4: High energy gamma-ray interacting with the GLAST LAT detector](image)
returning the or-ed ToT of all the strips). There are two algorithms for digitizing the signal. The simpler and faster one is schematically represented in Fig. 3.5. It divides the charge released (MC Hit) in the Si plane between adjacent strips, in agreement with the path of the track. The resulting ToT is linear with the value of the threshold.

![Diagram of Si Strips and MC Hit](image)

Figure 3.5: *Sharing of deposited charge in the simple digitization algorithm. The G4 active volume is segmented in strips, and the deposited charge is shared in agreement with the track orientation.*

A more detailed algorithm is also available. To implement a detailed digitization of the Tracker system a full simulation code has been developed. It takes into account all the main physical processes that take place in a silicon strip detector (SSD) when it is crossed by an ionizing particle [49]. The first version of the code has been written in FORTRAN and uses the HEED package for simulating the energy loss of charged particles in silicon. The present version of the code has been written in C++ and the process of energy loss is simulated by Geant4. The input parameters of the code are the entry and exit points of the particle in a silicon ladder and the energy deposited by the particle, provided by the simulation package. Starting from these parameters, the e-h pairs are generated along the track and are propagated towards the electrodes. The current signals induced on each strip are evaluated and are converted into voltage signals using the transfer function associated to the detector electronics, taking into account the detector noise as well as the noise associated to the electronics. The fired strips and the time over threshold (TOT) are then determined after imposing a threshold on the voltage signals. Figure 3.6 shows some results of this package, concerning the signal generated in a silicon ladder equipped with the GLAST LAT electronics.

The TOT gives information about the collected charge. The simulation of the GLAST Tracker front-end chip [49] shows that the TOT is linear with the input charge up to 50-60 fC.

Laboratory tests on the front-end tracker chip confirmed the results of our simulation, in good agreement with the PSPICE results (see figure 3.7).

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4http://www.pspice.com
Figure 3.6: Charge sharing for a 5 GeV electron, crossing the silicon wafer at large zenith angle (60°). The superimposed green line represents the readout threshold voltage.

Figure 3.7: Comparison of the time over threshold measured by the GLAST front-end electronics simulated with the Digitization package and with PSPICE.
3.5 The Reconstruction package

This package contains the code that reconstructs tracks from hit strips in the LAT tracker. It’s organized as a series of algorithms that act successively. Figure 3.8 shows the sequence of algorithms that operate to reconstruct the tracks.

- **TkclusterAlg** is the first step of the tracker reconstruction. It retrieves from the TDS the *Tkrdigit* collection, and search for adjacent strips for making clusters. It takes into account the eventuality of having dead strips or masked channels. While the strips have only a coordinate (x or y depending on the plane they belong to, the clusters are the intersection of x and y strips thus they have both x and y coordinates). The clustering algorithm fills the TDS with the collection of clusters (*TkClusterCol*).

- **TkFindingAlg** is a collection of algorithms that operate for finding the track candidates, connecting clusters belonging to different planes. These find “all” possible track candidates, taking as input the list of clusters and outputting *TkPatCand* objects (collected in the TDS object *TkCandidateCol*). More than one algorithm can be use for finding tracks, such as the Combinatorial Pattern recognition, which uses the centroid of the energy deposited in the calorimeter for finding the track candidate, the Link and Tree strategy, that build “trees” starting from each cluster and sorting them by means of their longness, and straightness. Finally the Neural Net algorithm uses a neural network for finding tracks.

- **TktrackfitAlg** The collection of pattern candidates is used for finding track applying the Kalman Filter fitter algorithm. This operation consists in the smoothing

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<sup>5</sup>http://www-glast.stanford.edu/cgi-bin/viewcvs/TkrRecon/
Figure 3.9: Different phases during the reconstruction of the same event (1 GeV gamma). 1) Digitization: The Montecarlo energy deposition is converted into digital signal. 2) Clusterization: subsequent hit strips are merged together forming clusters (crosses). 3) Path finding: the clusters are connected to find possible track candidates. 4) Track fitting: a Kalman filter is used for fitting tracks. Vertex finding: once that the tracks of electron and the positron have been reconstructed, the vertex is found and the incident gamma's direction is computed.

the pattern candidates found by the previous algorithms, by means of a fit operation. TkrTrackFitAlg retrieves tracks candidate from the TDS outputting fitted tracks.

- TkrVerte.xAlg The final step of the tracker reconstruction is the determination of the vertex position between the primary electron-positron pair. From the vertex the incident gamma direction is obtained.

Figure 3.9 shows a photon track reconstructed in the GLAST LAT. A slightly different approach is used to study the onboard reconstruction: the goal of this software is to quickly provide the reconstructed direction of the incoming photons and particles in order to provide the information needed to reject charged particles. Nevertheless the onboard direction information could be use for quickly determining the position of transient signal, such as Gamma Ray Bursts, in order to provide in few seconds the localization of the sources.

3.6 Background Rejection and classification tree

After the reconstruction of tracks the chain apply classification algorithms, with the goal to reject the charged particles. The selection is done on the basis of a classification tree, which is a visual statistical tool for separating data with similar characteristics, and for helping in the defining selection cuts. The idea is to tag each event with a series of probabilities, depending on their position in the classification tree.
Figure 3.10: VRML view of the xml file containing the detailed geometry of one tower (Trucker and Calorimeter).

- $IMgoodCalProb$ gives the probability of an event to have a good reconstructed energy.
- $IMvertexProb$ gives the probability that the reconstruction of the vertex gives a good estimation of the direction of the incoming particle.
- $IMcoreProb$ gives the probability that the event is in the “core” of the PSF. Which means that the event as an estimated error in the direction comparable with the PSF.
- $IMpsfErrPred$ is the estimation of the PSF for the event.
- $IMgammaProb$ is the probability of an event to be a gamma.

The background rejection and the selection of events is basically done by means of these variables. The effect of the cuts will be presented in Chapter 4 and it will be take into account in the determination of the Instrument Response Functions of the LAT detector.

### 3.7 The geometry database

The geometrical information of the detector and its materials are stored in an unique repository written using the XML language. A series of classes have been implemented to retrieve the geometry hierarchy from these files and represent it in memory; through the use of abstract classes and design patterns, it has been possible to design various visitors of the geometry hierarchy to accomplish different tasks like several graphical outputs, the Montecarlo geometry construction and reconstruction-digitization tasks. Figure 3.10 is an example of a vrml visitor of the geometry hierarchy, this is a graphical inspection with three dimensional capabilities, of the xml file which is shared between Montecarlo, digitization, and reconstruction.

### 3.8 Event Display and GUI

Although it is not part of the simulation, the visualization package is essential for the use of the simulation itself. A new version [50] of the event display based on the HepRep [51, 52] protocol has been developed and will be integrated in the offline software as soon as possible; such a framework will allow both local event browsers directly from the
Figure 3.11: GLAST LAT event display based on FRED

The GAUDI framework, serialization of the event with the use of XML and a CORBA server-client mode for remote analysis of events, with an high degree of interactivity (click and inspect) and the possibility to customize the graphical appearance of the Event. Since the HepRep protocol is completely open and transparent, it will be possible to use different graphical clients (for now WIRED [53] and FRED). The figure 3.11 shows a recent FRED-based event display of GLAST.
Chapter 4

LAT Instrument Response Functions

The instrument response functions (IRFs) describe the performance of the instrument in terms of transformation probability from a true physical quantity (i.e. energy and direction of photons) to the corresponding measured quantity. It is probably useful to underline that the IRFs depend not only on the instrument itself, but also on the reconstruction algorithms, on the background rejection algorithm, and on any eventual selection of the events. The observed count rate is basically the convolution between the real flux and the IRFs, thus, in order to calibrate the instrument the raw data has to be de-convoluted with the IRFs. In this chapter I will present the formalism of the Instrument Response Functions and the description of the LAT detector in terms of its IRFs.

4.1 Theory on the IRF

The IRF are matrices that describe the performances of the detector such as the detection efficiency (effective area $A_{eff}$), the angular resolution (Point Spread Function $PSF$), and the energy reconstruction (energy dispersion $\Delta E$). Let’s assume that $F(E, \Omega)$ is the differential incident flux (in units of number of photons per unit of area per unit of energy per unit of time), with $E$ and $\Omega$ are the “true” energy and direction, respectively. The most generalized version of the IRF can be introduced starting from the following equation, once that the instrumental set up has been fixed:

$$\frac{dN}{dt}(E', \Omega') = R(E', \Omega'|E, \Omega)F(E, \Omega)$$  \hspace{1cm} (4.1)

Here I have indicated $E'$ and $\Omega'$ the observed quantities. Eq. 4.1 computes the differential number of observed photons (in observable quaitities) coming from the source of flux $F(E, \Omega)$. $R(E', \Omega'|E, \Omega)$ is the Instrument Response Function of the detector. $R$ can also be interpreted as the probability to measure $E'$ and $\Omega'$ when the true energy is $E$ and the true direction is $\Omega$. To be notice that I have not included the temporal dependence of $R$ since this factor is important typically for degenerating detector such as gas chambers or detector with an high dead time after one event. Without loosing of generality, $R$ can be expressed in terms of an effective area $R_A(E, \Omega)$, and the probability $P$ to measure a photon with an energy $E'$ and direction $\Omega'$, given a photon with energy $E$ and $\Omega$:

$$R(E', \Omega'|E, \Omega) = R_A(E, \Omega)P(E', \Omega'|E, \Omega)$$  \hspace{1cm} (4.2)
Eq. 4.2 can be manipulated using the probability composition equation:

$$P(ab) = P(a|b)P(b)$$ (4.3)

The probability to have $ab$ is given by the probability of having $a$, once $b$ is given, multiplied by the probability of having $b$.

$$R(E', \Omega'|E, \Omega) = R_A(E, \Omega)P(E'|\Omega', E, \Omega)P(\Omega'|E, \Omega)$$ (4.4)

This equation contains three terms in their most general cases:

- $A_{eff}(E, \Omega) = R_A(E, \Omega)$ is the Effective Area, as a function of the “true” observables and of the detector set-up.
- $PSF(\Omega'|E, \Omega) = P(\Omega'|E, \Omega)$ is the general form for the Point Spread Function,
- $\Delta E(E'|E, \Omega) = P(E'|\Omega', E, \Omega) = P(E'|E, \Omega)$ is the Energy Dispersion, where I have assumed in the latter equation that $E'$ (the observed energy), does not depend on the observed direction since the dependence the “true” direction $\Omega$ is in the list of the “given” variables.

Note that the effective area can be expressed in terms of different contributions: $A_{eff} = A_{geo}P_{conv}\epsilon_{det}\epsilon_{cuts}$, where $A_{geo}$ and $P_{conv}$ are the geometrical area of the detector and the conversion probability, which is depending on the pair production cross section. The terms $\epsilon_{det}$ and $\epsilon_{cuts}$ represent the detection efficiency and the efficiency of the particle selection, for reconstruction and background rejection and, eventually, any other selection of events. For example, for the LAT detector one may choose to study separately the response of the instrument selecting only those events which have converted in the upper part of the tracker, where the trays are covered by thin tungsten foil or those which have converted in the lower part of the tracker where heavy trays are staked. Using the IRFs the detector response can be computed: putting everything together we find:

$$\frac{dN}{dt}(E', \Omega') = \int_E \int_{\Omega} \int_{\Omega_{gal}} A_{eff}(E, \Omega)PSF(\Omega'|E, \Omega)\Delta E(E'|E, \Omega)$$ (4.5)

$$R(\Omega|\Omega_{gal}, t)F(E, \Omega_{gal})dEd\Omega d\Omega_{gal}$$

here, $R(\Omega|\Omega_{gal}, t)$ is the rotation matrix from galactic coordinate system to spacecraft reference frame. The $A_{eff}$, $PSF$, and $\Delta E$, depends only on given “true” variables $E$, $\Omega$. From the computation point of view, this is the ideal situation. A scanning of the parameter space $E, \Omega$ gives as result the value for the matrices element. The response has been computed using the full Monte Carlo simulator of the LAT, using the SLAC farm for generating and storing a big amount of data. The idea is to generate photons isotropically distributed and with a uniform distribution in logarithm of energy, between 30 MeV and 300 GeV. They are then separated into different incident angle and energy bins. In this way is relatively simple to optimize the binning without re-generating the dataset. The data stored (a ROOT $TTree$ object) contains information regarding the Monte Carlo truth and the reconstruction information from the LAT software. The number of events generated is $4.66 \times 10^6$ photons over an area of $6 m^2$ that always contains the detector. The stored events are stored if triggered (722594 three-in-a-row triggers).
4.2 The selection cuts and the "Good Event" selection

A crucial point in the computation of the IRF is the selection of the events. Even if in our Montecarlo sample we generated only gammas, we have to consider the effect of the particle charge background rejection on photons. It is indeed necessary to apply the algorithms for background rejection also to the data sample: the discrimination of charged particles will affect also gammas, reducing the number of events and, consequently, the effective area. In the LAT experiment the background rejection is made by a selection of events by means of parameters that derives from a "classification tree" analysis. The idea, as already discussed briefly in Chapter 3, is to separate events which belong (with a probability estimator) to a particular gender. The events are in this way clusterized and visually discrimination helps the determination of the selection cuts to be applied on the sampled variables. For example the probability of an event to behave like a "good gamma" will be some combination of cuts on the variables outputted by the reconstruction algorithms (such as the charge released in the ACD, the opening angle of the vertex, the reconstructed direction, the goodness of fit from the tracker recon algorithm, and so on). Moreover, not only cuts for rejecting the background will be applied, but also a selection of events will be done in order to optimize the detection efficiency ($A_{eff}$), the angular resolution ($PSF$) and the energy dispersion ($\Delta E$). In general, the maximization of the detection efficiency by considering also events that have triggered the detector but that are not being well reconstructed, affects the angular resolution of the detector. Vice-versa considering only the events whose direction has been well reconstructed implies reject many events and the detector efficiency will be, as a consequence, low. For reaching the compromise between a good angular resolution (a narrow $PSF$) and a high detector efficiency (high $A_{eff}$) the selection cuts to be applied at the data are:

- "Good CAL": The events are selected requiring that the released energy in the calorimeter is greater than 5 MeV and that the number of radiation lengths in the calorimeter (extrapolating the direction of the reconstructed track to the calorimeter) is greater than 2. This selection discards all the tracks that release only a small fraction of their energy, probably because they left the CsI scintillators, and the energy released was too small for applying energy leak correction. The requirement that the events have been well reconstructed is also applied, estimating the "goodness" of the reconstruction by the goodness of fit performed by the calorimeter reconstruction algorithm and by the comparison with the reconstructed energy in the tracker.

- "Good PSF": even in this case the goodness of fit in the tracker reconstruction algorithm gives an estimator for the events that minimize the $PSF$.

- "Z Dir": the events for which the reconstructed direction is greater than a certain value are discarded. If the Montecarlo incident direction is expressed as $Z = \cos(\theta)$, with $Z = -1$ the normal direction, the selection requires $Z < -0.2$. The discarded events are outside the FOV, and are probably triggers resulting from calorimeter "back-splash" events.

- "Thin-Thick": it is sometimes convenient for understanding clearly the performance of the detector to separately select the events for which the photons converted in the first 12 layer (light trays, equipped with thin tungsten foil), or in the last part of the tracker (where 4 heavy trays are equipped with thick tungsten foils). In general the thin part of the tracker will have a small effective area (low
conversion probability) but a good PSF (low multiple scattering). On the contrary the thick part of the tracker will have an high conversion efficiency but the angular reconstruction will be affected by multiple scattering.

In terms of the stored variables (adopting as naming names of the the n-tuple variable), the selection cuts can be written as follows:

\[
\text{goodCAL} = \text{CalTotRLn} > 2 \cup \text{CalEnergySum} > 5 \text{ MeV} \\
\cup \text{IMgoodCalProb} > 0.2
\]

\[
\text{goodPSF} = \text{IMCoreProb} > 0.2 \cup \text{IMpsfErrPred} < 3.0
\]

\[
\text{goodZ Dir} = \text{MCZDir} < -0.2
\]

The “Good Event” selection is the summation of these cuts:

\[
\text{goodEvent} = \text{goodCAL} \cup \text{goodPSF} \cup \text{goodZ Dir};
\]

and its effect is represented in Fig. 4.1. The figure shows the distributions for the total radiation length in the calorimeter (\text{CalTotRLn}), the total energy measured in the calorimeter (\text{CalEnergySum}), the probabilities that the event has been well reconstructed (\text{IMgoodCal, IMCore, IMpsfErrPred}), and the reconstructed cosine of the polar angle (\text{Tkr1Theta}). The unfilled distributions are relative to all triggers while the filled distributions are for the selected events only. Fig 4.2 shows the distribution of the reconstructed energy for all triggered events and for selected events only (filled distribution).
Figure 4.1: Effect of the “good event” selection on the Montecarlo events. The vertical dashed lines represent the thresholds for the cuts. The filled distributions are the selected events, as result of the simultaneously application of the cuts. This is the “good event” selection.
Figure 4.2: The input spectrum is a $E^{-1}$ spectrum between 18 MeV and 180 GeV (the distribution of the logarithm of the energy is flat). The unfilled distribution is the logarithm of the energy for the triggered events, while the filled distribution is for the selected events only.
Figure 4.3: Effective Area of the LAT detector (in square meters) as a function of the log\((E)\), \(\cos(\theta)\).

4.3 The Effective Area

The effective area is computed as a function of the logarithm of the Montecarlo energy (\(\log(E)\)), and of the cosine of the polar angle (\(\cos(\theta) = Z\)) defined as the angle from the vertical z-axis (\(Z = -1\) is the normal incident direction). The number of generated events per log energy bin and per \(Z\) bin is:

\[
N_{\text{gen}}(E_i, Z_i) = \frac{N_{\text{gen}}}{\Delta \log(E) \Delta Z} \tag{4.8}
\]

Where \(N_{\text{gen}}\) is the total number of generated events. If \(A_{\text{gen}}\) is the area over which the photons have been generated. The effective area \(A_{\text{eff}}\) is expressed by the following equation:

\[
A_{\text{eff}}(\log(E), Z) = \frac{N_{\text{sel}}(\log(E), Z) A_{\text{gen}}}{N_{\text{gen}}(\log(E_i), Z_i)} \tag{4.9}
\]

where \(N_{\text{sel}}\) is the number of selected events per bin, considering both the trigger efficiency and the selection applied. Fig. 4.3 shows the two dimensional histogram of \(A_{\text{eff}}(\log(E), Z)\). The effective area as a function of the energy for different incident directions is plotted in Fig. 4.4, while the angular dependence of the effective area, for different energies is plotted in Fig. 4.5.

The effective area of the LAT detector for normal incident direction can be considered flat above 300 MeV, up to 300 GeV, with a value greater than 0.8 m\(^2\).

4.3.1 The Field of View (FOV)

The field of view is defined as the integral of the effective area over the solid angle divided by the peak effective area:

\[
FOV = \frac{\int_{\Omega} A_{\text{eff}}(\Omega) d\Omega}{A_{\text{peak}}} \tag{4.10}
\]
and basically represents the portion of the sky the detector can observe at the same time. From a geometrical point of view, the FOV mainly depends on the aspect ratio of the instrument (the ratio between the height \( h \) and the width \( w \)). In case of negligible aspect ratio, which is clearly the more favorable situation, we have:

\[
A_{\text{eff}}(\theta, \phi) = A_{\text{peak}} \cos(\theta)
\]  \hfill (4.11)

and the field of view (considering only the portion of the sky not occulted by the earth) is:

\[
\text{FOV} = \frac{\int_0^{\pi/2} \int_0^{2\pi} A_{\text{peak}} \cos(\theta) \sin(\theta) d\theta d\phi}{A_{\text{peak}}} = \pi
\]  \hfill (4.12)

A design with a low aspect ratio is therefore highly desirable in terms of field of view and in the limit \( h << w \), a pair conversion telescope would see roughly 1/4 of the sky (\( \pi \) sr) at the same time. Computing the previous integration by taking into account the effective area as a function of the polar angle, the Large Area Telescope covers more than 2 sr of the sky, a big improvement if compared to the 0.5 sr of its ancestor EGRET.

### 4.4 The Point Spread Function

The Point Spread Function is the response of a system to an input point source. It is the result of the image of a “point” source after the detector has reconstructed it. In gamma-ray telescopes with solid state detectors, the main cause of the spreading of the PSF is the multiple (coulomb) scattering. Not only gamma-ray cannot be focalized, but the elastic interaction of the produced pair with the atoms of the detector spread the PSF, reducing the angular resolution. Ignoring spin effect, the elastic collisions are determined by the well know Rutherford formula [54], and the theory of the multiple scattering is well described by Molière theory: the angular distribution it is roughly Gaussian for small deflection angles, but at larger angles it behaves like Rutherford...
Figure 4.5: Effective Area as a function of the polar angle, for different energy range.
scattering, having larger tails than does a Gaussian distribution. For many applications it is useful using the gaussian distribution with width defined as:

\[
\theta_0 = \frac{13.6 \text{ MeV}}{c\beta p} \sqrt{\frac{x}{X_0}} \left(1 + 0.038 \ln\left(\frac{x}{X_0}\right)\right),
\]  

(4.13)

where \( \beta \) and \( p \) are the velocity and the momentum of the electron, while \( x/X_0 \) is the thickness of the scattering medium in radiation length. High-energy electrons predominantly lose energy in matter by bremsstrahlung, and high-energy photons by \( e^\pm \) pair production. The characteristic amount of matter traversed for these related interactions is called the radiation length \( X_0 \), usually measured in \( g/cm^2 \). It is both (a) the mean distance over which a high-energy electron loses all but 1/e of its energy by bremsstrahlung, and (b) the mean free path for pair production by a high-energy photon [54]. The angular spreading goes approximately as the inverse of the energy of the scattering particles determining as improvement of the PSF increasing the energies. Increasing the energy of the particle (or the momentum) the mean scattering angle decreases, in principle, to an arbitrary small value. In the reality the Point Spread Function will depend also on the intrinsic resolution of the tracker, given by the strip pitch and the lever arm of the detector. Based on the Molière formula, the Point Spread Function will be decreasing as the inverse of the photon energy up to a plateau, determined by the intrinsic resolution of the tracker. Eq. 4.14 expresses this dependence on the energy:

\[
\text{PSF}(E) = p_0 \times \min\left(\frac{E}{100 \text{ MeV}}, 100\right)^{-p_1},
\]  

(4.14)

the parameters can be obtained by fitting the 68% containment radius as a function of the energy. The parametric formula has been chosen so that the first parameters represents the 68% containment radius at 100 MeV. The PSF reach a minimum around 10 GeV, where the intrinsic angular resolution of the instrument dominates.

For determining the Point Spread Function we repeat the procedure of binning the data in logarithm of the Montecarlo energy and in cosine of the incident angle. In principle the PSF for different energies have different shapes, in particular the PSF will be narrow for greater energies and wide for low energies. The angular resolution of the LAT detector expressed as the absolute value of the difference between the Montecarlo direction and the reconstructed direction (|\( \theta_{MC} - \theta_{rec} \)) is represented from Fig.4.6 to Fig. 4.9 for thin layer only and, for thick layers only, from Fig. 4.10 to Fig. 4.13. In each of following figures the PSF, computed as \( |\theta_{MC} - \theta_{rec} | \) has been plotted for different energies and for different incident directions. Each distribution has been fitted with a gaussian of equation \( p_0 \exp\left(\frac{0.5((x-p1)/p2)^2}{2}\right) \), where the parameters \( p0, p1 \) and \( p2 \) are in the legend of each panel. The parameter \( p2 \) is the 68% containment radius (in degrees) and gives direct information on the angular resolution of the LAT instrument.
Figure 4.6: Point Spread Function: Incident energy (18 MeV - 100 MeV) for different incidence angles. Thin Layer selection.

Figure 4.7: Point Spread Function: Incident energy (100 MeV - 1 GeV) for different incidence angles. Thin Layer selection.
Figure 4.8: Point Spread Function: Incident energy (1 GeV - 10 GeV) for different incidence angles. Thin Layer selection.

Figure 4.9: Point Spread Function: Incident energy (10 GeV - 180 GeV) for different incidence angles. Thin Layer selection.
Figure 4.10: Point Spread Function: Incident energy (18 MeV - 100 MeV) for different incidence angles. Thick Layer selection.

Figure 4.11: Point Spread Function: Incident energy (100 MeV - 1 GeV) for different incidence angles. Thick Layer selection.
Figure 4.12: Point Spread Function: Incident energy (1 GeV - 10 GeV) for different incidence angles. Thick Layer selection.

Figure 4.13: Point Spread Function: Incident energy (10 GeV - 180 GeV) for different incidence angles. Thick Layer selection.
Figure 4.14: 68% containment radius as a function of the energy for normal incident photons. If the photons convert in a thick layer then the efficiency will be high but the PSF will be worst (top curve). In a thin layer (the first 12 layers in each tower) the efficiency will be less but the angular resolution will be better (bottom curve). The middle curve is the 68% containment radius for all the events.

Fig. 4.14 shows the trend of the 68% containment radius at different energies, requiring that the conversion has been taken place in the first 12 layers (thin selection) or in the last four layers (thick selection). The plateau above 10 GeV is evident in the figure; above this energy the PSF does not scale, and maintains the same width. Fitting these curves with the parameterized Eq. 4.14 we obtain the best fit parameters: $p_0 = 1.55^\circ$ if the thin selection is applied, and 2.82 in the case of thick selection, $p_1 = 0.8$ in both cases. Fig. 4.15 shows the PSF described by Eq. 4.14 with the best fit parameters.
Figure 4.15: The PSF 68% containment radius parameterized by can be scaled applying this scale law. The scaled PSFs have similar shape and the fitting procedure results easier.
Figure 4.16: Ratio between the reconstructed and the generated energy for normal incident photons at different energies. The distributions have been fitted with a gaussian distribution whose parameters are in the legend of each plot.

4.5 The Energy Resolution

The energy resolution is computed by means of the ratio between the reconstructed energy (EvtEnergySumOpt) and the Monte Carlo energy (McEnergy). The reconstructed energy is the result of the subsequent iterations of the tracker reconstruction algorithm and of the calorimeter reconstruction algorithm which compute the energy leak. The distribution of the ratio EvtEnergySumOpt/McEnergy are shown in Fig. 4.16.

The distributions have been fitted with a simple gaussian law: the parameters are in the legend of each plot. The distribution are not always symmetric and the representation with a simple gaussian is not always satisfactory (as indicated also by the $\chi^2$). A better study of the energy resolution has been done finding that the fit results improve if a double gaussian is used. Fig. 4.17 shows the result of the fit for one of the cases where a single gaussian fit gave worse results. Anyway the single gaussian profile is in many cases detailed enough for describing the energy resolution: the trend of the width of the single gaussian fit as a function of the energy is plotted in Fig. 4.18. The low energy behavior is due to the difficulties in the energy reconstruction of low energy particles. Particles below 1 GeV release a significant part of their energy in the tracker and are not well reconstructed by the calorimeter. Moreover, the feature at 32 MeV can be only interpreted as lack of statistic due to the low conversion efficiency (intrinsically correlated to the cross section of pair production at low energy). The rising of the energy resolution at high energies is due to non-confinement effects of the high energy particles. This causes energy leaks outside the scintillators and, despite the leak correction in the calorimeter by means of algorithms such as the shower fitting profile, the reconstruction at these energies is more difficult.
Figure 4.17: Energy resolution at 10GeV for low latitude incident photons (between 66 and 78 degrees from the normal direction). The energy resolution can be well represented by a double gaussian distribution, which allows the description of the asymmetry of the distribution. The two gaussian are centered at $\sim 0.92$ and $\sim 1.04$.

Figure 4.18: The crosses represent the widths of the gaussians which best fit the energy resolution. Different crosses are referred to different Monte Carlo energies. The trend of the widths can be well describe with second order polynomial function, drawn in the figure with the Filled line.
Chapter 5

Gamma Ray Bursts

Gamma-Ray Bursts (GRBs), are short and intense pulses of high energy radiation whose duration varies from fractions of a second to several hundred of seconds. Their serendipity discovery in the late sixties has fascinated the astronomers and the astrophysicists. They were discovered by the four Vela satellites. The Vela nuclear test detection satellites were part of a program run jointly by the Advanced Research Projects of the U.S. Department of Defense and the U.S. Atomic Energy Commission, managed by the U.S. Air Force. The first two satellites (Vela- 5A and 5B) were launched on 23 May 1969, other two satellites (Vela- 6A and 6B) on 1970. Velas operated until 19 June 1979, although telemetry tracking was poor after mid 1976. While modest in its size and limited by its high background, Vela-5B’s long lifetime afforded it unique opportunity to make major scientific contributions in X-ray and gamma-ray astronomy. Both Vela 5A and 5B carried 6 gamma-ray detectors for a total volume of $\sim 60 \text{ cm}^3$ of CsI and could detect photons in the 150-750 keV energy range. It was in 1969-70 that the Vela spacecraft first discovered gamma-ray bursts. After having rejected the hypothesis of Russian nuclear experiments, they were firstly associated to Galactic objects; due to their transient behavior, they were associated with explosions of neutron stars. Given the high amount of energy registered in a short time by the satellites, this was then the most natural hypothesis.

5.1 Galactic or extragalactic?

The Galactic origin of GRB remained undisputed until the launch of the Compton Gamma Ray Observatory (CGRO) in 1991. CGRO had four instruments that cover an unprecedented six orders of magnitude in energy, from 30 keV to 30 GeV. Over this energy range CGRO had an improved sensitivity over previous missions of a full order of magnitude. It operated for almost 9 years and the mission ended on June 4 2000. The Burst and Transient Source Experiment (BATSE) was a burst dedicated instrument, covering the all sky in the energy band 20-1000 keV. In its operating period it recorded more than 2700 burst and their isotropic distribution ruled out the possibility of local origin. If the burst population were Galactic than their distribution in the sky should reflect the higher concentration of matter in the Galactic plane. Their origin was thus thought to be extragalactic and, as a consequence, the energy released increases. The overall observed fluences range from $10^{-6}\text{erg/cm}^2$ to $10^{-7}\text{erg/cm}^2$ (the lower limit depends, of course, on the characteristic of the detectors and not on the bursts themselves). This can be translated, considering a cosmological distance, into an isotropic luminosity of $10^{51} - 10^{52}\text{erg/sec}$, making GRB one of the most luminous
objects in the sky. The Galactic or extragalactic origin of GRB was anyway debated for several years and models of Galactic GRB still survive. In particular, GRB belong to two different class depending on their duration. The distribution of the duration of the emission of the GRB is expressed by the parameter $T_{90}$ and it shows a typical bimodal shape. Cline et al. [55] recently studied the shortest GRB population, finding that there is a significant anisotropy, consistent with the interpretation of GRB sources of Galactic origin. However, this group of bursts are difficult to detect and strong selection effects are involved in the identification of this particular subgroup. The most clear evidence about the extragalactic origin of GRB is the discovery of the of the x-ray afterglow that allows the measurement of the redshift of the host galaxy.

