Upper Limits on High Energy emissions from GRB

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Introduction

The intense and unpredictable flashes of gamma rays in the energy band (10 keV - 1 MeV), called Gamma-Ray Bursts (GRB), were discovered in the late 60’s. Since then several experiments were dedicated to detect and understand these phenomena. Up to now, we do not have yet a complete explanation for the GRB progenitors and their emission mechanism. In the first phase, the so-called prompt phase, lasting from few ms to tens of seconds, these bursts emit mainly in the band from hard-X to soft gamma. In a longer second phase, called afterglow, the GRB emission ranges from the radio frequencies to the X-ray band.

The hard gamma band (> 50 MeV), both in the prompt and in the afterglow phase, was poorly explored until the gamma-ray experiment EGRET [1] flown on the Compton Gamma-ray Observatory (CGRO). Nevertheless EGRET detected only 5 GRBs in the band > 50 MeV in 10 years of operation. Nowadays 2 γ-ray experiments AGILE [2] and Fermi/LAT [3] are currently in operation. The number of detected burst with emitted energy > 50 MeV is already triplicated by these two missions.

The two experiments are similar because they are based on the same high energy γ-ray detection technique: their core is made of a silicon tracker with tungsten conversion layers, surrounded by a plastic scintillator to veto cosmic-ray particles events. Below the tracker, a calorimeter provides the measure of the energy of the produced pairs.

The main differences between the experiments are the larger effective area of the Fermi/LAT (~ 10 times larger) and its deeper calorimeter. On board of the satellites that host LAT and AGILE there are other 2 experiments respectively: the Fermi/GBM [4] dedicated to the GRB science in the 8 keV-40 MeV band and the SuperAGILE [2] that is a X-ray detector operational in the 18-60 keV band.

Fermi/GBM, SuperAGILE and the Mini Calorimeter in the AGILE mission can independently trigger on a burst event respectively in the energy band (8 keV - few MeV), (18-60 keV) and (0.3-100 MeV). Their field of view is quite different however, ranging from 2 sr for SuperAGILE to almost 4 sr for MiniCalorimeter and 6 sr for Fermi/GBM.

If the burst, triggered by these instruments or by other missions, is in the field of view of one of the two γ-ray detectors a high energy signal is searched.

In the AGILE quick-look pipeline the GRB signal is searched in the burst T90. During this time interval both background and signal are supposed to follow a Poisson distribution and the signal to be non-negative. The background average rate is computed before the burst trigger, in the same signal extraction region (15deg from the GRB position), with the same analysis cuts and in a time interval at least 10 times longer than the signal duration. Instead in the Fermi/LAT pipeline a map of the test statistic variable is computed. The test statistic distribution indicates how much the data differ from
the background model used. In this thesis the non-detection cases are considered: a methodology for the computation of the upper limit on the signal is proposed. This method is based on the Bayesian statistics and was elaborated from Helene[5] it considers a Poisson fluctuations of the known background mean and an estimated signal in the region of interest.

The applications of this upper limit computing method to the AGILE and the Fermi/LAT data are also showed deriving upper limit on GRB flux. The AGILE energy coverage is smaller but starts from lower energy with respect the actual Fermi/LAT energy band. In the AGILE energy range above 30 MeV and till 3 GeV, the estimated GRB flux upper limits range between $1 \times 10^{-3}$ and $1 \times 10^{-2}$ ph s$^{-1}$ cm$^{-2}$. Instead the Fermi/LAT flux upper limit is roughly $5 \times 10^{-5}$ ph s$^{-1}$ cm$^{-2}$ in the energy range from 100 MeV to 100 GeV, but the analysis is still on-going.

The studies of the upper limits help to understand the GRB emission mechanisms: most of these burst are not detected in the highest energy band even if the extrapolation of their spectra from the low energy band predicts a detectable flux from those two instruments. On the other case there are some GRBs with low energy spectra predicting a non detectable high energy flux but with high energy photons clearly detected. This photons indicate the existence of a new component above 100 MeV in the GRB s photon spectrum extending up to the GeV region.

This thesis gives a new contribution on the computation of the upper limits on the GRB flux in both the gamma-ray experiments operating nowadays. The thesis will concentrate in particular on the study of the upper limits in interesting cases, when a high energy signal is predicted but not detected, giving some hints on the GRB source physics.

The upper limit analysis was performed within the AGILE collaboration and a paper is quite to be submitted (the analysis and results are presented in chapter §6). A similar, but more complex analysis is on-going within the LAT collaboration, some preliminary results are shown in chapter §7.

The first chapter is an overview on the gamma astrophysics, while the second concentrates on the GRB field. The AGILE and the LAT instruments are presented respectively in chapters 3 and 4. In chapter 5 the Helene method is presented, while the application and the results of this method are shown in chapters 6 and 7, respectively for AGILE and LAT data.
Chapter 1

Gamma-Ray Astrophysics

The study of high energy astrophysics is clarifying questions such as the origin of Cosmic Rays in Supernova Remnants, the composition and the velocity of the Extragalactic Jets in powerful Active Galactic Nuclei, the behaviour of electromagnetic fields in strong gravitational fields typical of Pulsars, the magnetic reconnection process in Solar Flares or the nature of the mysterious Gamma-ray Bursts. Furthermore fundamental questions as the possible evidence of Dark matter annihilation in the center of the Galaxy or the violation of Lorentz invariance. The main experiments are built and managed by researchers sharing both high energy particle physics and astrophysics expertise [6]. After the EGRET experiment [1] on CGRO ended in June 2000, there was no space based experiment able to look at the $\gamma$-ray sky above 100 MeV, until the AGILE and the Fermi satellites were launched, in April 2007 and June 2008 respectively. Since their designs and performance are significantly advanced compared to their predecessor, these two experiments reach an unprecedented sensitivity and allow a better and deeper understanding of the $\gamma$-ray sky.

1.0.1 Resolve the $\gamma$-ray sky: the origins of diffuse emission and the nature of unidentified sources

The EGRET heritage

The EGRET mission was very successful, with 271 sources reported in the Third EGRET Catalog, far more than the 25 sources detected by its predecessor COS-B. Among these sources, 6 were pulsars, 90 were blazars and 170 were unidentified. These numbers show the limitations of EGRET: 6 pulsars are not enough to perform a real population study, and it is nearly impossible to have a complete understanding of the sky when almost two thirds of the sources are unidentified. The relatively small number of detected sources and the lack of identification was due to the limited sensitivity of the detector, arising from a rather poor angular resolution ($5.8^\circ$ at 100 MeV and $0.5^\circ$ at 10 GeV) and a relatively small field of view. The successors of EGRET had to overcome these limitations in order to reach a higher sensitivity.

Population studies of the unidentified EGRET sources have also provided clues about their natures. For example, spatial-statistical considerations and variability studies provide evidence for a population of Galactic and variable GeV $\gamma$-ray emitters among the
unidentified EGRET sources [7]. Many sources may be related to star-forming sites in the solar neighborhood or a few kiloparsecs away along the Galactic plane [8]. These sites harbor compact stellar remnants, SNRs and massive stars, i.e., many likely candidate \(\gamma\)-ray emitters. Pulsar populations may also explain a large fraction of unidentified sources close to the Galactic plane [9] and possibly in the nearby starburst Gould Belt [10]. Other candidate objects among the unidentified sources include radio-quiet neutron star binary systems [11] and systems with advection-dominated accretion flows onto a black hole such as Cygnus X-1, detected as a flaring source by MAGIC [12].

With regard to extragalactic sources, understanding the nature of the unidentified sources is important because new \(\gamma\)-ray emitting source classes (e.g., normal galaxies, clusters, etc.) are likely to be found in addition to the well-established blazars. A census of these sources is important for establishing their contribution to the extragalactic \(\gamma\)-ray background (EGRB; see §1.0.1).

In order to detect \(\gamma\)-rays and measure their directions and energies, a space-based detector needs three sub-detectors: a tracker, in which \(\gamma\)-rays pair-convert, to measure their directions, a calorimeter to measure their energies and an anti-coincidence detector (ACD) to reject charged particles. EGRET used a spark chamber to track \(e^+e^-\) pairs. By using the silicon strip technique with tungsten converters, AGILE and Fermi are able to achieve a finer precision in the measurement of the direction of the incoming \(\gamma\)-ray. This technique also leads to a better aspect ratio: the height of the tracker is reduced and thus the field of view is greatly enhanced. The ACD of EGRET was a monolithic dome, which caused problems above \(\sim10\) GeV: electromagnetic showers in the calorimeter produced backslash which made a signal in the ACD, thus tagging high energy \(\gamma\)-rays incorrectly as charged particles. To overcome this vetoing problem, the ACDs of AGILE and Fermi are segmented. Another limitation of EGRET was its large deadtime, which was a serious drawback for measurement of gamma-ray bursts (GRBs). Thanks to the silicon tracker system, AGILE and Fermi have a very small deadtime.

These capabilities greatly facilitate the source identification process in the following ways:

1. Provide good source localization for the majority of \(\gamma\)-ray sources, including all of the EGRET detected sources, with an error box smaller than 0.5°.

2. Measure source spectra over a broad energy range. Determining \(\gamma\)-ray spectra will allow investigation of features intrinsic to the sources such as absorption signatures, spectral breaks, transitions, and cutoffs.

3. Measure \(\gamma\)-ray light curves over a broad range of timescales. The large effective area, wide field of view, stability, and low readout deadtime of the instruments enable measurement of source flux variability over a wide range of timescales.

Population studies for a prospective source class help to select the most promising individual candidate sources for carrying out deep multi-frequency identification campaigns based on their broadband non-thermal properties and also help with investigating common characteristics of the candidate population. For example, galaxy clusters, as a candidate population, can be characterized by mass as deduced from optical richness, by temperature and mass functions, by applying virial mass-over-distance constraints, and by observational characteristics such as the presence or absence of merger activity, the presence or absence of diffuse radio halos or indications of nonthermal spectral components.
in the hard-X-rays.

AGILE and Fermi observations should allow at least several members among each new candidate source populations to be individually discovered and characterized. In view of the large number of expected detections, most probably representing different source classes, confirmation of a given population as γ-ray emitters will require a common criteria for statistical assessment [13], as well as dedicated multiwavelength observing campaigns [14].

Interstellar emission from the Milky Way, nearby galaxies, and galaxy clusters

The diffuse emission of the Milky Way is an intense celestial signal that dominates the γ-ray sky. The diffuse emission traces energetic particle interactions in the ISM, primarily protons and electrons, thus providing information about cosmic-ray spectra and intensities in distant locations [15]. This information is important for studies of cosmic-ray acceleration and propagation in the Galaxy [16]. γ-rays can be used to trace the interstellar gas independently of other astronomical methods, e.g., the relation of molecular H$_2$ gas to CO molecule [17] and hydrogen overlooked by other methods [18]. The diffuse emission may also contain signatures of new physics, such as dark matter, or may be used to put restrictions on the parameter space of supersymmetrical particle models and on cosmological models (see §1.0.4). The Galactic diffuse emission must also be modeled in detail in order to determine the Galactic and extragalactic γ-ray backgrounds and hence to build a reliable source catalog.

One of the critical issues for diffuse emission remaining from the EGRET era is the so-called “GeV excess”. This puzzling excess emission above 1 GeV relative to that expected [15, 19] has shown up in all models that are tuned to be consistent with directly measured cosmic-ray nucleon and electron spectra [20]. The excess has shown up in all directions, not only in the Galactic plane. The origin of the excess is intensively debated in the literature since its discovery [15].

The excess can be the result of an error in the determination of the EGRET effective area or energy response or could be the result of yet unknown physics (for a discussion of various hypotheses see [16]). Recent studies of the EGRET data have concluded that the EGRET sensitivity above 1 GeV has been overestimated [21] or underestimated [22] or imply different cosmic-ray energy spectra in other parts of the Galaxy compared to the local values [20, 23].

Fermi reported on the Galactic diffuse emission at intermediate Galactic latitudes 10° ≤ |b| ≤ 20° [24], where most of the emission comes from interactions of CRs with the local gas. Fig. 1.1 shows that the Fermi spectrum is well described by the sum of three components: an a priori model for the Galactic diffuse emission (the black shaded region), a point source contribution (light blue dots with shaded region) and an isotropic diffuse emission composed by an extragalactic diffuse emission and residual background (black dots with grey solid region). Fermi does not detect the EGRET GeV excess.

Understanding the Galactic diffuse emission is critical to analysis of the GeV sources and important for cosmic ray and dark matter studies. The same basic considerations needed for the development of the model of Galactic diffuse γ-ray emission also apply to other galaxies that are candidates for study with the LAT. For example Fermi detected
Figure 1.1: Comparison of *Fermi* Galactic diffuse emission measurement (red dots) with model prediction (black shaded region) and contribution from point sources (light blue dots) and isotropic emission (black dots). [24].

and resolved the Large Magellanic Cloud [25]. The LMC is an excellent target for studying the link between CR acceleration and γ-ray emission since it is nearby, has a large angular extent, and is seen at a small inclination angle that avoids source confusion along the lines of sight. In addition, the LMC is relatively active, housing many supernova remnants, bubbles and superbubbles and massive star forming regions that are all potential sites of CR acceleration. The close correlation found by *Fermi* between CR density and massive star tracers supports the idea that CRs are accelerated in massive star forming regions as a result of the large amounts of kinetic energy that are input by the stellar winds and supernova explosions of massive stars into the interstellar medium.

Galaxy clusters emitting high-energy γ-rays are, although well hypothesized, observationally not yet established emitters in the GeV sky [26]. Predictions for galaxy clusters as a candidate source class for detectable high-energy emission relate to observations of diffuse radio signatures [27, 28], revealing the existence of relativistic electrons in a number of galaxy clusters.
Extragalactic diffuse emission

An isotropic, apparently extragalactic component of the high-energy $\gamma$-ray sky was studied by EGRET [29]. This extragalactic $\gamma$-ray background (EGRB) is a superposition of all unresolved sources of high-energy $\gamma$-rays in the universe plus any truly diffuse component. A list of the contributors to the EGRB includes “guaranteed” sources such as blazars and normal galaxies [30, 31], and potential sources such as galaxy clusters [32], shock waves associated with large scale cosmological structure formation [33, 34], distant $\gamma$-ray burst events [35], pair cascades from TeV $\gamma$-ray sources and UHE cosmic rays at high redshifts. A consensus exists that a population of unresolved AGN certainly contribute to the EGRB inferred from EGRET observations; however predictions range from 25% up to 100% of the EGRB [36, 37, 38, 39]. A number of exotic sources that may contribute to the EGRB have also been proposed: baryon-antibaryon annihilation phase after the Big Bang [40, 41, 42], evaporation of primordial black holes [43, 44, 45], annihilation of so-called weakly interacting massive particles (WIMPs) [46, 47, 48, 49, 50, 51], and strings [52].

Fluctuation analysis, where signatures of excess variance are searched for in the surface brightness of the EGRB, is a very general approach to estimating the contribution of any isotropically distributed source population to the diffuse flux. Application of this method to the EGRET data set revealed a point source contribution to the EGRB of 5%–100% from analysis on an angular scale of $3.5^\circ \times 3.5^\circ$, the scale of the Galactic diffuse emission model[53], [15]. With LAT’s sensitivity, point spread function and more uniform exposure, smaller spatial scales can be probed, thereby improving the detectability of a signal from contributing point sources to the EGRB.

1.0.2 Understand the mechanisms of particle acceleration in celestial sources

$\gamma$-ray observations are a direct probe of particle acceleration mechanisms operating in astrophysical systems. Advances with LAT observations in our understanding of these non-thermal processes can be anticipated by reference to discoveries made with EGRET in several important source categories: blazars, pulsars, supernovae remnants, and the Sun.

Blazar AGN jets

With high-confidence detections of more than 60 AGN, almost all of them identified with BL Lacs or Flat Spectrum Radio Quasars (FSRQs) [54], EGRET established blazars as a class of powerful but highly variable $\gamma$-ray emitters, in accord with the unified model of AGN and Blazar as supermassive black holes with accretion disks and jets. Although blazars comprise only several per cent of the overall AGN population, they largely dominate the high-energy extragalactic sky. This is because most of the non-thermal power, which arises from relativistic jets that are narrowly beamed and boosted in the forward direction, is emitted in the $\gamma$-ray band, whereas the presumably nearly-isotropic emission from the accretion disk is most luminous at optical, UV, and X-ray energies. Most extragalactic sources detected in the GeV band are therefore expected to be blazar AGNs, in
contrast with the situation at X-ray frequencies, where most of the detected extragalactic sources are radio-quiet AGN.

The blazar AGN spectra are usually well described by two broad humps. This is explained in purely leptonic models by an accelerated population of electrons in a magnetic field: the low energy peak is due to the synchrotron emission and the high energy peak is due to Inverse Compton scattering. There are two kinds of blazars: Flat Spectrum Radio Quasars (FSRQs), having strong emission lines and an intense radiation field due to the accretion disk and clouds, BLLacs (BLs), which have nearly featureless spectra and have a low radiation field. The synchrotron peaks of FSRQs lie at IR energies and their IC peak lies below 1 GeV. The IC emission is large because the intense radiation field provides a large density of IC targets. But this large density prevents the γ-rays from reaching very high energy, which explains why the IC peak does not reach higher energies. For BLs, the lower radiation field allows the IC peak to reach hundreds of GeV but the IC emission is less intense. BLs are subclassified into low/intermediate/high-frequency peaked BLs (LBLs/IBLs/HBLs), depending on the position of the synchrotron peak. With their broad energy ranges, AGILE and Fermi are very well suited to study AGN. AGILE [55] has detected 13 AGNs and Fermi [56] has detected 119 AGNs in 3 months.

Thanks to its good energy resolution, Fermi is able to perform a precise spectral measurement of AGN. The spectral index of an AGN as measured by Fermi is correlated with the position of the IC peak: Fermi measures the rising (falling) part of the IC peak of BLs (FSRQs), so the spectral index is greater (lower) than 2. Fermi has found that the spectral index changes continuously from FSRQs to HBLs. Since FSRQs show cosmic evolution but the BLs do not, it seems to indicate that the young FSRQs with standard accretion disk evolve to old BLs with radiatively inefficient accretion disk. Fermi also discovered that many AGN exhibit a spectral break around a few GeV. This is observed for essentially all FSRQs and some LBLs, but not for HBLs.