## 5.2 The afterglow

The prompt gamma emission from a GRB is sometimes followed by a second transient event at lower energies with longer lasting emission in the X-ray, optical and radio. The first x-ray GRB afterglow was measured by the BeppoSAX Mission (1996 - 2002). SAX was a program of the Italian Space agency (ASI) with participation of the Netherlands Agency for Aerospace programs (NIVR) (the acronymous stays for “Satellite per Astronomia X”, and was named in honor of Giuseppe Occhialini). On Feb 28 1997 BeppoSAX detected the x-ray afterglow from GRB 970228 [56]. The exact position given by BeppoSAX led to the discovery of optical afterglow [57]. Radio afterglow was detected in GRB 970508 [58]. By now more than forty x-ray afterglows have been observed (see http://www.mpe.mpg.de/~jcg/grb.html for complete up-to-date tables of well localized GRBs with or without afterglow. Another useful page is: http://grad40.as.utexas.edu/grbog.php). About half of these have optical and radio afterglow. The accurate positions given by the afterglow enabled the identification of the host galaxies of many bursts. In twenty or so cases the redshift has been measured. The observed redshifts range from 0.16 for GRB 030329 (or 0.0085 for GRB 980425) to a record of 4.5 (GRB 000131).

## 5.3 Global properties: the BATSE catalogue

The BATSE detector on board the CGRO observed more than 2700 burst, in its 9 years of observations. One of the eight identically configured detector modules of BATSE is shown schematically in Fig. 5.1. Each detector module contains two NaI(Tl) scintillation detectors: a Large Area Detector (LAD) optimized for sensitivity and directional response, and a Spectroscopy Detector (SD) optimized for energy coverage and energy resolution. The eight planes of the LADS are parallel to the eight faces of a regular octahedron, with the orthogonal primary axes of the octahedron aligned with the coordinate axes of the Compton spacecraft.

The LAD detector is a disk of NaI scintillation crystal 20 inches in diameter and one-half inch thick, mounted on a three-quarter inch layer of quartz. The large diameter-to-thickness ratio of the scintillation crystal produces a detector angular response similar to that of a cosine function at low energies where the crystal is opaque to incident radiation. At energies above 300 keV, the angular response is flatter than a cosine. A light collector housing on each detector brings the scintillation light into three 5-inch diameter photo-multiplier tubes (PMTs). The signals from the three tubes are summed

---

1The naming convention for GRB is the year, month, and day of GRB. So that 970228 is the burst at the second of February in the 1997
at the detector. A quarter-inch plastic scintillation detector in front of the LAD is used as an anticoincidence shield to reduce the background due to charged particles. A thin lead and tin shield inside the light collector housing reduces the amount of background and scattered radiation entering the back side.

The spectroscopy detector is an uncollimated NaI(Tl) scintillation detector 5 inches in diameter and 3 inches thick. A single 5 inch photo-multiplier tube is directly coupled to the scintillation detector window. The housing of the PMT has a passive lead/tin shield similar to that of the LADs. The crystal housing has a 3-inch diameter 50 mils thickness beryllium window on its front face in order to provide high efficiency down to 10 keV for exposures near detector normal.

BATSE detects γ-ray bursts on-board by examining the count rates of each of the eight LADs for statistically significant increases above background on each of three time scales: 64 ms, 256 ms, and 1024 ms. The discriminator rates in channels 2 and 3 (approximately 60 to 325 keV) are used. The background rate is determined for each detector over a commandable time interval usually set at 17.4 seconds. The data were daily sent to the MSFC where they are unpacked and distributed as burst data, scheduled data, and background data. The main objective of the BATSE detector was the extensive study of GRB. BATSE made several discoveries which help the understanding of GRB phenomena.

The recorded positions in the sky marked an important step forward in the GRB comprehension. Fig. 5.2 shows the distribution of the bursts observed by the BATSE observatory: from this image is evident that the distribution of the GRBs in the sky is isotropic and there are no preferred structures. This made the idea of the extragalactic origin the most favorable ruling out the possible connection with neutron starts in our Galaxy.

Since that the number of observed bursts is large enough a good statistic is available to summarize the GRB properties in terms of global observables. The most recent version of the BATSE catalogue cover all the detected bursts up to (and including) May 26, 2000. The catalogue can be found at the BATSE catalogue home page (http://cossc.gsfc.nasa.gov/batse/BATSE_Cat/index.html) and contains eight tables characterizing the GRB phenomena. During the work on this thesis I have reanalyzed the catalogue obtaining the distributions of fluxes and of durations of the BATSE catalogue and finding the correlation laws which can be applied for constraining
2704 BATSE Gamma-Ray Bursts

Figure 5.2: Gamma-Ray Burst angular distribution. The figure shows the position of each burst detected by the BATSE detector in Galactic coordinate.

The recorded burst duration is expressed by means of the parameter $T_{90}$ which measures the duration of the time interval during which 90% of the total observed counts have been detected. The start of the $T_{90}$ interval is defined by the time at which 5% of the total counts have been detected, and the end of the $T_{90}$ interval is defined by the time at which 95% of the total counts have been detected. $T_{50}$ is similarly defined using the times at which 25% and 75% of the counts have been detected. $T_{90}$ and $T_{50}$ are calculated using data summed over the 4 LAD discriminator channels and using data summed over only those detectors that satisfied the BATSE trigger criteria.

Figure 5.3: GRB duration distribution. The $T_{90}$ parameter is directly correlated with the intrinsic duration of the bursts. The distribution of this quantity shows a bimodal distribution in $\log(T_{90})$. The line in the plot correspond to two separate gaussian fit and their summation. The two separate distribution are related to two different class of GRB: short bursts with $T_{90}$ less than 2 seconds and long burst, with $T_{90}$ greater that 2 seconds.

The distribution off the $T_{90}$ is shown in Fig. 5.3. The bimodal structure (in logarith-
Figure 5.4: *Overall fluence measured by BATSE for the entire catalog. The two distributions are for short bursts and for long bursts. Short bursts are typically fainter than long bursts. The distributions have been separately fitted with gaussians, and the best fit parameters are in Table 5.1.*

mic scale of $T_{90}$) is evident. From this distribution “short bursts” have been defined as burst with $T_{90}$ less than 2 seconds and “long bursts” with $T_{90}$ greater than 2 seconds. In figure the distribution of the $T_{90}$ parameters is shown. A two gaussian fit has also been performed and over-imposed to the distribution. The equation for the gaussians is the following:

$$N(\log(T_{90})) = A \exp\left[-0.5 \left( \frac{\log(T_{90}) - \log(T_{90}^*)}{\sigma_{T_{90}}} \right)^2 \right]$$

while the best fit parameter are in Table 5.1.

The BATSE detector recorded the fluences of the GRBs in four different energy channels. They cover respectively the energy band from 20 to 50 keV, from 50 to 100, from 100 to 300 and greater than 300 keV (up to 1 MeV, nominally). The total (20 keV-1 MeV) fluence measured for all the bursts in the catalogue is shown in Fig. 5.4, while the distributions for the four channels are in the left side of Fig. 5.5. The two different distributions are for long and short burst separately. For the total fluence distribution a fit with a gaussian function of Eq. 5.2 has been performed, and the best fit parameters are in Table 5.1.

$$N(\log(f_{\text{tot}})) = A \exp\left[-0.5 \left( \frac{\log(f_{\text{tot}}) - \log(f_{\text{tot}}^*)}{\sigma_{f_{\text{tot}}}} \right)^2 \right]$$

From the previous figures it can be seen that short burst and long burst appear to belong to two different distinct populations. Moreover short bursts are usually dimmer than long bursts. An useful parameter that can be introduced to describe the “hardness” of a burst is the “hardness ratio” and correspond to the ratio between the third and the second channel of the BATSE detector. The relative intensity between this two channels
Table 5.1: Parameters for the gaussian fit of the duration distribution of Fig.5.3.

<table>
<thead>
<tr>
<th>Duration (s)</th>
<th>( \log(T_{90}) )</th>
<th>( \sigma_{T_{90}} )</th>
<th>( \log(f_{tot}) )</th>
<th>( \sigma_{f_{tot}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Short</td>
<td>-0.20</td>
<td>0.55</td>
<td>-6.35</td>
<td>0.57</td>
</tr>
<tr>
<td>Long</td>
<td>1.46</td>
<td>0.49</td>
<td>-5.39</td>
<td>0.62</td>
</tr>
</tbody>
</table>

Figure 5.5: Right: Fluences distributions for the four BATSE channels. The contribution of short and long bursts has been plotted separately. Left: The ratio between the third and the second channel of the BATSE detector defines the “hardness ratio” which is an indicator of how peaked the emission is at high energy.

are a good indicator of the position of the peak of the spectrum. The hardness ratio is shown in Fig. 5.5. From this figure another interesting correlation is evident: short bursts are harder than long bursts. The two scales laws are plotted in Fig. 5.6 where, the hardness ratio (top panel) and the fluence (bottom panel) have been plotted as a function of the duration of the sample. This relations can be used for developing GRB model simulator based on phenomenological quantities.

5.4 Individual properties: spectral shape and light curves

The general properties of GRBs viewed as celestial objects have been summarized in the previous section, analyzing the BATSE catalogue. In this section I will review some of the main features of the typical GRB observed emission.

5.4.1 Light curve

The typical light curve shows high variability at a time scale down to milliseconds. In the majority of the bursts, substructure are well visible and the emission peaks are separated. In some cases the peaks are overlapping and the result is a single peak
Figure 5.6: The picture shows the relationship between the hardness ratio and the duration (top) and between the fluence and the duration (bottom). The general trend is that short bursts are dimmer but harder with respect to long bursts, which, on the other hand are typically more intense and softer.
burst or a smooth profile burst. In Fig. 5.7 are some examples of GRB's light curves as observed by BATSE.

There are no equivalent light curves for the EGRET detector, due to the long dead time of the spark chambers and due to the low effective area: only occasionally high energy photons have been detected by EGRET during the flaring of a GRB in the BATSE energy range. GRB940217 is probably the most famous (Fig. 5.8).

The Ulysses mission is a joint mission with NASA and ESA to explore the solar environment at high ecliptic latitudes. It was launched 6 October 1990, and reached Jupiter for its "gravitational slingshot" in February 1992. It passed the south solar pole in June 1994 and crossed the ecliptic equator in February 1995. In addition to its solar environment instruments, Ulysses also carries X-rays detectors (15-150 keV) for studying X-rays and gamma-rays of both solar and cosmic origins.

The prompt emission recorded by Ulysses of GRB940217 is well visible as continuous counts rate, while EGRET photons have been marked as dot with error bars. Unfortunately the Earth occulted the burst location for more than an hour. This burst became a very famous because when the burst location was once again in the field of view of the CGRO, EGRET detected one photon at extraordinary energy (18 GeV) coming exactly form the burst location, while the trigger rate of the ULYSSES were registering only background counts.

These is indeed a very promising observation, letting think of possible scenarios of gamma afterglow, maybe due to the high-energy acceleration of particle due to relativistic reverse shock, or delayed GeV emission due to shower propagation effect or even due to quantum gravity effect which introduce a velocity dispersion in the velocity of the light.
Table 5.2: Typical spectral parameter of the Band function for the $N(E)$, $F(E)$ and $EF(E)$ spectra.

5.4.2 Spectral properties

The spectrum is typical non-thermal, the energy peaks at few hundred keV, and an excellent phenomenological fit has been proposed by Band et al. (1993) [59] using two power laws joined smoothly at a break energy at $(\alpha - \beta)E_0$:

$$
N(E) = N_0 \begin{cases} 
(E)^{\alpha} \exp\left(-\frac{E}{E_0}\right), & \text{for } E < (\alpha - \beta)E_0 \\
((\alpha - \beta)E_0)^{(\alpha-\beta)}(E)^{\beta} \exp(\beta - \alpha), & \text{for } E \geq (\alpha - \beta)E_0,
\end{cases}
$$

(5.3)

$\nu F(\nu)$ peaks at $E_p = E^2 N(E) = (\alpha + 2)E_0$. In their work Band et al. present a small catalogue of the spectra of 52 bright bursts which they analyze in terms of the Band function. Preece et al. (2000) [60] present a larger catalogue with 156 bursts selected for either high flux or fluence, considering several spectral shape including the Band function. Recently Ghirlanda et al. (2003)[61] pointed out that the time-resolved spectra at early times of intense GRBs can be well approximated with a thermal component. The Band model is purely phenomenological and there no particular theoretical model or physics hypothesis behind it. It is an excellent parametric representation of the GRB spectra in the BATSE energy range for most of the GRB. The typical value for the Band model are $\alpha > \beta \sim 2$, while $E_p$ can varies from below 100 keV to above than 1 MeV. The Band model predicts, merely extrapolating the spectrum at high energy, a power law decay with exponent $\beta$. The typical spectrum of a GRB as seen at BATSE energy is plotted in Fig. 5.9, where also the fit with the band model has been performed. The typical spectral parameters of the Band function are summarized in Table 5.2.
5.4.3 Evidence for high energy emission with EGRET

The energy range for spectroscopy studies of EGRET is between 0.6 and 140 MeV. If a BATSE trigger signal is received, spectra are recorded in four different time intervals (from 1 to 23 seconds) and then sent in the EGRET telemetry stream over the next 35 minutes. In addition, a spectrum between 0.6 and 140 MeV is accumulated every 33 seconds. These spectra where useful for the study of gamma-ray bursts and for the observations of the high energy spectral range. Due to the small field of view, limited mainly by angular acceptance of the detector, and due to the small effective area (∼ 1500 cm²) only few BURST were observed by the EGRET telescope, and due to the limited energy resolution the information on their spectral are not satisfactory. The composition of the 5 bursts observed by EGRET showed no clear evidence of cut-off at high energy (Fig. 5.10).

The intense burst GRB990123 is an example of simultaneously detection by the detectors onboard the CGRO, from BATSE energies to EGRET energies [62]. The right panel of Fig. 5.10 shows the overall spectrum of GRB990123. Even if most of the the EGRET data are only upper limits, there are no evidence of cut-off at high energies.

5.4.4 Spectral-temporal variability

The analysis of variation of the spectra with time is one of the most detailed analysis that one can perform on GRB data. Usually, in literature, there are two different approaches. The first approach is to analyze light curves at different energies and studying the correlation using method like the auto correlation function (ACF), as done by Fenimore et al. (1995) [63]. They found that the averaged ACF has a general shape in GRB (left panel of Fig. 5.11) and, moreover, the pulse width depends on the energy of the light curve, in particular, at high energy the pulses are narrower. The right panel of Fig. 5.11 shows the dependence of the half width of the averaged ACF (triangles) for the four
Figure 5.10: Left: composite spectrum of 5 bursts. Even if the error bars are quite large, a possible excess at high energy is visible and the fit with a pure power laws is not consistent with the data. Right example of a single burst (GRB 990123) observed simultaneously by several detectors. While the low energy range is well covered at high energy only upper limits are available, but that can not disclaim a high energy component.

BATSE different channels and the sum of the rise and the decay times for averaged pulses at the same energy bands.

Another procedure is to divide the light curve into different slices, usually determined by the constant signal-to-noise ratio or by other methods [64] which optimize the division of the light curve. For each method the spectrum is computed and fitted. This method is very useful for BATSE bursts, where the count rate is high enough to ensure a sufficient amount of counts in each spectrum. Although at the EGRET energies the count rate are low and the statistics is poor, recent investigations [65], which make uses of joint BATSE-EGRET data, show that the spectral evolution with time is from hard to soft energies. They also pointed out that the energy dependence on the peak width was not found in some bursts. And the effect can be only confined at BATSE energies, and cannot be, as a consequence, extrapolated to higher energies.

In this chapter I have presented some observational facts, that characterize GRB as astrophysics phenomena, building up a statistic for describing their properties as well defined source. Nevertheless there are many uncertainties related in particular to the high energy range of their spectrum. The lack of data is evident and many physical processes could affect the extrapolation from BATSE to EGRET energies. In more than one case, the EGRET data has shown a possible high energy extra component which increases the flux, deviating from the power law extrapolation. Following the observation in the BASTE energy range, for a typical millisecond variability in the BATSE energy range, one should expect a variation on time scales of the order of $10^2 - 10^3 \mu s$ at GeV energies. But, again, extrapolating on four order of magnitude can be risky and dangerous and misleading. For this reason we have adopted another approach. The physical model approach starts from the knowledge on the physics of the relative topics (relativistically expanding shells, shock’s acceleration, emission mechanisms), assumes a particular scenario (since the origin of the GRB is not known), and build an observational picture. The high energy emission in this way is the result of the Inverse Compton
Figure 5.11: Left: autocorrelation function for 45 averaged GRB. The Autocorrelation function is narrower at high energy. The GRB time scales are shorter at high energy, as also shown in the plot.

Figure 5.12: Examples of a GRB which showed an extra high energy component. Each spectrum, which is made by joint fit of BATSE and EGRET data, is at different time interval, showing the evolution of the low energy/ high energy components. The spectra is softening during the evolution of the burst. Data from [65].
reprocessment of the synchrotron photons, and the high energy excess can be simulated.
Chapter 6

GRB phenomenological model

In this chapter I will present a simulator for Gamma-Ray Bursts based on the observations of GRB made mainly by the BATSE detector. Several papers have been used for finding an empirical description for the spectral shape and for the pulse shape, and for finding the distributions for the parameters of the GRB phenomenological model presented here. Norris et al.(1996) [66] introduced a phenomenological description for the pulse shape of GRBs in the BATSE domain. They performed a series of temporal fits on BATSE bursts, fitting the observed pulse profiles with an empirical pulse shape. I will adopt the same pulse shape, using also the results of their fits for constraining the parameters of the model. Band et al.(1993) [59], introduced the well know “GRB” model for Gamma-Ray Bursts spectra at BATSE energies. This function, known also as “Band” model, has revealed very useful and very robust in the description of the GRB observed emission between tens of keV and few MeV (basically all the observed spectrum). Preece et al.(2000) [60] presented a catalogue of 156 bright bursts from the BATSE catalogue using high energy resolution data (covering an energy range between 28 keV to 1800 keV). They fitted a series of time resolved spectra, with a typical accumulation time of 128 ms, using different spectral shapes; most of the bursts were anyway best fitted with the Band function. Their catalogue contains the distribution of the fitted parameters and it is trivial to sample parameters from their distributions, in order to obtain an empirical description of GRBs spectra. Finally Fenimore et al.[63] and Norris et al.(1996) [66] observed that pulses at higher energies are narrower than the pulses at lower energies. This is a very important observation that characterize very precisely the temporal evolution of the spectrum. In the development of the GRB phenomenological model, there are no assumption related to the physics of the GRBs, in particular there are no assumptions on the emission processes which determine the observed spectrum. All the parameterized relations came from observations and the model are the results of a “best fit” approach. The spectral shape and the pulse shape are indeed parameterized function, which can be used as fitting functions for BATSE data. In particular, each pulse of each lightcurve is fitted, and several spectra for each burst have been fitted. The best fit parameters are then collected in distributions. The distributions can now be used for sampling random parameters (distributed as the parameters which represent the data), and a simulated burst signal can be obtained. The phenomenological model, which well describe the BATSE observation, are merely extrapolated to LAT energies. We do not know whether the extrapolation is valid or not (in terms of physical processes) but we obtain a “conservative” high energy description, without any assumption. In the next chapter I will approach the GRB simulations by considering the physics involved in GRB phenomena, defining the basis for a GRB physical model.
6.1 The pulse shape

The pulse is the basic element of a GRB light curve, the smallest spike that can be resolved in the counts rate as a function of time and that, combined with other pulses, forms the GRB light curve. Eventually some pulses may also partially overlaps forming complex structures. Although there is no a unique shape that describe every GRB pulse, a family of functions has been proposed by Norris et al. (1996) [66]. They gave a phenomenological description of the pulses, by means of a parameterized functions of equation:

\[ I(t) = A \begin{cases} 
\exp\left[-\left(\frac{t - t_0}{\sigma_r}\right)\nu\right], & t \leq t_0 \\
\exp\left[-\left(\frac{t - t_0}{\sigma_d}\right)\nu\right], & t > t_0 
\end{cases} \]  \hfill (6.1)

The parameter \( \nu \) is also known as “peakedness”. The previous equation simplifies in a gaussian function for \( \nu = 2 \), and in a exponential function if \( \nu = 1 \). Each pulse is divided in a rise phase (for \( t < t_0 \)), and a decay phase (for \( t > t_0 \)), \( \sigma_r \) and \( \sigma_d \) are, respectively, the rise time and the decay time. The width of the pulses can be studied by means of the Full Width at Half Maximum (FWHM) related to the rise and decay time through the following relation:

\[ W = (\sigma_r + \sigma_d) \ln(2)^{1/\nu}. \]  \hfill (6.2)

To study the trend of the pulse shape parameters, and to build up a statistic for GRB pulse shapes, they fit each GRB light curve in their sample with pulses described by Eq. 6.1. They visually inspected the light curve, identifying pulses and fitting each of them with the parameterized pulse shape. The distributions for \( \nu, \sigma_r, \sigma_d, W \), and the distribution of the interval between pulses are than obtained by fitting the pulse profiles of 41 long duration, bright bursts, correspondently to more than 400 pulses overall. The relation between \( \sigma_r \) and \( \sigma_d \) is, in a good approximation, linear with a ratio \( \sigma_r/\sigma_d \) equal to 1/3. Norris et al.(1996) found a more precise relation, given by \( \sigma_r = 0.33\sigma_d^{0.86} \), but, for modeling purposes the linear dependence is good enough and is much easier to use within Eq.6.2. Anyway this equation, which expresses basically the rise-to-decay ratio, shows that the pulses are typically asymmetric [67], with a shorter rise time and a slower decay time. They also found that this relation is independent of the energy, and it is valid in all the four BATSE channels. The duration of the pulses is for the majority of the bursts of the order of few hundred milliseconds in BATSE's Channel 1. Moreover, an important observed feature of GRB pulses is that the pulse width is narrower at higher energy [68, 69, 63]. This law has been observed in the BATSE energy range, while there is not enough statistic to observe a similar behavior at EGRET energies. In the model developed here I merely extrapolate this scale law at GLAST energies, obtaining pulses which are narrower than the pulses in the BATSE (or GBM) energies. Fenimore et al.(1995) [63] derived the dependence of the FWHM of the pulses on the energy using the Autocorrelation Function and they obtained:

\[ W(e) = W_0 \left( \frac{e}{20keV} \right)^{-0.4}, \]  \hfill (6.3)

result confirmed also by Norris et al.(1996) with different methods [66]. The equations for the pulse shape as a function of the energy and time are:

\[ I(t, e) = A \begin{cases} 
\exp\left[-\left(\frac{t - t_0}{\sigma_r(e)}\right)\nu\right], & t \leq t_0 \\
\exp\left[-\left(\frac{t - t_0}{\sigma_d(e)}\right)\nu\right], & t > t_0 
\end{cases} \]  \hfill (6.4)
Figure 6.1: Distribution of the Full Width at Half Maximum for pulses at 20 keV ($W_0$ in equation 6.3). (Data from [66]).

with $\sigma_r(e)$ and $\sigma_d(e)$ are given by the following equations:

$$
\begin{align*}
\sigma_d(e) &= 0.75 \times \ln(2)^{-1/\nu} W_0(e/20\text{keV})^{-0.4} \\
\sigma_r(e) &= 0.25 \times \ln(2)^{-1/\nu} W_0(e/20\text{keV})^{-0.4}.
\end{align*}
$$

(6.5)

6.1.1 The width distribution

Pulse widths, or durations, are likely to be characteristics of the physical processes that produce the bursts. Since it is always possible to link a time interval $\delta t$ to a length scale $\delta l$ through the simple relation $\delta t \leq c \delta l$ (supposing a causality relation at the source), then, the pulse duration carries informations not only on the typical time scale of the emitting processes, but also on the typical size of the emitting region. The shortest pulse duration will be the upper limit on the size of the Gamma Ray Burst emitter. In addition, since most of the GRBs are produced at cosmological distances, all the observed time scales (including widths) are affected by cosmological time dilatation. Unfortunately, since only for a small subset of GRB the redshift is known, the observed light curves cannot be corrected and the effect of cosmology is to spread all the distributions of the observed parameters. In order to provide a general description of the GRB phenomena, and in order to obtain a solid and easy model, we can proceed using a global fit function, assuming that the parameters are distributed accordingly to a log-normal distribution.

The Full Width at Half Maximum (FWHM) at 20 keV, the parameter $W_0$ in Eq. 6.3, is distributed accordingly with Fig. 6.1.

$$
P(\log(W_0)) = \exp\left[-0.5 \left(\frac{\log(W_0) - \mu}{\sigma}\right)^2\right],
$$

(6.6)

with the best fit parameters $\mu = -0.1 \pm 0.03$ and $\sigma = 0.46 \pm 0.02$. These parameters correspond to mean durations of the order of 800 ms, varying from 275 ms to 2.3 s at one sigma.

6.1.2 Interval between pulses

The interval between pulses is defined as the temporal distance between two consecutive peaks. In addition to pulse widths the time intervals between pulses within a burst
Figure 6.2: Interval between pulses distribution as obtained by Norris et al. (1996) by fitting BATSE GRB light curve at 20 keV (Channel 1). (Data from [66]).

are timescales that may also be related to the production mechanisms in GRBs. If the individual pulses are random realization of independent events, then the distribution of interval between consecutive pulses would obey to a Poisson statistics. Widths and interval between pulses can be, in general, independent, and if the interval between pulses is greater than the pulse duration the pulses will be well separated, on the other hand, if the interval between pulses is of the same order of the pulse duration, than the pulses are overlapping. Nevertheless this implies a selection effect: when the pulses are partially overlapping and the durations are of the same order of the pulse separations, than the identification of pulses becomes difficult and an overestimation of long duration pulses is introduced. Moreover this selection effect can be only partially solved by an improvement of the temporal resolution of the instrument, while it will anyway effect the cases in which pulses are close and partially overlap. As described above, the analysis procedure consists of fitting each GRB light curve in the sample for the Channel 1 (distribution in other channels are comparable) using as fitting functions several pulse shapes (Eq. 6.1). The interval between adjacent pulses is shown in Fig. 6.2, together with its log-normal fit.

The shown distribution has a broad maximum near 1 second, extending from 300 ms to ~ 4 seconds. Nevertheless the temporal resolution of the sample is 128 millisecond for most of the bursts, and the sharply decreasing trend below few hundreds milliseconds can be interpreted as consequence of poor resolution in the short pulses separation. The distribution shown is anyway representative of the characteristic time scale for the pulse separation. A log-normal distribution of equation:

\[ P(\log(\Delta t)) = \exp[-0.5 \left( \frac{\log(\Delta t) - \mu}{\sigma} \right)^2], \]  (6.7)

fits the observed data with the best fit parameters \( \mu = 0.13 \pm 0.02 \) and \( \sigma = 0.41 \pm 0.01 \), corresponding to mean intervals 1.35 seconds varying from 0.52 seconds to 3.47 seconds. It is interesting to compare the pulse width distribution (Fig. 6.2) with the separation of the pulses (Fig.6.2). The general trend for GRB pulses is to have comparable time scales for the pulse width and for the interval between pulses. The fact that most of the pulses are separable is also evident from the comparison of the mean values of the two distributions. The interval between pulses is slightly longer then the pulse width,
and pulses in GRB are only marginally overlapping. It is necessary to underline that the procedure adopted for studying the pulses (i.e. the isolation of pulses to fit), is not sensitive in the range of values for which the interval between pulses is much smaller than the pulse width. For example, several overlapping pulses can be systematically fitted with one pulse of longer duration. In the observed distribution the mean interval between pulses is slightly bigger than the duration of the pulses. The most important thing is that they are on the same time scale. A Gamma-Ray Burst model based on physical consideration (as the one developed in the next Chapter) has to explain this general trend of the GRB pulses.

6.1.3 The peakedness distribution

The relation between the peakedness parameter and the physical processes in gamma-ray bursts is less clear than other parameter. The peakedness $\nu$ is moreover a “form factor” whose variation may change the tails and the sharpness of the function. The pulse shape can be reduced to a double exponential is $\nu = 1$ and to a gaussian with $\nu = 2$. The distribution of the $\log(\nu)$ is shown in Fig. 6.3. The solid line represents a normal distribution of equation:

$$P(\log(\nu)) = \exp[-0.5 \left( \frac{\log(\nu) - \mu}{\sigma} \right)^2],$$

with the best fit parameters $\mu = 0.16 \pm 0.02$ and $\sigma = 0.3 \pm 0.01$, corresponding to a mean $\nu$ of 1.44, and varying from 0.72 to 3.89.

6.2 The spectral shape

The best phenomenological description for GRBs spectra is the “Band” function, proposed by Band et al. (1993) [59]. The function is expressed in Eq. 5.3 but it is reported here for clearness, adopting a different notation:

$$Band(e,e_b,\alpha,\beta) = N_0 \begin{cases} 
    e^{\alpha} \exp[-e(2 + \alpha)/e_p], & e < e_b \\
    e_b^{(\alpha-\beta)} \exp[\beta - \alpha]e^\beta, & e > e_b, 
\end{cases}$$

Figure 6.3: Distribution of the logarithm of the “peakedness” parameter. (Data from [66]).
here $e_b$ is the “break energy”, parameter of the model function, and $e_p = (2+\alpha)/(\alpha-\beta)e_b$ is the “peak energy” which correspond to the maximum of $e^2 Band(e, e_b, \alpha, \beta)$ function. In the model, $\alpha$ and $\beta$ are the low and high energy index. Preece et al. (2000) [60] have analyzed 156 bursts from the BATSE catalogue using high resolution energy data covering an energy range between 28 keV to 1800 keV. They performed a series of time resolved spectra, typically the accumulation time is 128 ms, but it can be as short as 16 ms depending on the data. They used different spectral shape, but a large amount of GRB’s spectra are well reproduced by the Band function (Eq. 5.3).

One of the main features of the GRB spectrum is that they can be well described with a Band function both if they are integrated and instantaneous (notice that instantaneous naturally means integrated on time scale shorter then the pulse width). In order to build up the model, we have to consider the energy dependence of the pulse shape as introduced by Eq.6.3. The temporal-spectral function $f(t, e)$ that describe the sample is the differential flux $[ph/cm^2/s/keV]$, and it is the product of a Band function (with spectral indices $\alpha'$ and $\beta'$) and a pulse shape, for which the width varies with the energy in agreement with Eq. 6.1, 6.3, and 6.5:

$$f(t, e) = I(t, e) \ Band(e, e_b, \alpha', \beta') \ [ph/cm^2/s/keV], \quad (6.10)$$

while $I(t, e)$ is given by Eq. 6.4. The integrated spectrum has to be itself a Band function (Eq. 6.9), with different spectral indices $\alpha$ and $\beta$:

$$\int_0^\infty f(t, e) dt = Band(e, e_b, \alpha, \beta) \ [ph/cm^2/keV] \quad (6.11)$$

with $\alpha$ and $\beta$ the observed spectral indices of the integrated spectrum. Using Eq. 6.10 into Eq. 6.11:

$$\int_0^\infty f(t, e) dt = A \times Band(e, e_b, \alpha', \beta') \times \left( \int_{-\infty}^{t_0} \exp\left(\frac{t_0-t}{\sigma_r(e)}\right)^\nu dt + \int_{t_0}^{\infty} \exp\left(\frac{t-t_0}{\sigma_a(e)}\right)^\nu dt \right), \quad (6.12)$$

Figure 6.4: Spectral fit parameters: distribution of low energy index (left), of the break energy (middle) and of the high energy index (right). In the middle panel the distribution of burst which is not well described by the standard Band model is shown as dotted curve. (From Preece et al. (2000) [60]).
or, changing variables, applying the transformation \((t_0 - t)/\sigma_r(e) \rightarrow x\), for the first
integral and \((t - t_0)/\sigma_d(e) \rightarrow x\) for the second, the above equation can be rewritten in
the following way:

\[
\int_0^\infty f(t,e)dt = A \times \text{Band}(e,e_b,\alpha',\beta') \times W(e) \times \left(\sigma_{r0} + \sigma_{d0}\right) \int_0^\infty \exp(-x^2)dx,
\]

where \(A\), \(\sigma_{r0}\), \(\sigma_{d0}\), and the integral at the right side are numerical constants. The integrated
spectrum \(\text{Band}(e,e_b,\alpha,\beta)\) is basically represented by the product of the terms:
\(\text{Band}(e,e_b,\alpha',\beta') \times W(e)\) which is, considering that \(W(e)\) is a power law with slope
\(-0.4\) equal to a Band function with the modified spectral index:

\[
\int_0^\infty f(t,e)dt = \text{Band}(e,e_b,\alpha,\beta) = A_0 \times \text{Band}(e,e_b,\alpha',\beta') \times W(e)
\]

\[
= A_0 \text{Band}(e,e_b,\alpha' - 0.4,\beta' - 0.4)
\]

where \(A_0\) contains all the numerical constants. The parameters of the Band function
\(\text{Band}(e,e_b,\alpha',\beta')\) as to be chosen in order to reproduce the observed distributions for
the low and for the high energy power law indexes \((\alpha\ and \ \beta)\) so that for obtaining a
mean value of low energy spectral index equal to \(-1\) (see Fig.6.4, left panel) the spectral
parameter \(\alpha\) of the Band function \(N^1(e)\) has to be set as \(-0.6\), while, for the high energy
part, a value of \(-1.85\) will return an observed spectral index equal to \(2.25\) (Fig.6.4, right
panel). We can then rewrite the phenomenological model function \(f(t,e)\) as:

\[
f(t,e) = I(t,e)\text{Band}(e,e_b,\alpha + 0.4,\beta + 0.4),
\]

where \(\alpha\) and \(\beta\) are the observed spectral indices for the integrated spectrum, which are
parameters of our model.

### 6.3 Normalization to the BATSE fluences

The basic idea of the GRB phenomenological model is to extrapolate the observation
at the BATSE energies up to the LAT energies, region of the electromagnetic spectrum still unexplored. The determination of the observed flux requires the knowledge of the
distance (more precisely, of the luminosity distance) and the knowledge of the
intrinsic luminosity. The luminosity at the source is something that only with the pre-
cise modelization of the physics inside the GRB can be derived, and, even in this case,
the distance of the source is unknown. Frail et al.(2001) [70] using a sample with 15
GRBs with known redshift, raise the suggestion that GRBs have similar intrinsic energy
reservoirs instead of having a spread of energies, and the different values of intrinsic
luminosities are due to different beaming angles. More recently, Bloom et al.(2003) [71]
have extend the significance of this statement using a greater sample of bursts with know
redshift (48 bursts), and the idea of the standard candles is more and more accepted.
Amati et al.(2002) [72] found a correlation between the isotropic emitted energy at the
source (corrected by the redshift but not for the beaming factor), and the energy at
which the \(vF_v\) spectrum peaks. Ghirlanda et al.(2004) [73] show that the tightest correla-
tion is instead between the peak energy and the collimated-corrected emitted energy,
underlining also the possibility to use GRBs as standard candle to probe the universe up
to redshift 10 [16]. This correlation can be used in principle in a GRB phenomenological
model, under the hypothesis of standard candles and assuming a redshift distribution.
In the development of the model presented here I have directly normalized the simulated burst fluence in the BATSE energy range, accordingly to the fluence distribution observed by the satellite onboard the CGRO, and already presented in this thesis (see Chapter 5, Table 5.1, Eq. 5.2 and Fig. 5.4). Let \( F_{BATSE} \) be the BATSE fluence between 20 keV and 1 MeV, the GRB spectrum \( f(t, e) \) is normalized to this value computing the following integral:

\[
f(t, e) = \frac{f(t, e) F_{BATSE}}{\int_0^\infty \int_{20 \text{ keV}}^1 e f(t, e) \, de \, dt} \quad [\text{erg/cm}^2]
\]  

(6.16)

### 6.4 Building up the model

The main ingredients for building up a phenomenological model have been already presented and will be summarized here. There is a minimal set of parameters for the model, that can be changed to yield different configurations: bursts with different intensities, temporal and spectral behaviors. Five parameters can be chosen by the user:

- The seed for the random number generator.
- The number of pulses to generate \( N \).
- The fluence in the BATSE energy range \( F_{BATSE} \) in \( \text{erg/cm}^2 \).
- The low energy spectral index \( \alpha \).
- The high energy spectral index \( \beta \).

If the fluence is set to zero, the distribution of fluences observed by BATSE is considered for sampling a random number. A similar solution has been implemented if the low energy spectral index or the high energy spectral index are associated to a non-physical values (or better a “non observed” values). The allowed ranges of values are \(-3 \leq \alpha \leq 1\), and \( \beta < \alpha \). In practice, a sequence of \( N \) pulses can be obtained by randomly extracting random numbers with the probability distribution given by equations 6.7, 6.6, 6.8. In particular, for each peak, the peakedness \( \nu \), the width \( W \), the pulse separation \( \Delta t \), the break energy \( e_b \) and the normalized (to one) pulse height \( A \) are sampled from their respective distribution (the pulse height is considered uniform from 0 to one):

\[
\begin{align*}
\nu & = 10 \text{Gauss}(0.16, 0.3) \\
W & = 10 \text{Gauss}(-0.1, 0.5) \\
\Delta t & = 10 \text{Gauss}(0.13, 0.4) \\
e_b & = 10 \text{Gauss}(2.5, 1) \\
A & = \text{Uniform}(0, 1)
\end{align*}
\]  

(6.17)

Where \( \text{Gauss}(\mu, \sigma) \) is a random number generated from a gaussian distribution of mean \( \mu \) and sigma \( \sigma \); similarly the pulse height is simply extracted from an uniform distribution between zero and one (\( \text{Uniform}(0, 1) \)). Notice that each pulse has its set of parameters, besides, the spectral indices \( \alpha \) and \( \beta \) are in common for all the pulses and are parameters of the simulated burst. Combining equation 6.4 and Eq. 6.5, for the pulse shape and
using Eq. 6.15 we can obtain a phenomenological description of GRBs. The integrated spectrum is computed by integrating the instantaneous spectrum over the time. In particular, \( N(e) \) is the number of photon per unit of area, computed as:

\[
N(e) = \int_{-\infty}^{\infty} f(t, e) \, dt \quad [\text{ph/keV/cm}^2] \tag{6.18}
\]

It is worth introducing two useful quantities deriving from \( N(e) \). In general, when data are displayed as plots, they are usually binned into histograms with fixed or variable bin widths (for instance logarithmically spaced). While the function \( N(e) \) is invariant for bin width transformation (i.e. rebinning), the quantity \( \Delta e \, N(e) \), obtained by multiplying each value \( N(e) \) computed in the bin center by its bin width is not. The advantage is that it carries direct informations on the data counts. The meaning and the usefulness of this quantity will be clear in the Chapter 8. The quantity \( e^2 \, N(e) \), which is invariant for rebinning, is an estimation of the repartition of the energy as function of the energy. It is a spectral energy distribution function.

The light curve \( L(t) \) in the energy band between \( e_{\text{min}} \) and \( e_{\text{max}} \) is the integral of \( f(t, e) \) over the energy, or:

\[
L(t) = \int_{e_{\text{min}}}^{e_{\text{max}}} f(t, e) \, de \quad [\text{ph/s/cm}^2] \tag{6.19}
\]

for obtaining the counts over a generation area \( A_{\text{gen}} \), the previous equation has to be multiplied by the area \( A_{\text{gen}} \) and the time bin width \( dt \), so that:

\[
C(t) = A_{\text{gen}} \, dt \int_{e_{\text{min}}}^{e_{\text{max}}} f(t, e) \, de \quad [\text{ph}] \tag{6.20}
\]

expresses the photons that illuminate the area \( A_{\text{gen}} \). This quantity is interesting for the aim of this thesis. The generation of photons over an area of 6 m², the area that contains the LAT viewed under any direction, allows to compute the response of the instrument using the Monte Carlo of the detector. \( C(t) \) gives in this sense the direct information about the number of photons that reach the detector (or, better, that reach the area that contains the detector) and corresponds also to the number of photons to process by the Monte Carlo simulation code. Figures 6.5, 6.6, 6.7, and 6.8 show the integrated spectra \( N(e) \), \( \Delta e \, N(e) \) and \( e^2 N(e) \) for some simulated bursts, with different parameters.
Figure 6.5: Simulated spectrum and light curve. Parameters are: \( N_{\text{pulses}} = 1, F_{\text{BATSE}} = 7.7 \times 10^{-7} \text{erg/cm}^2 \). The left panel shows \( N(e), \Delta e N(e), \) and \( e^2 N(e) \), while the right panel shows the light curves for different bandwidth. The four BATSE channels, and the GBM light curve have been displayed, for the low energy range. The high energy light curve corresponds to the LAT energy range (30 MeV, 300 GeV).
Figure 6.6: Simulated spectrum and light curve. Parameters are: $N_{\text{pulses}} = 2$, $F_{\text{BATSE}} = 1.4 \times 10^{-6}\text{erg/cm}^2$. The left panel shows $N(e)$, $\Delta e \ N(e)$, and $e^2 N(e)$, while the right panel shows the light curves for different bandwidth. The four BATSE channels, and the GBM light curve have been displayed, for the low energy range. The high energy light curve corresponds to the LAT energy range (30 MeV, 300 GeV).
Figure 6.7: Simulated spectrum and light curve. Parameters are: $N_{\text{pulses}} = 10$, $F_{\text{BATSE}} = 1.3 \times 10^{-7}$ erg/cm$^2$. The left panel shows $N(e)$, $\Delta e$, $N(e)$, and $e^2 N(e)$, while the right panel shows the light curves for different bandwidth. The four BATSE channels, and the GBM light curve have been displayed, for the low energy range. The high energy light curve corresponds to the LAT energy range (30 MeV, 300 GeV).
Figure 6.8: Simulated spectrum and light curve. Parameters are: \( N_{\text{pulses}} = 100 \), \( F_{\text{BATSE}} = 8.7 \times 10^{-6}\text{erg/cm}^2 \). The left panel shows \( N(e) \), \( \Delta_e N(e) \), and \( e^2 N(e) \), while the right panel shows the light curves for different bandwidth. The four BATSE channels, and the GBM light curve have been displayed, for the low energy range. The high energy light curve corresponds to the LAT energy range (30 MeV, 300 GeV).
Figure 6.9: Spectral evolution as a function of time. The spectra are taken from the simulated burst of Fig. 6.5 at different time (increasing, from top left to bottom right), and represents the instantaneous \( e^2 N(e) \) spectrum. The fourth plot is the instantaneous spectrum at the peak. In this case the spectral indices of the integrated spectrum are \( \alpha = -2.25 \) and \( \beta = -1 \). At peak time \( (t = t_0) \) the instantaneous spectrum is harder than the integrated spectrum and the spectral indices are \( \alpha' = -1.85 \) and \( \beta' = -0.6 \).
Chapter 7

The GRB physical model

For "physical model" I mean the description of an astrophysical source starting from the physical processes, and from the knowledge of the source dimensions, energetics and distance. A key point of the physical model approach is that the emission processes are studied and their formal theory is applied, taking into account the particular source set-up, for computing the observed spectrum. There are no extrapolations from observed quantities to unobserved quantities, at least without taking into account the physics possibility of such extrapolation. This is the main difference with compare to the phenomenological approach described in the previous Chapter, where the unobserved quantities (high energy range) are obtained by extrapolating from the observed quantities (low energy range), without considering the plausibility of the extrapolation. Nevertheless, the physical model approach allows one to correlate observed quantity, such as the temporal structure or the spectral shape to physical quantities (such as the typical dimension of the source or the energetics reservoir). On the other hand, the physical model approach requires simplifications, or worse, is strongly affected by the assumptions. This produces a bias and generates a model dependence (by definition) on the observable quantities to the parameters of the model. In the particular case of Gamma-Ray Bursts, the subject is the high energy astrophysics and the main problem, of crucial importance is the acceleration of particles to high energies. The observed high energy photons are indeed produced from accelerated particles, via non-thermal radiation (the observed spectrum is typically different from a black-body spectrum). In the model developed here the acceleration of particle is obtained via shock mechanism, converting of the kinetic energy of two shells of matter emitted from a central engine, into accelerated particles. The particles lose their energy by emitting radiation.

In this Chapter I will describe the physics of the model, the assumption and the basic formulas that I have used for describing a Gamma-Ray Burst. I have reserved two appendixes for deepening the general concept adopted in this chapter; in particular I present the shock dynamics in Appendix A while the theory for synchrotron and Inverse Compton radiation from a distribution of particles which are cooling rapidly is presented in Appendix B.

As in the case of the phenomenological model, the GRB physical model can be used within the structure of the GLAST LAT software and photons extracted accordingly to the flux and to the predicted light curves can be sent to the Monte Carlo of the detector and processed in order to obtain the simulated response of the instrument. In the next Chapter I will focus the attention on the algorithm needed for extracting photons from transient flux, and I will describe the interaction between the GRB simulators and the Monte Carlo for the LAT experiment. The series of developed classes has been plugged into the Monte Carlo code thanks to the software infrastructure called Gaudi
which represents basically the skeleton of GLAST simulation software and it acts as a sequencer for different processes and services.

7.1 The fireball model

For Gamma-Ray Bursts, several models have been developed, starting from different hypothesis and describing different scenarios. One of the most creditable model is the fireball model introduced by Piran, 1999 [74], starting from the evolution of a relativistic expanding shell. (For a complete review of the Fireball model, see also [75]). A good analytical description of a relativistic expanding shell has been provided by Blandford and McKee [76] commonly know as the Blandford- McKee self similar solution. They predict a first expansion phase, determined by an acceleration period due to radiation pressure from the central engine (which is actively radiating), up to a certain distance for which the shell became transparent to the radiation. At this phase the evolution of the shell is mainly with constant Lorentz factor. The requirement of having a relativistic expanding shell comes from the necessity to bypass the compactness problem. Consider a burst with a typical cosmological distance $D$ and fluence $F$, and to estimate the average opacity of the high energy gamma-ray to pair production. The total energy released from the burst is $E = 4\pi D^2 F$ which is, typically:

$$E = 4\pi D^2 F = 10^{50} \text{ergs} \left( \frac{D}{3000 \text{ Mpc}} \right)^2 \left( \frac{F}{10^{-7} \text{ergs/cm}^2} \right). \quad (7.1)$$

The rapid temporal variability on a time scale $\delta T \approx 10^{-2} \text{sec}$ can be used to derive the typical source size, $R_t < c\delta T \approx 3000$ km. The $\gamma$-rays (with energy $E_1$) may interact with lower energy photons (with energy $E_2$) and produce electron-positron pairs via $\gamma\gamma \to e^+e^-$ if $\sqrt{E_1E_2} > m_e c^2$. If $f_p$ is the fraction of photon pairs $(E_1, E_2)$ that satisfy this condition, then the average optical depth for this process is [74]:

$$\tau_{\gamma\gamma} = \frac{f_p \sigma_T F D^2}{R_t^2 m_e c^2},$$

or, expressing all the variables normalized to their typical values,

$$\tau_{\gamma\gamma} = 10^{13} f_p \left( \frac{F}{10^{-7} \text{ergs/cm}^2} \right) \left( \frac{D}{3000 \text{ Mpc}} \right)^2 \left( \frac{\delta T}{10 \text{msec}} \right)^{-2}, \quad (7.2)$$

where $\sigma_T$ is the Thompson cross-section. With typical values the optical depth for pair production is large, and there should not by high energy detected photons! However, the observed non-thermal spectrum indicates that the source is optically thin, and for accomplish this the optical depth $\tau$ should be less than the unity! A simple argumentation has been introduced for bypassing this apparent problematic. If we consider a bulk Lorentz factor $\Gamma = 1/\sqrt{1 - \beta^2} \gg 1$ then the energy of the emitted photon (at the source) is blue-shifted by a factor $\Gamma$, or $e_{em} \approx e_{obs}/\Gamma$. Since the energy at the source is lower, fewer photons have enough energy to produce pairs. In particular, assuming a high energy spectral index $\alpha$ then the fraction of photons that can produce pairs is smaller by a factor $\Gamma^{-2\alpha}$. Nevertheless, the relativistic effect allows the radius from which the radiation is emitted to be larger than the original estimation of a factor $\Gamma^2$, or $R_e < \Gamma^2 c \delta T$. We can now recompute the optical depth for the pair production taking into account the effect of the relativistic motion of the emitter. We have

$$\tau_{\gamma\gamma} = \frac{f_p \sigma_T F D^2}{\Gamma^{2\alpha} R_e^2 m_e c^2},$$
or
\[
\tau_{\gamma\gamma} \approx \frac{10^{13}}{\Gamma^{(4+2n)}} \int_p \left( \frac{F}{10^{-7} \text{ergs/cm}^2} \right) \left( \frac{D}{3000 \text{ Mpc}} \right)^2 \left( \frac{\delta T}{10 \text{ msec}} \right)^{-2},
\]
(7.3)
where the relativistic limit on \( R_e \) was included in the second line. The compactness problem can be resolved if the source is moving relativistically towards us with a Lorentz factor \( \Gamma > 10^{13}/(4+2n) \approx 10^2 \).

In the most schematic view of the fireball model, a hidden central engine emits "shells" of matter (plasma) into the interstellar medium with relativistic bulk Lorentz factors. If the central engine emits shells with different velocities, a faster shell can reach a slower one and produce a shock. The dissipated energy can be used both to accelerate particle and to generate magnetic fields. Charged particles in magnetic fields lose energy via synchrotron emission and, eventually, can boost the synchrotron photons via inverse Compton scattering producing high energy photons. In our simulations we are interested in the studies of the temporal variability during the prompt emission of GRBs. The fireball model in the internal shocks scenario gives a natural explanation to this feature.

With respect to the overall description of the fireball and to the complexity of the problem in the treatment of the evolution of the fireball our model is schematic. Since our main purpose is to develop a source simulator within the GLAST/LAT software, and since the basic requirements are the flexibility, and a rapid computational time, in the development of the physical model, we often approximate exact solutions with simple functions (power laws, exponential cut-off), avoiding the computation of integrals which always requires computational time. Nevertheless our model well reproduce the observed quantities and, moreover, is fully integrated in the GLAST simulation software.

7.2 Shell

Each shell is determined by its distance from the central source \( R \), its thickness \( \Delta R \), its total energy \( E \), its mass \( M \), and its Lorentz factor \( \Gamma \). After the initial stage of acceleration the shells evolve with constant speed following the law:

\[
R(t) = R_0 + c\beta t
\]
(7.4)

\[
\beta = \sqrt{1 - \frac{1}{\Gamma^2}}
\]

It is useful to introduce the parameter \( t_v \) which expresses the typical time scale of the central engine activity of ejecting material. This time scale can be correlated with the typical dimensions, such as the initial separation between shells and the typical shell's width, both are of the order of \( c t_v \).

Fig. 7.1 is a schema that shows the evolution of the shells in the distance-time plane. There are nine shell emitted (numerated from 1 to 9) at the same radius (the initial radius \( R_0 \)) at different time \( (t_v, 2t_v, 3t_v, \ldots) \). The time here is measured by an observer located at the central engine (at rest with respect to us). Each red line is a trajectory of a shell. The inclination of each line is the velocity of the shell: assuming the speed of light equal to one the 45° lines represent the trajectory of the light. Lines steeper then 45° are trajectories clearly not possible. Let's focus our attention on the first two shells. The first is emitted at \( t = 0 \) and the second at \( t = t_v \). The second shell is moving faster than the first emitted shell, so that calling their velocities \( \beta_F \) and \( \beta_S \) for the fast
and for the slow shell, their initial distance at \( t = t_v \), when the second shell has been emitted from the central engine, is:

\[
D = \beta_S t_v c. \tag{7.5}
\]

This distance will be covered after a time \( t_{sh} \), at which a collision (shock) occurs. This time is measured from an observer at rest in the central engine reference frame, and is given by the following equation:

\[
t_{sh} = \frac{D}{c(\beta_F - \beta_S)} \tag{7.6}
\]

The shock radius is simply:

\[
r_{sh} = t_{sh} \beta_F c = \frac{D \beta_F}{\beta_F - \beta_S} \tag{7.7}
\]

In our schematic view, \( t \) and \( r \) are the horizontal and vertical axes, and the shock times and radii are shown as horizontal and vertical dashed lines (T1-R1, T2-R2, T3-R3 and T4-R4). The numbering is so that are \( T1 < T2 < T3 < T4 \) in the central engine reference frame. Notice that \( T1 = t_v + t_{sh} \) and \( R1 = r_{sh} \). The time measured by an external observer far away from the burst site is slightly different from the time measured at the central engine, although the two frames are not moving one with respect to the other. There is a propagation effect, that plays a crucial role in the determination of the temporal behavior of GRB. Every event characterized by an \( T = R \) (with \( c=1 \)) lies on the bold line at 45°. That means that every pair of events \( T' = R' \) and \( T'' = R'' \) will appear at the same time in a distant reference frame (like the Earth). A distant observer will measure the temporal distance between a hypothetical signal propagating at the speed of light (the “Time=Distance” line) and the point of coordinates (R,T). In
practice, each shock will happen in the reference frame of a distance observer at time $t_{\text{obs}}$, related to the quantities in the central engine reference frame by the relation:

$$t_{\text{obs}} = t_{\text{sh}} - \frac{r_{\text{sh}}}{c} = t_{\text{sh}}(1 - \beta_F) = \frac{\beta_st_v(1 - \beta_F)}{\beta_F - \beta_S} \quad \text{(7.8)}$$

This result shows how the variability of the central engine is reflected in the variability of the light curve. In particular, when the condition $\beta_F > \beta_S \sim 1$ holds, then $t_{\text{obs}} \sim t_v$. Since that the typical variability is in a range from fraction of second to millisecond, then $t_v=1-0.01$ s and D~ $10^{10} - 10^8$ cm. The series of observed times is depicted in the schema as blue horizontal bold lines. The label $t_1$, $t_2$, $t_3$, $t_4$ are the observed shock times, sorted as they appear in the observed reference frame. Notice that the order of the last two shocks are inverted from the central engine frame and the observer frame.

### 7.3 Shock

A detailed simulation of the physics of the shock is difficult and required complicated codes, but, a well description of the quantities which describe a shock has been done by [77]. The general problem of the two shell’s shock can be viewed as follows.

Let $S_2$ be a shell that collides against the slower shell $S_1$. $\Gamma_1$, $R_1$, $\Delta R_1$, $m_1$, and $E_1$ are the Lorentz factor, the radius, the thickness, the rest mass, and the total energy of the shell $S_1$ (fastest), while the same quantities but with the index 2 are refereed to the shell $S_2$ (slower).

The merged shell has the following quantities, as a function of the two colliding shells:

| Radius $R$ | $R = R_2$ |
| Thickness $\Delta R$ | $\Delta R = (\Delta R_1 + \Delta R_2)/2$ |
| Mass $M$ | $M = m_1 + m_2$ |

In this simple model of colliding shells, the fast shell is replaced with a new shell with a compression in density. In particular I assume that the shells are compressing to conserve the thickness. This is equivalent to a compression ratio of about 2, dependently on the ratio between the radius of the shell and its thickness. Assuming the ideal case of spherical shells, the final to initial density ratio is:

$$\eta = \frac{(\Delta R_1 + \Delta R_2 + R_2)^3 - R_2^3}{\left(\frac{\Delta R_1 + \Delta R_2}{2} + R_2\right)^3 - R_2^3} \xrightarrow{\Delta R / R \ll 1} 2 \quad \text{(7.9)}$$

The available total energy before the shock is:

$$E_i = (\Gamma_1 m_1 + \Gamma_2 m_2)c^2, \quad \text{(7.10)}$$

while after the shock is $(m_1 + m_2 + \mathcal{M})\Gamma_f$, where $\mathcal{M}$ is the mass equivalent of energy dissipated by the shock. The initial momentum is given by $m_1 \sqrt{\Gamma_1^2 - 1} + m_2 \sqrt{\Gamma_2^2 - 1}$ while the momentum after the shock is $(m_1 + m_2 + \mathcal{M})\sqrt{\Gamma_f^2 - 1}$. The conservation of momentum and energy can be written as:

$$\begin{cases} m_1\Gamma_1 + m_2\Gamma_2 = (m_1 + m_2 + \mathcal{M})\Gamma_f \\ m_1 \sqrt{\Gamma_1^2 - 1} + m_2 \sqrt{\Gamma_2^2 - 1} = (m_1 + m_2 + \mathcal{M})\sqrt{\Gamma_f^2 - 1} \end{cases} \quad \text{(7.11)}$$
The total energy of the resulting shell is: \( E_f = (m_1 + m_2 + \mathcal{M}) \Gamma_f c^2 = \mathcal{M} \Gamma_f c^2 \). Therefore, the internal energy dissipated during the merging of the two shells, is simply given by the difference between the initial and final energies \( E_{int} = E_i - E_f = \mathcal{M}/c^2 \). This is the energy dissipated by the shock. Solving the previous equations as a function of \( \mathcal{M} \) and \( \Gamma_f \), one obtains:

\[
\begin{align*}
\mathcal{M} &= \sqrt{m_1^2 + m_2^2 + 2m_1m_2(\Gamma_1 \Gamma_2 - \sqrt{\Gamma_1^2 - 1} \sqrt{\Gamma_2^2 - 1})} - (m_1 + m_2) \\
\Gamma_f &= (m_1 \Gamma_1 + m_2 \Gamma_2)/(m_1 + m_2 + \mathcal{M})
\end{align*}
\]  

(7.12)

### 7.4 Internal shocks

The shock’s hydrodynamics require a relativistic treatment for GRBs. A shock can usually be seen as a discontinuity surface, where the pressure, the particle density, and the energy density are discontinuous. These variables can be computed by solving the “jump” conditions of Rankine-Hugoniot which, in the case of relativistic shock, are called Taub conditions. As exercise, the solution is presented in Appendix A for the case of a perfect fluid in the ultra-relativistic approximation. In the internal shocks scenario, the shells have comparable densities and the Lorentz factor of their relative motion is of the order of a few \( (\gamma_{12} < 10) \). Internal shocks are only mildly relativistically and a general adiabatic equation of state has to be used. In particular, if \( \gamma_{12}, n_{12} \) and \( e_{12} \) are the Lorentz factor, the particle density and the energy density of the fast shell as measured from the slow shell (upstream region), then, the Lorentz factor of the shock front \( (\gamma_{sh}) \), the post-shock density \( (n_{sh}) \) and the internal energy in the post-shock region \( (e_{sh}) \) are, for an adiabatic index \( (4/3) \):

\[
\begin{align*}
\gamma_{sh} &= \sqrt{(\gamma_{12}^2 + 1)/2} \\
n_{sh} &= 4\gamma_{sh} n_1 \\
e_{sh} &= 4\gamma_{sh}^2 n_1 m_p c^2
\end{align*}
\]  

(7.13)

This energy represents the supply of energy available in the comoving frame of the shell. This energy is used for accelerating particles, and for generating turbulent magnetic fields. The acceleration of particles via relativistic shocks and the generation of magnetic field in a shocked plasma are processes that are still not at all understood, despite the numerous research on GRB and our poor knowledge is reflected by the assumption of *equipartition*. It is commonly assumed that the energy that goes into the magnetic field and the energy that goes into accelerated particle are constant fractions of the internal energy behind the shock [78, 79]. Two constants are introduced for describe this quantities:

\[
\begin{align*}
u_b &= \alpha_B e_{sh} \\
u_e &= \alpha_e e_{sh}
\end{align*}
\]  

(7.14)

From the first equation, the value of the magnetic field can be easily obtained:

\[
B = \sqrt{8\pi\alpha_B e_{sh}}
\]  

(7.15)

Electrons and positrons are accelerated according to a power law distribution:

\[
N(\gamma) = C\gamma^{-p}d\gamma, \text{ with } \gamma_{min} \leq \gamma \leq \gamma_{max}
\]  

(7.16)
The values for the minimum Lorentz factor and from the constant $C$ can be obtained by solving these two equations:

\[
\begin{align*}
\int_{\gamma_{\text{min}}}^{\gamma_{\text{max}}} N(\gamma)d\gamma &= N_e^+ = n_{sh} V \\
\int_{\gamma_{\text{min}}}^{\gamma_{\text{max}}} m_e c^2 \gamma N(\gamma)d\gamma &= E_e^+ = e_{sh} V
\end{align*}
\]  

(7.17)

Assuming $\gamma_{\text{max}}$ much bigger than $\gamma_{\text{min}}$ the previous equations give:

\[\gamma_{\text{min}} = \frac{p - 2 m_p c^2}{p - 1} \alpha e \gamma_{sh} \]

(7.18)

In general, the maximum Lorentz factor of the accelerated electrons can be fixed by computing the "shock drift", or the energy an electron would acquire on drifting through the potential drop along the shock [80]:

\[m_e c^2 \gamma_{\text{max}} \approx e V_{sh} \approx e (v \times B) R_{sh}/c \approx e B R_{sh}, \]

(7.19)

where the velocity is $v \approx c$. The value for the maximum Lorentz factor in the case of intense magnetic field ($B \approx 10^5$) and for internal shocks ($R_{sh} \approx 10^{14}$), is very large:

\[\gamma_{\text{max}} \approx 10^{15} \left( \frac{B}{10^5} \right) \left( \frac{R_{sh}}{10^{14}} \right) \]

(7.20)

which yields a characteristic synchrotron energy greater than $10^{23}$ eV! This approach is useful only as an upper limit. In other words, the shock mechanism, in the presence of such intense magnetic fields, can accelerate electrons up to enormous energy. The limitation of this approach is that it does not consider the loss of energy due to the synchrotron radiation. Therefore, the maximum value for the Lorentz factor of the accelerated particles has to be determined by balancing the acceleration time for electrons with the cooling time scale ([81]). The synchrotron cooling time is determined by Eq. B.4, which expresses the time that an electron of energy $\gamma m_e c^2$ takes to lose half of its energy. The minimum acceleration time is given by $t_{\text{acc}} = 1/\nu_c$, where $\nu_c$ is the synchrotron characteristic frequency ($\nu_c = e B/2\pi \gamma m_e c$). Equating these two quantities, one obtains:

\[t_{\text{acc}} = \frac{2\pi \gamma M m_e c}{e B} = t_{\text{syn}} = \frac{3 m_e^3 c^5}{2 e^3 B^2 \gamma M} \]

(7.21)

Solving in $\gamma_M$:

\[\gamma_{\text{max}} = \frac{3.78 \times 10^7}{\sqrt{(B)}} \]

(7.22)

It is interesting to notice that the observed synchrotron characteristic energy can be computed from the emitted synchrotron energy (Eq. B.2) and from the doppler shift due to the relativistic motion of the emitter (which is moving with Lorentz factor $\Gamma$). Apart from numerical constants, the characteristic energy corresponding to $\gamma_{\text{max}}$ is independent of the magnetic field $B$ and depends only on the Lorentz factor of the emitter. Numerically:

\[E_M = 25 \Gamma M eV \]

(7.23)

This result, discussed in appendix B, determines a cut-off in the synchrotron spectrum at energies above $E_M$. It is worth to notice that a similar calculation has been done by
Figure 7.2: The broadband Crab nebula spectrum from 100 keV up to 100 TeV. From [81].