As an example, Fermi made the first simultaneous observations that cover the optical, X-ray, and high-energy gamma-ray bands of the BL Lac object PKS 2155-304. The gamma-ray bands were observed for 11 days, between 2008 August 25 and 2008 September 6, jointly with the Fermi Gamma-ray Space Telescope and the HESS atmospheric Cherenkov array, providing the first simultaneous MeV-TeV spectral energy distribution (SED) with the new generation of gamma-ray telescopes. The ATOM telescope and the RXTE and Swift observatories provided optical and X-ray coverage of the low-energy component over the same time period. The object was close to the lowest archival X-ray and very high energy (VHE > 100 GeV) state, whereas the optical flux was much higher. The light curves show relatively little (∼30%) variability overall when compared to past flaring episodes, but this campaign found a clear optical/VHE correlation and evidence for a correlation of the X-rays with the high-energy spectral index[57] as shown in fig. 1.2.

Most viable current models of formation and structure of relativistic jets involve conversion of the gravitational energy of matter flowing onto a central supermassive black hole. γ-ray flares are most likely related to the dissipation of magnetic accretion energy or extraction of energy from rotating black holes [58]. However, the conversion process itself is not well understood, and many questions remain about the jets, such as: How are they collimated and confined? What is the composition of the jet, both in the initial and
Figure 1.2: The SED of PKS 2155-304 between 2008 August 25 and 2008 September 6. The red squares are ATOM data, green and blue dots are respectively RXTE and Swift data, the black dots are Fermi data and the red ones are HESS data. The solid line is a SSC model. The dashed and the dot-dashed lines are the same model without electrons above $\gamma_1 = 1.4 \times 10^4$ and $\gamma_2 = 2.3 \times 10^5$, respectively. [57]
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in the radiative phase? Where does the conversion between the kinetic power of the jet into radiation take place, and how? What role is played by relativistic hadrons. There are also questions about the role of the magnetic field, such as whether the total kinetic energy of the jet is, at least initially, dominated by Poynting flux.

The first step in answering these questions is to determine the emission mechanisms in order to infer the content of the luminous portions of jets. This understanding should, in turn, shed light on the jet formation process and its connection to the accreting black hole. Determining the emission mechanisms, whether dominated by synchrotron self-Compton, external Compton, or hadronic processes, requires sensitive, simultaneous multiwavelength observations. Such observations can uncover the causal relationships between the variable emissions in different spectral bands and provide detailed modeling of the time-resolved, broadband spectra. The sensitivity and wide bandpass of AGILE and Fermi, coupled with well-coordinated multiwavelength campaigns, are essential.

Thanks to their sensitivity, AGILE and Fermi are able to perform much better variability measurements than EGRET, which is essential in order to understand the emission mechanism in AGN. AGILE made several multiwavelength campaigns. One of the most interesting objects studied by this means by AGILE is the blazar 3C 454.3. One simultaneous campaign was carried out on November 2007 with AGILE, INTEGRAL, Swift, the WEBT Consortium, and the optical-NIR telescope REM. AGILE detect significant day-by-day variability of the gamma-ray emission as shown in fig 1.3. A correlation analysis based on the entire data set is consistent with no time-lags between the gamma-ray and the optical flux variations[59].

Pulsars, pulsar wind nebulae and supernova remnants

Pulsars, with their unique temporal signature, were the only definitively identified EGRET population of Galactic point sources. There were five young radio pulsars detected with high significance, along with the radio-quiet pulsar Geminga and one likely millisecond pulsar (for a summary, see [61]). A number of other pulsars had lower significance pulse detections and many of the bright, unidentified γ-ray sources are coincident with known radio pulsars. Surrounding young pulsars are bright non-thermal pulsar wind nebulae (PWNe). In the case of the Crab pulsar, EGRET detected a clear signature of PWN emission on off-pulse phases; several other EGRET sources near young pulsars/PWNe show strong variability, possibly connected with variations in the wind shock termination. Even more encouraging has been the success in detecting PWN Compton emission in the TeV band [62] from a number of PWNe. Finally, it has long been noticed [63, 64, 9] that γ-ray sources are spatially correlated with massive star sites, including supernova remnants (SNRs). While EGRET was not able to make definitive associations with SNRs, AGILE and Fermi have the spatial and spectral resolution to do so. AGILE has detected 21 pulsars [65] among them the remarkable PSR B1509-58 with a magnetic field in excess of $10^{13}$ Gauss, PSR J2229+6114 providing a reliable identification for the previously unidentified EGRET source 3EG 2227+6122 and the powerful millisecond pulsar B1821-24, in the globular cluster M28 [66]. While Fermi has detected 46 pulsars [67] 16 young radio pulsars, 16 new pulsars discovered in a blind search and 8 millisecond pulsars, in addition to the 6 pulsars seen by EGRET.
Figure 1.3: Light curves acquired during the period 2007 November 6-December 3. Black circles represent AGILE data (30 MeV-50 GeV); red triangles represent INTEGRAL/IBIS data (20-200 keV); blue pentagons represent Swift/XRT data (0.3-10 keV); cyan-solid and green-open squares represent R-band WEBT and REM [60] data, respectively[59].

**Pulsar magnetospheric emission**

Rotation-induced electric fields in charge-depleted regions of pulsar magnetospheres (“gaps”) accelerate charges to ten’s of TeV and produce non-thermal emission across the electromagnetic spectrum. The coherent radio emission, through which most pulsars are discovered, is however a side-show, representing a tiny fraction of the spin-down power. In contrast ∼GeV peak in the pulsed power can represent as much as 20-30% of the total spin-down. This emission, with its complex pulse profile and phase-varying spectrum, thus gives the key to understanding these important astrophysical accelerators. A basic issue is whether the high energy emission arises near the surface, close to the classical radio emission (“the polar cap” model [68]) or at a significant fraction of the light cylinder distance (“outer gap” models [69, 70]). In addition to geometrical (beam-shape) differences, the two scenarios predict that different physics dominates the pair production. Near the surface $\gamma + B \rightarrow e^+ + e^-$ is important, while in the outer magnetosphere $\gamma + \gamma \rightarrow e^+ + e^-$ dominates; these result in substantially different predictions for the high energy pulsar spectrum. The peaks of the γ-ray light curve are appreciably offset from the radio peak, suggesting that the γ-rays arise at high altitude. This is confirmed by the spectral shape of the pulsars: all spectra are well modeled with a simple power law with
an exponential cut-off, as shown in Fig. 1.4 and treated extensively in [67]. Low altitude emission would imply an hyper-exponential cut-off because of pair attenuation with the strong magnetic field.

![Figure 1.4: Vela spectrum measured by Fermi fitted with a power law with an exponential cut-off [71].](image)

Related to these pulsars discoveries is the first detection at γ-ray energies of a globular cluster, 47 Tucanae, by Fermi [72]. Globular clusters contain from tens to several hundreds of millisecond pulsars (MSPs). Since Fermi had discovered a population of MSPs, it seemed possible to finally detect a globular cluster. So far 23 MSPs have been detected in 47-Tuc by radio and/or X-ray observations and the total population is estimated at 30-60. The spectrum measured by Fermi is well fitted by a power law with exponential cut-off, as are all pulsars seen by Fermi. The spectral index and cut-off are very similar to the mean spectral index and cut-off of the 8 MSPs detected by Fermi. Fermi reported an estimation of the total number of MSPs in 47 Tuc which is compatible with previous estimates.

**Pulsar wind Nebulae and unidentified sources**

For the Crab pulsar, EGRET detected unpulsed, possibly variable, emission below $\sim 150$ MeV (likely synchrotron) and Compton-scattered PWN emission at higher energies [73]. In this and other pulsars the connection with the IC flux observed in the TeV band is particularly valuable in constraining the PWN B field and the injected particle spectrum. Recent successes with detecting PWN at TeV energies show that the Galactic plane contains an abundance of such sources.

AGILE detected the Vela pulsar wind nebula in the energy range from 100 MeV to 3 GeV[74]. This discovery disfavours PWN hadronic models and constrains the electron population responsible for the GeV emission and establishes a class of gamma-ray emitters that could account for a fraction of the unidentified Galactic gamma-ray sources.
Fermi using 8 months of survey data examined the high energy behaviour of the Crab Pulsar and Nebula[75]. The spectrum of the nebula in the energy range 100 MeV - 300 GeV is well described by the sum of two power-laws describing the synchrotron and inverse Compton components of the Crab Nebula spectrum. No cut-off energy can be estimated for the synchrotron component. The IC rising edge studied in the LAT energy range extends up to the energy domain covered by Cherenkov experiments. No significant cut-off at high energy is observed in the Fermi energy range.

Supernova remnants

Cosmic rays with energy \( \leq 10^{15} \) eV have long been thought to be shock-accelerated in supernova remnants. For some time, non-thermal X-ray emission has implied a significant population of electrons accelerated to TeV energies [76]. Moreover, recently the HESS experiment has had great success in detecting TeV emission from Galactic SNR [62]. However the origin of this emission (inverse Compton scattering from a leptonic component or \( \pi^0 \) decay from a hadronic component) is still uncertain. AGILE and Fermi have the spatial and spectral sensitivity to resolve this question and thus constrain the origin of cosmic rays.

Fermi discovered a bright gamma-ray emission coincident with supernova remnant (SNR) W51C[77]. W51C is a middle-aged remnant (\( \sim 10^4 \) yr) with intense radio synchrotron emission in its shell and known to be interacting with a molecular cloud. The gamma-ray emission is spatially extended, broadly consistent with the radio and X-ray extent of SNR W51C. The energy spectrum in the 0.2–50 GeV band exhibits steepening toward high energies. The observed \( \gamma \)-rays can be explained reasonably by a combination of efficient acceleration of nuclear cosmic rays at supernova shocks and shock-cloud interactions. The decay of neutral \( \pi \)-mesons produced in hadronic collisions provides a plausible explanation for the \( \gamma \)-ray emission.

\( \gamma \)-ray emission from the Sun and solar system bodies

The 2005 January 20 solar flare produced one of the most intense, fastest rising, and hardest solar energetic particle events ever observed in space or on the ground. \( \gamma \)-ray measurements of the flare [78, 79] revealed what appear to be two separate components of particle acceleration at the Sun: i) an impulsive release lasting \( \sim 10 \) min with a power-law index of \( \sim 3 \) observed in a compact region on the Sun and, ii) an associated release of much higher energy particles having an spectral index \( \leq 2.3 \) interacting at the Sun for about two hours. Pion-decay \( \gamma \)-rays appear to dominate the latter component. Such long-duration high-energy events have been observed before, most notably on 1991 June 11 when the EGRET instrument on CGRO observed \( >50 \) MeV emission for over 8 hours [80]. It is possible that these high-energy components are directly related to the particle events observed in space and at Earth.

Solar activity was expected to rise in 2008 with a peak occurring as early as 2012 but so far low activity was observed by dedicated instruments. During normal operations Fermi will be able to observe the Sun about 20% of the time with the possibility of increasing
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that to about 60% during heightened solar activity. With LAT’s large effective area and field-of-view, and its low deadtime it is expected to observe tens of these high-energy events from the Sun. For intense events LAT may be able to localize the source to about 30′′, sufficient to determine if it originates from the flare’s X-ray footpoints or from a different location that might be expected if the high-energy particles were accelerated in a shock associated with a coronal mass ejection.

The quiet Sun is also a source of γ-rays which is detectable by LAT. Estimates of the cosmic-ray proton interactions with the solar atmosphere (solar albedo) were made by [81], it is expected that LAT will observe a flux of \( \sim 10^{-7} \text{ cm}^{-2} \text{ s}^{-1} \) above 100 MeV from pion decays that is at the limit of EGRET sensitivity [82]. In addition, a diffuse emission component with maximum in the direction of the Sun due to the inverse Compton scattering of solar photons on cosmic-ray electrons was predicted to be detected by LAT [83, 84, 85]. A detailed analysis of the EGRET data [85] yielded the flux of these two solar components at 4σ, consistent with the predicted level. For the first year of Fermi observations the solar modulation was at its minimum corresponding to a maximum cosmic-ray flux and, hence, maximum γ-ray emission from the Sun. LAT is able to detect the solar emission almost daily when the Sun is not close to the Galactic plane and brightest sources. Observations of the inverse Compton scattering of solar photons allow for continuous monitoring of the cosmic-ray electron spectrum from the close proximity of the solar surface to Saturn’s orbit at 10 AU, important for heliospheric cosmic-ray modulation studies. The fluxes of these components will vary over the solar cycle as solar modulation increases, thus we can expect the highest fluxes to be observed early in the Fermi mission. The overall solar emission has been detected at \( \sim 40 \) sigma level of confidence by Fermi; however there still is significant uncertainty in the determination of the relative contributions of the solar disk and inverse Compton components. A power law is used to represent the disk component and model for the inverse Compton component based on the measured electron spectrum > 100 MeV at Earth. The flux of the disk component is \( \sim 3.2 \times 10^{-7} \text{ cm}^{-2} \text{ s}^{-1} \), while that of IC component is \( \sim 1.5 \times 10^{-6} \text{ cm}^{-2} \text{ s}^{-1} \) within a region of 20° radius centered on the Sun [86].

The Moon is also a source of γ-rays due to CR interactions with its surface and has been detected by EGRET [82]. However, contrary to the CR interaction with the gaseous atmospheres of the Earth and the Sun, the Moon surface is solid, consisting of rock, making its albedo spectrum unique. The spectrum of γ-rays from the Moon is very steep with an effective cutoff around 3–4 GeV (600 MeV for the inner part of the Moon disk) and exhibits a narrow pion-decay line at 67.5 MeV, perhaps unique in astrophysics [87]. The gamma-ray emission from the Moon discovered by EGRET has been confirmed by Fermi and agrees in intensity for emission models that take into account the level of solar modulation. The preliminary flux estimation for the lunar γ-ray emission is \( F(E > 100\text{MeV}) = 1.1 \pm 0.2 \times 10^{-6} \text{ cm}^{-2} \text{ s}^{-1} \) with a spectral index of \(-3.13 \pm 0.03\) obtained by fitting a simple power law between 100 MeV to 1 GeV. The lunar flux measured is higher than previous measurements but reasonably in agreement with the cosmic ray flux increase due the solar minimum activity in this solar cycle.

Apart from other astrophysical sources, the albedo spectrum of the Moon is well understood, including its absolute normalization; this makes it a useful “standard candle”
for γ-ray telescopes. The steep albedo spectrum also provides a unique opportunity for energy calibration of γ-ray telescopes such as LAT. Finally, the brightest γ-ray source on the sky is the Earth’s atmosphere due to its proximity to the spacecraft. The Earth’s albedo due to the cosmic-ray interactions with the atmosphere has been observed by EGRET [89] and by LAT [90]. Its observations can provide important information about interactions of cosmic rays and solar wind particles with Earth’s magnetic field and the atmosphere.

1.0.3 Study the high energy behavior of GRBs and transients

Over the last decade the study of X-ray, optical, and radio afterglows of γ-ray bursts (GRBs) has revealed their distance scale, helping to transform the subject from phenomenological speculation to quantitative astrophysical interpretation. We now know that long-duration GRBs (τ > 2 s) and at least some short-duration GRBs lie at cosmological distances and that both classes involve extremely powerful, relativistic explosions. Long GRBs are associated with low metallicity hosts with high star formation rates, and have nuclear offsets of ∼10 kpc [91]. Long-duration bursts are typically found in star-forming regions of galaxies and are sometimes associated with supernovae, indicating that the burst mechanism is associated with the collapse of very massive stars [92]. Short-duration bursts are often located in much lower star-formation rate regions of the host galaxy, suggesting that in some cases these bursts arise from the coalescence of compact objects [93, 94]. For the ∼30% of long-duration bursts seen by Swift that have measured redshifts, the redshift distribution peaks near z ∼ 2.8 [95], comparable to Radio-quiet AGN. The sparse distribution for short bursts with spectroscopic redshifts spans a much lower range, z ∼ 0.1 – 1.1. However, a photometric study of the host galaxies of short bursts without spectroscopically determined redshifts indicates that the fainter hosts tend to lie at redshifts z > 1 [96].

EGRET detected two components of high-energy γ-ray emission from GRBs: >100 MeV emission contemporaneous with the prompt pulsed emission detected in the 10–1000 keV band, and a delayed component extending to GeV energies that lasted more than an hour in the case of GRB 940217 [97]. Analogous components were detected in the short burst GRB 930131 [98]. Most importantly, EGRET detected one burst (GRB 941017) in which a third power-law component was evident above the usual Band function spectrum [99], with an inferred peak in νF(ν) above 300 MeV during most of the prompt emission phase [100]. This indicates that some bursts occur for which the bulk of the energy release falls in the LAT energy band. The prompt pulsed component in these bursts was poorly measured by EGRET since the severe spark chamber deadtime (∼100 ms/event) was comparable to or longer than pulse timescales. The LAT is designed with low deadtime (∼26 µs/event) so that even very intense portions of bursts will be detected with very little (< few %) deadtime.

Internal and external shock models [101] are currently constrained primarily by spectral and temporal behavior at sub-MeV energies [102], where the most detailed observations have been made. But these observations span only a relatively narrow energy range. The LAT’s sensitivity will force comparison of models with observations over a dynamic range in energy of ∼ 10³ – 10⁴, and a factor of ∼10⁶ including joint GBM observations.
The AGILE calculation for the number of expected bursts is based on the number of GRBs detected with respect to the number of GRBs in the EGRET field of view: there were $\sim$10 GRBs per year in the EGRET field of view and only 1 per year was detected. In the first year of the AGILE operation 25 bursts were in the AGILE field of view, but only 1 was detected (GRB080524B [GCN 7716]). During the second year there were 30 GRBs in the AGILE and 2 were detected (GRB090401 [GCN 9069] and GRB090510 [GCN 9343]).