[80, 81] studying the Crab nebula high energy spectrum. The flow velocity associated with the inner nebula is \( \beta \approx 1/\sqrt{3} - 1/3 \approx 0.24 \), yielding a synchrotron cut-off around 25 MeV. The observation of this cut-off in the Crab nebula spectrum seems to be realistic. Fig. 7.2 taken from de Jager et al.,[81] shows the broad band spectrum for the crab nebula, with a cut-off of the synchrotron component around 25 MeV. Applying this calculation to the specific case of GRBs, the energy \( E_M \) is shifted to higher energy due to the Doppler effect. The region where the electrons are accelerated is moving towards us with a Lorentz factor of the order of a few hundreds, resulting in a cut-off energy of the order of the tens of GeV. This cut-off does not affect the spectrum at low energy, and could not be observed by BATSE (and will not affect the spectrum in the GBM energy range). On the other hand it affects the spectrum at LAT energies. The measurement of the position of this cut-off in the high energy tail of the synchrotron spectrum can give an indirect estimation of the Lorentz factor of the expanding fireball.

7.5 Time Scales

Temporal structure of GRB can be well understood by studying the temporal scales of the emitting regions. Relativistic corrections has to be apply in order to consider observed quantities. In particular the Doppler shift and the relativistic beaming determine the observed shape and observed intensity of an expanding fireball. There are two reference frame involved, but three transformations between times. The first frame is the shell comoving frame. I will indicate the time intervals as measured from an observer comoving with the shell as \( dt' \). The second frame is the central engine, located at the center of the expanding fireball. Let's indicate with \( dt \) the interval of times measured by an observer located in this reference frame. Between these two reference frame the time interval and the length scales transform with the Lorentz transformation:

\[
dt = \Gamma dt'
\]

\[
\Delta = \Delta' / \Gamma
\]  

(7.24)
Figure 7.3: There are two reference frames but three transformations. The reference frames are the emitting region (the shell) expanding relativistically, the central engine, located at the origin of the explosion. A distant observer is in the same reference frame of the central engine (no relative motion apart the expansion of the Universe, not considered here). There is anyway a transformation due to a pure propagation effect. The transformation of time interval between the shell’s comoving reference frame and the central engine is pure relativistically: if $dt'$ is the interval of time measured in the shell’s frame, then an observer located at the central engine will measure an interval of time: $dt = \Gamma dt'$ (left panel). An observer located far from the GRB site (on the Earth), will measure an interval $dt_{\text{obs}} = (1 - \beta \mu) dt = (1 - \beta \mu) \Gamma dt'$. 

There are another reference frame which we have to take into account, the observer reference frame, located at the Earth, far away from the burst. For it the time interval is $dt_{\text{obs}}$. Let’s consider a shell expanding with a velocity (in unit of $c$) $\beta$. Two signals are emitted at $R(t_1)$ and $R(t_2)$ from A and B (Fig. 7.3, left panel). An observer located at the central engine will measure an interval, $dt = (t_2 - t_1)$ corresponding to the dashed bold line in the left panel of Fig. 7.3 (an observer comoving with the fireball will measure an interval $dt' = dt/\Gamma$, due to Lorentz transformation. An observer located far from the GRB site (on the Earth), will measure a smaller interval because the signal and the expansion of the shell happen in the same direction (right panel of Fig. 7.3). Thus, the observed interval is $dt_{\text{obs}} = (1 - \beta \mu) dt$. The relations between the observer frame ($dt_{\text{obs}}$) and the shell’s comoving frame ($dt'$) is:

$$dt_{\text{obs}} = (1 - \beta \mu) dt = (1 - \beta \mu) \Gamma dt'$$  \hspace{1cm} (7.25)

Fig. 7.4 illustrates another propagation effect, due to the temporal distance between a photons emitted at A, along the line of sight, and a photon emitted at B, de-centered of an angle $\theta$ from the line of sight. The time lag between a photon emitted in A and a photon emitted in B is $dt_{\text{obs}} = R/c(1 - \mu)$ with $\mu = \cos(\theta)$. In case of relativistic fireball the opening angle $\theta$ is related to the Lorentz factor $\Gamma$ due to relativistic beaming. In particular $\theta \approx 1/\Gamma$. Morover, if $\Gamma \gg 1$ the approximation at small angle can be done: the cosine of the beaming angle can be approximated to second order as:

$$\mu \rightarrow 1 - \frac{1}{2\Gamma^2},$$  \hspace{1cm} (7.26)

and the transformations between the comoving frame, the central engine frame, and the observer frame are:

$$dt_{\text{obs}} = (1 - \beta \mu) dt \approx \frac{dt}{2\Gamma^2} = \frac{dt'}{2\Gamma}$$  \hspace{1cm} (7.27)

The characteristic time scales are:
The angular time lag is a propagation effect due to the time lag between a photon emitted at A and a photon emitted in B.

- The **hydrodynamic time**. If $\beta_{sh}$ is the shock’s velocity in the shell reference frame, then the comoving hydrodynamic time scale is just the time that the shock takes to cross the shell of comoving width $\Delta'$: $t'_{hyd} = \Delta'/(c\beta_{sh})$. The observed hydrodynamic time scale is shorter by a factor $\sim 1/(2\Gamma)$, thus, the observed hydrodynamic time is:

$$t_{hyd} = \frac{\Delta}{2c\beta_{sh}}$$  \hspace{1cm} (7.28)

- The **angular spreading** is the time difference between a photon emitted from the line of sight of the shell, and of a photon emitted from an angle $1/\Gamma$ from the line of sight. If $1/\Gamma$ is small then the small angle approximation can be applied and the time difference is:

$$t_{ang} = R/(2c\Gamma^2)$$  \hspace{1cm} (7.29)

- The **cooling time**. In the case of synchrotron emission the cooling time is given by eq. B.4. Note that the synchrotron cooling time depends on the electron energy, as the observed synchrotron energy does (Eq. B.2). This introduce a temporal dependence of the spectrum since that at higher energy the electrons cool more rapidly than at lower energies. If the pulse shape is affected somehow from this temporal scale, the pulses has to be narrower at higher energies. This seems to agree with the observations [63].

In general, the characteristic spreading of the pulses in GRB will be the summation of these different contributions:

$$t_{shape} = \sqrt{t_{hyd}^2 + t_{ang}^2 + t_{sym}^2}$$  \hspace{1cm} (7.30)

here $t_{shape}$ determines the width of the pulse associate to a shock. In GRB the cooling time is much shorter than the hydrodynamical time scale, which is shorter than (or of the same order of) the angular time spreading $t_{ang}$. Thus, the dominant contribution is determined by the geometry of the shell, not by its cooling time scale. To be notice that, if the shells are emitted with mean Lorentz Factor $\Gamma$, and the spread between the minimum and the maximum Lorentz Factor is again $\Gamma$ and their initial separation is $R_0$ (reflecting an intrinsic variability of the source on the order $t_v = R_0/c$), then the mean shock’s radius is at $R_{sh} \simeq R_0\Gamma^2$. Using equation 7.29, one easily obtains the relation:

$$t_{ang} \simeq R_{sh}/(2c\Gamma^2) \simeq R_0/(2c) \simeq t_v$$  \hspace{1cm} (7.31)
If the angular spreading time is the dominant contribution, one obtain a very important result: the observed pulse shape reflect the variability of the source (without any Lorentz transformation). Thus, the initial separation between shells \( R_0 \) can be estimated from this argument and \( R_0 \approx [10^7, 10^{10}] \) cm) considering the typical observed variability.

### 7.5.1 The pulse shape

A simple model can be derived from study the complex problem of the pulse shape. In general each spiky element in the GRB light curve is the summation of the contributions of different region of the fireball, connected by the property of “equal arrival time”. In practice, to compute the instantaneous spectrum at a certain time, one should consider all the surface of the fireball that emits at different time and at different position in space, whose photons reach the observer at the same time. This problem can be idealized as follow: the fireball can be approximated as a thin shell, ideally spherical, and it is expanding with a Lorentz factor \( \Gamma \). If the speed of the shell is \( \beta = \sqrt{1 - 1/\Gamma^2} \) then its radius at time \( t \) (as measured from the central engine reference frame) is:

\[
R(t) = R_0 + \beta ct
\]  

(7.32)

Where \( R_0 \) is the radius at which the shock occurs (and at which the shell can be visible). The shock crossing time is \( t_{\text{hyd}} = \Delta/(2c\beta_{\text{sh}}) \) with \( \Delta \) the width of the shell and \( \beta_{\text{sh}} \) the shock speed inside the shell. In the hypothesis that \( t_{\text{syn}} \) is much shorter than the hydrodynamical time scale, then \( t_{\text{hyd}} \) determines the casting time of the shell, or, in other words, the time during which the shell is emitting radiation. The final radius at which the shell emits is:

\[
R_f = R_0 + \beta ct_{\text{hyd}}
\]  

(7.33)

The photons emitted at time \( t \) from the point \( R(t) \) on the line of sight, will reach the observer together with the photons emitted at time \( t - \tau \) from the position \( x, y \) (or \( \rho, \theta \)) (see Fig.7.5). The light emitted at \( t - \tau \) from \( \rho, \theta \) has travelled a distance \( c\tau \) while the shell has increased its radius of \( c\beta\tau \). At every instant \( t \) there is a locus of point (a surface) that represents the surface of equal arrival time (isochrone). The two equations that describe the surface in terms of the look back time \( \tau \)

\[
\begin{align*}
\mu\rho(\tau) + c\tau &= R(t) \\
\rho(\tau) + c\beta\tau &= R(t)
\end{align*}
\]  

(7.34)

where we have defined \( \mu = \cos(\theta) \). From the previous equations and from Eq. 7.32, we obtain:

\[
\begin{align*}
\rho &= R_0 + c\beta(t - \tau) \\
x &= \rho\mu = R_0 + c(\beta t - \tau) \\
\mu &= \frac{x}{\rho} = \frac{R_0 + c(\beta t - \tau)}{R_0 + c\beta(t - \tau)} \\
y &= \rho\sqrt{1 - \mu^2}
\end{align*}
\]  

(7.35)

\( x, y, \rho, \) and \( \mu \) are parametric functions of the parameter \( \tau \). For every time \( t \), \( \tau \) can vary between \( \tau_1 = \text{Max}[0, (R_0 - R_f + ct\beta)/(c\beta)] \) and \( t \) so that \( \rho(\tau_1) = \text{Min}[R(t), R_f] \) and \( \rho(t) = R_0 \).

The analytical solution is depicted in Fig. 7.6 for a thick shell (left) case and for a thin shell case (right). Dimensions are rescaled so that \( c = 1, R_0 = 1 \); for the thick shell
Figure 7.5: Equi-arrival time surface. $R_0$ is the initial radius of the shell, $R(t)$ is the position of the emitting surface (the shock surface) at time $t$, $R_f$ is the surface which correspond to the end of the emission. At this surface the shock has travelled all the shell’s width. The dotted line is the equi arrival time surface, every photon which behaves to this curve, arrives in the same instant at a distant observer. This is a pure propagation effect. $\rho(\tau)$ and $\mu = \cos(\theta)$ are the parametric solution of the equi-arrival time surface (of coordinates $x$ and $y$). The parameter $\tau$ has the meaning of look-back time, so that if $\tau$ equal zero, the photons are emitted at time $t$ from the shell at $\rho(0) = R(t)$, $\theta = 0$, for $\tau$ greater than zero, the photons have been emitted at time $(t - \tau)$ from $\rho(\tau)$, $\theta \neq 0$.

For the case $R_f = 1.5$, while for the thin shell case $R_f = 1.05$. The figure shows the intersection with the emitting surfaces with the “yz” plane (the page sheet). Each dashed line corresponds to a different observed time while the bold circles are the limits $R_0$ and $R_f$ (at $R_0$ the shocks starts and at $R_f$ it has reached the end of the shell). For computing the pulse shape and the emitted radiation one has to consider the Doppler factor $\mathcal{D}$ as a function of the angle. In particular:

$$\mathcal{D}(\mu) = \Gamma(1 - c\beta\mu)$$ (7.36)

for which the emitted energy is: $E_{em} = E_{obs} \mathcal{D}(\mu)$, and the observed power is: $P_{obs} = \mathcal{D}(\mu)^4$.

In general, if $x(t, \tau), y(t, \tau)$ is the parametric equation of the line of equal arrival time at time $t$, and supposing that the emissivity per unit of surface is $\sigma$, then the observed power can be computed with the following integral:

$$P_{obs}(t, c) = 2\pi \int_{\tau_1}^{\tau_f} \frac{y(t, \tau) \sqrt{\dot{x}(t, \tau)^2 + \dot{y}(t, \tau)^2}}{\mathcal{D}(\mu(\tau))^{1/4}} P_{em}(t - \tau, c\mathcal{D}(\mu)) d\tau,$$ (7.37)

where the derivations are in $\tau$. Notice that the above integration is a convolution over the look back time: the observer receives the radiation resulting from the summation of the emission from different region of the shell at different “shell” time. The previous integration cannot be solved using simple methods: nevertheless we can restrict our model to the case of thin shells. In this case the shell emits all its radiation almost instantaneously since that the shock crossing time, in the central engine reference frame, is short. In a distant reference frame, the spike of light will be spread due to angular
Figure 7.6: Analytical solution of the equi-arrival time surfaces (dashed lines) for the thick shell case (left) and for the thin shell case. Bold lines represent the initial radius $R_0$, (when the shocks starts to cross the shell), and the final radius $R_f$, when the shocks reaches the end of the shells. In units where $c = 1$, $R_0 = 1$ while $R_f = 1.5$ for the thick shell case (left), and $R_f = 1.05$ for the thin shell case (right).

Figure 7.7: Three dimensional representation of the emitting surfaces at different observed time, in the case of thin shells.
spreading on time scales equal to $t_{\text{ang}}$. Analytically, we can imagine that in this case the equal arrival time surfaces are reduced to circle with radii $r(t) = y(t) = R_0 \sin \theta(t) = R_0 \sqrt{1 - \mu(t)^2}$, where $\mu(t) = 1 - ct/R_0$ and the surface emissivity $\sigma$ is replaced by the linear emissivity $\ell$. The above integration can be replaced by the following equation:

$$P_{\text{obs}}(t,e) = 2\pi R_0 \ell \frac{\sqrt{1 - \mu(t)^2}}{D(\mu(t))^4} P_{\text{em}}(eD(\mu(t))) \tag{7.38}$$

I have also used the emitted radiation $P_{\text{em}}(eD(\mu(t)))$, which is the integrated emission between $t = 0$ and $t = t_{\text{hyd}}$. In practice, in the approximation of spherical expanding shells, the thin shell case can be viewed as a circular region around the line of sight of radius which is increasing with time due to the lag introduced by the angular spreading. The spectrum of the emitted radiation is integrated up to the dynamical time scale (which is characterized by the shell’s width). This integration is of course possible only if the cooling time is shorter than the hydrodynamical time scales, a condition that is called fast cooling regimes. On the other hand, if the cooling time is longer than the hydrodynamical time scales the shell will radiate on longer time scales, determined by the cooling time, and the expansion will became significant so that the shell can not be simplified as “thin”. This can happen more likely in AGN, where the values of the magnetic fields are much smaller than in the case of Gamma-Ray Bursts.

The linear emissivity $\ell$ is depending on the radius $R_0$. If the total luminosity of the shell is not depending on the radius, then $\ell$ scales as $1/R_0$, and $P_{\text{obs}}(t,e)$ does not depend on the radius at which the shock occurs. Under this hypothesis the intensity of the pulses does not depend on the radius at which they occur. On the contrary, the duration of the pulses depends on the radius $R_0$, through the definition of $\mu(t) (\mu(t) = 1 - ct/R_0)$. The observed power $P_{\text{obs}}(t,e)$ can be written as the product between a pulse shape function $P(t)$ and a spectral shape function $S(t,e) = P_{\text{em}}(eD(\mu(t)))$ Fig. 7.8 shows the pulse shape $P(t/t_{\text{ang}})$. The spread of the pulse shape is determined by the angular spreading time. It is interesting to notice that, if the initial separation between the pulses is given by $t_v c \sim D$, then the typical separation between pulses is on the same order of $t_v$. Nevertheless the collision radius $R_0$ is approximately equal to $D\Gamma^2$, and the angular spreading is on the order of $t_{\text{ang}} \sim D/c \sim t_v$. This is a very interesting result because both the interval between pulses and the pulse width are of the same order. The variability time $t_v$ determines uniquely these two time scales. This result is important if compared with the observed distributions of the interval between pulses and of the full width half maximum, shown in the previous chapter. Both these time scales are of the same order.

Similar result has been obtained by Piran(1999) and Piran(2004), who concludes that the resulting spread of an instantaneous peak from a blast-wave is proportional to the angular spreading time [75, 74].
Figure 7.8: Pulse shape normalized to its maximum as a function of $t/t_{\text{ang}}$. 

$P/P_{\text{Max}}$ vs $T/T_{\text{ang}}$.
7.6 Emission Processes

The accelerated electrons live in a region where magnetic field are presents, and they lose energy by synchrotron radiation. Eventually, synchrotron photons can be up scattered via Inverse Compton by the electrons and a high energy component can be produced. In the model developed during this work both processes have been taken into account. A more detailed treatment of synchrotron and Inverse Compton emission processes is presented in Appendix B, while in this Chapter (in the next section) only the final formulas are considered. Accelerated electrons produce a non-thermal spectrum. In this work of thesis the emission spectrum has been studied assuming a power law distribution of electrons between a certain $\gamma_{\text{min}}$ and $\gamma_{\text{max}}$, typical of shock acceleration processes described with a first order Fermi mechanism. Some related reviews on the First order Fermi acceleration mechanism are [82, 83] while for a treatment of the non linear theory of shock’s acceleration, see [84]. Since the radiative processes are taking place in a relativistically moving emitter (the shell), the radiation is boosted to higher energy due to the relativistic doppler factor (as already introduced 7.37). The emission spectrum depends on the value of the distribution of the accelerated electrons (i.e. $\gamma_{\text{min}}, \gamma_{\text{max}}$, and the power law index $p$), and on the hydrodynamical time scale, which characterize the emission time scale. In particular, the emitted synchrotron spectrum from a thin shell whose hydrodynamical time scale is given by Eq. 7.28 will be the result of the integration of the instantaneous synchrotron spectrum from a distribution of electrons which are cooling fast. The Inverse Compton spectrum (in the Synchrotron Self Compton configuration) treatment is simplified; in particular, only one Compton scattering event is considered, assuming that after the first scattering process the energy of the photon high, above the Klein-Nishina regime. A very useful simplification is to consider a monochromatic distribution of electrons, assuming that all the electrons have energy $\gamma_{\text{min}}$. This is not a too stringent assumption since the Compton cross-section decreases with the energy of the scattering electron, and the distribution of electrons are also decreasing with their energy: the most probable scattering will be against low energy electrons. Another assumption in the treatment of the Inverse Compton theory is that the Compton scattering is not affecting the synchrotron scattering, which is a good approximation only if we are interested at high energy. The Inverse Compton process removes low energy electrons from the distribution of accelerated electrons, and produces high energy photons. The overall emission spectrum will be eventually harder, suppressed at energy lower than $\gamma_{\text{min}}$.

7.6.1 Synchrotron

In Appendix B I study the synchrotron emission spectrum firstly from an energetic electron, then I assume that the electron cools rapidly, and I derive the spectrum from a cooling electron. Finally I assume as initial distribution of electrons a power law between $\gamma_{\text{min}}$ and $\gamma_{\text{max}}$ with power law index $-p$. The integrated spectrum can be well approximated with a broken power law, with an exponential decay at high energy, for both fast and slow cooling. In particular, for fast cooling regime:

$$P(e) = \exp \left( -\frac{e}{E_M} \right) \begin{cases} 
\left( \frac{e}{E_c} \right)^{1/3} & e < E_c \\
\left( \frac{e}{E_c} \right)^{-1/2} & E_c < e < E_m \\
\frac{E_m}{E_c}^{-1/2} \left( \frac{e}{E_m} \right)^{-p/2} & e > E_m 
\end{cases}$$

(7.39)
while for slow cooling regime:

\[
P(e) = \exp\left( -\frac{e}{E_m} \right) \begin{cases} 
(\frac{e}{E_m})^{1/3} & e < E_m \\
(\frac{e}{E_m})^{-(p-1)/2} & E_m < e < E_c \\
(\frac{E_m}{E_c})^{-1/2}(\frac{e}{E_c})^{-p/2} & e > E_c 
\end{cases} \quad (7.40)
\]

Notice that in this treatment I do not approximate the upper limit of the Lorentz factor of the accelerated electrons to infinity, thus an exponential cut-off is obtained. For a \( \gamma_{\text{max}} \) large enough (as consequence, large \( E_M \)) the spectra reduce to the usual broken power law proposed by Sari et al. (1998) [85].

### 7.6.2 Inverse Compton

The Inverse Compton process boost up the synchrotron photons by means of scattering against the high energy electrons. Since that the electrons that scatter against the synchrotron photons, belong to the same seed of the electrons that have produced the synchrotron photons, this process is also called “Self Synchrotron Compton” or SSC. The electrons distribution is a power law and the most probable scattering is between the lowest energetic electrons (\( E_m \) against the synchrotron spectrum). In the relativistic case (when the energy of the electrons is much more greater than their rest mass) the photons are up scattered by a quantity \( \sim \gamma^2 \) where the \( \gamma \) is the Lorentz factor of the electrons. For a power law distribution of electrons, a good approximation for the Inverse Compton emission spectrum is to consider its the spectral shape equal to the spectral shape of its “seed” spectrum (i.e. the synchrotron spectrum) boosted at high energy by a factor \( \gamma_{\text{min}}^2 \). Additionally the conservation of the energy before and after the scattering yields to an upper limit for the scattered photon energy. The condition reduces to a high energy cut-off, and the spectrum can finally be computed with the formula:

\[
P_{IC}(e) = \frac{\tau}{\gamma_{\text{min}}^2} P_{\text{syn}}\left( \frac{e}{\gamma_{\text{min}}^2} \right) \exp\left[ -\frac{e}{\gamma_{\text{min}} m_e c^2 \gamma^2} \right], \quad (7.41)
\]
The parameter $\tau$ represents the intensity of the peak of the Inverse Compton component (of the $e \times P(e)$ spectrum) relative to the intensity of the synchrotron:

$$
(\gamma_{\text{min}}^2 E_m P_{\text{IC}}(\gamma_{\text{min}}^2 E_m)) = \tau (E_m P_{\text{syn}}(E_m))
$$

(7.42)

The resulting observed flux for both synchrotron emission and Inverse Compton emission can be finally written as:

$$
P_{\text{obs}}(t,e) = P(t)(P_{\text{syn}}(eD(\mu(t))) + P_{\text{IC}}(eD(\mu(t)))),
$$

(7.43)

where $P$ is the pulse shape (Fig. 7.8), $P_{\text{syn}}$ and $P_{\text{IC}}$ are respectively the synchrotron and the Inverse Compton emission, both computed at the emitted energy ($eD(\mu(t))$) (here $e$ is the observed energy, $D$ the Doppler factor).

### 7.7 The GRB simulator for GLAST

In this section I will describe how the simulator works referring to the physics already described. I will discuss the set of parameters chosen for reproducing the main observables. Constraining the parameters of the model it is indeed possible to reproduce both general properties, such as the distribution of peak energies, and the distribution of the duration, and both some individual properties such as the integrated and instantaneous spectral shape.

The simulator reads the parameter from a file. The parameters are:

- **Seed**: it is the seed for the random number generator. The choice to put this number as parameter arises from the need of being able to reproduce the sequence of random numbers. In particular the extraction of the Lorentz factors of the shells. This number identifies the sequence of their Lorentz factors.

- $l$ is the galactic longitude, from $-180,180$.

- $b$ is the galactic latitude, from $-90,90$.

- **Fluence**: it is the value of the fluence (erg/cm$^2$) in the BATSE energy range (20 keV-1 MeV). This value is used for normalize the spectrum. The idea is indeed to have the possibility to simulate a GRB with a defined value in the BATSE range, and investigate its emission at LAT energies.

- $N_{\text{shells}}$: it is the number of shells to be emitted from the central engine. Greater is the number of shells, greater is the expected number of shocks. It can be set as a number greater than 2 (minimum condition to have a shock). Typically it is smaller than 100.

- $E_{\text{tot}}$. It is the total amount of energy available. Each shell has an energy $E_{\text{shell}} = E_{\text{tot}}/N_{\text{shells}}$ and a mass $M_{\text{shell}} = E_{\text{shell}}/(\Gamma_{\text{shell}}c^2)$. Notice that, since also the fluence is a parameter, the distance of the burst from the satellite is automatically set.

- $R_0$ is the initial separation between the shells. The time when the shock occurs, the spreading time (Eq. 7.29), the energy density and the particles density depend on this parameter. Large value of $R_0$ means low densities and, as a consequence, small value for the peak energy. On the other hand, large $R_0$ means longer bursts. It is related to the interval of time that the central engine is inactive. The typical value for $R_0$ is $10^8 - 10^{10}$.  


- $\Delta R_0$ is the initial thickness of the shells. This scale reflects the activity period of the central engine. The light crossing time of a shell $t_c = \Delta R_0/c$ is correlated with the rise time of the spikes. Typically $\Delta R_0$ is $10^7 - 10^8$.

- $\Gamma_{\text{min}}$ is the minimum Lorentz factor of a shell when emitted ($\sim 100$).

- $\Gamma_{\text{max}}$ is the maximum Lorentz factor of a shell when emitted ($\sim 1000$).

- $\tau$ is the Inverse Compton parameter, it is the ratio between the peak of the IC and of the synchrotron $e^2 N(e)$ spectrum. If $\tau = 0$ the GRB emits only for synchrotron spectrum. $\tau = 1$ corresponds to an equal amount of energy in Inverse Compton and in synchrotron radiation. Generally $\tau$ can vary between 0, and 10. The lower bound is for simulating pure synchrotron GRB, while the upper bound derives from the observation of some AGN (i.e. 3C 279).

The shells are then created accordingly with the parameters. The Lorentz factor of the shells are sampled from an uniform distribution between $\Gamma_{\text{min}}$ and $\Gamma_{\text{max}}$. The evolution of the shells and the radii of the shocks are computed as follows: at each step all the times of each possible shock between consecutive shells are computed, using the relation:

$$t_{\text{shock}} = \frac{D}{\beta_f - \beta_s} \quad (7.44)$$

where $D = R_s - (R_f + \Delta R_f)$ is the distance between a fast shell $f$ and a slower $s$. The minimum $t_{\text{shock}}$ is then stored and all the shells expand for this time. Note that the Lorentz factor of the shell and its thickness is considered constant during the evolution (the radius evolves accordingly with the eq. 7.4). The colliding shells merge together and form a resulting shell. The shocks occur at different radii and at different times, but, since the shells are moving relativistically, an observer at rest with the ISM and far from the burst will observe all the shocks almost simultaneously. In particular, neglecting the distance of the observer from the burst, the time at which a shock occurs is $t_{\text{obs}} = t_{\text{int}} - r/c$ where $t_{\text{int}}$ is the time as measured from the central engine, and $r$ the distance from the central engine (radius of the shock). For each shock, Eq.7.10 is adopted for computing the internal energy, Eq. 7.12 computes the final energy and the Lorentz factor of the resulting shell. The particle density, the energy density and the magnetic fields behind the shock are given by Eq 7.13, Eq. 7.14, and Eq. 7.15. The minimum and maximum Lorentz factors for the electrons distribution are then computed (Eq. 7.18, and 7.22): they are converted into synchrotron and Inverse Compton characteristic energies (Eq. B.2, and Eq. B.21). The synchrotron and Inverse Compton spectrum are simultaneously computed by means of the Eq. 7.43.

A grid of $N_e \sim 50$ bins in energy, logarithmically scaled between a certain value $E_{\text{MIN}} \sim 10\text{keV}$ and $E_{\text{MAX}} \sim 10^9\text{keV}$, and of $N_i \sim 1000$ is computed for storing the flux. Remembering that $P$ is a power per unit of energy and area (keV/s/keV/m$^2$), the number of photons per square meter (1/m$^2$) is given by summing all the contribution for all the shocks:

$$N(t_i, e_j) = \sum_{l=1}^{N_{\text{shocks}}} P(t_i) \left[ P_{\text{syn}}(e_j D(\mu(t_i))) + P_{\text{IC}}(e_j D(\mu(t_i))) \right] / e_j \, de_j \, dt \quad (7.45)$$

where I have used the index $l$ to indicate the sum over all the shocks. This two dimensional histogram contains all the information needed for the remaining simulation. The visualization of the 2D histogram $N(e_i, t_j)$ is in fig 7.10. The computation of the light
curve is now trivial. The counts per square meter between the energy $E_1$ and the energy $E_2$ are given by:

\[ \sum_{i_{1}}^{i_2} N(e_i, t_j) \]  

(7.46)

where $i_{1}$ and $i_2$ are the bin corresponding to the energies $E_1$ and $E_2$. Fig. 7.11 shows the expected light curves for a simulated burst in the BATSE energy range and in the GBM energy range (top panel) and the expected light curve at LAT energies (bottom panel). The fluence (erg/cm$^2$) in computed by summing over the energies between $E_1$, and $E_2$:

\[ \sum_{i_{1}}^{i_2} E_i N(e_i, t_j) \text{(keV/m}^2 \rightarrow \text{erg/cm}^2) \]  

(7.47)

where I have also put the conversion factor.

The spectral shape in the GBM energies remains unchanged. I have performed a fit using the Band model for spotlight that the spectral shape is in agreement with the BATSE observations. The LAT detector is contrariwise been affected by the different intensities of the Compton peak. The joined observation and the joined fit of the GRB spectrum will estimate the relative importance of this high energy “extra” component. The overlapping region between GBM and LAT energy ranges will certainly help the calibration of the fluxes in order to broadly resolve the GRBs spectra.

The number of theoretical generated photons and the expected fluence for GBM and LAT can be computed. For this particular burst the dependence of the flux and number of expected photons in the LAT energy range with the parameter $\tau$ that varies between 0, and 1 are depicted in Fig. 7.14.
Figure 7.11: Light curves for a simulated burst. Top panel: Low energy light curves: The four BATSE energy channels (20-50 kev, 50-100 keV, 100-300 keV, 300-1000 keV) and the total GBM light curve (10 kev-30 MeV). Bottom: expected light curve at LAT energies (30 MeV-300 GeV).
Figure 7.12: Integrated spectrum for the simulated GRB whose light curves are in Fig. 7.11. Filled lines are (from top to bottom): $e^2 N(e)$, $\Delta e N(e)$, $N(e)$. The dashed line is the band model for GRB, which is the phenomenological model that better describe GRB integrated spectrum.