Fermi can provide time-dependent spectral diagnostics of bright bursts and will be able to measure high-energy exponential spectral cutoffs expected for moderately high redshift GRBs caused by $\gamma\gamma$ absorption in the cosmic UV-optical background (complementing AGN probes).

To estimate the LAT sensitivity to GRB, a phenomenological GRB model is adopted that assumes the spectrum of the GRB is described by the Band function, and the high-energy power law extends up to LAT energies. In order to compare the LAT sensitivity to GRB with the BATSE catalog of GRB, we compute the fluence of GRBs in the 50–300 keV energy band as shown in fig. 1.5.

Detailed simulations, based on extrapolations from the BATSE-detected GRBs, and adopting the distribution of Band parameters of the catalog of bright BATSE bursts [103], suggest that the LAT may detect one burst per month, depending on the GRB model for high energy emission (see fig. 1.5). These estimations are in good agreement with the observed number of GRBs. In the first few months of operations LAT has already detected high-energy emission from ten GRBs: GRB080825C [GCN 8183], the bright GRB080916C [GCN 8246], GRB081024B [GCN 8407], GRB081215A [GCN 8684], GRB090217 [GCN 8903], GRB090323 [GCN 9021], GRB090328 [GCN 9077], GRB090510 [GCN 9334], GRB090626 [GCN 9584] and GRB090902B [GCN 9867].

For more than one-third of LAT-detected bursts, LAT localizations should be sufficiently accurate for direct X-ray and optical counterparts searches. For instance, $\sim$50% of the LAT bursts are projected to have localization errors commensurate with the field of view of Swift’s XRT (23"), which very efficiently detects afterglows with few arc-second error radii. Burst positions are also calculated rapidly onboard, albeit with less initial accuracy, by the LAT flight software, as well as on the ground by the science analysis software pipeline, and distributed via the GCN network. Searches are conducted during ground analysis for fainter bursts not detected by the on-board trigger of the LAT.

Simulations show that LAT observations may constrain quantum gravity scenarios that give rise to an energy-dependent speed of light and consequent energy-dependent shifts of GRB photon arrival times [104, 105]. Short-duration GRBs, which exhibit negligible pulse spectral evolution above $\sim$10 keV may represent the ideal tool for this purpose [106]. Under the assumptions described in [107] and [108], the lower limit on quantum gravity mass ($M_{QG}$) obtained in this fashion is an order of magnitude lower the Plank mass ($M_{Plank}$) for GRB 080916C and exceeds its value for GRB 090510 ($M_{QG} > 1.2 \ M_P$)[108]. The *Fermi* LAT properties important for such measurements are its broad energy range, sensitivity at high energies, and <10 $\mu$s event timing. The LAT’s low deadtime and simple event reconstruction, even for multi-photon events, enable searches for evaporation of primordial black holes [109].
Figure 1.5: Model-dependent LAT GRB sensitivity. The GRB spectrum is extrapolated from BATSE to LAT energies. The all-sky burst rate is assumed to be 50 GRB yr$^{-1}$ full sky (above the peak flux in 256 ms of 10 ph s$^{-1}$ cm$^{-2}$ in the 50-300 keV or with an energy flux in the 20-2000 keV band greater than $2 \times 10^{-5}$ erg/cm$^2$s), based on BATSE catalog of bright bursts. The effect of the EBL absorption (see section §1.0.5) is included. Different curves refer to different energy thresholds. Dashed curves are the result of the analysis excluding very hard bursts, with a beta greater than -2.

1.0.4 Probe the nature of dark matter

Compelling evidence for large amounts of nonbaryonic matter in the Universe is provided by the rotation curves of galaxies, structure-formation arguments, the dynamics and weak lensing of clusters of galaxies, and, most recently, WMAP measurements of the CMB ([110], for review see, [111]). One of the most attractive candidates for Dark Matter is the Weakly Interacting Massive Particle (WIMP). Several theoretical candidates for WIMPs are provided in extensions of the Standard Model of Particle Physics such as Super-Symmetry. Searches for predicted particle states of these theories are one of the prime goals of accelerator-based particle physics, in particular the experiments at the Large Hadron Collider (LHC), which was planned to be operational in 2008 and now is running with $\sim 0.2$ TeV as central mass energy.

Annihilations of WIMPs can lead to signals in radio waves, neutrinos, antiprotons and positrons and $\gamma$-rays. $\gamma$-ray observations have the advantage over charged particles that the direction of the $\gamma$-rays points back to the source, and they are not subject to additional flux uncertainties such as unknown trapping times [49, 50]. However, predicted rates are subject to significant astrophysical uncertainties. Substructure in Dark Matter Halos is especially uncertain, with the predicted flux, for a given annihilation cross section, varying by several orders of magnitude.

Different astrophysical sources can be used to search for a signal from WIMP annihilations, each with advantages and challenges.

Generally, sensitivities are in the cosmologically interesting region of $\langle \sigma v \rangle \sim 10^{-26} - 10^{-25}$ cm$^3$s$^{-1}$, in the mass range between 40 and 200 GeV [112].

The intensity needed to detect a $\gamma$-ray line with $5\sigma$ significance is in the vicinity of
10\(^{-9}\) ph cm\(^{-2}\) s\(^{-2}\) sr\(^{-1}\) for an annulus around the Galactic Center (masking the galactic plane to ±15\(^{\circ}\)).

In [113], information obtainable with Fermi is compared with what may be learned at upcoming accelerator-based experiments, for a range of particle Dark Matter models. Over sizable ranges of particle model parameter space, Fermi has significant sensitivity and will provide key pieces of the puzzle. The challenge will be to untangle the annihilation signals from the astrophysical backgrounds due to other processes.

### 1.0.5 Use high-energy γ-rays to probe the early universe

Photons above 10 GeV can probe the era of galaxy formation through absorption by near UV, optical, and near IR extragalactic background light (EBL). The EBL at IR to UV wavelengths is accumulated radiation from structure and star formation and its subsequent evolution in the universe with the main contributors being the starlight in the optical to UV band, and IR radiation from dust reprocessed starlight (see [114, 115, 116, 117]).

Since direct measurements of EBL suffer from large systematic uncertainties due to contamination by the bright foreground (interplanetary dust, stars and gas in the Milky Way, etc.), the indirect probe provided by absorption of high-energy γ-rays via pair production (γ + γ → e\(^+\) + e\(^-\)), emitted from blazars, during their propagation in the EBL fields, can be a powerful tool for probing the EBL density. For example, observations of relatively nearby TeV blazars by the HESS [118] and the MAGIC [119] atmospheric Cherenkov telescopes have placed significant limits on the EBL at IR energies in the local universe. With the expected LAT flux sensitivity the number of detected γ-ray loud blazars will increase to potentially several thousand sources (see §1.0.2) with redshifts up to \(z \sim 5 - 6\). Such a large number of sources will be required for a statistically meaningful search for evolutionary behavior of spectral absorption features in bright and hard-spectrum AGNs. Any of the analysis methods employed requires disentangling source intrinsic opacity effects, particularly if they are evolutionary with redshift, from the absorption due to EBL. Absorption in the local environment of AGN but external to the jet radiation fields has been shown to mimic an absorption pattern similar to what is expected from EBL attenuation of γ-rays [120], i.e. higher γ-ray opacities from higher redshift sources. Careful source selection and a statistical assessment of the radiation field density at the γ-ray source site will be an integral part of the analysis. Monitoring of external photon fields in AGN (e.g., broad-line region lines) and correlating with the observed γ-ray cutoff energy may offer verification, and possibly quantification, of this effect.

### 1.0.6 Cosmic-ray electrons

Prior to Fermi, available data on high energy electrons were obtained mainly in balloon-borne experiments (except AMS-01) and had limited statistics. Since the only important difference between e\(^+\)e\(^-\) and γ-rays in the Fermi-LAT instrument is a signal detected by the ACD, the Fermi team carefully investigated the capability of the LAT to measure cosmic-ray electrons. As a result, a high statistics spectrum of electrons for the energy range 20 GeV - 1 TeV was obtained [121]. This spectrum and the recent PAMELA
positron fraction result suggests that there is one or several nearby sources of $e^+e^-$ (believed to be pulsars or SNRs) responsible for the excess with respect to the conventional model (based on contribution from quasi-uniformly distributed distant sources). A possible primary source of high-energy cosmic-ray electrons: the annihilation or decay of particle dark matter in the Galactic halo, but the pulsar interpretation seems to be favored by Fermi-LAT cosmic-ray electrons data [122].
Chapter 2

GRB observations and theory

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 by the four Vela satellites in the late sixties has fascinated since then the astronomers and the astrophysicists. The first two satellites of the program (Vela-5A and 5B) were launched on 23 May 1969, other two satellites (Vela-6A and 6B) on 1970. It was in 1969-70 that the Vela spacecraft first discovered gamma-ray bursts [123] with the position information. The first GRB was discovered in July 1967 with an earlier version of the Vela 5 satellites (Vela 4) that did not permit to measure the GRB position. 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.

The Galactic origin of GRB remained undisputed until the launch of the Compton Gamma Ray Observatory (GCRO) 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 some models 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 $10^{-4}$erg/cm$^2$ to $10^{-7}$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 $10^{51} - 10^{52}$erg/s (for $z \sim 1$), making GRB one of the most luminous objects in the sky. The Galactic or extragalactic origin of GRB was anyway debated for several years till the measurement of their redshift clarified their extragalactic origin.
2.1 The GRB observations

2.1.1 Global properties

The BATSE catalogue

The BATSE detector on board the CGRO observed more than 2700 burst, in its 9 years of observations. Each of the eight detector modules contain 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.

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_Ctlg/index.html) and contains eight tables characterizing the GRB phenomena.

Spatial properties

The recorded positions in the sky marked an important step forward in the GRB comprehension. Fig. 2.1 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.

**2704 BATSE Gamma-Ray Bursts**

![Gamma-Ray Burst angular distribution](image)

Figure 2.1: Gamma-Ray Burst angular distribution. The figure shows the position of each burst detected by the BATSE detector in Galactic coordinate.
2.1 The GRB observations

Temporal properties

The typical GRB 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 burst or a smooth profile burst. In Fig. 2.2 are some examples of GRB’s light curves as observed by BATSE.

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.

The distribution of the $T_{90}$ is shown in Fig. 2.3. The bimodal structure (in logarithmic 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.

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) [99] using two
GRB observations and theory

Figure 2.3: GRB duration distribution from the BATSE catalogue [124]. 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.

power laws joined smoothly at a break energy at $(\alpha - \beta)E_0$:

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

The eq.2.1, twice integrated on the energy, is the so called $\nu F(\nu) = E^2 N(E)$ spectrum. This spectrum peaks at $E_p = (\alpha + 2)E_0$ that is a parameter that can be easily measured. 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) [125] present a larger catalogue with 156 bursts selected for either high flux or fluence, considering several spectral shape including the Band function. Ghirlanda et al. found that the spectra of short GRBs can be better fitted by a power law combined with an exponential cutoff at high energies [126]. 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 $\alpha \sim -1$, $\beta \sim -2$, 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
2.1 The GRB observations

The typical shape of a GRB spectrum can be well described, in most of the cases, by a broken power law, joined smoothly at a break energy [99]. A GRB as seen at BATSE energy is plotted in Fig. 2.4, where also the fit with the band model has been performed.

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). 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 are a good indicator of the position of the peak of the spectrum. Short bursts were found to have on average higher hardness ratios than long bursts, as shown on figure 2.5. The existence of two distinct populations of bursts implied the existence of two kinds of progenitors and inner engines.

2.1.2 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 (the acronyms stays for “Satellite per Astronomia X”, and was named in honor of Giuseppe Occhialini). On Feb 28 1997 BeppoSAX detected the
Figure 2.5: Hardness ratio versus duration ($T_{90}$) for BATSE GRBs. Short bursts ($T_{90} \lesssim 2 \text{s}$) have higher hardness ratios than long bursts ($T_{90} \gtrsim 2 \text{s}$), supporting the hypothesis that short and long bursts constitute two separate populations, probably originating from different progenitors. [127]

x-ray afterglow from GRB 970228 [128]. The exact position given by BeppoSAX led to the discovery of optical afterglow [129], and consequently the measurement at the redshift which established the extragalactic nature of these bursts and solved what had for some 25 years been one of the greatest problems of astrophysics. Radio afterglow was detected in GRB 970508 [130]. These observations lead to the detection of spectral breaks in the afterglow emission (Figs. 2.6 data from Swift instruments), which provided support to the collimated-emission model of GRBs and allowed us to significantly constrain the energetics of GRBs (see subsection §2.2.5). By 2005, although afterglows had been detected from about fifty long GRBs, there were no such detections for short GRBs. The afterglows of short GRBs were hard to detect because the detectors had to achieve precise localizations using smaller numbers of photons, which required more computational time than the case of long GRBS. By the time a precise localization was achieved and an X-ray sensitive instrument was pointed toward the acquired location, the already weak afterglow of short GRBs had decayed to the point of becoming undetectable. The first afterglow from a short GRB was detected by the Swift satellite thanks to its high sensitivity and fast slewing (re-pointing) capabilities.

A new satellite, called Swift [131], that could observe the afterglow of the burst swiftly after its detection, was launched in 2004. Swift has a GRB detector combined with a wide

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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
field X-ray and an optical/ultraviolet telescope, and the ability to do automated rapid slewing. Thus, it could localize afterglows with arcsec accuracy a minute or so after the burst at γ-ray, X-ray, and optical wavelengths.

Swift’s capabilities enable to study the transition between the energetic and chaotic prompt emission, and the smoothly decaying softer afterglow. Furthermore, it provides, for the first time, observations of the afterglows of short ($T_{90} \lesssim 2$ sec) bursts, which lead to redshift measurements of short GRBs and verifies the cosmological origin for them too.

Swift’s observations of short GRBs showed that, unlike long GRBs, they usually originate from regions with a low star-formation rate. This suggested that short GRBs are related to old stellar populations, possibly from mergers of compact-object binaries (i.e., neutron star-neutron star or neutron star-black hole). Furthermore, even though supernova features such as red bumps and late-time rebrightening were detected in the afterglows of most long GRBs close enough to allow such a detection, there were no evidence of such features in the afterglows of short GRBs. These observations strengthened the case for long and short GRBs having different kinds of progenitors: compact-object binaries for short GRBs versus massive stars for long GRBs.

The GRB afterglows, as observed by Swift, decayed on a power law and progressively softened from X-rays, to optical, to radio. As of December 2009, Swift had detected 461 bursts in γ-ray, with almost all of them having an X-ray afterglow.

Swift is sensitive to a lower energy range (15 − 150, keV) and to bursts of longer durations than other detectors. Therefore it is more sensitive to GRBs of higher redshifts, since the signal from such GRBs is more redshifted and time dilated. Due to its increased sensitivity to distant GRBs, Swift observed GRB090423, the most distant GRB ever observed. GRB090423 had a redshift of $z \sim 8.1$, and when it exploded the age of the universe was only $\sim 4\%$ of its current age. The redshift distribution of Swift GRBs and pre-Swift GRBs is shown in Fig. 2.7. As can be seen, Swift GRBs are on average more distant than pre-Swift GRBs.

### 2.1.3 Evidence for high energy emission

Due to the small field of view, limited mainly by angular acceptance of the detector, and due to the small effective area ($\sim 1500 cm^2$) only few bursts 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. 2.8).

For the EGRET detector, due to the long dead time of the spark chambers and due to the low effective area the lightcurves showed not the high variability seen with BATSE. EGRET detected only 5 GRBs out of the 300 in its field of view in the ten years of operation.

GRB940217 is probably the most famous (Fig. 2.9)[97] GRB detected with EGRET and it was detected also with the Ulysses detector. 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. 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 (see Fig. 2.9). Unfortunately the Earth occulted the burst location for more
GRB observations and theory

Figure 2.6: Light curves of four well-sampled GRBs exhibiting a characteristic range of potential jet break behavior at $\sim 10^5$ s after the trigger. The light curves are composed of measurements by two of Swift’s detectors: the Burst Alert Telescope (BAT-red) and the X-Ray Telescope (XRT - blue). [132] and an optical telescope.

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 form the burst location, while the trigger rate of the Ulysses were registering only background counts.

The energy range for spectroscopy studies of EGRET is between 0.6 and 140 MeV. These spectra where useful for the study of gamma-ray bursts and for the observations of the high energy spectral range. Two important discoveries made by EGRET on the GRB field: a very late emission of high energy photons (up to 90mins) in the GRB 940217 and a spectral extra component at energies $> 10$ MeV lasted for more than 200s in the GRB 941017 (see Fig.2.10) [100]. Both these properties are inconsistent with a pure electron synchrotron model.

More recently, also the Astro-rivelatore Gamma ad Immagini LEggero (AGILE), described in chapter §3, detected three GRBs with energy $> 30$ MeV: 080514B [134] with a high energy delayed component, 090401B [135] and 090510 [136] which shows an extended high energy emission. GRB080514B is the first GRB detected with a pair-conversion
2.1 The GRB observations

Figure 2.7: Redshift distributions of GRBs detected by Swift in blue and of GRBs detected by pre-Swift satellites in grey. The average redshift of the Swift sample is higher than redshift of the previous observations (2.5 vs 1.2), because of the greater sensitivity of Swift to distant GRBs[133]. The solid (broad) theory curve illustrates the evolution of a comoving volume element of the universe while the dotted (narrow) curve is a convolution of the comoving volume with a model for the star formation rate.

tracker telescope above several tens of MeV more than ten years after the EGRET era. The highest photon energy detected is about 300 MeV, while most of the detected GRB photons have energies in the range 25 - 50 MeV, consistent with a spectrum with a power law photon index of 2.5. This spectrum is also consistent with the extrapolation of that obtained in the MeV range by other instruments. The most remarkable feature of GRB080514B is its high energy extended emission, i.e. the fact that the arrival times of the high energy photons detected with the GRID are not coincident with the brightest peak detected in hard X-rays. This feature, potentially capable to place significant constraints on emission models, was already suggested concerning the EGRET bursts, then further confirmed by the Fermi detection of GRB080916C [107] and by the AGILE and Fermi detection of GRB090510.

Eight years after the end of the CGRO mission, Fermi was launched on June 11th 2008. The Fermi/LAT instrument has an effective area 10 times larger than the EGRET one and together with a larger field of view and a smaller dead time it collects more statistics to perform a detailed temporal-spectral analysis see chapter §4 and [3]. The possibility to re-point itself autonomously when a bright GRB happens and the synergy with the Fermi Gamma-Ray Burst Monitor instruments dedicated to the GRBs monitoring, make the LAT a perfect instrument to investigate the problems opened by EGRET on the GRB high energy emission.
Figure 2.8: 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.

Figure 2.9: GRB940217 time history of the Ulysses (continuous line) satellite and the received EGRET photons (dot with error bars)[97]

In the first 15 months of science operations more than 300 bursts were detected with the Gamma-ray Burst Monitor also on board of the Fermi satellite. Among those, 12 were detected also by the LAT instrument, both long and short with at least 10 photons $> 100$MeV, but only few GRBs have also photons at energies $> 1$GeV.

The two properties of high energy GRBs identified by EGRET are not seen in all the GRBs detected by Fermi/LAT. The extended emission, still present after several tens of seconds after the trigger when the low energy component is returned to the background level, is present in almost all the LAT GRBs observed. Two bursts do not show this
2.1 The GRB observations

Figure 2.10: Time divided spectrum of the GRB941017 observed simultaneously by several detectors. An high energy extra component is clearly visible from the time bin (b), this extra component arises at later time bins instead the low energy component is decreasing.

feature: the 081215 burst (GCN 8684) and the “featureless” burst 090217 (GCN 8903). The GRBs 090323 (GCN 9021) and 090328 (GCN 9077), on the contrary, show a very long lasting high energy tail still present 300s after the trigger.

The other feature the EGRET GRBs showed, the presence of an extra-component in the spectrum, is even less confirmed by the LAT GRBs: only two bursts have it, two don’t, while for the other bursts the extra-component hypothesis is not statistically significant.

The GRBs 090510 (GCN 9334) and 090902 (GCN 9867) are respectively a short and a long burst but they have very similar characteristics. With more than 150 photons above 100 MeV and more than 20 above 1 GeV, they are the brightest GRBs seen so far by the Fermi/LAT. For both the highest energy photon is $\sim 30$ GeV but emitted at different times: in the short one this photon comes in the first second when the GBM emission is still present, while for the long burst this photon is received 82 seconds after the trigger when the GBM emission is no more present. As well as other bursts also these two have an extended emission lasting longer than the GBM emission, but the feature
that is clearly detected in these bursts is the spectral extra-components (shown in fig. 2.11 for the GRB090510). This component is present not only in the highest energies (> 100 MeV) but also in the lowest GBM energy band (8 – 20 keV) [108], [137].

Thanks to the Fermi/LAT large field of view and its timing capabilities a new feature (already seen in GRB080514B by AGILE but with low significance) was confirmed: the delayed onset of the > 100 MeV component. In 4 bursts (080916C (GCN 8246), 081024B (GCN 8407), 090510, 090902B) this delay is clearly detected as shown in fig. 2.1.3. In the first 3 seconds of GRB 080916C the lightcurve from the GBM detectors shows a first peak, instead there are no photons in the LAT lightcurve when the > 100 MeV “transient” (see §4.2.3 for details) events are selected. In this first time interval also the spectrum shows a different behaviour with respect the others time bins as shown in fig. 2.1.3 right panel: there is a soft to hard evolution from bin a to bin b, but a hard to soft evolution later on [107].

The first GBM peak is missing in the LAT > 100 MeV events also in the short GRB 081024B (GCN 8407). The emission in the GBM lasts for less than 1 second and the LAT data still shows a signal 3 seconds after the trigger. As for the burst 080916C[107] the spectrum of this first peak has a softer high energy spectral index and the spectra of the later emission are hardening. A summary of the LAT GRB properties can be found in the table 2.1.
2.1 The GRB observations

<table>
<thead>
<tr>
<th>GRB</th>
<th>Duration</th>
<th>Events</th>
<th>Delayed Onset</th>
<th>Long Lived Emission</th>
<th>Extra Component</th>
<th>Highest Energy (GeV)</th>
<th>Redshift</th>
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Table 2.1: Summary of the LAT GRB properties

Figure 2.12: Left: multi-detector light curve of GRB 080916C[107]. The insets are a zoom of the first 15 seconds after the GBM trigger. Right: Time-resolved spectral fits in the 5 time bins. Both the delayed onset (time bin a) and the long lived emission (time bin d) are present in other bursts detected by Fermi/LAT.
2.2 The GRB Model

2.2.1 Inner engine of GRBs

The light curves of the prompt emission show a variability of milliseconds to many minutes. These short time scales imply that a compact object is involved in the emission, with size of the order of tens of kilometers, typical for black holes and neutron stars. The fact that the burst duration is usually longer than the variability suggests a prolonged and intermittent inner-engine activity in two or three different simultaneous time scales. This disfavors any explosive model that releases the energy at once. The total energy emitted in $\gamma$-rays is very high, about $10^{51}$ erg, an amount comparable to the energy release from supernovae. The above suggest that the inner engine of GRBs consists of a massive object, most likely a newborn black hole, with a massive ($mass \gtrsim 0.1 M_\odot$) disk accreting into it. The accretion explains the prolonged activity and the different time scales, and the black hole satisfies the size and energy requirements.

2.2.2 Progenitors of GRBs

There are multiple observational pieces of evidence that suggest that not all GRBs are the same, and that there are different kinds of progenitors and inner engines. Specifically, the duration and the hardness ratio-duration distributions (Figs. 2.3 and 2.5) show that there are two kinds of bursts: short-hard bursts and long bursts. Deep long-duration observations of the optical afterglows of short bursts did not show any evidence of an associated supernova [93, 127, 143]. On the other hand, supernova-emission spectra were detected superimposed on the afterglows of most of the long GRBs ($\sim 20$ GRBs) that were close enough ($z \lesssim 1$) to allow for such a detection [144].

Short duration bursts are primarily observed in regions with low or no star formation, therefore they are likely to be related to old stellar populations. This suggests that these bursts could be the result of mergers of compact binaries, such as neutron star-neutron star or neutron star-black hole. The binary loses rotational energy through the emission of gravitational radiation and eventually merges, forming a black hole and an accretion disk surrounding it. The resulting system, then, produces a GRB in a way similar to the collapsar model described above.

Long bursts are observed in regions with high star formation and are usually accompanied by supernovae, implying that they are related to the death of massive stars. The massive star involved is most likely a Wolf-Rayet star, given that absorption features in the afterglow of long GRBs [145] were explained by the presence of the fast-moving wind of such a star. Furthermore, the fact that long-GRB counterparts are located within the blue parts of galaxies argues against high-velocity progenitors (such as merging neutron stars). The above suggest that long GRBs likely come from the collapse of the core of a Wolf-Rayet star that for some reason created a GRB instead of just a supernova. Some of the differences between short and long GRBs come from the fact that the engine of long

\footnote{Massive stars ($Mass > 20 M_\odot$) that rapidly lose their outer envelope by means of a very strong stellar wind.}
GRBs operates at the center of a collapsing star, therefore it is covered by the mantle of the star, while the engine of short GRBs is more or less exposed.

**Long GRB-supernova connection**

In 1998, the optical telescope ROTSE discovered a transient emission coincident in space and time with BeppoSAX/BATSE long GRB980425 [146]. The location, spectrum and light curve of the optical transient lead to its identification as a very luminous Type Ic supernova\(^3\) (SN 1998bw) [147, 148]. This detection was a first of its kind, and suggested that long GRBs are related to supernovae, and therefore to the deaths of massive stars. Because GRB980425 was very subenergetic comparing to other GRBs (isotropic energy emitted was \(\sim 8 \times 10^{47} \text{erg} \) instead of the usual \(10^{51} - 10^{54} \text{erg} \)), the supernova-GRB connection was initially called into question. However, a few years later, a similar event happened. Emission from a supernova (SN2003dh [149]) was detected on the afterglow of long GRB030329. This time, the associated GRB had a normal energy. In addition to those events, there have also been red emission “bumps” superimposed on the afterglows of GRBs, with color, timing, and brightness consistent with the emission of a Type Ic supernova similar to SN 1998bw (see [150] and references therein).

Based on the above, it is now believed that most, if not all, long GRBs are accompanied with a Type Ic supernova. It should be noted, however, that not all Type Ic supernova create a GRB. The specific conditions that lead to the creation of a GRB is one of the open questions of the field. Observational and theoretical evidence imply that high rotational speeds, high progenitor masses, and regions of low metallicity [151, 152] favor the creation of GRBs.

The collapsar model of GRBs can accommodate the existence of a Type Ic supernova. Specifically, the GRB and the underlying supernova are powered by different sources. The supernova and the \(^{56}\text{Ni}\) that makes it bright are produced by a sub-relativistic disk wind [152]. The wind begins as protons and neutrons, in about equal proportions, and after it cools, it ends up as \(^{56}\text{Ni}\). The nickel comes out in a large cone surrounding the GRB jet.

### 2.2.3 Jet formation

According to the generally accepted model of the progenitor and the emission mechanism of GRBs, GRBs start with a cataclysmic event, such as the merger of two compact objects or the collapse of the core of a rotating massive star, followed by the creation of a rapidly spinning black hole and an accreting envelope around it (Fig. 2.13). This model, called the ”Collapsar model”, was initially proposed to explain long GRBs [152]. However, it was realized that the mergers of compact-object binaries that create short GRBs also result a black hole-accretion disk system similar to the one in the collapsar model.

The collapse of the accreting material that is near the equator of the envelope is somewhat inhibited by the strong centrifugal forces. Most of the accretion happens through two funnels that form on the poles of the black hole (on the axis of rotation). Large amounts of energy (\(\sim 10^{50} \text{erg/s}\)) are deposited locally on the polar regions, possibly

---

\(^3\)A Type Ic supernova has no hydrogen in its spectrum and lacks strong lines of HE I and Si II.
through neutrino-driven winds [154], magneto-hydrodynamic processes [58], magnetic instabilities in the disk [155]. The sources for the deposited energy are the gravitational and rotational energy of the accreting envelope and the spinning black hole. The relative contribution of each source (envelope or black hole) is unknown and depends on which energy-transfer mechanism is more efficient. It is more likely that the largest fraction is supplied by the gravitational energy of the envelope.

Outward radiation and matter pressure gradually build up at the poles; however, they are initially smaller than the pressure from the in-falling material. A point is reached, at which the matter density over the poles and the accretion rate are reduced to a large enough degree that they cannot counter-balance the outward pressure. At that point an explosion occurs. A hot baryon-loaded $e^-, e^+, \gamma$ plasma (also called the “fireball”) pushes outwards through the layers of the envelope. Matter and pressure gradients and magnetic fields collimate the outflow, until it finally manages to erupt from the surface of the object and break free in the form of two opposite narrow jets of half-opening angle $\sim 10^\circ$ (Fig. 2.14). Because the baryon load of the fireball plasma is small ($M_b c^2 \ll E$, where $M_b$ is the total mass of the baryons, and $E$ is the total energy of the fireball) the fireball is quickly accelerated to relativistic velocities.
In the first stages following the ejection of the jet (preburst), the density of the jet is very high, and any radiation produced in it is readily absorbed instead of escaping. As a result, the jet accumulates energy, and its bulk Lorentz factor increases further. However, as it expands, the optical depth is reduced, and radiation can escape from it. The fact that the observed radiation has a power law and shows great variability disfavors a model of a uniformly dense fireball expanding smoothly in the interstellar space and radiating on a thermal spectrum. It was realized that the observed prompt emission and the afterglow could be produced during internal [157] and external shocks [158], respectively. The internal shocks happen inside the jet and between shells of material moving at different velocities. Such shells can be created if the energy-deposition mechanism is intermittent. During these shocks, the jet’s electrons are accelerated to ultra-relativistic velocities and emit synchrotron radiation. Each peak of the prompt light curve is considered to be created during such an internal shock.

The external shock occurs when the jet eventually collides with the ambient circum-burst medium, and smoothly and slowly decelerates. Similarly to internal shocks, relativistic electrons emit synchrotron radiation observed as an afterglow that starts from γ-rays and gradually softens to longer wavelengths, down to radio as the jet is attenuated by the circumburst medium.

While the general picture described by the collapsar model is accepted by the scientific community, the detailed mechanisms of GRB production continue to be a subject of active research.
community, there is little consensus regarding some of its details. The inner engine of GRBs is hidden from us, so we can make only indirect inferences about its nature. As a result, there is still uncertainty regarding many aspects of the model, such as how exactly the jets are formed; which mechanism transfers energy from the inner engine to the jets; the baryonic load of the jets; the jets’ bulk Lorentz factor; which physical processes are involved in the internal shocks; what specific circumstances lead to the creation of a GRB instead of just a supernova, etc.

2.2.4 Relativistic expansion

The GRB fireball has a high radiation density, so photon pairs of center of mass energy \( \geq 2m_e c^2 \) should readily annihilate and create \( e^- e^+ \) pairs, instead of escaping from the fireball. A calculation using typical values yields an optical depth \( \tau_{\gamma\gamma} \sim 10^{15} \) [159]. In such a case, the emitted spectrum should be thermal and should not contain an MeV or higher-energy component. This, in a first view creates a paradox, the “Compactness problem,” since the observed spectrum is a power law and extends up to energies of at least tens of GeV, with no indication of a cutoff for both long and short GRBs.

The paradox can be solved if the radiating material is moving with relativistic velocities towards us. In such a case, the observed GeV/MeV photons actually have a lower energy in the fireball frame of reference. Therefore, the optical depth of the fireball for the observed photons is actually lower, since there is now a smaller number of photon pairs with a center of mass energy over the annihilation threshold \( (2m_e c^2) \). If we assume that the photon energies inside the fireball are distributed on a power law \( I_o E^{-a} \), then this effect will decrease the opacity by factor \( \Gamma^{-2a} \), where \( \Gamma \) is the bulk Lorentz factor of the fireball [160]. Furthermore, because of relativistic contraction, the implied dimensions of the source moving towards us will be smaller by a factor of \( \Gamma^2 \) than its proper size. The power of two comes after considering the curvature of the emitting region (spherical-cap shape). As a result, the source’s density is actually smaller by a factor of \( \Gamma^{-4} \) and the optical depth smaller by a factor \( \Gamma^{-2} \). The combined effect is that the optical depth is actually lower by a factor of \( \Gamma^{-2a-2} \) than what it would be for a non-relativistic jet, thus solving the paradox. Based on the above considerations and the amount of detected MeV/GeV radiation from GRBs, lower limits on the bulk Lorentz factor of \( \Gamma \gtrsim 1220 \) were placed for short GRBs [108] and \( \Gamma \gtrsim 1000 \) for long GRBs [137].

Another piece of evidence supporting the case for relativistic motion of the ejecta comes from the fact that estimates of the size of the afterglow two weeks after the burst, independently provided by radio scintillation [161] and lower-frequency self absorption [162], can be explained only by assuming relativistic expansion.

2.2.5 Energetics and collimated emission

The afterglow light curves of GRBs exhibit achromatic spectral breaks (Fig. 2.6) that can be explained by assuming that the geometry of the ejecta is conical (on two opposite jets) instead of spherical.
Figure 2.15 shows how this can happen. Because the fireball is moving with relativistic velocities, its emission is beamed. Consider an observer that is inside the projection of the emission cone of the fireball. Initially, when the bulk Lorentz factor of the fireball is very high, the relativistically-beamed radiation will be emitted in a very narrow cone. As a result, the observer will not be able to see the emission from a part of the fireball. Such a case is shown in the top picture of figure 2.15, in which radiation from the sides of the fireball is clearly not visible by the observer. As the GRB progresses, the surface of the fireball expands (as \( \propto t^2 \)), and the emitted radiation density drops with the same rate, causing a gradual decrease in the observed brightness of the burst. However, because of the expansion, the bulk Lorentz factor is reduced, and the relativistic beaming becomes wider. As a result, a larger fraction of the surface of the fireball will come in the field of view of the observer (middle picture), reducing the decay rate of the observed GRB brightness (now \( \sim \propto t^{-1.2} \) instead of \( \sim \propto t^{-2} \)). Eventually, all of the surface of the burst becomes visible to the observer, and a gradually increasing fraction of the fireball is no longer able to be seen. The decay rate of the burst’s brightness now depends only on the expansion of the fireball’s surface and becomes proportional to \( t^{-2} \). This transition, appearing as an achromatic break on the afterglow light curve, has been observed on many GRBs. For the GRB afterglows with no observed jet breaks, it is assumed that the breaks happened at a time long after the bursts, when no observation data exist.

The typical energy emission of \( 10^{53} \) erg emitted in few seconds is considerably higher than the emission from a typical supernova (\( 10^{51} \) erg emitted in few months or \( 10^{49} \) erg in hundreds of seconds), and is difficult to explain. However, the fact that the emission geometry is conical ameliorates these energy requirements. If the emission actually happened in a solid angle \( \Delta \Omega \), then the true amount of emitted energy is

\[
E_{\text{true}} = 2 \frac{E_{\text{iso}} \Delta \Omega}{4\pi} \\
= 2 E_{\text{iso}} \frac{1 - \cos(\theta_{\text{jet}})}{\pi} \\
\approx E_{\text{iso}} \frac{\theta_{\text{jet}}^2}{2},
\]

where \( \theta_{\text{jet}} \) is the half opening angle of the emission cone. Frail et al. [163] estimated
\( \theta_{\text{jet}} \) for a sample of GRBs, based on the occurrence time of the achromatic break in their afterglow curves. Based on \( \theta_{\text{jet}} \), they calculated the true amount of emitted energy from the isotropic-equivalent amount. Their result (Fig. 2.16) showed that even though the isotropic-equivalent emitted energy spans a wide energy range (\( 4 \times 10^{52} - 2 \times 10^{54} \) erg), the true amount of emitted energy spans a considerably narrower energy range centered at \( \sim 3 \times 10^{50} \) erg. This shows that the energy emission of GRBs is comparable to that of supernovae, and suggests that GRBs have a standard energy reservoir. The fact that the emission is conical also increases the implied rate of GRBs by the same factor (\( \sim \theta_{\text{jet}}^2 \)), since only GRBs with their emission cones pointing to the earth are detected.