Figure 7.13: Studying the Inverse Compton component: $e^2 N(e)$, $\Delta e N(e)$, $N(e)$ for different Compton emissivity. The parameter $\tau$ (see text) represents the ratio between synchrotron and Inverse Compton peak emission. From top left in clockwise: $\tau = 0$ (Only synchrotron emission), $\tau = 0.1$, $\tau = 1$, $\tau = 10$. 
Figure 7.14: Flux (left) and number of photons expected in the LAT energy range (right) for the simulated burst of figure 7.13, with different value of the parameter $\tau$. The synchrotron component is unvaried and, consequently, the flux in the GBM energy range is unvaried (and indicated in text label of the figures).

### 7.7.1 Constraining the model

Some of the equations written in this chapter can be used for directly obtaining the observables quantities as a function of the input parameters. Nevertheless, these set of equations can be inverted to obtain the parameters as a function of the observables quantities. At this point, it is possible by varying the observables quantities in agreement with the CGRO observations simulate a catalog of bursts. Firstly it is useful to define some scaled variables:

$$E_{\text{tot}} = E_{52} \times 10^{52}$$

$$\Delta R = \Delta 7 \times 10^7$$

$$R_0 = R_{10} \times 10^{10}$$

$$\Gamma = \Gamma_2 \times 10^2$$

$$\alpha_B = 1/3 \alpha_{B3}$$

$$\alpha_e = 1/3 \alpha_{e3}$$

The typical radius of an internal shock is approximately given by:

$$R_{\text{sh}} \approx R_0 \Gamma^2 = 10^{14} R_{10} \Gamma_2^2, \quad (7.49)$$

the particle density of the “unshocked” material (upstream fluid) is given by $n_1 = E_{\text{tot}}/(4\pi n_p c^2 R^2 \Delta R \Gamma^2)$ while the particle density of the post-shock material (or the density of the downstream fluid) is given by $n_{\text{sh}} = 4 n_1 \gamma_{\text{sh}}$ with $\gamma_{\text{sh}}$ is of the order of the unity. The post-shock material’s particles and energy densities can be written as:

$$n_{\text{sh}} = \frac{2.11 \times 10^{15} E_{52}}{R_{10}^2 \Gamma_2^6 \Delta 7} \gamma_{\text{sh}}, \quad [1/cm^3]$$

$$e_{\text{sh}} = \frac{3.18 \times 10^{12} E_{52}}{R_{10}^2 \Gamma_2^6 \Delta 7} \gamma_{\text{sh}}, \quad [\text{erg/cm}^3]$$
The intensity of the magnetic field, given by Eq. 7.15, is:

\[
B = \frac{5.1 \times 10^7 \sqrt{E_{52} \gamma_{sh} \alpha_{B3}}}{R_{10} \Gamma_2^3 \Delta_7}, \quad [\text{Gauss}]
\]  

(7.51)

The observed synchrotron energy (Eq. B.2) for an electron of energy \(\gamma m_e c^2\), is:

\[
E_{\text{syn}}(\gamma) = \frac{0.01 \sqrt{E_{52} \gamma_{sh} \alpha_{B3} \gamma^2}}{R_{10} \Gamma_2^2 \sqrt{\Delta_7}}, \quad [\text{keV}]
\]

(7.52)

while, the synchrotron cooling time (Eq. B.4) can be rewritten as:

\[
t_{\text{syn}}(\gamma) = \frac{9.8 \times 10^{-8} R_{10}^2 \Gamma_2^5 \Delta_7}{E_{52} \gamma_{sh} \alpha_{B3} \gamma}, \quad [\text{s}]
\]

(7.53)

In this simple model, the crossing time is approximately given by \(t_c = 3 \times 10^{-4} \Delta_7 \text{ s}\), and the angular spreading time scale, which determines the duration of the spikes, is 0.16 \(R_{10} \text{ s}\). The electrons are accelerated with a power law distribution from \(\gamma_m\) up to \(\gamma_M\). Assuming the standard power law index \(p = 2.5\), \(\gamma_m\) and \(\gamma_M\) are given by:

\[
\gamma_m = 202 \alpha_{e3}
\]

\[
\gamma_M = \frac{1.6 \times 10^4 R_{10}^{1/2} \Gamma_2^{3/2} \Delta_7^{1/4}}{E_{52}^{1/4} \gamma_{sh}^{1/4} \alpha_{B3}^{1/4}}
\]

(7.54)

The electrons cool rapidly and the spectrum shows a break energy corresponding to \(\gamma_{\text{cool}}\) given by:

\[
\gamma_{\text{cool}} = \max(1, \frac{7.2 \times 10^{-5} R_{10}^2 \Gamma_2^5}{E_{52} \gamma_{sh} \alpha_{B3}})
\]

(7.55)

Finally, the characteristic energies for the synchrotron spectrum are:

\[
E_m = \frac{363.7 \sqrt{E_{52} \gamma_{sh} \alpha_{B3} \alpha_{e3}^2}}{R_{10} \Gamma_2^2 \sqrt{\Delta_7}}, \quad [\text{keV}]
\]

\[
E_c = \frac{7.6 \times 10^{-10} R_{10}^3 \Gamma_2^8}{E_{52}^{3/2} \gamma_{sh}^{3/2} \alpha_{B3}^{3/2} \sqrt{\Delta_7}}, \quad [\text{keV}]
\]

\[
E_M = 2.5 \Gamma_2 \quad [\text{GeV}]
\]

(7.56)

The spectrum is given by the fast cooling regime. In appendix B the spectral shape is computed and the broken power law approximation is obtained (Eq. B.19). The spectrum for synchrotron fast cooling regime is also reported in Eq. 7.39. This equation is used for computing the emission for a GRB. The \(e^2 N(e)\) spectrum peaks at \(E_m\), whose value is few hundreds keV. For well reproducing the observed characteristic of the GRB class, the previous equation can be inverted and observable quantities can be used as parameters. In this way the parameters of the model can be reduced to a minimal set. The parameter set comprehends: the parameter \(t_w\), which is the characteristic time scale of GRB light curve, directly measurable observing the light curve; the peak energy \(E_P\), which corresponds to the maximum of the \(e^2 N(e)\) spectrum, and the cut-off energy \(E_M\) (expressed in GeV). Assuming that GRB are standard candles the total energy can be
fixed \( E_{\text{tot}} = 10^{52} \text{ erg} \). The parameter of the developed model can be found by using the following equations:

\[
\begin{align*}
R_0 &= 5.99 \times 10^{10} \ t_v \quad [\text{cm}] \\
\Delta R &= \frac{1.36 \times 10^8 \ E_{52} \ \gamma_{sh} \ \alpha_{B3} \ \alpha_{E3}^4}{E_p^2 \ \tau_v^2 \ E_M^4} \quad [\text{cm}] \\
\Gamma &= 40.5 \ E_M
\end{align*}
\]

Fig. 7.15 shows the relationship between the cut-off energy \( E_M \) as a function of the Lorentz factor of the expanding shell. It is worth noticing that in order to bypass the compactness problem (Eq. 7.3) the value of the \( \Gamma \) Lorentz factor has to be of the order of hundreds, which means that this model predicts a cut-off energy of the order of some tens of GeV, directly observables at LAT energies. Fig. 7.16 shows the effect of the different Lorentz factor of the expanding shells to the spectrum of the GRB. The cut-off energy has been set to 1 GeV, 5 GeV and 10 GeV, or, in terms of Lorentz factor \( \Gamma = 40, 200, 400 \). The flux of a single GRB at this range of energy is anyway low and only few photons will be detected above GeV. We suggest that an interesting measurement could be the observation of the high energy cut-off collecting several GRB spectra of long-intense bursts, analyzing the cumulative spectrum in order to improve the statistics and studying the general trend for the GRB class despite of considering only one GRB.

### 7.7.2 Simulated GRB catalog

The model can now be used for generating a simulated catalog of bursts: we have generate a sample of 10000 bursts. The number of shell can be used as free parameters. The bimodal distribution of the BATSE duration is reproduced if we impose that short bursts emits only few shells \( N_{\text{shells}} < 4 \), allowing the possibility of one or two shocks. Moreover the parameter \( \log(t_v) \) is sampled from a log-normal distribution, such as the mean \( t_v \) is equal to 0.1. For long bursts the number of emitted shells can be as large as hundreds, and we set the mean \( t_v \) to 1. This values have been tuned by the observation made by BATSE (see Fig.6.6) and by the correlation between the parameter \( t_v \) and the
Figure 7.16: Effect of the Lorentz factor of the expanding shells on the cut-off energy. The cut-off energy has been set to (from top to bottom) 1 GeV, 5 GeV and 10 GeV. The corresponding Lorentz factor are 40, 200, 400 respectively.
duration of the spikes (see Fig. 7.8). In nature, it has been observed that short bursts have a higher hardness ratio, or equivalently a higher peak energy. This scale law can be reproduced with a simple assumption. If we assume that the total energy emitted is fixed ($E_{52} = 1$), and the width of the shell is fixed for all the bursts ($\Delta T = 1$) then the peak energy, which is expressed by the first of the Eq. 7.56, goes as $\approx 1/t_v$. The two different distributions for the number of shells, and for the values for the parameter $t_v$ reproduce the observed bimodality in the distribution of the durations (Fig. 7.17), nevertheless the correlation between the peak energy and the duration is reproduced (Fig. 7.18). In practice short bursts are characterized by a smaller number of emitted shells and by a smaller initial radii. This is naturally translated in small duration and in a higher peak energy.

The computation of the fluences and of the number of generated photons has been done for the sample of bursts. The relation between the fluence in the LAT energy range, and the fluence in the BATSE energy range is shown in figure 7.19. The left panel shows the relation for the case of pure synchrotron spectrum ($\tau = 0$) while the right panel shows the relation for Inverse Compton emission ($\tau = 1$). The distributions of the logarithm of the fluences can be fitted with a simple law:

$$
\log(F_{LAT}) = (0.93 \pm 0.02) \log(F_{BATSE}) - (1.3 \pm 0.1), \quad \tau = 0
$$

$$
\log(F_{LAT}) = (1.06 \pm 0.02) \log(F_{BATSE}) - (0.2 \pm 0.1), \quad \tau = 1
$$

$$
\log(F_{LAT}) = (1.06 \pm 0.02) \log(F_{BATSE}) - (1.1 \pm 0.1), \quad \tau = 10
$$

where also the result of the fit for $\tau = 10$ has been reported (figure not shown).

The cumulative distributions of the fluences for the BATSE, LAT and GBM detectors are shown in Fig. 7.20 for both pure synchrotron spectrum (left) and for IC component (right). A more detailed study has been done for the fluences in the four BATSE channels, separating the contribution of the fluences for short and long bursts. In Fig. 7.21 the cumulative distribution of the fluences in the four BATSE energy band
Figure 7.18: Correlation between the peak energy (log(\(E_p\))) and the duration (log(T_{90})) for long and short simulated bursts. Short bursts are harder, with a peak energy greater than the peak energy of the long bursts.

is displayed. It is visible the trend for short bursts to have a higher fluence in the fourth channel, or in other words a higher Hardness Ratio with respect to long bursts. This plot can be directly compared (apart from normalization factors) with the plot showing the real BATSE distributions (top panel of Fig. 5.5).

7.7.3 Spectral-temporal variation

The temporal evolution of the spectra depends on the characteristic time scales considered. Synchrotron cooling would explain naturally the observed trend at BATSE energy that the duration of the pulses are shorter at higher energy. Nevertheless, the synchrotron cooling time is too short in GRB where magnetic fields are intense. The observed synchrotron cooling time can be as short as few \(\mu\) s. The pulses, in a regime for which the synchrotron cooling time is the dominant time scale, could not last few second, as has been observed. In the model developed the temporal structure of the GRB signal is determined by the geometry, since the angular spreading is the dominant time scale. Moreover, the doppler factor depends on the time, since at different observed time we are viewing different region, with a different Lorentz factor. A rough explication, is that the emitted radiation (which is integrated over the time, so it does not depend on it) is suffering a different doppler effect depending on the angle of the region of the shell which is emitting (in the “observer time” meaning). High energy light curves, which have been more blue-shifted, come from the region of the emitting shells at small angle (higher doppler effect). On the other hand these regions are the first to emit (again, in terms of observed time), so their radiation reach us before the low energy light curves. The evolution of the spectrum will be from hard to soft. The dependence on the time of the observed spectrum is not trivial. Note that the model effectively introduces such a spectral dependence on the time, as shown in Fig 7.22 where the light curves at different energies of one single pulse have been scaled to their maximum.
Figure 7.19: The relation between the flux in the LAT energy band vs the flux in the BATSE energy bands for short and long bursts. Left: GRBs with only the synchrotron component. Right: burst with Inverse Compton component. Lines are linear fit (see the text for parameters).

Figure 7.20: Distribution of the normalized fluences for the sample of simulated catalog with pure synchrotron emission and with an Inverse Compton component (τ = 1), left and right respectively.
Figure 7.21: Distribution of the fluences in the four BATSE channel for the simulated catalog. All bursts included.
The pulse at high energy (MeV-GeV) is shorter with compared to the low energy light curve. The spectral-temporal dependence introduced by this simple model is anyway too weak with compared to the observed relation $W \propto E^{-0.4}$ (Fenimore et al.1995 [63]). In order to explain such a spectral-temporal dependence, a more complex picture has to be introduced, and a more realistic description of the shell’s geometry and of the shock’s propagation into the shell may enhance this feature. In figure 7.23 three different snapshots of a GRB spectral evolution are shown. The spectrum evolves from high energies to soft energies in agreement with the observation [65].
Figure 7.23: Evolution of the spectrum with time. Left: only synchrotron component. The evolution of the spectrum is from the top spectrum to the bottom spectrum, following the direction of the arrow. The spectrum evolves from high energy to soft energy (hard to soft), as indicated by the arrow. Right: synchrotron and Inverse Compton component for the same burst. The Inverse Compton component remains does not present the hard to soft evolution at low energy. This is due to the cut-off of the Inverse Compton spectrum.
Chapter 8

The Event Generator

The case of stationary sources, where the photon counting probability is given by Poissonian probability, the interval of time to wait between two consecutive photons is given by $\Delta t = -\log(1 - \zeta)/R$, where $R$ is the count rate of the sources and $\zeta$ is a random number between $[0, 1]$. If the source is not stationary, the probability to count a photon at time $t$ cannot be expressed with a Poissonian distribution. During this work of thesis, we have shown that GRB are anomalous phenomena in terms of diffusion processes [86]; the central limit theorem hypothesis no longer holds. We have characterized GRB by means of an index ($\delta$) indicating how the Diffusion Entropy [87, 88] scales as a function of the time. GRBs have typically a $\delta$ index close to 1, which means high correlation, non-stationary/memory effects, indicating the “complex” nature of GRB phenomena. For these characteristics the light curve form GRB cannot be caused by random extraction of time from a “normal” Poissonian distribution otherwise the $\delta$ index would be 0.5, as shown by Feller (1971) [89].

In general, when the rate is a function of the time, other algorithm has to be developed in order to extract photons in agree with the rate. The case of transient sources this definition is no longer valid, and a more general treatment has to be done. In terms of software development this means implement the class Spectrum with a new definition of “Interval”.

Given a photon flux $N(t, e)$ (in $\text{ph/cm}^2/\text{s/keV}$) as a function of the energy and of the time, the method described below permits to compute possible sequence of photons that hits the detector. The basic idea is to integrate the photon flux $N(t, e)$ over the energy, obtaining the flux $F(t)$:

$$F(t) = \int_{\epsilon_m}^{+\infty} N(t, e) \, de \quad [\text{ph/cm}^2/\text{s}]. \quad (8.1)$$

A dimensionless quantity, which we call probability for simplicity, can be defined as a function of time, as:

$$P(t, t_0) = A \cdot \int_{t_0}^{t} F(t') \, dt' \quad [\text{ph}] \quad (8.2)$$

Where $A$ is the area of the detector. In practice the arrival time of the first photon is given by solving $P(t, 0) = 1$ in $t$. The arrival time of the $n-th$ photon is given by solving the equation $P(t, t_{n-1}) = 1$ where $t_{n-1}$ is the arrival time of the $n-1-th$ photon.

$$Interval(t_0) = t - t_0 : P(t, t_0) = 1 \quad (8.3)$$

Fig. 8.1 explains schematically the procedure used for extracting photons from a transient flux. The top panel shows the spectrum $F(t)$ as a function of time. The
Figure 8.1: Schematic view of the photon extraction algorithm. The top panel shows the spectrum $F(t)$ as a function of time. The bottom panel shows the integration of the flux over time, obtaining the “probability” function. Starting from $t_0$ equal to zero, every time that the probability reach the unity (an integer number on the $y$ axis) a photon is generated. This is the meaning of the horizontal lines on the plot. From each horizontal line a time flag can be obtained just inverting the probability function: the vertical lines are “drawn”. These lines are also reported as reference on the top panel plot, for viewing the correspondence between the arrival photons and the peak shape.
bottom panel shows the integration of the flux over time, obtaining the “probability” function. Starting from $t_0$ equal to zero, every time that the probability reach the unity (an integer number on the y axis) a photon is generated. This is the meaning of the horizontal lines on the plot. From each horizontal line a time flag can be obtained just inverting the probability function: the vertical lines are “drawn”. These lines are also reported as reference on the top panel plot, for viewing the correspondence between the arrival photons and the peak shape. There is no physical motivation for having the extracted photons which fall exactly at the maximum of the peaks. Statistically (and this is the meaning of integrating the flux obtaining such as probability function) photons will fill the light curve of the first plot, with a certain random distribution (with the probability distribution function given by the $P(t)$). With large number of extraction (few hundreds) the pulse shape can be exactly reproduced. Fig. 8.2 shows the result from the same simulation (same simulated Burst) with different values of the minimum photon extracted energy ($E_{ph}=30$ MeV, 300 MeV, 1 GeV). In the first panel, which is also representative on the typical LAT energies, the shape of the pulses are well reproduced, while for energy greater than 300 MeV (the second panel) the spikes are only marginally reconstructed. The third plot shows photons with energy greater than 1 GeV. Even if the flux of photons at this energy is still high, compared to the background flux, the temporal profile is difficult to reconstruct. There is still a correlation between the arrival time of the photons at 10 GeV and the position of the intense spikes of the light curve.

Once that the arrival time has been computed, the energy distribution $E(t,e)$, defined as:

$$E(t_n,e) = \int_{t_{n-1}}^{t_n} N(t',e)dt'de \quad [ph/cm^2],$$

(8.4)

is numerically computed. This function, represents the probability distribution per unit of area to have a photon with energy $e$. The energy of the photon that arrives at time $t_n$ is given by extracting a random number accordingly with the probability distribution given by equation 8.4.

The numerical computation uses discrete intervals of energy and times thus, the photon flux is a two dimensional histogram where $N(t_i,e_j)$ is the number of photons per unit of area in the time bin $t_i$ and in the energy bin $e_i$. In figure 8.3 two simulated spectra have been represented as two dimensional histograms. Each bin contains the number of photons per second per unit of energy per square meters. From this matrix the number of photons that reach the area of the detector (in the LAT simulation the photons are generated over an area of 6 square meters, which contains the detector viewed from all the possible directions), can be computed with the following equation:

$$N(t_i,e_j) = Area \times N(t,e)dedt \quad [ph]$$

(8.5)

If $t_M$ is the maximum time at which the flux is computed, and $N_t$ the number of time bins, the $i-th$ time bin is given by:

$$t_i = i \cdot dt \quad \text{with} \quad i \in [0,N_t]$$

(8.6)

with $dt = t_M/(N_t - 1)$ is the bin width. The energy axis is logarithmically binned, from $e_m$ to $e_M$ in $N_e$ bins, in practice, the $j-th$ energy bin is given by:

$$e_j = e_m (e_M/e_m)^{j/(N_e - 1)} \quad \text{with} \quad j \in [0,N_e]$$

(8.7)
Figure 8.2: Extraction of photons from the same simulated GRB with fluence in the BATSE energy range $F_{\text{BATSE}} = 2.24 \times 10^{-5}$ erg/cm$^2$ with different minimum photon energy for the extraction. In the left panel, photons greater than 30 MeV are extracted (typical LAT energies). In the middle panel only photons above 300 MeV are extracted, and in the right panel, only photons with energy above 1 GeV.
Figure 8.3: Three dimensional representation of the two dimensional histogram containing the number of photons per unit of time, of energy band and are as computed by the GRB physical model simulator. The left panel shows a spectrum computed for synchrotron emission only, while the right panel shows the spectrum of the same burst with synchrotron and Inverse Compton. The three dimensional representation is the most intuitive for visualize the computed flux as a function of time and of energy. It is the input for extracting the photons.

The integrals of the previous equations, are replaced by summations. In detail, the energy integrated flux is a 1-D histogram:

\[
F(t_i) = \sum_{j=0}^{j<N_i} N(t_i, e_j)/\text{Area} \quad [\text{ph/m}^2],
\]  

(8.8)
as the probability at time \( t_i \), which is:

\[
P(t_i) = \text{Area} \times \sum_{i=0}^{i<l} F(t_i) \quad [\text{ph}]
\]

(8.9)
The apparent useless multiplication for the Area in eq. 8.8 followed by the division for the area in eq. 8.9 is just for maintaining the default definition of flux, while the probability has dimensionless values. The arrival time of the photons is computed as follows: let \( t_i \) the starting time (\( t_i = 0 \) for the first photon). The index \( l \) is incremented starting from \( i \), while \( P(t_l) - P(t_i) < 1 \) and \( l < N_i \). If \( l \) reach the final value \( N_i \) and \( P(t_l) - P(t_i) \) is still less than one, no photon are extracted in the interval \( t_i, t_M \). This means that the flux is too low. The case with \( P(t_l) - P(t_i) > 1 \) and \( l < N_i \) is more interesting. In this case the algorithm computes the arrival time by means of a linear interpolation, knowing the probabilities \( dP_1 \) and \( dP_2 \), where:

\[
dP_1 = P(t_l) - P(t_{l-1})
\]

(8.10)
\[
dP_2 = 1 - P(t_l) - P(t_{l-1})
\]

The first \( (dP_1) \) is the increment of probability in the last bin computed, while \( dP_2 \) is increment of probability which miss to reach the unitary value from \( t_{l-1} \) \( (P(t_{l-1}) - P(t_l) < 1) \). The value for the arrival time will be:

\[
t_f = t_{l-1} + \frac{dP_2}{dP_1} dt,
\]

(8.11)
where \( dt \) is the bin width. The interval to wait for the next iteration is just \( t_f - t_i \). The energy of this photon is extracted from the energy distribution \( E(t_f, e_j) \), defined as:

\[
E(t_f, e_j) = \sum_{i=1}^{i<j} N(t_i, e_j) \quad [\text{ph/cm}^2]
\]

(8.12)

8.1 Extraction of photons from GRB spectrum

Both the “phenomenological” and “physical” model developed in the Chapters 6, 7 can be used as generator of photons for the Montecarlo propagator. Both the models produce a two dimensional histogram containing the input definition of \( N(t, e) \), computed using two different models (i.e. the first model extracts the basic parameters for a phenomenological description of GRB from the observed distributions, the second model computes the spectrum starting from the theory of the emission processes and imaging a scenarios of colliding shells). Since the produced histogram contains all the information needed for the photon extraction, many models can be developed and tested within this logic. Fig. 8.4 shows the schema of the data flow between the GRB simulator and the Montecarlo of the LAT instrument. This schema is general and both models developed in the previous two chapters can be plugged-in. Each model computes the synthetic GRB and, after all the equations have been computed, depending on the model and on the set of parameters, a two dimensional histogram is passed to \( SpectrObj \). This object computes the matrix \( N(t_i, e_j) \) using eq. 8.5. This ends the initialization phase. The interaction with the Montecarlo has been already discussed in section 3.2, so I will omit some details. The basic concept is that the Flux package (not represented in the diagram, but simply indicated as “Montecarlo”) asks for a photon to the \( SpectrObj \), passing the initial time \( t_0 \). At this point the simulator computes the flux, the interval, and the energy by means of equations 8.8, 8.11 and 8.12. The galactic position of a GRB is computed only once, and, finally the simulator passes this informations to the Montecarlo which will process the event. The extracted photons can be collected into histograms and saved for inspections (like comparing the generated with the reconstructed events). Figure 8.6 shows the synthetic spectra for two GRBs, one with synchrotron emission only and one with inverse Compton component. In the plots are shown both the “theoretical fluxes” computed by the simulation and the extracted photons (the error bars are statistical errors). The usual fit with the band function is also plotted in the figure. The fluence in the BATSE energy range is \( F_{BATSE} = 10^{-5} \text{ erg/cm}^2 \). In the LAT energies,
Figure 8.5: Light curve for a long GRB for synchrotron spectrum (left) and with the Inverse Compton component (right). The top panels show the synthetic light curves computed for BATSE and GBM energies, while the bottom panels show the light curves at LAT energies. The histograms filled with the extracted photons arrival time are also plotted in the bottom panels (LAT energies). The algorithm which extracts photons from the synthetic bursts reproduces correctly the variability of the light curves.

for pure synchrotron model 390 photons have been extracted (resulting in a fluence of $5 \times 10^{-7}$ erg/cm$^2$) and 1597 with Inverse Compton component ($5 \times 10^{-6}$ erg/cm$^2$).

Figure 8.5 shows the light curves for the two simulated bursts. The histograms of the arrival time of the extracted photons as results from the computational of the “interval” equation (8.11) are drawn in the bottom panels together with the theoretical expectations.

Finally, to allow the generation of many bursts during a Montecarlo run (the observed rate would be one GRB per day, but for GRB detection studies we can generate even more bursts per day), several GRB simulation has been concatenated by means of a GRBmanager which takes into account the end of a burst, and starts the next burst simulation, changing the galactic location and loading a different set of parameters. The “interval” computed between the last photon of a burst and the first photon of the next burst is, of course, the time interval between the bursts. In this way the GRB simulator has been inserted in the Montecarlo simulation of the LAT detector, which is now capable to generate different burst from different location in the sky, selecting a particular set of parameters. The physical model developed is indeed useful for studying the physics of GRB, especially at high energies, and making previsions on the LAT observational capability. The GRB phenomenological model, shares the same structure, with the difference that the bursts are generated “one by one” and the parameters are set via an XML file. Several bursts can be simulated also with this model, by adding their parameter to the XML file. This is, nevertheless, the usual way to define the parameters of the sources within the LAT framework.
Figure 8.6: Spectral shape for pure synchrotron model (top) and with Inverse Compton emission (bottom). The extracted photons at LAT energies are indicated in the figure: error bars are the statistical errors. The two bursts, which differ only for the Inverse Compton component, have the same BATSE fluence ($10^{-5}$ erg/cm$^2$). The synchrotron spectrum produces a fluence of $5 \times 10^{-7}$ erg/cm$^2$ in the LAT energy range while the same burst with Inverse Compton component produces a fluence of $5 \times 10^{-6}$ erg/cm$^2$ for LAT energies. The number of photons extracted is 390 in the first case and 1597 in the second case.
Chapter 9

Gamma Ray Bursts and GLAST

In this chapter I will present the “Standard Analysis Environment”, the scientific software for the LAT detector developed jointly with the GLAST Science Support Center. This tools are a collection of utilities, databases, and general tools for retrieving, manipulating, and analyzing scientific LAT data. Analysis software has been applied to simulated data, but, in terms of data structure, there is no difference with the real data. GLAST, as a NASA experiment, adopts the HEASARC protocol and the data will be released in standard FITS format to the astronomer community. The series of tools that will be available for analyzing data are called Science Tools (ST). At the moment only few packages have been developed, but some basic data analysis can be already done. In the first part of this chapter I will briefly introduce the ST for the GLAST/LAT experiment, and I will concentrate my attention on those tools dedicated for the analysis of transient signal, analyzing some (simulated) GRBs. Finally I will describe the tools developed during my work for visualizing and analyzing the data.

9.1 The Science Tools and the Science data

Two communities will analyze LAT data. LAT team members are affiliated at a various institutions in different countries: these are the users which presumably be heavy users of the LAT data. The LAT Instrument Operator Center (IOC) will provide the LAT team with LAT Level 1 data, the scientific database contains the relevant information for doing science. LAT team members may use the analysis tools on the same servers on which the databases are located, or the databases may be cross-mounted on the analysis computers. On the other hand, the typical member of the general astrophysical community will analyzing the data independently of the LAT instrument team, using the desktop computer generally available at the time of the launch of GLAST (for the Moore’s Law, at the beginning of Phase 2 the average desktop computer will be 10 times more powerful than current computers). The GLAST Science Support Center (SSC) at Goddard Space Flight Center will make available both data and analysis tools to this community. The Level 1 data will reside on the SSCs servers. The user will extract data from the SSCs databases, and export the resulting data files back to his/her home institution over the internet. Before starting the description of the tools, some consideration may help to understand the general framework of the scientific analysis with the LAT.

The basic concept of the data analysis with an observatory (GLAST is an observatory) is to accumulate counts storing the basic observable: the direction relative to the satellite, the energy, the time of the events. Since that the instrument response depends
on the incident direction, also the orbit, the inclination and the GPS time will be simultaneously monitored. The direction of the incoming photon will be converted in galactic coordinates. Moreover, almost all the data will be accumulated while GLAST is observing the sky in scanning mode. Even during “pointed observations” the field-of-view (f.o.v) will drift. Consequently, each photon will be detected at a different orientation between the source and the detector normal. Different instrument responses have to be applied. Even with the LAT’s greater effective area relative to EGRET, the data space (e.g., apparent energy, apparent origin on the sky, orientation to the LAT) will be large and sparsely populated with detected photons. Finally, concerning the source identification, the effective area of the instrument is larger then the effective area of EGRET by a factor of $\sim 10$. The PSF at low energy is about $3.5^\circ$, this means that at low energy fainter sources will be detected, but, at these energies, could be difficult for disentangle sources.

9.1.1 Event data, pointing history, and response functions

The astronomical data ready for the community are the already-processed “Level 1” data, the LAT pointing, the lifetime information, and the instrument response functions that provide the high-level characterization of the LAT. The Level 1 event data are assumed to have charged particle backgrounds already removed and gamma rays characterized by energy, time, and direction in celestial coordinates. The event data contains also a set of flags indicating the status of the reconstruction, expressing the probability of being a “good gamma”, or a “good reconstructed events”. The pointing and lifetime history is needed to calculate exposure, and ultimately calibrated fluxes. The response functions are also used in high-level analyses, such as the comparison of emission models with observations.

9.1.2 Event Display

The Standard Analysis Environment (SAE) will contains also an event display for visualizing the so called Level 0.5 events. They will be the reduced events which have passed the background rejection, but on those events the information will be complete. The display of the tracks in the tracker and the possibility to investigate the morphology of event will indeed be possible.

9.1.3 Exposure

The computation of the exposure is needed for calibrating the astronomical data and obtaining calibrated fluxes. The computation of the exposure uses the lifetime history of the instrument (its position in orbit and its orientation) and the IRF, as described in Chapter 4. The IRFs may also depend on time, and the possibility to update the responses is also taken into account.

9.1.4 Likelihood analysis

Owing to the limited number of gamma-rays the statistical workhouse for model fitting and source founding will be the Likelihood analysis. Given the pervasiveness of the diffuse gamma-ray emission from the Milky Way (approximately 60% of the gamma rays that EGRET detected were diffuse emission from the Milky Way) a model for interstellar emission, that describes the spectral distribution of the emission across the sky, will be also provided. As for other high-energy gamma-ray astronomy missions,
for the LAT we expect that the model fitting tool will implement maximum likelihood analysis. The likelihood analysis can be used to detect gamma-ray point sources and characterize their positions, fluxes, and spectra.