![Figure 2.16: GRB energetics: distribution of the isotropic-equivalent emitted energy for a selection of GRBs with known redshifts (top), distribution of the geometry-corrected emitted energy for the same GRBs (bottom). Arrows are plotted for five GRBs to indicate lower or upper limits to the geometry-corrected energy[156].](image)

Figure 2.16: GRB energetics: distribution of the isotropic-equivalent emitted energy for a selection of GRBs with known redshifts (top), distribution of the geometry-corrected emitted energy for the same GRBs (bottom). Arrows are plotted for five GRBs to indicate lower or upper limits to the geometry-corrected energy[156].
2.2.6 Emission mechanisms

According to the collapsar model, the observed radiation is produced at internal or external shocks. During these shocks, energy is transferred to the jet’s electrons through a diffusive shock acceleration mechanism \[164\] in which magnetic field irregularities keep scattering the particles back and forth so they cross the same shock multiple times. During the first crossing, an electron gains an amount of energy of the order of \( \Gamma_{sh}^2 \), where \( \Gamma_{sh} \) is the Lorentz factor of the shock front measured in the rest frame of the jet \[165\]. Subsequent crossings are less efficient, and the gain is of the order of unity \[165\]. During these shocks, the electrons are accelerated to ultra-relativistic velocities (\( \Gamma_e \) up to \( \sim 1000 \)) and emit synchrotron radiation. The shocks may also accelerate protons. However, the power of the synchrotron emission from protons is considerably smaller than the power from the electrons. Therefore the detected radiation is likely produced by electrons.

The shock energy is converted into kinetic energy and magnetic field energy, the kinetic energy is divided between both the electrons and the protons that are in the outflow. The fraction of energy carried by each of them can be represented as \( \epsilon_e \), \( \epsilon_p \) and \( \epsilon_B \) respectively and \( \epsilon_e + \epsilon_p + \epsilon_B = 1 \). These parameters are dimensionless and depending from their value the emission will be dominated by electrons or by protons. If \( \epsilon_e \) is very small \( < 10^{-3} \) the high energy emission component in the prompt phase is dominated by the protons \[166\]. Protons and electrons can emit photons via synchrotron emission. Electrons can emit also through inverse Compton (IC) processes and synchrotron-self Compton processes (SSC).

Even if the same processes emits photons in the prompt and in the afterglow phase the two stages are characterized by different environmental situation. The following description of the emission mechanisms is referred to only the prompt phase and not to the afterglow phase. The relative importance between the electron synchrotron emission and the electron IC emission depends on the parameter:

\[
Y \equiv \frac{P'_{IC}}{P'_{syn}} = \frac{U'_\gamma}{U'_B} \tag{2.2}
\]

where \( P'_{IC} \) and \( P'_{syn} \) are the power from the IC and synchrotron emissions respectively; while \( U'_\gamma \) and \( U'_B \) are the energy density of the seed of the up-scattered photon in the IC interaction and of the magnetic field respectively. If \( E_e \gg \Gamma^2 m_e^2 c^4 / E_{se} \) (where \( E_{se} \) is the energy of the seed photon scattered by electrons) the IC effect is unimportant and the synchrotron emission is dominant. On the contrary if \( E_e \ll \Gamma^2 m_e^2 c^4 / E_{se} \) the photon spectrum from electrons is dominated by the IC emission.

In the particle interactions that take place in the outflow, also pions are produced. In the case of charged pions, photons are emitted via synchrotron radiation, in the case of neutral pions, instead, photons are emitted by the decay: \( \pi^0 \rightarrow \gamma \gamma \).

**Synchrotron radiation**

The spectrum of the GRBs in the keV-MeV range is usually explained with a synchrotron radiation from the electrons (as shown in fig. 2.17). As electrons also protons can emit synchrotron radiation but they are weaker emitters because their mass is \( \sim 2000 \) times the electron mass. To describe some quantities two frames are defined usually: the observer frame and the comoving frame (denoted with a “‘” superscript). The
synchrotron frequency in the observer frame is given by [167]:

$$\nu_{\text{syn}} = \frac{eB'}{2\pi(1+z)m_e c} \Gamma \gamma'_e$$

(2.3)

where $B'$ is the magnetic field in the comoving frame, $\gamma'_e$ is the Lorentz factor of the electron in the comoving frame and $\Gamma$ is the bulk Lorentz factor of the jet. To compute the maximum energy can be reached by the synchrotron emission the synchrotron cooling time and the acceleration time must be balanced [167]:

$$h\nu_M = \frac{9h m_e c^3}{16(1+z)^2 e^2 \Gamma} \approx 30\Gamma \frac{1+z}{MeV}$$

(2.4)

that is, for $\Gamma \sim 100$, few GeV.

The synchrotron radiation from the protons if $\gamma_p = \gamma_e$ is weaker by a factor $(m_e/m_p)^2$ so it could not be dominant in the sub-MeV region. But the proton population can reach an higher Maximum Lorentz factor: $\gamma'_{M,p} = (m_p/m_e)\gamma'_{M,e}$. As a consequence the highest energy emitted is higher than the maximum energy from electrons by a factor $(m_p/m_e)$. The proton synchrotron emission is highly suppressed by the interaction of the protons with the synchrotron photons from electrons [168].

**Electron Inverse Compton scattering**

An electron moving in a background of soft photons can up-scatter them to high energy through the Inverse Compton (IC) process. The up-scattered photons could be from the shell plasma or could be emitted by the electron population via synchrotron process. The latter mechanism is called Synchrotron-self Compton (SSC). The IC frequency is [167]:

$$\nu_{IC} = \frac{2\Gamma \gamma'^2_e \nu'_se}{1+z}$$

(2.5)

where $\nu'_se$ is the frequency of the seed photon and the parameter $g \equiv \gamma'_e h\nu'_se/m_e c^2 = \gamma'_e E'_se/m_e c^2$. When the parameter $g \ll 1$ the scatter is in the Thompson regime and

$$\nu'_{IC} \approx \gamma'^2_e \nu'_se.$$

(2.6)

Instead when $g \geq 1$ than means that $E_e \geq \Gamma^2 m_e^2 c^4/E'_se$ the regime is called Klein Nishina (KN).

In the KN regime the cross section of the scatter decreases and this produce a spectral break in the photon spectrum. The electron emissivity decreases by a factor $g^2$ and the photon spectrum follows the electron spectrum [168]. The contribution of the IC component to the GRB spectrum is showed in fig. 2.17.

**$\gamma$-ray from pion production**

The interactions between the protons and the low energy photons or between the protons and other adrons produce neutral and charged pions:

$$p + n \rightarrow n + n + \pi^+,$$  $$p + n \rightarrow p + p + \pi^-$$

$$p + p \rightarrow p + n + \pi^+,$$  $$p + p \rightarrow p + p + \pi^0$$

$$p + n \rightarrow p + n + \pi^0$$

42
\[ p + \gamma \rightarrow \Delta^+ \rightarrow n + \pi^+, \quad p + \gamma \rightarrow \Delta^+ \rightarrow p + \pi^0. \]  

(2.7)

Subsequently the charged pions can decay producing positrons and electrons: \( \pi^\pm \rightarrow \mu^\pm + \nu_\mu(\bar{\nu}_\mu) \rightarrow e^\pm + \nu_e(\bar{\nu}_e) + \nu_\mu(\bar{\nu}_\mu) \). These charged particles can produce radiation through the synchrotron process and their contribution to the GRB spectrum can be seen in fig. 2.17. As showed in the figure the typical range of energies of this emission component is from GeV to TeV, this is because the processes involved to produce them happen when the protons are very energetics [168]. For example when the protons interact with the \( \gamma \) the minimum proton energy required is \( E_p \sim 120 \text{ TeV} \) for a bulk Lorentz factor of 400[168].

High energy photons can also be produced via \( \pi^0 \) decay: \( \pi^0 \rightarrow \gamma\gamma \). As before also this radiation component is in the GeV-TeV range because in the rest frame of the outflow the threshold energy for the production of a \( \pi^0 \) is 140 MeV. Moreover because the pion carries the 20% of the proton energy, the \( \gamma \)-ray resulting in the observer rest frame has a minimum energy of \( 30\Gamma\text{GeV} \)[168].

![Figure 2.17: Broad-band spectrum of the GRB prompt emission within the internal shock model (from [168]). (a) A long GRB with the observed sub-MeV luminosity of \( \sim 10^{51} \text{ erg s}^{-1} \), is modeled for parameters as given in the figure. The solid black lines represent the final spectrum before (thin line) and after (thick line) including the effect of internal optical depths. The long dashed green line (mostly hidden) is the electron synchrotron component; the short-dashed blue line is the electron IC component; the double short-dashed black curve on the right side is the \( \pi^0 \) decay component; the triple short-dashed dashed line represents the synchrotron radiation produced by \( e^\pm \) from \( \pi^\pm \) decays; the dash-dotted (light blue) line represents the proton synchrotron component. (b) The analogous spectrum of a bright short GRB with \( 10^{51} \text{ erg isotropic-equivalent energy release.} \)
Chapter 3

The AGILE scientific instruments

AGILE is an Italian Space Agency mission dedicated to the observation of the gamma-ray Universe. The AGILE very innovative instrumentation combines for the first time a gamma-ray imager (sensitive in the energy range 30 MeV - 50 GeV), a hard X-ray imager (sensitive in the range 18-60 keV) together with a Calorimeter (sensitive in the range 300 keV - 100 MeV) and an anticoincidence system. AGILE was successfully launched on April 23, 2007 from the Indian base of Sriharikota and was inserted in an equatorial orbit with very low particle background. The satellite commissioning phase was carried out during the period May-June, 2007. The scientific Verification phase and the in-orbit calibration (based on long pointings at the Vela and Crab pulsars) were carried out during the period July-November 2007. The nominal scientific observation phase (AGILE Cycle-1, AO-1) started on December 1, 2007.

The Gamma-Ray Imaging Detector (GRID) is sensitive in the energy range \( \sim 30 \text{ MeV} - 50 \text{ GeV} \), and consists of a Silicon-Tungsten Tracker, a Cesium Iodide Calorimeter, and an Anticoincidence system.

The GRID trigger logic and data acquisition system (based on Anticoincidence, Tracker and Mini-Calorimeter information) allows for an efficient background discrimination and inclined photon acceptance [169, 170]. The GRID is designed to achieve an optimal angular resolution (source location accuracy \( \sim 12' \) for intense sources), a very large field-of-view (\( \sim 2.5 \text{ sr} \)), and a sensitivity comparable to that of EGRET for sources within 10-20 degree from the main axis direction (and substantially better for larger off-axis angles).

The hard X-ray Imager (Super-AGILE) is a unique feature of the AGILE instrument (for a complete description, see [171]). The imager is placed on top of the gamma-ray detector and is sensitive in the 18-60 keV band.

A Mini-Calorimeter operating in the "burst mode" is the third AGILE detector. It is part of the GRID, but also also capable of independently detecting GRBs and other transients in the 350 keV - 50 MeV energy range with excellent timing capabilities.

3.1 The Anticoincidence System

The Anticoincidence (AC) System is aimed at a very efficient charged particle background rejection [172]; it also allows a preliminary direction reconstruction for triggered photon events through the Data Handling logic. The AC system completely surrounds all AGILE
### The AGILE Scientific Instruments

#### Gamma-ray Imaging Detector (GRID)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy range</td>
<td>30 MeV – 50 GeV</td>
</tr>
<tr>
<td>Field of view</td>
<td>( \sim 2.5 \text{ sr} )</td>
</tr>
<tr>
<td>Flux sensitivity ((E &gt; 100 \text{ MeV}, 5\sigma \text{ in } 10^6 \text{ s}))</td>
<td>(3 \times 10^{-7} \text{ (ph cm}^{-2} \text{ s}^{-1}))</td>
</tr>
<tr>
<td>Angular resolution at 100 MeV (68% cont. radius)</td>
<td>3.5 degrees</td>
</tr>
<tr>
<td>Angular resolution at 400 MeV (68% cont. radius)</td>
<td>1.2 degrees</td>
</tr>
<tr>
<td>Source location accuracy (high Gal. lat., 90% C.L.)</td>
<td>(\sim 15 \text{ arcmin})</td>
</tr>
<tr>
<td>Energy resolution (400 MeV)</td>
<td>(\Delta E/E \sim 1)</td>
</tr>
<tr>
<td>Absolute time resolution</td>
<td>(\sim 2 \mu s)</td>
</tr>
<tr>
<td>Deadtime</td>
<td>(\sim 100 – 200 \mu s)</td>
</tr>
</tbody>
</table>

#### Hard X–ray Imaging Detector (Super-AGILE)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy range</td>
<td>18 – 60 keV</td>
</tr>
<tr>
<td>Single (1-dim.) detector FOV (FW at zero sens.)</td>
<td>(107^\circ \times 68^\circ)</td>
</tr>
<tr>
<td>Combined (2-dim.) detector FOV (FW at zero sens.)</td>
<td>(68^\circ \times 68^\circ)</td>
</tr>
<tr>
<td>Sensitivity (18–60 keV, 5\sigma in 1 day)</td>
<td>(\sim 15 \text{ mCrab})</td>
</tr>
<tr>
<td>Angular resolution (pixel size)</td>
<td>6 arcmin</td>
</tr>
<tr>
<td>Source location accuracy (S/N (\sim 10))</td>
<td>(\sim 1-2 \text{ arcmin})</td>
</tr>
<tr>
<td>Energy resolution (FWHM)</td>
<td>(\Delta E \sim 8 \text{ keV})</td>
</tr>
<tr>
<td>Absolute time resolution</td>
<td>(\sim 2 \mu s)</td>
</tr>
</tbody>
</table>

#### Mini-Calorimeter

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy range</td>
<td>0.35 – 50 MeV</td>
</tr>
<tr>
<td>Energy resolution (at 1.3 MeV)</td>
<td>13% FWHM</td>
</tr>
<tr>
<td>Absolute time resolution</td>
<td>(\sim 3 \mu s)</td>
</tr>
<tr>
<td>Deadtime (for each of the 30 CsI bars)</td>
<td>(\sim 20 \mu s)</td>
</tr>
</tbody>
</table>
detectors (Super-AGILE, Si-Tracker and MCAL). Each lateral face is segmented in three plastic scintillator layers (0.6 cm thick) connected to photomultipliers placed at the bottom of the panels. A single plastic scintillator layer (0.5 cm thick) constitutes the top-AC whose signal is read by four light photomultipliers placed at the four corners of the structure frame. The segmentation of the AC System and the ST trigger logic contribute in an essential way to produce the very large field of view of the AGILE-GRID.

### 3.2 The Silicon-Tracker

The Silicon Tracker (ST) is the AGILE gamma-ray imager based on photon conversion into electron-positron pairs [173, 174]. It consists of a total of 12 trays with a repetition pattern of 1.9 cm (Fig. 3.1). The first 10 trays are capable of converting gamma-rays by a Tungsten layer. Tracking of charged particles is ensured by Silicon microstrip detectors that are configured to provide the two orthogonal coordinates for each element (point) along the track. The individual Silicon detector element is a tile of area $9.5 \times 9.5$ cm$^2$, microstrip pitch of 121 $\mu$m, and 410 $\mu$m thickness. Four Silicon tiles are bonded together to provide a ladder. Four ladders constitute a ST plane. The AGILE ST readout system is capable of detecting and storing the energy deposited in the Silicon microstrips by the penetrating particles. The readout signal is processed for half of the microstrips by an alternating readout system characterized by ”readout” and ”floating” strips. The analog signal produced in the readout strips is read and stored for further processing. Each Silicon ladder has a total of 384 readout channels (242 $\mu$m readout pitch) and 3 TAA1 chips are required to process independently the analog signal from the readout strips. Each Si-Tracker layer is then made of $4 \times 4$ Si-tiles, for a total geometric area of $38 \times 38$ cm$^2$. The first 10 trays are equipped with a Tungsten layer of 245 $\mu$m (0.07 $X_0$) positioned in the bottom part of the tray. The two orthogonal coordinates of particle hits in the ST are provided by two layers of Silicon detectors properly configured for each tray that therefore has $2 \times 1$, 536 readout microstrips. Since the ST trigger requires a signal from at least three (contiguous) planes, two more trays are inserted at the bottom of the Tracker without the Tungsten layers. The total readout channel number for the GRID Tracker is then 36,864. The 1.9 cm distance between mid-planes has been optimized through extensive Montecarlo simulations. The ST has an on-axis total radiation length near 0.8 $X_0$. Special trigger logic algorithms implemented on-board (Level-1 and Level-2) lead to a substantial particle/albedo-photon background subtraction and a preliminary on-board reconstruction of the photon incidence angle. Both digital and analog information are crucial for this task. Fig. 3.2 shows a typical read-out configuration of a gamma-ray event detected by the AGILE Silicon Tracker. The positional resolution obtained by the ST is excellent, being below 40 $\mu$m for a wide range of particle incidence angles [175].