### 9.1.5 Point source catalog, astronomical catalogs, and source identification

An important issue in the data analysis is the definition of catalogs of astronomical sources, useful both for counterpart identifications (flat spectrum radio sources or X-ray sources) and for the point sources cataloging. These will be available both to the source model definition tool (which define also model to be used with the likelihood tool) and to a source identification tool, which allow the search for correlation and coincidences between gamma-ray sources and those in other catalogs.

### 9.1.6 Pulsar analyses

All of the routine analysis of point sources can be carried out for pulsars as well. Pulsar analysis foreshadows the search for time dependent signal quasi periodic. The observed data arrival times has to be corrected considering both the motion of the satellite and the position of the Earth for retrieving gamma-ray arrival times to the solar system barycenter. At this point both blind searches for unknown pulsar and folding tools for know pulsar will be available, as tools for cataloging the Pulsar.

### 9.1.7 Map generator

The map generation utility will generate gamma-ray, exposure, and intensity maps for user-specified regions of the sky, time ranges, energy ranges, and other sets of parameters.

### 9.1.8 GRB analyses

The tools dedicated to GRB analysis are, in general, multi instrument. The input of different instruments dedicated to the analysis of transient (GBM, Swift, Integral) will, indeed, considered. Here I will present the tools developed for the LAT instrument. Similar tools for the other instrument on board the satellite, the GBM, will be developed elsewhere. GRB are intense flares of radiation that, in many cases, exceed by far the background level. For intense GRB, the basic tools chosen by the community is the binned analysis.

Fig. 9.1 shows the data flaw for the typical GRB analysis. The level 1 data are two FITS file: the “events” data file, which contain information on the reconstructed photons (time, energy direction...), and the “space craft” data, which contain information on the orbit and orientation of the satellite and are needed to compute the exposure. The first tool needed for the analysis (not only for GRB) is the dataSubselector program. It allows the selection of a region of the sky and of a interval of time to analyze. A smaller set of events is extracted and save in an “event” FITS file.

The evlBin program allows the user to bin, or re-bin, the data. Several options are available such as binning the data in time, obtaining the light curve. Binning the data in energy means obtaining a spectrum, saved into a “PHA1” format file, to be used with xspec, a common tool for x-ray and gamma-ray spectral analysis [90]. Also “PHA2” files can be obtained: they are spectra at different time. Finally a contour map can be obtained by binning in a two dimensional table the right ascension (ra) and the celestial declination (dec). A special tool has been developed for computing the response of
the detector, in order to provide the right calibration in spectral analysis. *rspbGen* uses the space craft data and the spectral file (the PHA1) for computing the exposure of the detector (needed for translating the raw counts into fluxes). It provides a modified version of the IRF: the *Detector Response Matrices* (DRM) contain the response of the detector for the particular selected time of the burst and for the selected energy bins.

The spectral file PHA1 and the detector response (named RSP file) are inputted to *xspec*. The visualization of the spectrum and the fit of the spectrum using a large varieties of model is now possible. Other tools for temporal fitting (finding pulses and temporal correlations), or for spectral-temporal fitting (studying the evolution of the spectrum with the time) will be developed but are not available at the moment. Spectral-temporal modeling of GRBs will be accomplished via a third likelihood analysis tool that is implemented to model the full time and spectral dependence of bursts using detailed physical models (e.g., for the gamma-ray production from colliding relativistic shells) with adjustable parameters. This tool is to be implemented with well defined interfaces for additional physical models as they are developed or contributed. Joint fits to the LAT and GBM data will be standard. Supplementary graphical tools dedicated to the GRB analysis, will also be developed.

### 9.1.9 Alternative data source

A fast observation simulator is also under development. The idea is to use the IRF for generating simulated observational data. This is something different from the full LAT simulation software, which uses the power of the full Montecarlo propagator. The parameterized response matrices are instead used for gaining in speed and *cpu* time. The observation simulator produces data in the same data format of the real flight data,
and can be used both for helping in the Science Tools development, for training users and for planning observations.

9.2 The case of the GRB analysis

In this section I will apply the developed Science Tools software for the GRB analysis. The simulated sky is composed by an isotropic component for the extragalactic diffuse emission, and a galactic diffuse component, derived from the diffuse map observed by EGRET. All the 3rd EGRET catalog has been added to the simulated sky. Each EGRET source can be describe with a power law with a given power index and with a given normalization, in agreement of the observed EGRET source. Each source position is extracted from the catalog end correctly positioned in the sky. The orbital motion of the instrument is given by a text file which contains the position and the inclination of the satellite every 30 seconds. The flux package compute the correct illumination of the satellite from a given sources. The photons from the sources are then extracted and feed the simulation taking into account the respective fluxes. For GRB sources the physical model has been used and the photons are extracted as describe in Chapter 7. The data are produced within the observation simulator. More then one day of data has been simulated. For having enough statistic I have decide to simulate one burst every 1000 seconds. This is not a true physical situation, in which we expect one GRB per day, but, in the specific case of testing the Science Tools I have decided this trick for improve the statistic significance of the analysis. The bursts have been generated using different configuration of parameters, in particular I have generated half GRB including an Inverse Compton component and half GRBs with only the synchrotron emission component. All of the GRB have fluxes comparable in values with the BATSE observations. After the simulation has produced the events and the space craft data, the data can be analyzed. The events data file contains the incoming observed direction (both in galactic right ascension $ra$ and galactic declination $dec$ and in instrument coordinates $theta$ and $phi$), its energy and its arrival time. The space craft data contain the instrument position (orbit and inclination). The evtbins tool, needed to bin the data, is applied for binning the data in time, producing a light curve, in energy, producing a spectrum, or in celestial coordinates, producing a sky map. It needs both the events data file and the file containing the spacecraft data (position and inclination). It produces a fits file containing the desired binned data.

The rspgen compute the Detector response matrix. In practice it uses the information of an input spectral file produced by event bin, and the lifetime of the detector, for producing a matrix containing the response of the detector taking into account the energy dispersion and the effective area.

$$DRM(E, E_r) = \Delta(\theta; E, E_r)/A_{eff}(\theta; E, E_r) \quad (9.1)$$

The matrices $\Delta(\theta; E, E_r)$, and $A_{eff}(\theta; E, E_r)$ are extracted from the IRF, once the region of the sky is selected. In general the resulting DRM is not diagonal due to the energy dispersion. To be notice that when the effective area goes to zero, the DRM diverges. This causes big uncertainties on the flux estimation at low energies due to, basically, high inefficiencies in the detection.

A preliminary version of these tools has been developed and tested. Examples of the time history of the simulated data is in Fig. 9.2. The figure shows the comparison of the time history (binned at 1 second bin) of the simulated observation. In the first plot only the contribution of the diffuse galactic and extragalactic emission, plus the 3rd EGRET
catalogue has been considered. In the second light curve one GRB every 1000 second has been added to the data. Bright GRBs are very well visible, and their rate (up to $10^2$ Hz) dominates the all gamma-background rate ($\sim 10$ Hz$^1$). The LAT event rate telemetered to the ground is expected to be $\sim 300$ Hz. In the simulation done so far, only the gamma-ray sky has been taken into account and no charge particle background has been considered. The application of the on-board background filter, based on selection cuts, would affect the count rate. Figure 9.3 shows the detail of the light curve of an intense burst. For bright bursts the background in negligible, and the development of alert algorithms can be based on simple computation, as the direct comparison of the differential count rate. More complicate algorithms have to be provided for detecting also faint bursts, whose signals are comparable to the “noise”. I will discuss these algorithms in the next chapter.

The simulated data can also be binned in galactic coordinates with ewbin for obtaining a “sky map”. In Fig. 9.4 the reconstructed directions are displayed weighting the incident photons with their reconstructed energies. The figure shows the comparison between an only gamma-background map, and a sky with the 86 simulated bursts. Fig. 9.5 is an zoomed region around the intense GRB. The left figure shows the selected region of the sky with the burst located at coordinates $RA \approx 136^\circ$ and $DEC \approx 14^\circ$. The background photons are visible in the plot but the GRB dominates. The right panel shows a profile histogram cutting the left figure just in the middle of the GRB, as the horizontal line shows.

Finally, Fig. 9.2 is an example of a simulated GRB with an exponential cut-off and Inverse Compton component. The cut-off is at 4 GeV, and the fluence of this GRB in the BATSE range is $3.17 \times 10^{-5}$ erg/s. The figure shows the result of the fit using xspec as external tool. The spectrum has been fitted with a power law model with an exponential cut-off (cutoffpl model), resulting in an estimated cut-off energy of $3.2 \pm 0.8$ GeV, (with a Chi-Squared $= 8.75$ using 12 energy bins, resulting in a probability of 46.1%).

$^1$The simulated background rate is probably too low. Refinement on the background simulation would rise the background rate by a factor of 3 or more.
Figure 9.3: Zoomed light curve for a simulated GRB: the interval of time and the region of sky that contains the burst have been selected. Peaks are visible as sub-structures of the light curve.

9.3 The analysis software

In this section I will describe the tools that I have developed for analyzing GRB simulated data. The idea is to developed a series of classes for handling the data stored in the ROOT files (or in FITS file). The advantage of having a flexible object like the TTree object for storing the data, is that the data are organized in events and all the properties of an event are connected. It is very easy, for instance, making selections on multiple variables or display the results plotting histograms or scatter plots. Moreover, developing software within the ROOT framework allows the development of graphical interfaces, and sophisticated algorithms can be easily used in the analysis (as C++ source code or as external libraries). We can summarize the developed component as:

- **Event extractor.** The first step of my analysis tools is the extraction of the events. It is indeed necessary apply the background rejection and other selection cuts in order to prepare the data for the analysis.

- **Events Viewer.** The main idea of this software is to allow the user of having the possibility to simultaneously visualize light curves, spectrum and sky map for a given data selection. The starting point is indeed the visualization of the GRB simulated data. The first think that anyone would try is to see if the photons arrived during the burst prompt emission came from the same region of the sky. The task is to select a number of events making a selection on one or more variables, and to evaluate the effect on the other variables (such as the coordinates or the energy). The visualization software comprehends a fitting routine which makes use of the IRF for calibrating the fluxes, and for fitting the convoluted signal.

- **Trigger algorithm** A separate set of classes has been developed for triggering transient signal.
Figure 9.4: Top: *Sky map for simulated gamma-ray sky, with isotropic diffuse, galactic diffuse component, and with the 3rd EGRET catalogue sources.* Bottom: 86 intense GRBs have been added to the simulated sky. The sky maps are FITS images produced by the *evtBin* tool.
Figure 9.5: Zoom of the sky map around an intense GRB (the same shows in Fig. 9.3). Left: the map with the GRB and the background (integrating over one day of exposure) is shown. With standard tools, like fv, for displaying and analyzing FITS file it is easy to obtain profile histogram of the sky map. Right: Profile histogram cutting the sky map close to the maximum value, as shown by the horizontal line displayed in the left map.

Figure 9.6: Example of GRB binned spectral analysis using xspec as external tool. The GRB selected is the one at $t = 7800$ s. The model used for the spectral fitting the the power-law with an exponential cut-off. The estimated cut-off energy is at $3.2 \pm 0.8$ GeV, the simulated cut-off is around $4$ GeV.
9.3.1 The event extractor

The events produced by the LAT Montecarlo simulator are ROOT TTree objects. As in the case of the FITS file, they contain the exposure Tree and the merit Tree. Montecarlo, digi and recon file are at this point not necessary, and they can be inspected for cross-check, but, in the case of real data, the recon file and the digi file will not be available for the general user. In the case of the observationSim the output file is a FITS file, but it can be easily converted into a ROOT TTree object using AstroROOT\(^2\). The events in the merit tree are all the events which trigger the detector. Some of those events are not well reconstructed, and the information about the reconstructed events or reconstructed energy are missing. The selection of the events has been done applying the same selection cuts that we have applied in the estimation of the IRF (see Chapter 4). The knowledge of the IRF is indeed necessary for the scientific analysis of the data, as we will see briefly, for the calibration of the astronomical fluxes. It is necessary that the selection cuts which allowed the determination of the IRF are the same cuts which are applied to the data for selection. For this reason the selection has to be done with the same constrains that we chose for studying the response of the detector. The event extractor open the file containing data, reads the tree structure and apply the selection cuts in order to both reject the background and to select the “Good Event” selection. The selected events are between the 20\% and the 30\%. The event extractor dumps the remaining events in a separate file, which will be used in the analysis. It is important to notice that, the observationSim uses the IRF for reproducing the observation of the LAT detector, thus no cuts are necessary to the predicted data since the observation Simulator has intrinsically already used the selection cuts, has they are part of the IRF.

9.3.2 Visualization and spectral analysis

The data are then loaded into a graphical visualizer. The data are displayed by means of four canvases. The light curve, the spectrum, and the sky map both in galactic coordinates, and both in GLAST coordinates are displayed (see Fig. 9.7). The figure shows the recorded data for 10000 second of simulated observation. GLAST is orbiting in this simulation in scanning mode, and it crosses the galactic plane around \( t \sim 4000 \) The observed count rate increases by a factor of 2. The first plot is the light curve, the time history of the arriving photons. The bin size is 0.1, but it can be change using a command line interface. The second canvas is representing the convoluted spectrum. The visualization software uses indeed the IRF for normalizing the flux. The algorithm takes as input the two dimensional histogram of Fig. 4.3, which is the effective area as a function of the energy for different incident directions \( A_{\text{eff}}(\log(E), Z) \) as it was computed in the determination of the IRF in Chapter 4. The histograms of the energy dispersion and of the PSF are passed to the visualizer (one histogram corresponds to a certain energy bin and incoming direction). For the energy dispersion the distributions for the variable \( E_{MC}/E_r \) are computed: they represent, for a given Montecarlo energy \( E_{MC} \) and for a given incoming direction, the probability distributions that the Montecarlo energy will be \( E_{MC} \), having measured \( E_r \). If we want to estimate the real incoming energy \( E = E_{MC} \) having measured and reconstructed \( E_r \) we can consider the energy dispersion \( \Delta(E_r, E) \) as probability density function. In practice for every measured energy \( E_r \), a random number \( E \) is extracted using the energy dispersion as probability distribution. Similarly, the PSF(\( \theta_r, \theta \)) is considered for the direction reconstruction. From a measured polar angle \( \theta_r \), a predicted \( \theta \) is computed by extracting a random

\(^2\text{http://isdc.unige.ch/Soft/AstroRoot/}\)
Figure 9.7: Visualization of the events: light curve (top left), spectrum (top right), galactic sky map (bottom left) and sky map in GLAST coordinates (bottom right). The fluctuation of the background of figure 1, is due to the scanning of the galactic plane during the GLAST orbit.
number from the distribution $|\theta - \theta_r|$. Since the PSF depends, in good approximation, only on the polar angle $\theta$, there is no need to take into account the azimuthal angle $\phi$. For determining the correct flux, each event is weighted with a factor $1/A_{eff}(\log(E), Z)$, where $\log(E)$ is the estimated energy and $Z$ is the estimated $\cos(\theta)$. Finally, putting everything together, if $Z_r$ and $E_r$ are the direction and the energy measured, the estimated flux is:

$$N_{em}(\log(E), Z) = \sum_{\log(E_r)} \sum_{Z_r} \frac{N_{meas}(\log(E_r), Z_r)}{A_{eff}(\log(E), Z)} \times \Delta(\log(E_r), \log(E)) \times PSF(Z_r, Z)$$

The procedure I have adopted is to apply the IRF to each single measured photon (instead of computing the summation on binned data): for each photon detected, the expected energy $E$ and the direction $Z$ are computed by sampling a random number from the distributions $\Delta(\log(E_r), \log(E))$, $PSF(Z_r, Z)$, respectively. Thus the new variables $E$, and $Z$ are used for computing the effective area. Notice that for a large number of data (if the central limit theorem holds), this algorithm is equal to the operation of integration:

$$N_{em}(\log(E), Z) = \int_{E_r} \int_{Z_r} \frac{N_{meas}(\log(E_r), Z_r)}{A_{eff}(\log(E), Z)} \times \Delta(\log(E_r), \log(E)) \times PSF(Z_r, Z) \ dE_r \ dZ_r$$

or, numerically, Eq. 9.2. In this way the counts rate is converted in observed flux (photons/m$^2$). This operation is required for fitting the spectrum.

![Counts vs Energy](image.png)

Figure 9.8: Comparison between the simulated “raw” data (left) and the calibrated flux photons/MeV/m$^2$ (right) resulting from the convolution between the effective area and the raw counts (taking also into account the energy dispersion and the PSF, as described in the text). The effect of this convolution is evident, especially at low energies.

Fig. 9.9 shows a selected interval of time comprehending only the burst photons. All the graphs reflected the selection of the events: the temporal structure of the burst is visible in first plot; the reconstructed directions are strongly correlated indicating the location of the burst in the sky (bottom left) and in instrument coordinates (bottom right). The spectrum, which also reflects the selection done, has been fitted using a power law function. The best fit parameters with their errors are in the legend.
Figure 9.9: Visualization of the events: selecting a interval of time containing the GRB light curve all the graphs will be affected by such cut. The spectrum normalize spectrum, containing only those photons coming in the selected interval of time (and coming from a restricted region of the sky) has been fitted using a power law function.

9.4 Analysis of some GRBs

There are some interesting key studies that can be performed with the GLAST/LAT detector. The contribution of the GBM detector to the GRB physics will be certainly enormous, but is in the range of energies of the LAT detector, not yet covered by any previous experiment, where we expect most of the surprises. I will focalize the attention on three measurements, that can be performed with the GLAST/LAT detector. The GRB physical model is a suitable tool for investigating the high energy behavior of GRB. The spectral shape can be characterized, as we have already seen, by the presence of a cut-off and by the presence of Inverse Compton component. The goal of this section is to simulate such components and to investigate the possibility of their detection. Finally, a more exotic measurement is proposed.

9.4.1 Measurement of the high energy cut-off

The idea is to study the high energy spectrum of simulated GRB, and to apply standard analysis in order to investigate the possibility to distinguish different spectral shapes, and different features at high energy. First of all high energy emission can be characterized by an exponential cut-off determined by the maximum electron Lorentz factor. The physical model can also be forced to reproduce the cut-off at a desired energy, it has the capability to set the fireball parameters in order to reproduce the cut-off. In particular
the high energy cut-off depends only on the value of the Lorentz factor of the relativistic expanding fireball, and the observation of the high energy cut-off could be a direct technique to measure it. It is necessary to remember that, in order to bypass the compactness problem, the typical Lorentz factor of the expanding shells has to be at least few hundreds, determining a cut-off energy of the order of few GeV. Unfortunately bursts on average, lasts only few seconds. Given their fluxes we cannot expect to have always a great number of photons so the measure of the cut-off is not an easy and trivial task, as it is for stationary source (or at least non destructive source...). The high energy resolution of the LAT and the large effective area allow the study of this feature in some intense GRBs. For example, we can simulate a GRB with a BATSE fluence $3.17 \times 10^{-5}$erg/cm$^2$, which generates, thanks also to an Inverse Compton component that powers the high energy emission, 1220 photons above 100 MeV, whose result in 408 triggered and reconstructed for a total fluence of $1.17 \times 10^{-4}$ erg/cm$^2$ above 100 MeV. In Fig. 9.10 the simulated data are shown. The data have been fitted with a power law, in figure the dashed line, and with a power law, with an exponential cut-off. The chi-squared is computed and the probability to obtain a greater $\chi^2$ (for the given number of degree of freedom) is obtained. This probability indicated how well the model reproduces the data. This test tells that the simple power law function is clearly unsatisfactory, while the power law with the exponential cut-off is in agreement with the (simulated) data. The cut-off estimated energy is $5.5 \pm 1.5$ GeV.

9.4.2 The Inverse Compton Component

The typical synchrotron spectrum (without considering any high energy cut-off) is a power law with power law index less then two, dependently on the power law index of the accelerated electron distribution. The distribution of the high energy spectral index of the Band functions (right panel of Fig. 6.4), shows this behavior. Nevertheless, the Inverse Compton (IC) will affect only the high energy part of the spectrum. If the peak of the synchrotron spectrum $E_{\text{peak}}$ and the typical electron have an energy $\gamma m_e c^2$, then the IC component will have a peak $\gamma^2$ greater then the synchrotron peak. In particular, in GRBs $E_{\text{peak}}$ is of the order of hundreds of keV and $\gamma \approx 10^2$, therefore we expect the typical IC peak is around the GeV energy. We have already seen (see Section 7.6.2) that the Inverse Compton is not affecting the BATSE (or GBM) energy range. The typical signature of the IC is the change of the spectral index at high energy (in the range between the MeV and the tens of GeV). The spectrum $N(E)$ has a spectral index less then two in the case of synchrotron radiation and greater then two in the case of Inverse Compton radiation. In particular if we consider the $E F(E)$ spectrum\(^3\) we expect a change of slope from negative values to positive values. Using this representation is trivial detecting the Inverse Compton component, as shown in Fig. 9.11.

9.4.3 Test for Quantum Gravity

On the basis of recent quantum-gravity results, the possibility of space experiments to search for quantum properties of space-time has been recently proposed[91]. In quantum-gravity phenomenology [92], one is looking for the small effects predicted by quantum-gravity theories, effects with magnitude set by the ratio between the energy of the particles involved and the huge Planck energy scale ($E_P \sim 10^{19}$) GeV. In several approaches to the quantum-gravity problem one finds some evidence of departures from ordinary Lorentz symmetry with the possible emergence of Planck-scale-modified

\(^3\)also known as $\nu F(\nu)$ spectrum or $E^2 N(E)$. 
Figure 9.10: Study of the high energy cut-off. The simulated data have been produced using the GRB physical model forcing a high energy cut-off at 4.5 GeV. The reconstructed data are displayed in the plot and have been fitted with a power law distribution (dashed line) and with a power law distribution with an exponential cut-off (solid line). In the legend the value of the $\chi^2$ test are reported which denote the probability to obtain a greater $\chi^2$ by chance. The cut-off estimated energy is $5.5 \pm 1.5$ GeV.
Figure 9.11: Detecting the Inverse Compton component: the typical signature of this high energy component is the increasing of the spectrum at high energy and a change of slope between values smaller then \(-2\) typical of synchrotron spectrum, to values greater then \(-2\). Considering the \(E F(E)\) spectrum the slope changes from negative values to positive values, making this feature easy to detect. Left: pure synchrotron emission from an intense burst. Its fluence in the BATSE energy range is \(F(20 \text{ keV} - 1 \text{ MeV}) = 10^{-4} \text{erg/cm}^2\). The fluence in the LAT energy range (50 MeV-300 GeV) is indicated on top of each plot. Right: same burst with an Inverse Compton component (\(\tau_{IC} = 10\)). The spectrum is in this case incompatible with a pure synchrotron spectrum for which the power law index is less or equal -2. The peak of the Inverse Compton component (of the \(E F(E)\) spectrum) is at \(\approx 2 \text{GeV}\), as shown by the figure.

dispersion relations:
\[
E^2 = m^2 + \vec{p}^2 + f(\vec{p}^2, E, E_p),
\]
(9.4)

Such a deformation in the dispersion relation leads to a small energy dependence of the speed of photons: this dependence could be significant in the analysis of GRB coming from cosmological distance[93]. Two photons emitted by a GRB at distance \(L\) at the same time with energy difference \(\Delta E\), will be detected with a relative time delay, given by the following equation:
\[
dt = \frac{L \Delta E}{cE_{QG}}
\]
(9.5)

where \(E_{QG}\) is the energy scale of the Quantum Gravity effect. If \(\Delta E = 100 \text{ MeV}\), the GRB is at \(z = 1\) (\(L \approx 10^{28} \text{cm}\)), and the Quantum Gravity effect is of the same order of the Planck energy (\(E_{QG} = 10^{19} \text{ GeV}\)), then \(\Delta t \approx 10^{-3} \text{ s}\). Therefore such a quantum-gravity-induced time-of-arrival delay could be detected by GLAST upon comparison of the structure of the signal in different energy channels[94].

To investigate such effect, a detailed simulation of the time structure of the GRB is necessary, nevertheless a correct computation of the fluxes has to be done. The model presented in this thesis is able to generate GRB light curves at different energies and to feed the LAT detector with the photons extracted from the spectrum. However, since the intrinsic time lag could mimic the expected phenomena due to quantum gravity, the final analysis will need to correlate the measured delay between peaks at different energy bands with the measured source distance. Using a sample of observed GRB with measured redshift, the quantum gravity, which depends on redshift, can be isolated from the intrinsic delay, which does not. Some preliminary results of this analysis where the effects of quantum gravity are included in the photon propagation show that the LAT
Figure 9.12: Studying the quantum gravity effect on the photon propagation by measuring the time lag due to this effect. Left: light curves at different energies (from top to bottom: 30 MeV-100 MeV, 100 MeV-300 MeV, > 1 GeV) of a simulated short- single spike GRB without the effect of the Quantum gravity. All the curves peak at the same time (t=100 s). Right: when the quantum gravity is taken into account the photons of different energies suffer a delay. The Lorentz symmetry is broken: high energy photons reach the detector with a time lag respect to low energy photons. This effect is directly observable with the LAT detector: the light curve at high energy are delayed and spread. Better results can enhanced by comparing the GBM light curve and the LAT light curve of the same GRB.

Sensitivity permits to reconstruct the time structures of GRB at high energies allowing to measure the delay induced by the quantum space time structure[19]. In Fig. 9.12 a short single-peak GRB has been simulated. In the left panel the effect of quantum gravity on photon propagation has been ignored. The three light curves, relative to different energy bands from 30 MeV (top curve) to 1 GeV (Bottom curve), are peaking at the same time (100 s). If the effect of quantum gravity is considered, and assuming a quantum gravity energy scale \( E_{QG} = E_p = 10^{19} \) GeV, high energy photons suffer a delay due to the “quantum foam” and arrives later with respect to low energy photons. The effect is visible in the right panel of Fig. 9.12. The high energy light curve peaks at late time, the delay is of the order of tens of milliseconds, directly measurable with the LAT detector. It is also evident the effect of the spreading on the light curves: since that the speed of the photons depends linearly on the energy, and that the energy bands are wider at higher energy, then the dispersion of the arrival times is greater for light curves at higher energies. It is important to underline that GALST will have the capability of direct comparing low energy light curve at GBM energies (hundreds of keV) with the high energy LAT light curves (tens of GeV), reaching a large lever arm (5 order of magnitudes), necessary for direct observing the Quantum Gravity effect. If no time delay will be observed (within a certain temporal resolution), an upper limit on the quantum gravity energy scale would be placed:

\[
E_{QGmin} = \frac{L \Delta E}{c dt} = \frac{(10^{28} \text{cm})(10 \text{GeV})}{(10^{10} \text{cm/s})(10^{-3})} = 10^{22} \text{GeV}
\]  

(9.6)

for a \( z=1 \) GRB, with a lever arm of 10 GeV, assuming a temporal resolution of 1 ms. For other measurements and upper limits on the quantum gravity energy scale for the breaking of the Lorentz symmetry, see [95, 96]
9.5 GLAST sensitivity for GRB

The simulation of GRB and the detailed knowledge of the GLAST/LAT effective area, can be applied for computing the sensitivity of the LAT detector for GRB. I have simulated 10000 bursts using the GRB physical model described in section 7, so that we can investigating how the high energy spectral component affects the sensitivity. Having a good statistics we can simulate bursts with different Inverse Compton components, the parameter \( \tau \) varies uniformly from 0 (pure synchrotron spectrum) to 10 (high Inverse Compton Component). Each burst has been normalized between 20 keV and 1 MeV to the BATSE fluence distribution. The model allows the computation of the number of generated photons above a certain energy per square meter. The effective area allows the computation of the “triggered” and selected photons. The IRF contains all the selection cuts, and the effect of the reconstruction efficiency is also taken into account. A useful approximation that allows to strongly simplify the computation is to consider only photons above 100 MeV (the region where the Effective area starts to be almost constant), and to consider the effective area flat above 100 MeV. As we can see from the GLAST/LAT effective area this is a reasonable assumption. To be more exhaustive we consider the “on-axis” effective area, which is the response of the instrument to a normal incident photon (this is the most favorable situation and the effective area at 100 MeV is \( A_{\text{on-axis}} = 0.84 m^2 \)), and the “off-axis” effective area, which corresponds to an incident direction of 67° degrees from the normal (\( A_{\text{off-axis}} = 0.05 m^2 \)). There is another efficiency that we have to taken into account, and for that we will anticipate a result from the next Chapter. Any algorithm for detecting transients has its own efficiency, that can be easily translated in a minimum number of GRB triggered photons.

We will see that the LAT GRB trigger alert is able to detect a burst if more then five photons are detected and reconstructed. The distribution of the 10000 simulated bursts is shown in Fig. 9.13. The x axis corresponds to the fluence in the BATSE energy range, while the y axis corresponds to the number of generated photons above 100 MeV. Each point corresponds to a simulated bursts. The two horizontal lines represent the burst detection thresholds for on-axis and off-axis incident directions. They represent the number of photons per square meter to generate in order to have at least 5 photons detected by the LAT. They are at \( \log(5/0.84) = 0.77 \text{ ph/m}^2 \) for on-axis detection, and \( \log(5/0.05) = 2 \text{ ph/m}^2 \) for off-axis detection. This means that for having 5 detected photons above 100 MeV a GRB has to have a flux of 5.95 photons per square meter for on-axis detection and 100 photons per square meter if its location is at 67° from the normal incidence direction. The dots above the thresholds are detectable bursts.

It is also interesting displaying the distribution of bursts detected as a function of their fluence in the BATSE energy range. Fig. 9.14 represents the fluence distributions fro the detected bursts. The cases of on-axis detection and off-axis detections are compared with the total number of bursts generated. The efficiencies in the GRBs detection are 89.4% for on-axis and 46.9% for off-axis.

Fig. 9.15 shows the fraction of GRBs detected as a function of the parameter \( \tau \), for on-axis detection and for off-axis detection.

It is important to underline that this statistics are referred only for LAT detections. The Large Area Telescope will indeed have an on-board GRB alert algorithm, but the main trigger efficiency will be given by the GLAST Burst Monitor that will operate at BATSE energies. The GBM will detect all the BATSE bursts, sending a trigger message to the LAT detector.

Another interesting study that can be done using this approach, is to determine the distribution in redshift, and the highest observable redshift assuming GRB as standard
Figure 9.13: Distribution of the 10000 simulated bursts. The plot shows the number of generated photons per square meter above 100 MeV (y axis) versus the fluence in the BATSE energy range (x axis). The Inverse Compton parameter varies from $\tau = 0$ (pure synchrotron emission to $\tau = 10$, which is the case of a high Inverse Compton component. The two horizontal lines represent the burst detection thresholds for on-axis and off-axis observation. They represent the number of photons per square meter to generate in order to have at least 5 photons detected by the LAT. They are at $\log(5/0.84) = 0.77$ for on-axis detection, and $\log(5/0.05) = 2$ for off-axis detection. The dots above the thresholds are detectable bursts.
Figure 9.14: Distribution of detectable bursts. The not-filled distribution represents the distribution of the fluences of 10000 simulated bursts. The fluences are in agreement with the BATSE catalogue. The filled distributions are the distribution of detectable bursts taking into account the on-axis and off-axis effective area of the LAT detector. In the legend are reported also the percentage of these two distributions relative to the overall number of simulated burst.
Figure 9.15: Fraction of detected GRBs as a function of the parameter $\tau$. The situation of pure synchrotron spectrum yields a detection percentage of 73% for on-axis detection, and 18% for off-axis detection. For high Inverse Compton Component the on-axis detection approaches the 96% of the total generated bursts, while, for off-axis detection, the 61%.

candle (in agreement with Frail (2001) [70], Bloom et al. (2003) [71], and [17]). Assuming a flat universe ($\Omega = \Omega_m + \Omega_\Lambda = 1$, with $\Omega_m = 0.3$ (and $\Omega_\Lambda = 0.7$) as observed by WMAP experiment. The relation between the observed fluence $F$ and the emitted energy $E_{em}$ is:

$$F(z) = \frac{E_{em}}{4\pi d_L^2(1+z)} \quad (9.7)$$

where $z$ is the redshift of the source and $d_L$ is the luminosity distance. The luminosity distance can be computed solving the following integration:

$$d_L(z) = (1+z)\frac{c}{H_0} \int_0^z \frac{dz'}{\sqrt{(1-\Omega)(1+z')^2 + \Omega_m(1+z')^3}} \quad (9.8)$$

which, in case of flat universe gives:

$$d_L(z) = (1+z)\frac{2c}{H_0\sqrt{\Omega_m}} \frac{\sqrt{1+z} - 1}{\sqrt{1+z}} \quad (9.9)$$

where $H_0$ is the value of the Hubble constant at the present epoch as measured by WMAP [97, 98]:

$$H_0 = 0.71^{+0.04}_{-0.03} \text{ km/s/Mpc.} \quad (9.10)$$

Using Eq. 9.9 in Eq. 9.7, and solving with respect to the redshift $z$, one obtains the following relation between the observed fluence $F$ and the universal emitted energy $E_{em}$:

$$z(F) = \frac{8cH_0\sqrt{\pi} E_{em} F \Omega_m + E_{em}H_0^2\Omega_m}{16\pi c^2 F} \quad (9.11)$$
Figure 9.16: Redshift distribution for the simulated bursts. The distributions are for different values of the emitted energy. The vertical dashed lines correspond to the minimum detectable fluence corresponding to the threshold of Fig. 9.14 for on-axis observations. Depending on their energetic reservoir Gamma-Ray Bursts can be use as probe up to early universe. For an intrinsic luminosity $E_{\text{em}}$ of $10^{51}$ erg, the maximum redshift reachable by the GLAST/LAT detector is $z_{\text{max}} = 2.3$. For $E_{\text{em}} = 3 \times 10^{51}$, $z_{\text{max}} = 4.8$ and for $E_{\text{em}} = 1 \times 10^{52}$, $z_{\text{max}} = 11.7$ (for a flat universe with $\Omega_{m} = 0.3$, and $H_{0} = 75$ km/s/Mpc).

Computing the quantity $z(F)$ for each detected bursts, and assuming different values for the energy $E_{\text{em}}$ it is possible to predict the distribution of redshift, for the given cosmological model. Finally, the maximum observable redshift is computed taking into account the minimum fluence above threshold. Fig. 9.16 shows the distribution of redshift for three different values of the emitted energy. The emitted energy is assumed to be corrected by the beaming angle, so that even if the “isotropic equivalent” energy covers almost three decades of energy ($10^{51}$ ergs - $10^{54}$ erg), the emitted energy is a narrow distribution centered at $1.3 \times 10^{51}$ (From Bloom et al. [71]). We can conclude saying that depending on the Gamma-Ray Bursts energetic reservoir, GLAST will be able to scan the universe up to early epoch ($z=10$ for an intrinsic luminosity of $10^{52}$ ergs). In a more conservative view, assuming that the intrinsic luminosity ranges between $10^{51}$ and $3 \times 10^{51}$ GRB will be seen by the GLAST/LAT instrument up to redshift 5.
Chapter 10

Data Challenge 1

The Data Challenge One (DC1) has represented the first opportunity to test the complete simulation chain by simulating one day of observation of the full sky. In DC1 only the gamma-ray sky has been adopted while the Cosmic Ray flux (about $10^4$ times greater) has been ignored. DC1 represented also the first attempt to perform scientific analysis on simulated data, testing and developing analysis software. In DC1 an extraordinary high rate of GRBs have been simulated and one of the most excited items are represented by the development of alert algorithms for searching and triggering these transient signals. In this Chapter I will present the simulated sky and I will present my work done on developing simple alert algorithms. I will finally conclude presenting the results and the comparison between different algorithms developed.

10.1 The description of the sky

The DC1 gave the first opportunity to analyze data which looks like scientific one, including the gamma background and the orbital motion of the satellite. The typical problematic was to disentangle point sources to localized them using methods like likelihood analysis or wavelet analysis or to discover the “physics surprises” as the gamma-ray excess in the galactic center, artifact that was invented for simulating the neutralino annihilation, proof for darkmatter existence. The gamma-ray sky is made by different sources of different kind. As discribed in Chapter 3, the flux package takes into account the relative fluxes and compute from which sources arrives the photon to be processed by the Montecarlo propagator. The diffuse extragalactic source is an isotropic component with a power law spectral shape with exponent 2.1. The galactic diffuse radiation has been obtained extrapolating the galactic map observed by EGRET at LAT energies. Furthermore, the third EGRET catalogue has been used for adding the contribution of all the point sources observed by EGRET. Each of these sources can be represented by a power law with a fixed exponent and a certain flux normalization. Similar sources have also been added close to the galactic center for investigating the capability of GLAST in the observation of low latitude galactic sources, region where the resolution of faint sources is more difficult due to the presence of the galactic plane. In figure 10.1 is represented the galactic Sky Map above 30 MeV, as results of one day of simulated data. All the different contributions are merged together and the plot is indeed an estimation of how LAT detector will see the sky. For having a more complete view of the entire gamma ray sky, I have also reported the galactic sky map above 100 MeV, 1GeV and 50 GeV (Fig. 10.2), using the visualization software developed and described in the previous Chapter.
Figure 10.1: The gamma-ray sky above 30 MeV as observed by the LAT-GLAST instrument in one day. The colors scale with the photon energies.

One of the most exciting target opportunity for the GLAST mission is the observation of Gamma Ray Bursts. Two different simulators for GRB have been developed for Data Challenge purposes. One is based on the physical fireball model, described in Chapter 7 and has been used for simulating the first day of the DC1, the other is based on the phenomenological model and is also available in the GLAST software\(^1\). For the simulation of GRB for the first day of Data Challenge we decide to generate Gamma-Ray Bursts isotropically distributed in the sky, thus, some of the simulated GRBs felt outside the LAT FOV (or were obscured by the Earth!). In the first day we simulated 21 bursts, but only 11 bursts fell in the LAT FOV. The fluences of the GRB were extracted from the BATSE distribution as describe in Chapter 7.

### 10.2 Trigger and Alert algorithms

In the observation of GRB, the LAT detector will be, in most of the cases, driven by the alert signal coming from the GBM. At few hundreds KeV there is the bulk of the emission for a typical GRB and the great success of BATSE suggests that at these energies GRB are easy to detect. The GBM will also have a wide filed of view, and will always comprehend the LAT FOV. However, the possibility to provide the LAT detector with an alert algorithm is considered. The possibility to have on on board trigger algorithm depends strongly on the capability of the on board reconstruction: the full reconstruction algorithm will be available only on ground. With this software, the estimated angular resolution of the LAT instrument is comparable to the angular resolution of the GBM at 100MeV (about 3°) but is much better at higher energies.

\(^1\)See http://glast.stanford.edu/cgi-bin/cvsweb/SLAC/GRB/
Figure 10.2: The gamma-ray sky above 100 MeV, 1GeV, 500GeV as observed by the LAT-GLAST instrument in one day. The last graph reports for each photon its energy in MeV
(<0.15°) at 10GeV. On the other hand having the possibility to trigger on-board is needed for alerting other telescopes as soon as possible. If a dim burst has a peak energy above the MeV range, probably nor BATSE or EGRET would have detected it, due to their respective effective area. Two previously detected gamma-ray bursts were independently detected from EGRET, and one new possible detection was made on a timescale of 3 minutes, although the significance is subject to systematic errors [99]. Moreover, Cohen et al. (1998) [100], pointed out that the narrow range of the hardness ratio could not be a real feature of GRBs, but it could be due to an observational difficulty of the BATSE satellite in detecting harder bursts. Nevertheless they suggest that a large population of unobserved hard gamma-ray bursts may exist. LAT detector, thanks to the large effective area that abates the flux level of a factor of 30 with respect to EGRET, could detect these bursts and discover a new class of high energy GRB. Moreover, the great improvement in the time resolution would help in the identification of GRB and, in the common case of a GBM combined observation, correlation of the light curves between the two detector would be possible.

The "raw" data produced during the first day of the DC1, including all the triggered and reconstructed photon (this means all the photons for which the reconstructed algorithm has found a vertex) are about 10^6 events, for a total count rate of 12 Hz. The background rejection and the "good event" filter reduce the events drastically down to an average rate is 2.92 Hz. Many of the low energy photons are dropped away, and unfortunately, many GRB photons got lost. In Fig. 10.4 is shown the comparison between unfiltered data (top) and filtered (bottom). The plots are the count rates for the first simulated data. In the figure is evident how the selection of events reduces the events. It is interesting the GRB located at t ~ 47000. It is a quite intense bursts in the raw data (≈ 60 photons), but it vanishes in the filtered data. This effect is because the GRB illuminated the LAT detector at low latitude (it is at 60° from the normal): the "good event" selection is sensitive to the estimated error on the PSF that is greater at low GLAST latitudes and many GRB photons were discarded as "bad events".

Simple and fast trigger algorithms as the first I am going to present, give good results if applied to unfiltered events. Trigger based on the increment of count rate due to a
Figure 10.4: Count rate for the first day of the Data Challenge 1 for unfiltered data (top panel) and filtered data (bottom panel). The unfiltered data average count rate is 12 Hz, the selection of the events abates the average rate down to 2.92 Hz. Intense GRBs are very well visible. The periodic oscillations are the scanning of the galactic plane due to the orbiting of the satellite.
transient signal are indeed sensitive to fast variation of the trigger rate, even if many photons are not considered “good event”.

10.2.1 The “rate trigger”

The oscillation of the background are due to the galactic plane which crosses the LAT FOV. In the time history, there are some visible bursts, which exceed the background level by a factor of few. There is also a very intense burst at $t \approx 75000$ which exceeds the background by a factor of $\sim 60$. The idea of the “rate trigger” algorithm is to roughly trigger on suddenly increasing of the differential count rate. In particular the rate trigger detects a transient if the differential flux exceeds a fixed threshold. Let’s assume that $t_i \in [0, N]$ is the temporal series containing the tagged time of the $N$ events (the $N$ arrival time). The idea is to compute the count rate by fixing a window of $M$ events:

$$R_j = \frac{M}{t_{M(j+1)} - t_{Mj}},$$

where $(j \in [0, N/M])$. The goal of the differential count rate is to maximize the steep increments and to smooth the background fluctuations. The first panel of Fig.10.5 shows the count rate for the simulated day for the entire field of view. The most intense GRBs ($time \sim 3000, 43000, 71000, 75000, 83000$) are visible in the time history.

The differential count rate is the quantity $R_{j+1} - R_j$ and it is shown in the second panel of Fig.10.5 with $M = 200$. The long period oscillations are not yet visible while short transient phenomena are enhanced by the differential operator. The third panel of Fig.10.5 represents the histogram of the differential count rate. The gamma background photons built the exponential distribution, while Gamma Ray Bursts, for which the differential count rate is high, are the “outliers” of this distribution. This method is efficient for bright GRBs, for which the flux exceeds the background flux, while faint bursts, for which the flux is comparable to the gamma background, may not be triggered. An efficient improvement of the rate trigger is the segmentation of the sky in different regions where the rate trigger is successively applied.

10.2.2 Segmentation of the sky

An efficient improvement of the rate trigger algorithm is the segmentation of the sky into sub regions. This allows to reduce significantly the background of the non burst’s photons, and to increment the chance of a faint burst to be triggered. There are basically two ways for dividing the sky, depending on which coordinate system one chooses. The galactic coordinate system or the instrument system. The main difference between the two is that, the non stationarity of the background due to the orbital motion can be reflected as false trigger if the instrument coordinate system is chosen, especially in the “rocking mode” of the satellite. In the “scanning” mode there is no a big difference between the two method, at list for short burst, since GLAST is scanning 360° is approximately 5400 seconds, or 0.07°/s. In this work of thesis will be presented the segmentation of the sky in galactic coordinates, but it is important to remind that a different choice has been taken from other member of the GRB working group, preferring to work in the instrument coordinate system.

In figure 10.6 is shown a possible division of the sky in an array of $5 \times 5$ regions. In each region the rate trigger is separately applied. In different regions of the sky the average background rate is different (the presence of the galactic plane is increasing the background rate by a factor of $\sim 2$) and the threshold cannot be unique. We compute the
Figure 10.5: Top: count rate for the simulated day of the DC1 for the entire FOV.. Middle: differential count rate. Bottom: histogram of the differential count rate. GRB are the outliers of the distribution.
Figure 10.6: Segmentation of the sky in galactic coordinates

RMS of the distributions of the count rates in each sub regions, and we set the threshold by choosing a fixed number of RMSs. In the analysis of the DC1 data the threshold was set to 10 times the RMS of the differential count rate distribution. In figure 10.7, is depicted the array of differential count rates corresponding to the segmentation of the sky of fig 10.6.

The described algorithms have been applied to unfiltered data. The goal is to perform a quick look analysis on the raw data, considering as much events as possible. In DC1 the particle background was not simulated and the filter algorithm was not fully developed, so that the real effect of the definitive background filter could not be evaluate at the moment. The application of the "rate trigger" algorithm on filtered data has been done using the selection cuts named "good event" selection, whose goal is to obtain a good PSF losing in efficiency (smaller effective area). The result is shown in Fig. 10.8.

Finally, it is important to underline that a selection of events which reach the compromise between high efficiency in the detection and good angular reconstruction of the instrument can negatively affect algorithm that trigger on the trigger rate (like the "rate algorithm"). For blindly searches of GRB for alert porpoises a different selection of events, with the goal of taking as many events as possible (or in other words to maximize the effective area) can be taken into account. A more interesting and complete scheme will be to study when also particles will be introduced as Data Challenge source.

If the events selection is applied, more sophisticated algorithms have to be applied. The basic idea of the Strawman GRB tracker trigger algorithm, developed by the Gamma-Ray Bursts and Solar Flare science team, is to look for clustering events in space and in time, and to compute the probability of such cluster as realization of the background. If the probability is behind a certain threshold is unlikely that the cluster of events is background and is probably a GRB.
Figure 10.7: Result of the application of the “rate trigger” algorithm on different sky regions. Each light curve corresponds to a recorded signal from the sky region of Fig 10.6. The highlight boxes are the region for which the “trigger rate algorithm” detects one or more transients.
Figure 10.8: Result of the application of the “rate trigger” algorithm on different sky regions for filtered events. The selected events are approximately the 27% of the total events. The highlight boxes are the region for which the “trigger rate algorithm” detects one or more transients. In this case many Gamma-Ray Burst photons have been discarded by the filter. The selection is the standard “good event” selection.
10.2.3 Strawman GRB tracker trigger algorithm

The Strawman GRB tracker trigger algorithm makes maximal use of the unbinned photon data coming into the GRB buffer to form probabilities from the temporal and spatial information. The idea is to look for aggregations in time and in space of events, by means of a sliding window. A buffer of $N_{\text{range}}$ photons (typically 20) is moved by $N_{\text{move}}$ photons (typically 5). The $N \times (N - 1)$ distances on the sphere between the $N_{\text{range}}$ photons are computed. Each of the $N_{\text{range}}$ photons is considered the potential nucleus of a spatial cluster. Thus for each photon there are $N_{\text{range}} - 1$ distances. The cluster with the smallest average distance for the retained photons is selected, while the other cluster will no longer considered. The selected photon is the “cluster tag” and it determines the time flag and the position of its cluster. For each photon in the cluster, the localization error radius is estimated by computing the Point Spread Function corresponding to the energy of the photon. The $N_{\text{range}} - 1$ distances between the selected photon and the other photons in the cluster are recomputed, and photon farther than the summation of the two error radii considered are discarded. In this way, we consider aggregation of of photons the ensemble of photons which come from the same direction, considering the error in the reconstruction. After this operation few photons survive in the cluster, and for those photons the space probability of aggregation is computed by comparing their distances (the distances between the selected photon and the retained photons in the cluster) with a random positional occurrence in the sky. Let $d_i$ be the $N_i - 1$ distances between the select photon and the retained photons, then the spatial probability is expressed by the following equation:

$$\log P_{\text{dist}} = \sum_{i=1}^{N_i-1} \log[(1 - \cos(d_i))/2] \quad (10.2)$$

Similarly, if the background count rate is $R$, the chance probability of having an interval between two consecutive photon $\Delta t_i$ when the background rate is $R$ is expressed by:

$$\log P_{\Delta t} = \sum_{i=0}^{N_i-1} \log[1 - (1 + R\Delta t_i) \exp(-R\Delta t_i)] \quad (10.3)$$

Notice that the background (the non bursts photons) depends on the position in orbit, and it is not stationary. We compute the background rate for the cluster $i$ considering the average rate for the cluster $i-1$. The total probability is than computed: the Joint spatial and temporal probability for a given cluster is:

$$\log P = \log P_{\text{dist}} + \log P_{\Delta t}. \quad (10.4)$$

$\log P$ tells the probability that a given cluster is a “background” cluster. Therefore we are looking for the minimum of the logarithm of the joint likelihood. This algorithm, which is basically the implementation in C++ of the already existing algorithm developed as IDL program by some colleagues, is very efficient in detecting transients: it makes use of both spatial and temporal information considering also the reconstruction error due to the Point Spread Function, depending on the energy. The information on time, direction, and energy are in this way mixed in order to maximize the probability of detecting a transient. Other algorithms, such as the rate trigger, which are not using, or only partially using, the information on the directions of the photons are less efficient basically due to the intrinsic use of few informations. Moreover the strawman trigger algorithm gives direct information on the localization of the triggered burst.
Figure 10.9: Temporal evolution of the logarithm of the spatial probability ($\log(P_{\text{dist}})$) (top panel), of the temporal component (middle) ($\log(P_{\Delta t})$) and of the logarithm of the joint probability ($\log P$) (bottom). Triangles are triggered bursts.
10.3 Comparison between alerts algorithms

Different algorithms have been successfully applied for searching transient signal in DC1 data. It is worth summarizing in a table all the informations needed to compare the different GRB alert algorithms. Table 10.1 summarizes the “Monte Carlo truth” for the generated bursts. The GRB number, the starting time, the ending time, the duration, and the position in the sky in galactic coordinates are available in the table.

Table 10.2 summarizes the results of the different algorithms applied to filtered and unfiltered DC1 data. For each burst the number of generated photons, the GRB starting time is indicated. Then the results of each algorithm is indicated in case of success. A ”U” indicates that the algorithm has been applied to unfiltered data, and a ”F” to filtered data. Bright bursts (with more than 300 generated photons) can be detected with simple and trivial algorithms. More sophisticated algorithms have to be developed for detecting faint GRBs. The segmentation of the sky into sub-regions gave good results, maintaining the algorithm easy and the execution fast. The rate-trigger algorithm is anyway negatively affected by the selection cuts. The reduction of statistics of the almost 30% is reducing the rate and statistical fluctuations are more evident. In practice, many GRB photons even if their direction has not been well reconstructed, contribute to increase the rate during a GRB event, increasing also the probability of detection. The best results in terms of triggered GRBs has been obtained using the Strawman GRB tracker trigger algorithm, based on the joint log probability. In this case the application of the of selection cuts on the events and the reduction of statistics has had a positive effect, increasing the number of triggered GRB. This effect happens probably because with the selection cuts many events that have low probability to have been well reconstructed are discarded. In practice, the selected events are less but they are likely well reconstructed. The Strawman GRB trigger alert needs an accurate direction reconstruction for looking at the possibility of clustering events. On the contrary the wrong reconstructed events are considered as background and the probability to find a cluster decreases. The Strawman GRB trigger alert allows also an estimation of the localization of the GRB. To each cluster a photon is selected as most probable aggregation center. The arrival time of this photon and its reconstructed direction can be taken as trigger time and GRB direction. Table 10.3 compares the Monte Carlo truth (number of generated photons, starting time, and galactic position), with the estimated starting time and localization given by the Strawman GRB trigger alert. Notice that the sixth column contain the number of selected photons, which is the number of photons that have been triggered and passed the selection cuts (see Chapter 4 for details on the selection criteria).

Further studies will include the particles background, and the possibility to implement an on-board LAT alert algorithm will be taken into account. All of these items will be target for the next Data Challenge (DC2), in which one month of simulated data will be produced.
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Table 10.1: Monte Carlo truth for the generated bursts in the first day of the DC1 data. The columns are: the burst number, the number of photons generated, the starting time, the ending time, the duration.
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Table 10.2: Comparison between different algorithms. In case of detection the label "U" indicates that the algorithm has been applied to unfiltered data, while a "F" to filtered data. The last line of the table contains the total number of generated bursts and the total number of detected bursts by each algorithm, for Unfiltered-Filtered data. The total number of burst detectable by the LAT is 11 if considered the Field of View of the LAT detector.
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Table 10.3: Comparison between the Monte Carlo truth and the reconstructed GRB position. Columns are: The GRB number, the generated photons, the time of the first photon (starting time), the galactic coordinates $l$ and $b$, the number of photons detected and selected after the cuts, the time, $l$ and $b$ reconstructed by the Strawman GRB alert algorithm. Every bursts in the FOV of the LAT detector has been detected. Bursts 12 and 20 are quite intense but they felt outside the LAT FOV.
Conclusions

Gamma-Ray astronomy is a relatively new branch of the astrophysics and the main reason of the late emergence is technological. With the advent of the solid state devices the high energy astrophysics is entering in a new era. The Gamma-Ray Large Area Space Telescope (GLAST) is an international mission on satellite that will make a huge leap in key capabilities including a largely majored energy range. GLAST will have a great potential for discoveries. In the first Chapter of this Thesis I have reviewed the main scientific interests in the observation of the gamma-ray sky. Starting from the discoveries of the ancestors of GLAST, like OSOIII, SAS-2, COS-B and EGRET, I have considered the main scientific topics that brought to the development of a new generation gamma-ray observatories, like GLAST. The gamma-ray sky is reach of sources like Active Galactic Nuclei (AGN), whose emission has been seen up to TeV energies. Considering the LogN-LogS distribution of the observed energies, and extrapolating it to GLAST sensitivity ($\approx 6 \times 10^{-9}$cm$^2$/s above 100 MeV, for high latitude sources, in one year exposure in all sky survey), the number of detectable AGN is incrementing from tens, as for EGRET, to few thousands.

Despite the impressive work done by EGRET, more than 60% of the sources observed are still unidentified. There are reason to believe that, thanks to the better resolution, the larger effective area, and the wider energy range, GLAST will be able to resolve many of these sources, living space to the discovering of new class of celestial objects.

Extragalactic background was the first sources of gamma ray observed, and its origin is still unknown. Three hypothesis on its origin are briefly reviewed: the possible contribution of a large number of AGN sources that could resolve the entire isotropic emission, the possibility of relic radiation from the primordial universe and the annihilation of supersymmetric particles in the Milky Way Halo. The possibility of observing line and a continuum flux from the annihilation of the lightest supersymmetric particle has been taken into account. The possibility of direct observing the annihilation line from the neutralino would be a direct measurement of the mass of the most promising candidate for dark matter in the universe.

The observation of the high energy excess by EGRET and recently by H.E.S.S. (the High Energy Stereoscopic System) in proximity of the Galactic Center (GC) is also reviewed. The Galactic Center region harbors a variety of potential sources of high-energy radiation, such as the supermassive black hole Sgr A* and a number of supernova remnants, among them the Sgr A East remnant of a giant supernova explosion which happened about 10000 years ago. The mysterious dark matter, which accumulate at the Galactic Center, undergoes pair annihilation provide another speculative mechanism for gamma ray production. The Galactic Center is therefore a prime target for gamma-ray observations.

The knowledge of the cosmic-ray acceleration mechanism is, without any doubts, one of the most important consequences of gamma-ray observations. Charged particles are indeed deviated by the Galactic Magnetic Field and are loosing completely the infor-
mation on their provenience. The observation of gamma-rays, which are not deflected by magnetic fields, allows the direct observation of the cosmic rays accelerators, and allows their identification. The observation of the Supernovae Remnants (SNR) is, in this context, of central importance. It is thought, indeed, that SNR represents the accelerators of cosmic rays due to shocks mechanism between the supernovae expanding shell and the Interstellar medium. What GLAST would see is the production of gammas via Bremsstrahlung, $\pi^0$ decay or via Compton Scattering.

Pulsars are fast rotating neutron stars, whose gamma ray emission has been observed since the seventies by the satellite SAS-2. EGRET observed seven pulsars, but many gamma-ray pulsar candidates can be found by looking at other wavelengths, especially at radio catalogues. In one year of observation GLAST would help to discriminate between high energy emission from the polar cap and outer gap by looking at the cut-off energy. Searches for periodic and quasi periodic signal will be done continuously in order to discover new "Geminga" like pulsar.

Finally, one of the most powerful sources are Gamma-Ray Bursts (GRBs). Rapid flashes of high energy radiation that lasts from some milliseconds to hundreds of seconds, maybe related to the explosion of high massive stars at cosmological distances. GRBs, have been deeply discussed in this Thesis and most of the work done is related to this topic.

Science topics are, at all the effects, design drivers for the development of a gamma-ray telescopes. The faintness of the fluxes, for example, sets the need to have a large collective area; the requirement of resolving spatially different sources is translated into high spatial resolution and into the choice of a detector with high resolution power. The Large Area Telescope (LAT) is the main instrument onboard the GLAST experiment. It is made by a modular structure consisting in an array of 4x4 identical towers. Each tower is a tracker module and a calorimeter. The arrays of towers is shielded by an ACD to veto cosmic-rays triggers. The tracker is by far the most challenging module of the entire GLAST satellite in terms of technological achievement needed to satisfy the tight requirements. All of the sixteen flight towers of the LAT tracker are built in Italy. Two flight towers have been already developed and tested, two spare towers and two engineering models have been developed and tested at the "Istituto Nazionale di Fisica Nucleare" (INFN), locating the Italian collaboration in a privileged position in the GLAST collaboration. In Chapter 2 I describe the LAT detector in its components. The GLAST Burst Monitor (GBM), a detector which helps the Large Area Telescope in the observation of bursts studying the low energy gamma-ray emission, is also presented. Together with the hardware development a very important activity is the development of the software, needed both for simulate the instrument and for analyzing the simulated data in order to improve the detector knowledge. An overview of the full GLAST/LAT software has been presented in Chapter 3. Given the typical fluxes of the gamma-ray sources it is possible to simulate the interaction of a single photon coming from the sky by means of a Montecarlo simulator, which treats all the interaction between the particles and the different materials of the detector. This approach is closer to a typical particles physics experiment based on accelerators, but is relatively a new approach in astrophysics. The GLAST/LAT community has set up a complete simulation chain that starts from the description of the gamma-ray sky, where the simulated photons are processed and propagated trough the detector using Geant4, a Montecarlo toolkit developed at CERN. The released charge in each active volumes (Silicon Sensors) is converted in to digits and then the digitized signal is processed by the reconstruction algorithms. Background rejection is also applied so that the final reconstructed gammas are available. Many of these algorithms (reconstruction and charge particle rejection)
will be the same that process the real data once GLAST will be operative.

On the other hand, the typical point of view of an astronomer is the description of the detector performance by means of parameterized function (called the Instrument Response Functions, or IRFs) which describe the detector in terms of detection efficiency (effective area), energy resolution (or Energy Dispersion) and angular resolution (Point Spread Function). The IRF for the LAT detector has been computed during this work of Thesis using a Montecarlo data taken in mid 2003 at SLAC computer farm. The algorithms for analyzing the data and the tool for displaying the results have been developed during this work of Thesis. The results are presented in Chapter 4. A particularly interesting aspect is the definition of the selection of the events for optimizing the IRF. In particular a “good” PSF, a “good” energy resolution and a “good” Effective area (i.e. which satisfy the requirements) have been obtained.

The Chapter 5 introduces the main topic of this Thesis, the Gamma-Ray Bursts. In this chapter I have reviewed the main observation related to the physics of GRB. Tools have been developed for displaying the available data of the BATSE on-line catalogue, studying the global properties of the GRB phenomena, building up a statistics which describe this class of celestial sources. Then, I have reported some observation on the evidence of an high energy component which locate GRB in one of the most interesting science topic for the GLAST/LAT experiment.

The knowledge of GRB phenomena, both in terms of individual properties (such as individual spectrum, pulse shapes, etc.) and in terms of global properties (distribution of intensities, of durations, etc.) have been used for developing two GRB simulators, which can be used in the official GLAST/LAT software. The two models I have developed are interfacing the generator package, feeding the Montecarlo of the LAT detector with photons coming from the simulated bursts. The models are based on two different approaches, one is the phenomenological one, which basically extrapolates the observation made at BATSE energy range to LAT energies, and the other is based on physical motivations. The phenomenological model is basically a review of analysis made in the past using BATSE data that characterize GRBs light curve and spectra by fitting individual burst using parameterized functions. The collection of these parameters for many bursts builds up a series of distributions that have been used, in this Thesis, for sampling randomly synthetic bursts. It is worth underlining that the time scale that characterize the pulse width is of the same order (or slightly smaller) of the time scale that characterize the separation between pulses (of the order of hundreds of milliseconds). This define an unique scale of variability in GRB, a requirement that also physical models have to satisfy. High energy emission has been obtained by merely extrapolating the BATSE observed flux at high energies and a temporal-spectral variability has been introduced using the relation observed Fenimore et al.[63] and Norris et al.(1996) [66]: the Full Width at Half Maximum of the same peak observed in different energy channels decreases with the energy as a power law. In the model, both the time integrated spectrum and the time resolved spectrum are “Band” functions: a relation between the spectral indexes of the time resolved spectrum and of the time integrated spectrum, taking into account the spectral-temporal variability, has been found.

The other model developed during this Thesis is the GRB physical model, based on a completely different approach. It was developed starting from the well known scenario of expanding fireballs in the internal shock configuration. Shells of matter are ejected from a central engine into the Interstellar Medium with different Lorentz factors. Internal shocks occur when a fast moving shell reaches a slower one. Every physical ingredient has been described in Chapter 7 (and also in Appendix A and Appendix B), and a complete picture has been derived. The GRB physical model is not only a tool which
reproduces the observed properties of GRBs, but is a machinery for previewing possible scenarios for the observation at high energies. Particularly interesting results are:

- A detailed computation of the pulse shape in the approximation of thin shell case gives a simple description of the pulse shape of GRBs. Only one time scale, the central engine variability, is needed for describing both the pulse width and the separation between pulses.