### 3.3 Super-AGILE

Super-AGILE (SA), the ultra-compact and light hard-X-ray imager of AGILE [171] is a coded-mask system made of a Silicon detector plane and a thin Tungsten mask positioned 14 cm above it (Fig. 3.3). The detector plane is organized in four independent
3.4 The Mini-Calorimeter

The Mini-Calorimeter (MCAL) is made of 30 Cesium Iodide (CsI(Tl)) bars arranged in two planes, for a total (on-axis) radiation length of $1.5X_0$ (see Fig. 3.4). A detailed description of the MCAL detector can be found in [177, 178]. The signal from each CsI bar
3.4 The Mini-Calorimeter

is collected by two photodiodes placed at both ends. The MCAL aims are: (i) obtaining information on the energy deposited in the CsI bars by particles produced in the Silicon Tracker (and therefore contributing to the determination of the total photon energy); (ii) detecting GRBs and other impulsive events with spectral and intensity information in the energy band $\sim 0.35 - 100$ MeV. An independent burst search algorithm is implemented on board with a wide range of trigger timescales for an MCAL independent GRB detection. Following a GRB trigger, MCAL is indeed able to store photon-by-photon information for a duration dynamically determined by the on-board logic. The MCAL segmentation and the photon-particle hit positioning along the bars allow to obtain the general configuration of "hits" across the calorimeter volume.
3.5 The event reconstruction and classification

The AGILE Standard Analysis Pipeline. A first step aligns all data times to Terrestrial Time (TT) and performs preliminary calculations. In a second step, an ad-hoc implementation of the Kalman Filter technique is used for track identification and event direction reconstruction in detector coordinates. Subsequently, a quality flag is assigned to each GRID event: (G), (P), (S), and (L), depending on whether it is recognized as a $\gamma$-ray event, a charged particle event, a single-track event, or if its nature is uncertain, respectively. Then, an AGILE log-file is created, containing all the information relevant to the computation of the exposure and live-time. A third step creates the AGILE event files, excluding events flagged as particles. This step also reconstructs the event direction in
3.6 The AGILE instrument calibration

The AGILE scientific instrument was fully calibrated on the ground during a set of calibration campaigns dedicated to the three instrument detectors.

3.6.1 The gamma-ray imager calibration

The AGILE-GRID calibration was carried out at the INFN National Laboratories in Frascati during the period November 1-25, 2005.

A beam of gamma-ray photons in the energy range 20-700 MeV was produced by Bremsstrahlung of electrons and tagged by a dedicated set-up in the Beam Test Facility of the INFN Laboratori Nazionali di Frascati based on the measurement with silicon strip detectors of the electron trajectory in a magnetic field. A total of 100,000 tagged events was accumulated for several incidence directions and instrument configurations. Both the GRID spectral and PSF response were carefully studied and compared with results of extensive simulations. Furthermore, the leptonic background was studied by using the direct electron and positron beams interacting with the AGILE GRID for different geometries. A sequence of runs was obtained for both direct incidence on the instrument as well as for events originating by interactions with the spacecraft.
3.6.2 The hard X-ray imager calibration

The Super-AGILE imager was calibrated at different stages during the instrument integration and testing. It was first calibrated at the detection plane and stand-alone detector level in the clean room of INAF-IASF Rome on April and August 2005, respectively. The SA effective area and intrinsic imaging properties were investigated by means of a highly collimated X-ray tube and point-like radioactive sources (see [179], [180] for details). A dedicated procedure was developed [181] to correct the SA images for the beam divergence in order to derive imaging calibration properties from measurements with radioactive sources at finite distance (about 200 cm from the experiment).

Once integrated with the instrument and satellite, the SA imager was then fully calibrated during in January, 2007 at the CGS facility in Tortona. A sequence of measurements were carried out with radioactive sources positioned at different angles with respect to the instrument axis. The imaging response was studied as a function of the source position in the field of view (in more than 40 positions), and energy (at 22, 30 and 60 keV). The calibration campaign envisaged a total of more than 110 measurements and 340 ks livetime, with more than $10^7$ source photons collected. The data analysis allowed us to calibrate the imaging and spectral response of SA. Fig. 3.6 shows a sample of the results achieved during the final ground calibrations, confirming the expected 6 arcmin (FWHM) point spread function (PSF) and the $\sim$1-2 arcmin point source location accuracy (see [182] and [183] for more details). SA on-board imaging was also tested in Tortona. A sequence of GRB simulating tests were carried out to check the on-board trigger logic and parameter setting.

3.6.3 The Calorimeter calibration

Several calibration sessions of MCAL were carried out after its integration [178]. A first stand-alone calibration session was performed at instrument level, prior to integration into the AGILE payload, using a collimated $^{22}$Na radioactive source. By these measurements the bars physical parameters such as the light output and the light attenuation coefficients were obtained. After the instrument integration, MCAL was tested at the DAΦNE accelerator Beam Test Facility in Frascati during the GRID calibration session. MCAL was then calibrated after satellite integration at the CGS facility in Tortona, exposing the instrument to an uncollimated $^{22}$Na radioactive source placed at different positions with respect to the satellite axis in order to evaluate the MCAL efficiency and the overall contribution of the spacecraft volumes to the detector response.

The MCAL response to impulsive events and GRBs was studied by reproducing the conditions for GRB events of durations between 30 ms and 2 s by means of a dedicated setup mainly based on moving a radioactive source behind a collimator; the speed of the source determining the duration and rise time of the Burst [184]. With this setup all time windows of the burst search logic above 16 ms have been stimulated and tested.

3.6.4 The Anticoincidence system calibration

An excellent anticoincidence system is required for an efficient background rejection of the AGILE instrument. The AC flight units (scintillator panels and photo-multiplier
3.7 Early operations in orbit

After the nominal launch and the correct satellite attitude stabilization within approximately 2 days, the operations focused on two different tasks: (1) the commissioning of both the satellite platform and instrument; (2) in-orbit scientific calibration of the instrument. We briefly describe here these two main activities, postponing a detailed description to forthcoming publications.
The AGILE scientific instruments

3.7.1 The satellite in-orbit Commissioning and instrument checkout phase

The satellite platform was tested and functionally verified in all its main capabilities during the last days of April 2007. The checkout sequence of tests ended with the satellite fine pointing attitude finalization that implies the nominal $\sim 1$ degree pointing accuracy and the 0.1 degree/s stabilization. Attitude reconstruction, both on-board and on the ground, was tested to be initially within a few arcminute accuracy. A sequence of early pointings was carried out, typically lasting for a few days.

The instrument subsystem switch on started in early May and proceeded with nominal behavior of all detectors. A first check of the instrument housekeeping telemetry indicated a nominal particle background rate as predicted by extensive simulations [185, 186]. Fig. 3.7 shows a typical background count rate on a lateral AC panel throughout the equatorial orbit.

The GRID acquisition rate after a complete on-board processing and Earth gamma-ray albedo rejection turned out to be stable throughout the orbit with a modulation induced by the Earth sweeping the GRID FOV (within 1-7 Hz). The GRID subsystem was extensively tested first, and the baseline trigger logic photon acquisition started on May 10th.

The overall particle background turned out to be within the expected rate, both at the level of the Anticoincidence rate, and especially at the so called Level-1 and Level-2 event processing [187].

The Super-AGILE detector was tested immediately afterwards with a dedicated pointing of an extragalactic field. A detailed scan and test of the individual SA strip thresholds was carried out with an optimized parameter stabilization procedure [188]. Hard X-ray
3.7 Early operations in orbit

Figure 3.8: Super-AGILE deconvolved sky image (one detector unit) of the Galactic plane obtained on June 2, 2008 (total effective exposure of 45 ks). Several hard X-ray sources are detected as marked in the figure.

Figure 3.9: The lightcurve (128 ms time bin) of GRB 080319C (Pagani et al., 2008; Marisaldi et al., 2008) detected by the AGILE Mini-Calorimeter in the energy band 0.3-5 MeV.

data were obtained with a nominal performance and very low-background. These operations ended successfully in mid-July, 2007 [189]. Fig. 3.8 shows an example of a typical 1-day pointing in the Galactic plane with the detection of Cyg X-1, Cyg X-2, Cyg X-3, and GRS 1915+105.

The MCAL detector optimization and configuration checkout was performed in parallel with other instrument testing. A satisfactory detector configuration was obtained at the end of June, 2007 [190]. Fig. 3.9 shows an example of a typical GRB detected by the MCAL in the energy range 0.3-5 MeV.

3.7.2 In-orbit tracker calibration

Preliminary gamma-ray data obtained for the Vela pulsar in early June, 2007 confirmed immediately the good quality of the GRID background rejection and its imaging capa-
The AGILE scientific instruments

...ility. The scientific operations started in early July, 2007 with a 2-month observation of the Vela pulsar region. At the end of August, 2007, AGILE devoted about 1 week to a pointing of the Galactic Center region. Finally, AGILE carried out the gamma-ray and hard X-ray calibration with the Crab pulsar during the months of September and October, 2007. Fig. 3.10 shows a 1-day integration of the gamma-ray sky of the Galactic anticenter region (containing the Crab, Geminga as well as the Vela gamma-ray pulsars). This field was repeatedly observed with 1-day pointings with the Crab pulsar position at different angles with respect to the Instrument axis. The in-orbit calibration phase was successfully completed at the end of October, 2007 achieving a good performance for both the gamma-ray and hard X-ray imagers.

Figure 3.10: AGILE 1-day gamma-ray counts map for photons above 100 MeV obtained on September 28, 2007. The large-field of view sky counts map shows in the same picture all three most important gamma-ray pulsars: Vela, Crab and Geminga.
Many high-energy sources revealed by EGRET (one of the instrument [1]) on the Compton Gamma-Ray Observatory CGRO have not yet been identified. The AGILE experiment launched on 2007, April 23 and the Large Area Telescope (LAT) on the Fermi Gamma-ray Space Telescope (Fermi), formerly the Gamma-ray Large Area Space Telescope (GLAST), launched by NASA on 2008, June 11 on a Delta II Heavy launch vehicle, offer enormous opportunities for determining the nature of these sources and advancing knowledge in astronomy, astrophysics, and particle physics.

Figure 4.1: Schematic diagram of the Large Area Telescope. The telescope’s dimensions are 1.8 m $\times$ 1.8 m $\times$ 0.72 m. The power required and the mass are 650 W and 2,789 kg, respectively.

To make significant progress in understanding the high-energy sky, the LAT, shown in Figure 4.1, has good angular resolution for source localization and multi-wavelength stud-
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value or Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy range</td>
<td>20 MeV – 300 GeV</td>
</tr>
<tr>
<td>Effective area at normal incidence(^1)</td>
<td>9.500 cm²</td>
</tr>
<tr>
<td>Energy resolution (equivalent Gaussian 1(\sigma)):</td>
<td></td>
</tr>
<tr>
<td>100 MeV – 1 GeV (on axis)</td>
<td>9%–15%</td>
</tr>
<tr>
<td>1 GeV – 10 GeV (on axis)</td>
<td>8%–9%</td>
</tr>
<tr>
<td>10 GeV – 300 GeV (on-axis)</td>
<td>8.5%–18%</td>
</tr>
<tr>
<td>&gt;10 GeV (&gt;60° incidence)</td>
<td>(\leq6)%</td>
</tr>
<tr>
<td>Single photon angular resolution (space angle) on-axis, 68% containment  radius</td>
<td></td>
</tr>
<tr>
<td>&gt;10 GeV</td>
<td>(\leq0.15^\circ)</td>
</tr>
<tr>
<td>1 GeV</td>
<td>0.6°</td>
</tr>
<tr>
<td>100 MeV</td>
<td>3.5°</td>
</tr>
<tr>
<td>on-axis, 95% containment radius</td>
<td>&lt; 3 (\times) (\theta_{68%})</td>
</tr>
<tr>
<td>off-axis containment radius at 55°</td>
<td>&lt; 1.7 (\times) on-axis value</td>
</tr>
<tr>
<td>Field of View (FoV)</td>
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<tr>
<td>Timing accuracy</td>
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<tr>
<td>Event readout time (dead time)</td>
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<tr>
<td>GRB location accuracy on-board(^2)</td>
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<tr>
<td>GRB notification time to spacecraft(^3)</td>
<td>&lt;5 sec</td>
</tr>
<tr>
<td>Point source location determination(^4)</td>
<td>&lt;0.5′</td>
</tr>
<tr>
<td>Point source sensitivity (&gt;100 MeV)(^5)</td>
<td>(3 \times 10^{-9}) ph cm(^{-2}) s(^{-1})</td>
</tr>
</tbody>
</table>

Table 4.1: Summary of Large Area Telescope Instrument parameters and estimated performance

...ies, high sensitivity over a broad field-of-view to monitor variability and detect transients, good calorimetry over an extended energy band to study spectral breaks and cut-offs, and good calibration and stability for absolute, long term flux measurement. The LAT measures the tracks of the electron (\(e^-\)) and positron (\(e^+\)) that result when an incident \(\gamma\)-ray undergoes pair-conversion, preferentially in a thin, high-\(Z\) foil, and measures the energy of the subsequent electromagnetic shower that develops in the telescope’s calorimeter. Table 4.1 summarizes the scientific performance capabilities of the LAT.

Figure 4.2 illustrates the sensitivity and field-of-view (FoV) achieved with the LAT.

---

\(^1\) Maximum (as function of energy) effective area at normal incidence. Includes inefficiencies necessary to achieve required background rejection. Effective area peak is typically in the 1 to 10 GeV range.

\(^2\) For burst (<20 sec duration) with >100 photons above 1 GeV. This corresponds to a burst of \(~5\) cm\(^{-2}\) s\(^{-1}\) peak rate in the 50–300 keV band assuming a spectrum of broken power law at 200 keV from photon index of –0.9 to –2.0. Such bursts are estimated to occur in the LAT FoV \(~10\) times per year.

\(^3\) Time relative to detection of GRB.

\(^4\) High latitude source of \(10^{-7}\) cm\(^{-2}\) s\(^{-1}\) flux at >100 MeV with a photon spectral index of –2.0 above a flat background and assuming no spectral cut-off at high energy; 1\(\sigma\) radius; 1-year survey.

\(^5\) For a steady source after 1 year sky survey, assuming a high-latitude diffuse flux of \(1.5 \times 10^{-5}\) cm\(^{-2}\) s\(^{-1}\) sr\(^{-1}\) (>100 MeV) and a photon spectral index of –2.1, with no spectral cut-off.
4.1 Large Area Telescope

The LAT is designed to measure the directions, energies, and arrival times of $\gamma$-rays incident over a wide FoV, while rejecting background from cosmic rays. First, the design approach [191] that resulted in the instrument described in detail in §4.1.1 made extensive use of detailed simulations of the detector response to signal (celestial $\gamma$-rays) and backgrounds (cosmic rays, albedo $\gamma$-rays, etc.). Second, detector technologies were chosen that have an extensive history of application in space science and high-energy physics with demonstrated high reliability. Third, relevant test models were built to demonstrate that critical requirements, such as power, efficiency, and detector noise occupancy, could be readily met. Fourth, these detector-system models, including all subsystems, were studied in accelerator test beams to validate both the design and the Monte Carlo programs used in the simulations [192].
4.1.1 Technical description

High-energy \( \gamma \)-rays cannot be reflected or refracted; they interact by the conversion of the \( \gamma \)-ray into an \( e^+e^- \) pair. The LAT is therefore a pair-conversion telescope with a precision converter-tracker and calorimeter, each consisting of a \( 4 \times 4 \) array of 16 modules supported by a low-mass aluminum grid structure. A segmented anticoincidence detector (ACD) covers the tracker array, and a programmable trigger and data acquisition system (DAQ) utilizes prompt signals available from the tracker, calorimeter, and anticoincidence detector subsystems to form a trigger. The self-triggering capability of the LAT tracker in particular is an important new feature of the LAT design that is possible because of the choice of silicon-strip detectors, which do not require an external trigger, for the active elements. In addition, all of the LAT instrument subsystems utilize technologies that do not use consumables such as gas. Upon triggering, the DAQ initiates the read out of these 3 subsystems and utilizes on-board event processing to reduce the rate of events transmitted to the ground to a rate compatible with the 1 Mbps average downlink available to the LAT. The on-board processing is optimized for rejecting events triggered by cosmic-ray background particles while maximizing the number of events triggered by \( \gamma \)-rays, which are transmitted to the ground. Heat produced by the tracker, calorimeter, and DAQ electronics is transferred to radiators through heat pipes in the grid.

The overall aspect ratio of the LAT tracker (height/width) is 0.4, allowing a large FoV\(^6\) and ensuring that nearly all pair-conversion events initiated in the tracker will pass into the calorimeter for energy measurement.

Precision converter-tracker

The converter-tracker has 16 planes of high-Z material in which \( \gamma \)-rays incident on the LAT can convert to an \( e^+e^- \) pair. The converter planes are interleaved with position-sensitive detectors that record the passage of charged particles, thus measuring the tracks of the particles resulting from pair conversion. This information is used to reconstruct the directions of the incident \( \gamma \)-rays. Each tracker module has 18 \( x, y \) tracking planes, consisting of 2 layers \((x \text{ and } y)\) of single-sided silicon strip detectors. The 16 planes at the top of the tracker are interleaved with high-Z converter material (tungsten). Figure 4.3 shows the completed 16 module tracker array before integration with the ACD. See [193] for a more complete discussion of the tracker design and performance. We summarize here the features most relevant to the instrument science performance.

The single-sided SSDs are AC-coupled, with 384 56-\( \mu \)m wide aluminum readout strips spaced at 228 \( \mu \)m pitch\(^7\). They were produced on \( n \)-intrinsic 15-cm wafers by Hamamatsu Photonics, and each has an area of 8.95x8.95 cm\(^2\), with an inactive area 1 mm wide around the edges, and a thickness of 400 \( \mu \)m. Sets of 4 SSDs were bonded edge to edge with epoxy and then wire bonded strip to strip to form “ladders,” such that each amplifier channel sees signals from a 35 cm long strip. Each detector layer in a tracker module consists of 4 such ladders spaced apart by 0.2 mm gaps. The delivered SSD quality was very high, with a bad channel rate less than 0.01% and an average total leakage current of 110 nA.

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\(^6\)FoV = \( \int A_{\text{eff}}(\theta, \phi)d\Omega/A_{\text{eff}}(0,0) = 2.4 \text{ sr} \) at 1 GeV, where \( A_{\text{eff}} \) is the effective area of the LAT after all analysis cuts for background rejections have been made.

\(^7\)pitch = distance between centers of adjacent strips.
The wafer dicing was accurate to better than 20 $\mu$m, to allow all of the assembly to be done rapidly with mechanical jigs rather than with optical references.

The support structure for the detectors and converter foil planes is a stack of 19 composite panels, or “trays,” supported by carbon-composite sidewalls that also serve to conduct heat to the base of the tracker array. The tray structure is a low-mass, carbon-composite assembly made of a carbon-carbon closeout, carbon-composite face sheets, and a vented aluminum honeycomb core. Carbon was chosen for its long radiation length, high modulus (stiffness) to density ratio, good thermal conductivity, and thermal stability.

The tray-panel structure is about 3 cm thick and is instrumented with converter foils, detectors, and front-end electronics. All trays are of similar construction, but the top and bottom trays have detectors on only a single face. Figure 4.4 shows a flight tracker tray and Figure 4.5 shows a completed tracker module with one sidewall removed.
The strips on the top and bottom of a given tray are parallel, while alternate trays are rotated 90° with respect to each other. An $x, y$ measurement plane consists of a layer of detectors on the bottom of one tray together with an orthogonal detector layer on the top of the tray just below, with only a 2 mm separation. The tungsten converter foils in the first 16 planes lie immediately above the upper detector layer in each plane. The lowest two $x, y$ planes have no tungsten converter material. The tracker mechanical design emphasizes minimization of dead area within its aperture. To that end, the readout electronics are mounted on the sides of the trays and interfaced to the detectors around the 90° corner. One fourth of the readout electronics boards in a single tracker module can be seen in Figure 4.5. The interface to the data acquisition and power supplies is made entirely through flat cables constructed as long 4-layer flexible circuits, two of which are visible in Figure 4.5. As a result, the dead space between the active area of one tracker module and that of its neighbor is only 18 mm.

Incident photons preferentially convert in one of the tungsten foils, and the resulting $e^-$ and $e^+$ particles are tracked by the SSDs through successive planes. The pair conversion signature is also used to help reject the much larger background of charged cosmic rays. The high intrinsic efficiency and reliability of this technology enables straightforward event reconstruction and determination of the direction of the incident photon.
4.1 Large Area Telescope

The probability distribution for the reconstructed direction of incident $\gamma$-rays from a point source is referred to as the Point Spread Function (PSF). Multiple scattering of the $e^+$ and $e^-$ and bremsstrahlung production limit the obtainable resolution. To get optimal results requires that the $e^-$ and $e^+$ directions be measured immediately following the conversion.

![Diagram of tracker design principles](image)

Figure 4.6: Illustration of tracker design principles. The first two points dominate the measurement of the photon direction, especially at low energy. (Note that in this projection only the $x$ hits can be displayed.) (a) Ideal conversion in W: Si detectors are located as close as possible to the W foils, to minimize the lever arm for multiple scattering. Therefore, scattering in the 2nd W layer has very little impact on the measurement. (b) Fine detector segmentation can separately detect the two particles in many cases, enhancing both the PSF and the background rejection. (c) Converter foils cover only the active area of the Si, to minimize conversions for which a close-by measurement is not possible. (d) A missed hit in the 1st or 2nd layer can degrade the PSF by up to a factor of two, so it is important to have such inefficiencies well localized and identifiable, rather than spread across the active area. (e) A conversion in the structural material or Si can give long lever arms for multiple scattering, so such material is minimized. Good 2-hit resolution can help identify such conversions.

One of the most complex LAT design trades was the balance between the need for thin converters, to achieve a good PSF at low energy, where the PSF is determined primarily by the $\sim 1/E$ dependence of multiple scattering, versus the need for converter material to maximize the effective area, important at high energy. The resolution was to divide the tracker into 2 regions, “front” and “back.” The front region (first 12 $x, y$ tracking planes) has thin converters, each 0.03 radiation lengths thick, to optimize the PSF at low energy, while the converters in the back (4 $x, y$ planes after the front tracker section) are $\sim 6$ times thicker, to maximize the effective area at the expense of less than a factor of two in angular resolution (at 1 GeV) for photons converting in that region. Instrument simulations show that the sensitivity of the LAT to point-sources is approximately bal-
anced between the front and back tracker sections, although this depends on the source spectral characteristics.

The tracker detector performance was achieved with readout electronics designed specifically to meet the LAT requirements and implemented with standard commercial technology [194]. The system is based on two Application Specific Integrated Circuits (ASICs). The first ASIC is a 64-channel mixed-mode amplifier-discriminator chip and the second ASIC is a digital readout controller. Each amplifier-discriminator chip is programmed with a single threshold level, and only a 0 or 1 (i.e., a “hit”) is stored for each channel when a trigger is generated. Each channel can buffer up to 4 events, and the system is able to trigger even during readout of the digital data from previous events. Thus the system achieves high throughput and very low deadtime, and the output data stream is compact and contains just the information needed for effective tracking, with $<10^{-6}$ noise occupancy, and with very little calibration required. The system also measures and records the time-over-threshold (TOT) of each layer’s trigger output signal, which provides charge-deposition information that is useful for background rejection. In particular, isolated tracks that start from showers in the calorimeter sometimes range out in the tracker, mimicking a $\gamma$-ray conversion. The TOT information is effective for detecting and rejecting such background events because at the termination of such tracks the charge deposition is very large, often resulting in a large TOT in the last SSD traversed.

The tracker provides the principal trigger for the LAT. Each detector layer in each module outputs a logical OR of all of its 1536 channels, and a first-level trigger is derived from coincidence of successive layers (typically 3 $x, y$ planes). There is no detectable coherent noise in the system, such that the coincidence rate from electronics noise is immeasurably small, while the trigger efficiency for charged particles approaches 100% when all layers are considered.

High reliability was a core requirement in the tracker design. The 16 modules operate independently, providing much redundancy. Similarly, the multi-layer design of each module provides redundancy. The readout system is also designed to minimize or eliminate the impact of single-point failures. Each tracker layer has two separate readout and control paths, and the 24 amplifier-discriminator chips in each layer can be partitioned between the two paths by remote command. Therefore, failure of a single chip or readout cable would result in the loss of at most only 64 channels.

**Calorimeter**

The primary purposes of the calorimeter are twofold: (i) to measure the energy deposition due to the electromagnetic particle shower that results from the $e^+e^-$ pair produced by the incident photon; and (ii) image the shower development profile, thereby providing an important background discriminator and an estimator of the shower energy leakage fluctuations. Each calorimeter module has 96 CsI(Tl) crystals, with each crystal of size $2.7 \text{ cm} \times 2.0 \text{ cm} \times 32.6 \text{ cm}$. The crystals are optically isolated from each other and are arranged horizontally in 8 layers of 12 crystals each. The total vertical depth of the calorimeter is 8.6 radiation lengths (for a total instrument depth of 10.1 radiation lengths). Each calorimeter module layer is aligned 90° with respect to its neighbors, forming an $x, y$ (hodoscopic) array [195]. Figure 4.7 shows schematically the configuration of a calorimeter.
Figure 4.7: LAT calorimeter module. The 96 CsI(Tl) scintillator crystal detector elements are arranged in 8 layers, with the orientation of the crystals in adjacent layers rotated by $90^\circ$. The total calorimeter depth (at normal incidence) is 8.6 radiation lengths.

The size of the CsI crystals is a compromise between electronic channel count and desired segmentation within the calorimeter. The lateral dimensions of the crystals are comparable to the CsI radiation length (1.86 cm) and Molière radius (3.8 cm) for electromagnetic showers. Each CsI crystal provides 3 spatial coordinates for the energy deposited within: two discrete coordinates from the physical location of the crystal in the array and the third, more precise, coordinate determined by measuring the light yield asymmetry at the ends of the crystal along its long dimension. This level of segmentation is sufficient to allow spatial imaging of the shower and accurate reconstruction of its direction. The calorimeter's shower imaging capability and depth enable the high-energy reach of the LAT and contribute significantly to background rejection. In particular, the energy resolution at high energies is achieved through the application of shower leakage corrections.

Each crystal element is read out by PIN photodiodes, mounted on both ends of the crystal, which measure the scintillation light that is transmitted to each end. The difference in light levels provides a determination of the position of the energy deposition along the CsI crystal. There are two photodiodes at each end of the crystal, a large photodiode with area 147 mm$^2$ and a small photodiode with area 25 mm$^2$, providing two readout channels to cover the large dynamic range of energy deposition in the crystal.

The position resolution achieved by the ratio of light seen at each end of a crystal scales with the deposited energy and ranges from a few millimeters for low energy depositions ($\sim$10 MeV) to a fraction of a millimeter for large energy depositions (>1 GeV). Simple analytic forms are used to convert the light asymmetry into a position (see Figure 4.8).

Although the calorimeter is only 8.6 radiation lengths deep, the longitudinal segmentation enables energy measurements up to a TeV. From the longitudinal shower profile, an unbiased estimate of the initial electron energy is derived by fitting the measurements to an analytical description of the energy-dependent mean longitudinal profile. Except at the low end of the energy range, the resulting energy resolution is limited by fluctuations in the shower leakage. The effectiveness of this procedure was evaluated in beam
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tests with the flight-like calibration unit at CERN (see §4.3) [196]. Figure 4.9 shows the measured energy loss and the leakage-corrected energy loss in the calorimeter for electron beams of various energies. Further details of the calorimeter are in [197], [198], and [199]. Details of the energy reconstruction are discussed in §4.2.2.

Figure 4.8: Light asymmetry measured in a typical calorimeter crystal using sea level muons. The light asymmetry is defined as the logarithm of the ratio of the outputs of the diodes at opposite ends of the crystal. The width of the distribution scales with energy deposition as $E^{-1/2}$.

Anticoincidence detector

The purpose of the ACD is to provide charged-particle background rejection; therefore its main requirement is to have high detection efficiency for charged particles. The ACD is required to provide at least 0.9997 efficiency (averaged over the ACD area) for detection of singly charged particles entering the field-of-view of the LAT.

The LAT is designed to measure $\gamma$-rays with energies up to at least 300 GeV. The requirement to measure photon energies at this limit leads to the presence of a heavy calorimeter ($\sim 1800$ kg) to absorb enough of the photon-induced shower energy to make this measurement. The calorimeter mass itself, however, creates a problem called the back-splash effect: isotropically distributed secondary particles (mostly 100–1000 keV photons) from the electromagnetic shower created by the incident high-energy photon can Compton scatter in the ACD and thereby create false veto signals from the recoil electrons. This effect was present in EGRET, where the instrument detection efficiency above 10 GeV was a factor of at least two or more lower than at 1 GeV due to false vetoes caused by back-splash. A design requirement was established that vetoes created by back-splash (self-veto) would reject not more than 20% of otherwise accepted photons at 300 GeV. To suppress the back-splash effect, the ACD is segmented so that only the ACD segment nearby the incident candidate photon may be considered, thereby dramatically reducing the area of ACD that can contribute to back-splash [200]. In addition, the onboard use of the ACD veto signals is disengaged when the energy deposition in the calorimeter is larger.
Figure 4.9: Energy resolution as a function of electron energy as measured with the LAT calibration unit in CERN beam tests. Each panel displays a histogram of the total measured energy (hatched peak) and the reconstructed energy (solid peak), using the LK method, at beam energies of 5, 10, 20, 50, 99.7 and 196 GeV, respectively. The beams entered the calibration unit at an angle of 45° to the detector vertical axis. As long as shower maximum is within the calorimeter, the energy measurement and resolution are considerably improved by the energy reconstruction algorithms. The measured energy resolutions ($\Delta E/E$) are indicated in the figure.
than an adjustable preset energy (10 to 20 GeV). Such events are subsequently analyzed using more complex software than can be implemented on board.

Numerous trade studies and tests were performed in order to optimize the ACD, resulting in the design shown schematically in Figure 4.10. Plastic scintillator tiles were chosen as the most reliable, efficient, well-understood, and inexpensive technology, with much previous use in space applications. Scintillation light from each tile is collected by wavelength shifting fibers (WLS) that are embedded in the scintillator and are coupled to two photomultiplier tubes (PMTs) for redundancy. This arrangement provides uniformity of light collection that is typically better than 95% over each detector tile, only dropping to \( \geq 75\% \) within 1–2 cm of the tile edges. Overall detection efficiency for incident charged particles is maintained by overlapping scintillator tiles in one dimension. In the other dimension, gaps between tiles are covered by flexible scintillating fiber ribbons with \( \geq 90\% \) detection efficiency.

![Figure 4.10: LAT Anticoincidence Detector (ACD) design](image)

The ACD has a total of 89 plastic scintillator tiles with a \( 5 \times 5 \) array on the top and 16 tiles on each of the 4 sides. Each tile is readout by 2 photomultipliers coupled to wavelength shifting fibers embedded in the scintillator. The tiles overlap in one dimension to minimize gaps between tiles. In addition, 2 sets of 4, scintillating fiber ribbons are used to cover the remaining gaps.

All ACD electronics and PMTs are positioned around the bottom perimeter of the ACD, and light is delivered from the tiles and WLS fibers by a combination of wavelength-shifting and clear fibers.

**Data acquisition system (DAQ) and trigger**

The Data Acquisition System (DAQ) collects the data from the other subsystems, implements the multi-level event trigger, provides on-board event processing to run filter algorithms to reduce the number of downlinked events, and provides an on-board science analysis platform to rapidly search for transients. The DAQ architecture is hierarchical as shown in Figure 4.11. At the lowest level shown, each of 16 Tower Electronics Modules (TEMs) provides the interface to the tracker and calorimeter pair in one of the towers. Each TEM generates instrument trigger primitives from combinations of tower subsys-
The time between a particle interaction in the LAT that causes an event trigger and the latching of the tracker discriminators is 2.3 to 2.4 $\mu$s, much of this delay due to the analog rise times in the tracker front-end electronics. Similarly, the latching of the analog sample-and-holds for the calorimeter and the ACD are delayed (programmable delay of $\sim 2.5 \mu s$) until the shaped analog signals peak.

The minimum instrumental dead time per event readout is 26.50 $\mu$s and is the time required to latch the trigger information in the Global-Trigger Electronics Module (GEM) and send it from the GEM to the Event Builder Module (EBM). The calorimeter readout can contribute to the dead time if the full four-range CAL readout is requested. During readout of any of the instrument, any TEM and the AEM (ADC Electronics Module) send a “busy” signal to the GEM. From these signals, the GEM then generates the overall dead time and the system records this information and adds it to the data stream transmitted to the ground.

Any of the TEMs can generate a trigger request in several ways: (i) If any tracker channel in the tracker module is over threshold, a trigger request is sent to the module’s TEM which then checks if a trigger condition is satisfied, typically requiring triggers from 3 $x, y$ planes in a row. If this condition is satisfied, the TEM sends a trigger request to the GEM. (ii) If a predetermined low-energy (CAL-LO) or high-energy (CAL-HI) threshold is exceeded for any crystal in the calorimeter module, a trigger request is sent to the GEM.
The prompt ACD signals sent to the GEM are of two types: (i) a discriminated signal (nominal 0.4 MIPs threshold) from each of the 97 scintillators (89 tiles and 8 ribbons) of the ACD, used to (potentially) veto tracker triggers originating in any one of the sixteen towers, and (ii) a high-level discriminated signal (nominal 20 MIPs threshold) generated by highly ionizing heavy nuclei cosmic-rays (carbon-nitrogen-oxygen or CNO). The high-level CNO signal is used as a trigger, mostly for energy calibration purposes. During ground testing the CNO signal is only tested through charge injection.

4.1.2 Instrument modeling

The development and validation of a detailed Monte Carlo simulation of the LAT’s response to signals (γ-rays) and backgrounds (cosmic-rays, albedo γ-rays, etc.) has been central to the design and optimization of the LAT. This approach was particularly important for showing that the LAT design could achieve the necessary rejection of backgrounds expected in the observatory’s orbit. The instrument simulation was also incorporated into an end-to-end simulation of data flow, starting with an astrophysical model of the γ-ray sky, used to support the pre-launch development of software tools to support scientific data analysis.

The instrument simulation consists of 3 parts: (i) particle generation and tracking uses standard particle physics simulators of particle interactions in matter to model the physical interactions of γ-rays and background particle fluxes incident on the LAT. In particular, the simulation of events in the LAT is based on the Geant4 (G4) Monte Carlo toolkit [201, 202], an object-oriented simulator of the passage of particles through matter. G4 provides a complete set of tools for detector modeling. In the LAT application, the simulation is managed by Gleam, our implementation of the Gaudi software framework [203], and so we use only a subset of the G4 tools. (ii) For a given simulated event the instrument response (digitization) is calculated parametrically based on the energy deposition and location in active detector volumes in the anticoincidence detector, tracker, and calorimeter. (iii) From the digitized instrument responses, a set of trigger primitives are computed and a facsimile of the Trigger and On-board Flight Software Filter is applied to the simulated data stream. Events that emerge from the instrument simulation (or real data) then undergo event reconstruction and classification (§4.2), followed by background rejection analysis (§4.2.3). As discussed in §4.2.3, the background rejection can be tuned depending on the analysis objectives.

G4 contains a full suite of particle interactions with matter, including multiple scattering and delta-ray production for charged particles, pair production and Compton scattering for photons, and bremsstrahlung for $e^-$ and $e^+$, and low-energy interaction with atoms, as well as several models of hadronic interactions. The set of processes implemented is controlled by a “physics list,” which allows for considerable flexibility. In fact, a special version of the model of multiple scattering is used to provide better agreement with our measured data.

Detector calibration data (thresholds, gains, non-uniformities, etc.) are used to convert the energy deposited in the active elements to instrument signals. For the tracker, dead channels are removed from the data at this stage, as well as any signals which would have overflowed the electronic buffers. (These same effects are taken into account again during
4.2 Event reconstruction and classification

The event reconstruction processes the raw data from the various subsystems, correlating and unifying them under a unique event hypothesis. The development of the reconstruction relies heavily on the Monte Carlo simulation of the events. In the following subsections, the basic blocks of the reconstruction are described. We start with track reconstruction, as it is key to developing the subsequent analysis of the other systems: the found tracks serve as guides as to what should be expected in both the calorimeter as well as the ACD for various event types. The analogous reconstruction processing for EGRET, a spark-chamber pair conversion telescope, which did not benefit from a detailed Monte Carlo model of the instrument, is described in [1].