- Assuming that electrons are accelerated via shocks mechanisms with a power law initial distribution between $\gamma_{\text{min}}$ and $\gamma_{\text{max}}$, then they emits via synchrotron radiation in agreement with a fast cooling spectrum, with an exponential cut-off at high energy. The cut-off depends uniquely on the Lorentz factor of the emitting shell via this simple relation:

$$E_M = 25 \Gamma \text{ MeV}$$

(10.5)

for GRB typically $\Gamma \approx 10^2$, corresponding to a cut-off at GeV energies, observable by the LAT.

- The three parameters of the model ($R_0$, $\Delta R$, $\Gamma$) can be expressed as a function of observed quantities (i.e. $t_v$, which is the the variability time-scale, directly observable from the light curve; $E_p$, which is the peak energy observable at hundreds of keV; $E_M$ the cut-off energy, observable at GeV energies).

- The parameters of the model can be constrained to BATSE observations, the fluences at BATSE energy can be normalized to the observed distribution and a catalogue of BATSE bursts at LAT energy has been obtained, investigating, in particular, the effect of the Inverse Compton emission.

The two models developed here are connected to the MonteCarlo of the LAT trough a event generator algorithm which is responsible to extract photons in agreement with the light curve and with the spectrum of the synthetic GRB. In this way it is possible to directly investigate the capability of GLAST in the observation of GRBs using the GRB models within the full LAT monteCarlo simulator.

The data produced by the simulations has been analyzed with the Science Tools, the official software for analyzing the LAT data. The series of algorithm is briefly introduced, especially for define the standard step defined in a typical analysis. They are simple algorithms that the Science Support Center will release to the astronomer community for analyzing data. A series of “alternatives” tools, based on the ROOT object oriented data analysis framework, has been developed and applied for analyzing and visualizing the data. Extraction and binning of the events, visualization of the light curve, of the sky map in different coordinates, and of the spectrum are fully implemented options. Moreover, the normalization of the spectrum taking into account the IRFs has been already implemented. In this Thesis the development of this software is presented, with particular emphasis on the treatment of the IRF for calibrating the observed flux, a typical problematic of astronomy and astrophysics. Three measurement related to GRB have been considered as possible key studies for GLAST.

- The measurement of the high energy cut-off: We have shown that for relatively intense GRBs a direct measurement of the high energy cut-off it is possible.

- The inverse Compton component: we have shown that the spectral analysis can discriminate between synchrotron model and inverse Compton component, in particular studying the change of spectral slope from a high energy index greater then
2 (a negative index of the $e^2 N(e)$ spectrum) for pure synchrotron spectrum, to an index less than 2 (a positive index of the $e^2 N(e)$ spectrum).

- Measure of the Quantum Gravity effect: In several approaches to quantum-gravity, one find a departure from ordinary Lorentz symmetry with a possible emergence of a dispersion relation. Such dispersion relation leads to a small energy dependence of the speed of photons. We have shown that, assuming a standard value for the planck energy of $10^{19}$ GeV, the expected delay for a $z = 1$ burst would be of the order of tens of milliseconds, if light curves at 30 MeV are compared to those at 10 GeV. GLAST will be able to directly measure time lags of the order of few tens of milliseconds, scanning the Quantum Gravity energy, scale for the Lorentz symmetry violation, up to $10^{22}$ GeV.

- The GLAST/LAT sensitivity for GRB has been studied in detail. A catalogue of 10000 bursts with different IC component and with fluences comparable with the BATSE observation has been simulated. For each bursts the number of photons viewed by the LAT above 100 MeV has been computed by taking into account the effective area for on-axis observation and for off-axis (67°) observations. Two detectability threshold have been set by considering the minimum number of detected photons required for triggering a Gamma-Ray Burst by GRB alert algorithm. For on-axis observations are required a flux greater then $\approx 6 \text{ ph/m}^2 \text{ incident flux, or GRB with BATSE fluence greater then } \approx 10^{-7} \text{erg/cm}^2$, corresponding roughly, to 89% of the BATSE fluence distribution. For the unfavorable case off-axis observation the estimated threshold is $\approx 200$ generated photons per square meters, and a minimum detectable fluence of $\approx 10^{-6} \text{erg/cm}^2$, depending, of course on the spectral shape. In case of pure synchrotron radiation, the minimum detectable fluence for on-axis bursts is $\approx 3 \times 10^{-7} \text{erg/cm}^2$ (73%) and for off-line bursts is $\approx 3 \times 10^{-6} \text{erg/cm}^2$ (18%).

- Assuming that GRB are standard candles, and assuming a cosmological model, the sensitivity of GLAST to GRB can be converted in redshift by means of the luminosity distance. For a flat universe with $\Omega_m = 0.3$ and $H_0 = 75 \text{ km/s/Mpc}$, we have found that, GLAST will be able to scan the universe up to early epoch ($z=10$ for an intrinsic luminosity of $10^{52}$ ergs). In a more conservative view, assuming that the intrinsic luminosity ranges between $10^{51}$ and $3 \times 10^{51}$ GRB will be seen by the GLAST/LAT instrument up to redshift 5.

During the period of Thesis I had the opportunity to participate to the Data Challenge 1 (DC1), one simulated day of observation using the full Montecarlo for the LAT detector. In the description of the sky, GRB sources have been simulated using the physical model developed in this Thesis. 21 GRBs have been simulated isotropically distributed in the sky with different intensities. Six bursts were occulted by the Earth and Four were outside the Field Of View: the number of detectable bursts were eleven. One of the main tasks in the DC1 was to search for transient. Trigger algorithms for detecting transient have been developed, facing several aspects of the scientific data analyses. The application of data selection filters the 30% of the events, reducing the average count rate from 12 Hz to 3 Hz. Different transient alert strategies have been developed and here are the main results:

- The rate trigger algorithm is an transient alert algorithm which triggers on rapid variations of the count rate. It has been successfully applied to unfiltered data, detecting 5 bursts.
• The segmentation of the sky into sub-region decrease the background level, and
the application of the rate trigger on separate regions allows the detection of 10
bursts.

• The rate trigger algorithm is not satisfactory if applied to filtered data (5 bursts
detected), and more complicated algorithms have to be developed.

• A new version of the already existing strawman GRB LAT alert has been developed
and applied to filtered data, detecting all the 11 detectable bursts.

The aim of the next Data Challenge will be to include charged particles background
to test the capability of the background filter in more realistic situation. The GRB trig-
ger algorithm will be implemented on-board, using the on-board available informations
for providing a fast alert signal.

The work presented in this Thesis has shown, trough the development of a source
model for GRB, the simulation of the LAT detector and the analysis of the simulated
data, the perspectives of science related to the GRB that GLAST will face in orbit.
The LAT telescope will observe an unobserved region of the Gamma-Ray Burst spectra,
shading light on a various unsolved problems related to the exciting Gamma-Ray Burst
science.
Appendix A

Relativistic hydrodynamics and shocks

As every field theories, the relativistic hydrodynamic needs a stress-energy tensor $T_{\mu\nu}$. For a perfect fluid with pressure $p$ and energy density $e$ (no viscosity, no heat conduction), in a (locally) Minkowskian space with the metric of signature $(1,-1,-1,-1)$, the stress energy tensor in the fluid’s frame has this simple form:

$$
\begin{pmatrix}
e & 0 & 0 & 0 \\
0 & p & 0 & 0 \\
0 & 0 & p & 0 \\
0 & 0 & 0 & p \\
\end{pmatrix}
$$

(A.1)

while, in a generic frame we have to introduce the 4-velocity $u^\mu = (\gamma, \gamma \vec{v})$ and the stress energy tensor becomes:

$$
T^{\mu\nu} = (e + p)u^\mu u^\nu - \eta^{\mu\nu},
$$

(A.2)

with $\eta^{\mu\nu}$ the metrics tensor. Eq.A.2 is the stress-energy tensor for a perfect fluid in relativistic hydrodynamics. The conservation laws for hydrodynamics (not only in the specific case of a perfect fluid) are expressed by the elegant equation:

$$
\nabla T = 0,
$$

(A.3)

or, in the covariant form:

$$
\partial_\mu T^{\mu\nu} = \partial_0 T^{0\nu} + \partial_j T^{j\nu},
$$

(A.4)

where the first derivative on the right hand of the equation is the derivative with respect to time. $T^{00}$ is the energy density and $T^{j0}$ is the energy flux in the j-th component. $T^{0i}$ is the density of the momentum of the i-th coordinate, while $T^{ji}$ is the flux of the momentum. Let be $n$ the particles density, then the conservation of the particle number can be written as:

$$
\partial_\mu (nu^\mu) = 0.
$$

(A.5)

The shock dynamics can be now described using the hydrodynamic formalism. In the simpler case of parallel shock, with the propagating direction of the shock parallel to the fluid’s velocity, a shock can be thought as a discontinuity surface between the upstream region, which is not shocked yet, and the downstream region, which is shocked. Left panel of Fig. A.1 show a schematic view of the problem. The fluid (which is the shell in which the shock is propagating) is moving from left to right. Upstream region is the unshocked shell while downstream region is the shocked region of the shell. The
Figure A.1: Schematic view of the shock dynamics. Left: in the “far observer” reference frame both the upstream region, the downstream region and the shock front (vertical line) are moving from left to right, and the shock is propagating into the upstream region. The shocked downstream fluid is moving faster. In proximity of the shock front a discontinuity in pressure and density can be thought. Right: in the shock’s front reference frame, both the upstream and the downstream fluids are moving towards the shock surface. The upstream fluid if moving faster.

shock surface, which is represented by a thick vertical line, is also propagating from left to right into the upstream region. The deceleration and compression of the fluid occur in a very thin layer, and we may approximate the entire process as a single discontinuous jump (the shock discontinuity surface). It is more convenient to study the problem in the shock comoving frame (right panel of Fig. A.1). In this frame both the upstream fluid and the downstream fluid are moving towards the shock surface. Even in the presence of this discontinuity, the conservation of the number of particles, of the the energy and of the momentum hold between the upstream and downstream regions. In particular, considering $x$ the propagating direction, and considering that: $\{a\} = 0$ means $a_1-a_2 = 0$ with $a_1$ and $a_2$ the quantity before and after the shock, then:

$$\begin{align*}
\{ T^{0x} \} &= \{(e + p)\gamma^2\beta \} = 0 \\
\{ T^{xx} \} &= \{(e + p)\gamma^2\beta^2 - p \} = 0 \\
\{ n\beta\gamma \} &= 0
\end{align*}$$

(A.6)

The general solution of the previous system is not trivial, and the knowledge of the state equation is needed. The extreme relativistic case is, fortunately, more simple: the source is relativistic and the fluid, which is expanding with relativistic velocity, can be described with the ultra-relativistic state equation $(p = e/3)$. Notice that in internal shock this is not always true: the colliding shells have similar Lorentz factor and their relative motion, which determines the shock dynamics, is only mildly relativistic. In the ultra relativistic case, considering the upstream fluid cold (before the shock, the internal motions are negligible), the upstream and downstream equations of state are:

$$\begin{align*}
p_1 &= 0 \\
 e_1 &= n_1 m_p c^2 \\
p_2 &= e_2/3
\end{align*}$$

(A.7)

Assuming that the velocity of the upstream fluid viewed by an observer at rest in the shock reference frame is close to the speed of light $(\beta_1 \approx 1)$, then the Taub equations (system A.6), which express the relativistic Rankine-Hugoniot equations, can be written
in a simplified form:

\[
\begin{align*}
  e_1 \gamma_1^2 &= \left( \frac{4}{3} \right) \gamma_2^2 - 1 \varepsilon_2 \\
  e_1 \gamma_1^2 &= \frac{4}{3} \varepsilon_2 \gamma_2 \sqrt{\gamma_2^2 - 1} \\
  e_1 \gamma_1 &= n_2 \varepsilon_c^2 \sqrt{\gamma_2^2 - 1}
\end{align*}
\]  

This system can be solved and the speed, the energy, and the density of the downstream fluid are:

\[
\begin{align*}
  \gamma_2 &= \frac{3}{\sqrt{8}} \\
  n_2 &= \sqrt{8} n_1 \gamma_1 \\
  \varepsilon_2 &= 2 e_1 \gamma_1^2
\end{align*}
\]  

The relative motion between the upstream and downstream fluid is \( \gamma_{rel} = \frac{\gamma_1}{\sqrt{2}} \). In the reference frame of the upstream region (1) the shock is moving with a Lorentz factor \( \gamma_{sh} = \gamma_1 \). Expressing Eq. A.9 in terms of this variable, using the substitution \( \sqrt{2} \gamma_{rel} = \gamma_1 = \gamma_{sh} \), I obtain:

\[
\begin{align*}
  n_2 &= \sqrt{8} n_{sh} \gamma_1 = 4 n_1 \gamma_{rel} \\
  \varepsilon_2 &= 2 e_1 \gamma_{sh}^2 = 4 e_1 \gamma_{rel}^2
\end{align*}
\]  

for the particle density and for the energy density in the downstream region. Even if the extreme relativistic case is an approximation of the general case of Internal shocks, the main results are still valid in the mildly relativistic case, in particular: the Lorentz factor of the shock front is proportional to the Lorentz factor of the relative speed between shells; the particle density in the shocked region increases by a factor \( \gamma_{sh} \), due to compression; the energy density increases by a factor \( \gamma_{sh}^2 \). In internal shocks, for an adiabatic index \( 4/3 \) and comparable densities \( n \), the Lorentz factor of the shock satisfies:

\[
\gamma_{sh} = \sqrt{\left( \frac{\gamma_{rel}^2}{\gamma_1^2} + 1 \right) / 2}
\]  

and the densities in the shocked region are\[75]:

\[
\begin{align*}
  n_{sh} &= n_1 (4 \gamma_{sh} + 3) \approx 4 n_1 \gamma_{sh}; \\
  \varepsilon_{sh} &= 4 e_1 \gamma_{sh}^2.
\end{align*}
\]
Appendix B

Emission Processes

In this appendix the emission processes which have been taken into account in the development of the GRB physical model are presented. Synchrotron radiation is, very simply, radiation from relativistic electron moving in a uniform magnetic field. It is the relativistic extension of the cyclotron radiation. The scenario is that relativistically electrons, initially distributed by the shock with a power law distribution, lose energy by synchrotron emission and eventually re-interact with the synchrotron emission spectrum via Inverse Compton, producing high energy photons. The magnetic field is suppose to be randomly oriented. Since the radiative processes are taking place in a relativistically moving emitter (the shell), the observed radiation is boosted to higher energy due to the relativistic doppler factor. Here the emitted spectrum, comoving with the shell, is computed.

B.1 Synchrotron spectrum from a relativistic electron

The characteristic synchrotron energy, averaged over the pitch angle, of an electron moving with Lorentz factor \( \gamma \) across a randomly oriented magnetic field of straight \( B \) is:

\[
\nu_{\text{syn}}(\gamma) = \frac{3}{2} \frac{qB}{m_e c} \gamma^2 \approx 4.2 B \gamma^2 [\text{MHz}]
\]  

(B.1)

that is the synchrotron characteristic frequency averaged over the pitch angle, which corresponds to an energy:

\[
E_{\text{syn}}(\gamma) = \frac{3 \hbar q B}{2 m_e c} \gamma^2 \approx 1.73 \times 10^{-11} B \gamma^2 [\text{keV}]
\]  

(B.2)

The power, frequency integrated, radiated by an electron is:

\[
P_{\text{syn}}(\gamma) = \frac{2 q^4 B^2 \gamma^2}{3 m_e^2 c^3} = \frac{1}{6\pi} \sigma_T c B^2 \gamma^2 \approx 10^{-3} B^2 \gamma^2 [\text{eV/sec}]
\]  

(B.3)

The comoving cooling time for synchrotron emission, which is the time that an electron takes to lose its energy via synchrotron radiation, is:

\[
t_{\text{syn}}(\gamma) = \frac{\gamma m_e c^2}{P_{\text{syn}}(\gamma)} \approx 5.1 \times 10^8 \frac{1}{B^2 \gamma} [\text{sec}]
\]  

(B.4)

From equation (6.33) in Rybicky & Lightman 1979 [101], the synchrotron power per unit of energy \( e \) of an electron with energy \( \gamma m_e c^2 \) can be written as:

\[
P_{\gamma}(e) = \frac{3^{5/2}}{8\pi} \frac{P_{\text{syn}}(\gamma)}{E_{\text{syn}}(\gamma)} F\left( \frac{e}{E_{\text{syn}}(\gamma)} \right) = \frac{\sqrt{3} q^3 B}{2\pi m_e c^2} F\left( \frac{e}{E_{\text{syn}}(\gamma)} \right),
\]  

(B.5)
Figure B.1: Synchrotron function (Eq. B.7). Represents the functional dependence of the synchrotron spectrum to the parameter \( x = e/E_{\text{syn}}(\gamma) \).

where

\[
F(x) = \int_x^\infty K_{5/3}(\xi) d\xi
\]  

(B.6)

is the synchrotron function, with \( K_{5/3} \) is the modified Bessel function of 5/3 order.

To be notice that the ration between the emitted power and the energy of the electron (\( P_{\text{syn}}(\gamma)/E_{\text{syn}}(\gamma) \)) does not depend on the energy of the electron (\( \gamma \)), thus only the function \( F(x) \) describes the spectral shape. The instantaneous synchrotron spectrum of a single electron with an initial energy \( \gamma m_e c^2 \) given by equation B.5 can be approximated with a power law with \( P_\gamma(e) \sim e^{1/3} \) up to \( E_{\text{syn}}(\gamma) \) and an exponential decay above it, or, in formula:

\[
F(x) \approx x^{1/3} e^{-x}.
\]  

(B.7)

This approximation is needed for further computations. The function \( F(x) \) is depicted in Fig. B.1. Its maximum is at \( e = 1/3 E_{\text{syn}} \) where the bulk of the emission take place (not in \( e = E_{\text{syn}} \)). The formula B.5 is the instantaneous spectrum from an electron of energy \( \gamma m_e c^2 \), it can be rewritten as:

\[
P_\gamma(e) = 3.5 \times 10^4 B F\left(\frac{e}{E_{\text{syn}}(\gamma)}\right) \quad \text{[keV/keV/s]},
\]  

(B.8)

B.2 Integrated synchrotron emission from a relativistic electron

If an electron emits via synchrotron radiation, then it will loses energy and the synchrotron spectrum itself will be shifted to lower energy. In astrophysics, generally, we are observing sources not instantaneously, but integrating its emission over a certain observation time. If the spectrum is evolving on time scales much greater than the exposure (as in most of the cases, like observing a (non-compact) star, or an AGN) then the observed (integrated) spectrum is almost identical to the instantaneous spectrum. On the contrary, if the time that the electrons take to loose their energy (the cooling time) is on the order or shorter than the integration time, then the observed spectrum has to be computed by integrating the instantaneous spectrum taking into account the effect of cooling. This happens in the case of GRB, where the magnetic field are strong and the
cooling time are short. The integration time, in this case, is the dynamical time scale, which is the characteristic time for the emission. In the model developed, it coincides with the time that the shock takes to cross the shell, assuming that this is the duration of the emission (in the frame of the shell). We will refer to this time as $t_{\text{hyd}}$. Let's start with computing the integrated spectrum for a single cooling electron. The energy loss equation is:

$$\frac{m_e c^2}{dt} d\gamma = -P_{\text{syn}} = -\frac{2}{3} \frac{q^4 B^2}{m_e c^2} \gamma^2 = -\frac{1}{6\pi} \sigma_T c B^2 \gamma^2$$  \hspace{1cm} (B.9)

solving the previous equation with the initial condition that $\gamma(0) = \gamma_0$, we find that the Lorentz factor of the electron after a time $t$ is:

$$\gamma(t) = \frac{\gamma_0}{1 + \gamma_0 t/t_s}$$  \hspace{1cm} (B.10)

where I have defined $t_s = (6\pi m_e c^2) / (\sigma_T h c B^2)$, so that the synchrotron cooling time (Eq. B.4) is simply given by $t_{\text{syn}}(\gamma) = t_s / \gamma$. The integrated spectrum is the summation of many instantaneous spectrum whose generating electron is cooling. Thus, integrating over the time:

$$P(e) = \int_0^{t_{\text{hyd}}} P(\gamma)(e) \, dt = \int_0^{t_{\text{hyd}}} \frac{\sqrt{3} q^3}{2\pi m_e c^2} \int_0^{t_{\text{hyd}}} F\left(\frac{e}{E_{\text{syn}}(\gamma)}\right) \, dt$$  \hspace{1cm} (B.11)

The solution of the previous integration is depicted in Fig. B.2. The solid line represents the exact numerical solution for the synchrotron spectrum of an electron with $\gamma_0 = 100$, $B = 10^6 \, G$, and the hydrodynamical time scale, which is the integration time, has been set equal to 0.1, 1, and 10 times the cooling time of the electron ($t_{\text{syn}}(\gamma_0)$). The trend of the solution is a power law with index $(1/3)$ up to $E_c = E_{\text{syn}}(\gamma(t_{\text{hyd}}))$ and an exponential cut-off above it. A good approximation is represented by the dashed line in Fig. B.2, with equation:

$$P(e) \approx \begin{cases} \left(\frac{e}{E_c}\right)^{1/3} & e < E_c \\ \left(\frac{e}{E_c}\right)^{-1/2} \exp\left[-\frac{e - E_c}{E_m}\right] & e < E_c \end{cases}$$  \hspace{1cm} (B.12)
Figure B.2: Time integrated spectrum for a single electrons which cools via synchrotron emission. The initial Lorentz factor of the electron and the magnetic field intensity are, respectively: $\gamma_0 = 100$, $B = 10^6$ G. The integration time $t_{hyd}$ has been set equal to $0.1 \ t_{\text{syn}}(g_0)$, $1 \ t_{\text{syn}}(g_0)$, and $10 \ t_{\text{syn}}(g_0)$.
B.3 Integrated synchrotron spectrum from a distribution of electrons

The final step to build up the spectrum from an astrophysical object where particles have been accelerated (i.e. from shocks), and cool rapidly loosing their energy via synchrotron emission is to integrate the synchrotron power for a single electron over the distribution of electrons. Firstly, let’s consider that electrons have been accelerated to a power law distribution, between $\gamma_{\text{min}}$ and $\gamma_{\text{max}}$, with a power law index $p$:

$$N(\gamma) = N_0 \gamma^{-p}, \quad \gamma_{\text{min}} \leq \gamma < \gamma_{\text{max}}.$$  \hfill (B.13)

Each electron will lose energy via synchrotron emission thus, the distribution of electrons at time $t$ is:

$$N(\gamma, t) \, d\gamma = N_0 \gamma^{-p} \frac{d\gamma_0}{d\gamma} \, d\gamma, \quad \gamma_{\text{min}} \leq \gamma_0 < \gamma_{\text{max}}.$$  \hfill (B.14)

with $\gamma_0$ the initial Lorentz factor of an electron that after the time $t$ has a Lorentz factor equal to $\gamma$. Using Eq. B.10, we can rewrite the previous equation as:

$$N(\gamma, t) = N_0 \left( \frac{\gamma}{1 - \gamma t/t_s} \right)^{-p} \frac{d\gamma}{(1 - \gamma t/t_s)^2},$$

$$\frac{\gamma_{\text{min}}}{1 + \gamma_{\text{min}} t/t_s} \leq \gamma < \frac{\gamma_{\text{max}}}{1 + \gamma_{\text{max}} t/t_s}.$$  \hfill (B.15)

The integrated spectrum is now the result on a double integration, one on the electron Lorentz factor and one over the time.

$$P(e) = \int_0^{t_{\text{hyd}}} \int_1^\infty N(\gamma, t) P_\gamma(e) \, d\gamma \, dt$$

$$= \frac{\sqrt{3}}{2\pi} \frac{q^3 B}{m_e c^2} \int_0^{t_{\text{hyd}}} \int_1^\infty N(\gamma, t) F\left( \frac{e}{E_{\text{syn}}(\gamma)} \right) \, d\gamma \, dt$$  \hfill (B.16)

The previous integral can be solve numerically, or an approximated expression can be found. In the model here developed, and contrary to the majority of the model developed in literature that follow a similar approach, the upper bound of the electron distribution is not approximated to infinity. In most of the cases, GRB models are developed for studying and reproducing the low energy spectrum (below the observed MeV range). Here we are particularly interested on the high energy spectrum, and the study of an high energy cut-off due to the upper limit in the electrons energy distribution is crucial.

The integration can be solved numerically, and the result spectral shape can also be approximated with broken power law. Firstly two characteristic energies will determines the spectral properties of the integrated synchrotron spectrum of a distribution of electrons. The first is the synchrotron energy of an electron with Lorentz factor $\gamma_{\text{min}}$: $E_m = E_{\text{syn}}(\gamma_{\text{min}})$. The second is depending on the integration time (the hydrodynamical time scale). It is the synchrotron energy of an electron whose cooling time is equal to the hydrodynamical time scale. The characteristic cooling energy for an electron is given by the condition $t_{\text{syn}}(\gamma) = t_{\text{hyd}}$, where $t_{\text{hyd}}$ is the hydrodynamic time scale. From this identity one gets:

$$\gamma_c = \frac{6\pi m_e c^2}{\sigma_T c B^2 t_{\text{hyd}}} = 5.1 \times 10^8 \frac{1}{B^2 t_{\text{hyd}}}$$  \hfill (B.17)
Figure B.3: Evolution of the electron population. The dashed line is the analytical solution (Eq. B.15) the solid histogram is a Monte Carlo simulation of $10^4$ particles generated accordingly to the initial distribution of Eq. B.13 and evolving individually with Eq. B.10.
Figure B.4: Integrated synchrotron spectrum for different integration time ($t_{hyd} = 0.01, 0.1, 1, 10 \ t_{syn}$). The bold solid line is the result of the numerical integration (Eq. B.16), the thin dashed line is the broken power law approximation, the thin solid line is the broken power law approximation with an exponential cut-off. The last spectral shape is the approximation used in the development of the model.
consequently: \( E_c = E_{\text{syn}}(\gamma_c) \). Two regimes are possible, the Slow Cooling regime (SC), with \( E_m < E_c \) and the Fast Cooling regime (FC), with \( E_c < E_m \) [102, 85]. Every electron with \( \gamma \) greater than the hydrodynamic time scale radiates its energy faster than the hydrodynamic time scale. In GRB prompt emission, given the high magnetic field intensity \( (10^4 G) \) and hydrodynamical time scales of the order of a second (or fraction of second), the gamma cooling is of the order of a few, smaller than the characteristic Lorentz factor of accelerated electron \( (\gamma_{\text{min}}) \). This is the case of fast cooling regime, in which the accelerated electrons cool rapidly before than the hydrodynamic time scale.

For computing the integrated spectrum of a power law distribution of electron with \( \gamma_c < \gamma_{\text{min}} \), we can consider that all the electron with energy above \( E_m \) will radiate all their energy, thus:

\[
P(e) = N(\gamma) m_e e^2 \gamma d\gamma / de \propto e^{-p+1} / 2 e^{-1/2} \propto e^{-p/2},
\]

where the equation B.2 has been used with its differential. Between \( E_c \) and \( E_m \) the spectrum is a power law with index -1/2, and below the cooling energy it is a power law with index 1/3. Moreover, we do not approximate the value of \( \gamma_{\text{max}} \) at arbitrary high energies as done by other authors, but we consider that the electron have been accelerated up to the value \( \gamma_{\text{max}} \) given by 7.22. Hence, the integrated spectrum is a broken power law, with an exponential decay at high energy, for both fast and slow cooling:

\[
P(e) = \exp\left(-\frac{e}{E_M}\right) \begin{cases} 
\left(\frac{e}{E_c}\right)^{1/3}, & e < E_c \\
\left(\frac{e}{E_c}\right)^{-1/2}, & E_c < e < E_m \\
\left(\frac{E_m}{E_c}\right)^{-1/2} \left(\frac{e}{E_m}\right)^{-p/2}, & e > E_m
\end{cases}
\]

For slow cooling case, we have \( P(e) \propto e^{1/3} \) for the lower part, \( P(e) \propto e^{-p/2} \) for the highest one (electron are still radiating all their energy above \( E_c \)), and for the intermediate we have to integrate equation B.16, obtaining the usual case case \( P(e) \propto e^{-(p-1)/2} \) [101]. This is in fact the most common case in astrophysics for distribution of electron radiating via synchrotron spectrum. Usually, they are accelerating in conditions such as the cooling time scale is much longer that the hydrodynamical scale, yielding a \( \gamma_c \) greater than their minimum Lorentz factor. For the slow cooling regime, thus:

\[
P(e) = \exp\left(-\frac{e}{E_M}\right) \begin{cases} 
\left(\frac{e}{E_m}\right)^{1/3}, & e < E_m \\
\left(\frac{e}{E_m}\right)^{-0.5}, & E_m < e < E_c \\
\left(\frac{E_m}{E_c}\right)^{-1/2} \left(\frac{e}{E_m}\right)^{-p/2}, & e > E_c
\end{cases}
\]

For a \( E_M \) big enough (or for a magnetic field small enough) the spectra reduce to the usual broken power law proposed by Sari et al.(1998) [85].

### B.4 Inverse Compton

The Inverse Compton process can be viewed as a transfer of energy between the distribution of electron and the emission spectrum. In particular a “seed” spectrum is
reprocessed by the distribution of electrons, which scatter against the photons. In practice the photons are boost up by means of scattering against the high energy electrons. Since that the electrons that scatter against the synchrotron photons, belong to the same seed of the electrons that have produced the synchrotron photons, this process is also called “Self Synchrotron Compton” or SSC. The electrons distribution is a power law and the most probable scattering is between the lowest energetic electron ($E_m$ against the synchrotron spectrum). In the relativistic case (when the energy of the electron is much more greater than its rest mass) the photon is up scattered by a quantity $\sim \gamma^2$ where the $\gamma$ is the Lorentz factor of the electron.

$$E_{ic} = \gamma_{\text{min}}^2 E_{\text{syn}}$$  \hspace{1cm} (B.21)

Additionally, the conservation of the energy before and after the interaction yields an upper limit to the scattered photon energy:

$$E_{ic} \leq \gamma_{\text{min}} m_e c^2 + E_{\text{syn}}$$  \hspace{1cm} (B.22)

Assuming $m_e c^2 \gamma_{\text{min}} \gg E_{\text{syn}}$ the above condition can be replaced with $E_{ic} \leq \gamma_{\text{min}} m_e c^2$, which determines a cut-off in the spectrum at energy higher than $\gamma_{\text{min}} m_e c^2$. Assuming a power law distribution of electron, the spectral shape of the Inverse Compton spectrum can be approximated with a shape similar to the one of the synchrotron spectrum, shifted by a factor $\gamma_{\text{min}}^2$, with an exponential cut-off at high energies. In practice, the Inverse Compton component can be written as:

$$P_{\text{IC}}(e) = \frac{\tau}{\gamma_{\text{min}}^2} P_{\text{syn}} \left( \frac{e}{\gamma_{\text{min}}^2} \right) \exp \left[ -\frac{e}{\gamma_{\text{min}} m_e c^2} \right],$$  \hspace{1cm} (B.23)

The parameter $\tau$ represent the intensity of the peak of the Spectral Energy Distribution function ($e \times P(e)$) for the Inverse Compton component relatives to the intensity of the peak of the Spectral Energy Distribution function for the synchrotron component, or:

$$(\gamma_{\text{min}}^2 E_m P_{\text{IC}}(\gamma_{\text{min}}^2 E_m)) = \tau (E_m P_{\text{syn}}(E_m))$$  \hspace{1cm} (B.24)
Bibliography