4.2.1 Track reconstruction

Spatially adjacent hit tracker strips are grouped together, forming clusters, and the coordinates of these clusters are used in the track finding and fitting. Each cluster determines a precise location in $z$ as well as either $x$ or $y$. Because the planes of silicon detectors are arranged in closely spaced orthogonal pairs, both the $x$ and $y$ determinations can be made, albeit the choice of tracker technology (single-sided silicon strip detectors) imposes the ambiguities associated with projective coordinate readout on the initial pairing of the $x$ and $y$ coordinates when 2 or more particles pass through a detector plane. This ambiguity is resolved for tracks associated with particles that pass through more than one tracker module. For events with tracks confined to one module, the coordinate-pairing ambiguity is resolved for $\sim 90\%$ of these events using calorimeter information. Strictly, resolution of the coordinate-pairing ambiguity is only of secondary importance, having primarily to do with background rejection.

At the heart of track-finding algorithms is a mechanism to generate a track hypothesis. A track hypothesis is a trajectory (location and direction) that can be rejected or accepted based on its consistency with the sensor readouts. The generation algorithm is combinatoric, with a significant constraint imposed on the number of trial trajectories considered because of the available computing power. Two algorithms, described below, are used.

*Calorimeter-Seeded Pattern Recognition (CSPR):* For most of the LAT science analysis, some energy deposition in the calorimeter is required. When present, both the centroid and shower axis of the calorimeter energy deposition can be computed using a moments analysis (see §4.2.2) in most cases. The first and most-often selected algorithm is based on the assumption that the energy centroid lies on the trajectory. The first hit on the hypothesized track, composed of an $x, y$ pair from the layer in the tracker furthest from the calorimeter, is selected at random from the possible $x, y$ pairs. If a subsequent hit is found to be close to the line between the first hit and the location of the energy centroid in the calorimeter, a track hypothesis is generated. The candidate track is then populated with hits in the intervening layers using an adaptation of Kalman fitting (e.g.,[204]). The
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process starts from the first hit. A linear projection is made into the next layer. The covariance matrix is also propagated to the layer and provides an estimate of the error ellipse that is searched for a hit to add to the track. The propagation of the covariance matrix includes the complete details of the material crossed, thereby providing an accurate estimate of the error caused by multiple scattering. If a candidate hit exists in the layer, it is incorporated into the trajectory weighted by the covariance matrices. The procedure is then iterated for subsequent layers, allowing for missing hits in un-instrumented regions. Adding more hits to the track is terminated when more than a specified number of gaps (planes without hits associated with the track) have accumulated (nominally 2). The whole process is repeated, starting with each possible \( x, y \) pair in the furthest plane from the calorimeter and then continued using pairs from closer layers. After a track of sufficient quality is found and at least two layers have been looped over, the process is terminated.

A byproduct of this process is the first Kalman fit to the track, providing the \( \chi^2 \), the number of hits, the number of gaps, etc. From these quantities a track quality parameter is derived and used to order the candidate tracks from “best” to “worst”.

At high energies (\( >1 \text{ GeV} \)) the first-hit search is limited to a cone around the direction provided by the calorimeter moments analysis in order to minimize confusion with hits caused by secondary particles generated by backsplash. The cone angle is narrowed as the energy increases, reflecting the improved directional information provided by the calorimeter.

Following the completion of the CSPR, only the “best” track found is retained. The biasing caused by the track quality parameters makes this “the longest, straightest track” and hence, for \( \gamma \) conversions, preferentially the higher-energy track of the \( e^+e^- \) pair. The other tracks are discarded. The hits belonging to the best track are flagged as “used” and a second combinatoric algorithm is then invoked.

**Blind Search Pattern Recognition (BSPR):** In this algorithm, calorimeter information is not used for track finding. Events having essentially no energy deposition in the calorimeter are analyzed using this algorithm as well as for subsequent track finding following the stage detailed above. The same procedure described for the CSPR is used, but here the selection of the second hit used to make the initial trajectory is now done at random from the next closest layer to the calorimeter. The trajectory formed by these two hits is projected into the following layer and if a hit in that layer lies sufficiently close to the projection a trial track is generated. The mechanism of populating the track candidate with hits follows that used in the CSPR, but without any estimation of the energy of the track, the multiple scattering errors are set by assuming a minimum energy (default: 30 MeV). Hits are allowed to be shared between tracks if the hit is the first hit on the best track (two tracks forming a vertex) or if the cluster size (number of strips) is larger than expected for the track already assigned to that hit. The total number of tracks allowed to be found is limited (default: 10).

The final track fits must await an improved energy estimate to be made using the best track to aid in estimating the fraction of energy deposited in the calorimeter (see §4.2.2). Once this is done, the energy is apportioned between the first two tracks according to the amount of multiple scattering observed on each. A subsequent Kalman fit is done but without re-populating the tracks with hits.
The final stage of track reconstruction combines tracks into vertices. The process begins with the best track. The second track is selected by simply looping over the other tracks in the event. The distance of closest approach between the best track and the candidate second track is computed and if within a specified distance (default: 6 mm) a vertex solution is generated by covariantly combining the parameters of the two tracks. The $z$-axis location (coordinate along the instrument axis) of the vertex candidate is selected using the detailed topology of the first hits and is assigned either to be in the center of the preceding tungsten foil radiator, in the silicon detector itself, or within the core material of the tracker tray directly above the first hit. A quality parameter is created taking into account the $\chi^2$ for the combination of tracks, the distance of closest approach, etc. The first track is paired with the second track having the best quality parameter. These tracks are marked as “used” and the next unused track is selected and the process repeated. If a track fails to make a satisfactory vertex it is assigned to a vertex by itself. Thus all tracks are represented by a vertex.

In addition to the “standard” vertexing discussed above, an additional improvement is possible if calorimeter information is included. In events where either during the conversion process or immediately thereafter much of the energy is in $\gamma$-rays (due to Bremsstrahlung or radiative corrections), the charged tracks can point well away from the incident $\gamma$-ray direction. However the location of the conversion point is usually well determined and, when combined with the energy centroid location in the calorimeter, can give a fair estimate of the direction. The “best” track as well as the first vertex are combined covariantly with this direction using weights to apportion the total energy between these directions. These “neutral energy” solutions result in significantly reducing the non-gaussian tails of the PSF.

### 4.2.2 Energy reconstruction

Energy reconstruction begins by first applying the appropriate pedestals and gains to the raw digitized signals. Then, for each calorimeter crystal, the signals from the two ends are combined to provide the total energy in the crystal (independent of location) and the position along the crystal where the energy was deposited. The result is an array of energies and locations.

The three-dimensional calorimeter energy centroid is computed along with energy moments (similar to the moment of inertia, but with energy in place of mass). The shower direction is given by the eigenvector with the smallest eigenvalue. Initially, the overall energy is taken to be the sum of the crystal energies (“CALEnergyRaw” in Figure 4.9). Further improvements must await the completion of the fitted tracks.

The trajectory provided by the best track (or best track vertex when available) is used as input to estimate the energy correction necessary to account for leakage out the sides and back of the calorimeter and through the internal gaps between calorimeter modules. Three different algorithms are applied to each event: a parametric correction (PC) based on the barycenter of the shower, a fit to the shower profile (SP) taking into account the longitudinal and transverse development of the shower, and a maximum likelihood (LK) fit based on the correlations of the overall total energy deposited with the number of hits in the tracker and with the energy seen in the last layer. Because the SP method starts
to work beyond 1 GeV and the LK method works below 300 GeV, only the PC method covers the entire phase space of the LAT. Figure 4.9 shows the results of the LK method applied to data obtained with electron beams at CERN entering the LAT calibration unit at an angle of 45° to the detector vertical axis. The energy resolutions obtained vary between 4% at 5 GeV and 2% at 196 GeV.

At low energy (∼100 MeV), a significant fraction (∼50%) of the energy in a γ conversion event can be deposited in the tracker and hence the determination of this contribution to the total energy becomes important. For this purpose the tracker is considered to be a sampling calorimeter where the number of hit silicon strips in a tracker layer provides the estimate of the energy deposition at that depth. The total number of hits in the thin radiator section, the thick radiator section and the non-radiator last layers is computed within a cone with an opening angle which decreases as $E^{-1/2}$, where $E$ is the apparent energy in the calorimeter. The “tracker” energy is added to the corrected calorimeter energy.

Because the PC method gives an energy estimate for all events, it is used to iterate the Kalman track fits as mentioned in §4.2.1.

### 4.2.3 Background rejection

The vast majority of instrument triggers and subsequently downlinked data are background events caused by charged particles as well as earth albedo γ-rays. The task of the hardware trigger is to minimize their effects on the instrumental deadtime associated with reading out the LAT. Subsequently the task of the onboard filter is to eliminate a sufficient number of background events without sacrificing celestial γ-ray events such that the resulting data can be transmitted to the ground within the available bandwidth. The final task is for the analysis on the ground to distinguish between background events and γ-ray events and minimize the impact of backgrounds on γ-ray science. The combination of these 3 elements reduces the background by a factor of almost $10^6$ while preserving efficiency for γ-rays exceeding 75%. For reference, the average cosmic γ-ray event rate in the LAT is ∼2 Hz.

### Background model

In order to facilitate the development of the on-board triggering and filtering and subsequent event reconstruction and classification algorithms, a model of the background the LAT encounters in space has been developed.

As shown in Table 4.2, the background model includes cosmic rays and earth albedo γ-rays within the energy range 10 MeV to $10^6$ MeV. Any particles that might either make non-astrophysical γ-rays and/or need to be rejected as background are included. The model does not include X-rays or soft γ-rays that might cause individual detectors within the LAT to be activated. The model is meant to be valid outside the radiation belts and the South Atlantic Anomaly (SAA); no particle fluxes from inside the radiation belts are included. The boundaries of the belts are defined to be where the flux of trapped particles is 1 proton cm$^{-2}$ s$^{-1}$ (E > 10 MeV). LAT does not take data inside the SAA. The fraction of time spent in the SAA is 14.6%.
4.2 Event reconstruction and classification

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<td>Galactic Cosmic Rays</td>
<td>protons + antiprotons</td>
<td>AMS</td>
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</table>

Table 4.2: Data sources for background model: AMS: [205]; Nina: [206]; Mariya: [207], [208]; EGRET: [89]; HEAO-3: [209]; neutrons: [210]

The AMS [205] and BESS [211] experiments provided important and accurate new measurements of the spectra of the protons and alpha particles, the most abundant of the various galactic cosmic-ray (GCR) components. AMS made detailed latitude-dependent measurements of the splash and reentrant albedo particles (\(e^+, e^-\) and protons) in the energy range from \(\sim 150–200\) MeV up to the cutoff energies where the earth albedo components become lost in the much greater GCR fluxes. These fluxes will be updated with results from the Pamela satellite [212].

For albedo fluxes of particles with energies below \(\sim 150\) MeV, inaccessible to the AMS and other large instruments, measurements made by NINA and NINA-2 and a series of Russian satellite experiments with an instrument known as Mariya are used. The albedo γ-ray fluxes are taken from a reanalysis of the data collected by EGRET when the CGRO satellite was pointed at the Earth.

The model is based on empirical fits to the referenced data. No time variability is included. The GCR fluxes are taken to be the same as those observed near solar minimum (maximum GCR intensities). The albedo fluxes may vary with time and be correlated with the GCR fluxes. The fluxes as observed by the NINA and Mariya experiments are used without correcting them for solar cycle variations. While an East-West cutoff variation was included that affects galactic cosmic ray components, all fluxes except albedo protons are assumed to be isotropic. The measurements are not complete enough for us to be able to account for variation in parameters such as the zenith angle of the particles or their pitch angles with respect to the local field. We have attempted to model some the zenith
angle dependence for albedo protons, based not on measurements, but on modeling of the albedo [213]. Further verification and improvement to the model are being done on orbit.

The orbit averaged background fluxes in the model are shown in Figure 4.12. For charged particles, these fluxes are integrated over solid angle. It is straightforward to obtain fluxes per unit solid angle. For galactic cosmic ray components, divide by 8.7 sr, the solid angle of the visible sky that is not blocked by the Earth at Fermi’s orbital altitude. For the albedo components we have taken the reentrant and albedo fluxes to be the same.

2.3.0.0 Event classification and background rejection

After track reconstruction, vertexing, and energy reconstruction, the events are analyzed to determine the accuracy of the energy determinations, the directional accuracy, and whether they are γ-rays.

All of the estimates are based on classification tree (CT) generated probabilities. This statistical tool was found to give the highest efficiency with the greatest purity, exceeding that which we obtained with either a more traditional cut-based analysis or with neural nets. Our usage of classification trees involves training a modest number of trees (a few
to $\sim 10$) and averaging over the results. The trees are “grown” by minimizing “entropy” as defined in statistics [214].

The final energy estimate for each event is made by first dividing the sample up into subsets according to which energy methods were reporting results (PC+LF+SP, PC+LF, PC+SP, and PC). When more than one energy method is available, the method selected is determined using a CT. The subsets are then merged, now with a single “best” energy and a probability “knob” that can be used to lessen the presence of tails (both high and low) in the distribution of reconstructed energies at the expense of effective area.

The analysis sorts the events according to where they occurred in the LAT tracker. (Events in the thick radiator portion have about a factor of 2 worse angular resolution due to increased multiple scattering.) When there is sufficient energy in the calorimeter (default: $>10$ MeV), the neutral energy solutions are used. If a 2-track vertex is present, a CT determines whether the vertex derived direction or the best track direction is used.

The background rejection is by far the most challenging of all the reconstruction analysis tasks. This is due to the large phase space covered by the LAT and the very low signal-to-noise ratio in the incoming data ($\sim 1:300$ for down-linked data). The first task is to eliminate the vast majority of the charged particle flux that enters within the FoV using the ACD in conjunction with the found tracks. One cannot simply demand that there are no triggers from the ACD because high-energy $\gamma$-rays generate a considerable amount of back splash, from the shower that develops in the calorimeter, in the form of hard X-rays that can trigger several ACD tiles. Consequently only the tiles pointed at by the reconstructed tracks are used to establish a veto by the presence of a signal in excess of $\sim 1/4$ of a minimum ionization event. Because the accuracy of the pointing is energy dependent due to multiple scattering, at low energy, only tiles within the vicinity of the track intersection with the ACD are used, while at high energy the region is restricted to essentially the one tile being pointed to.

The considerations for rejecting backgrounds involve the detailed topology of the events within the tracker and the overall match of the shower profile in 3D in both the tracker and the calorimeter. The tracker provides a clear picture of the initial event topology. For example the identification of a 2-track vertex immediately reduces the background contamination by about an order of magnitude. However a majority of events above 1 GeV don’t contain such a recognizable vertex due to the small opening angle of the $e^+e^-$ pair along the incoming $\gamma$-ray direction. The observation of a significant number of extra hits in close proximity to the track(s) indicates they are electrons and hence from the conversion of a $\gamma$-ray while the presence of unassociated hits or tracks are a strong indicator of background. These as well as other considerations are used for training background rejection CTs.

The final discriminator of background is the identification of an electromagnetic shower. Considerations such as how well the tracker solution points to the calorimeter centroid, how well the directional information from the calorimeter matches that of the track found in the tracker, as well as the width and longitudinal shower profile in the various layers of the calorimeter, are important in discrimination of backgrounds. Again the information from the reconstruction is used to train CTs and the resulting probability is used to eliminate backgrounds.

The broad range of LAT observations and analysis, from GRBs to extended diffuse
Table 4.3 lists 3 analysis classes that have been defined based on the backgrounds expected in orbit, current knowledge of the γ-ray sky, and the performance of the LAT. Our estimates of LAT performance are given in terms of these analysis classes. Common to all of these analysis classes is the rejection of the charged-particle backgrounds entering within the field of view. The classes are differentiated by an increasingly tighter requirement that the candidate photon events in both the tracker and the calorimeter behave as expected for γ-ray induced electromagnetic showers. The loosest cuts apply to the Transient class, for which the background rejection was set to allow a background rate of <2 Hz, estimated using the background model described in §4.2.3, which would result in no more than one background event every 5 sec inside a 10° radius about a source. The Source class was designed so that the residual background contamination was similar to that expected from the extragalactic γ-ray background flux over the entire field of view. Finally, the Diffuse class has the best background rejection and was designed such that harsher cuts would not significantly improve the signal to noise. The various analysis cuts and event selections will be optimized for the conditions found on-orbit during the 1st year all-sky survey phase. Note that these 3 analysis classes are hierarchical; that is all events in the Diffuse class are contained in the Source class and all events in the Source class are in the Transient class.
4.3 LAT calibration: the beam test program

The GEANT4 model is used to study reconstruction algorithms (including event filtering for background rejection both on-board and off-line) and instrument response functions (IRF) like angular and energy resolution and effective area. It is indeed not feasible to scan the whole space phase of the LAT in terms of angle, position and energy with a $\gamma$-ray beam provided by an accelerator facility. However an experimental characterization of the instrument must be performed to verify that the response of the actual instrument matches the simulation prediction. It is important to reach a good reproducibility of both directly measured quantities (energy deposit, hit multiplicity) and high-level analysis (reconstructed energy and direction). Moreover, a direct measurement of the IRF is required for some critical configurations, in particular with low energy photons. For all these reasons a small fraction of the LAT hardware was assembled in the so called Calibration Unit (CU) and a beam test campaign was carried out using the CERN beam lines at PS and SPS in summer 2006 [196].

4.3.1 The calibration unit

The CU is made with spare and flight-like hardware of the LAT, assembled in a $1 \times 4$ grid and placed horizontally on a remotely controlled motion stage, used to vary the beam angle and impact point. The CU is composed of two tracker modules and three calorimeter modules. Since the flight hardware must be kept in a clean and dry atmosphere, the CU was protected by an aluminum container that can be flushed with nitrogen and liquid.
cooled. All the electronic equipment, with the obvious exception of the front-end boards and the tower control modules (the TEM see §4.1.1), was placed outside the container. Five anticoincidence tiles were placed around the container to study shower backsplash.

The CU used the same control system of the LAT. All the front-end boards successfully completed the space qualification tests while the remaining electronics was flight-like. Several computers shared a local network with a central server. This machine had the role of locally storing the raw data, save beam and moving table information in a database, send events to other machines for event display and online monitoring, send data to a remote site for storage and complete automatic processing: events are reconstructed at SLAC and ready for analysis a few hours after the end of the run.

4.3.2 The CERN campaign

The T9 line at CERN PS was used in August 2006 for about 15 days of data collection. The line provides a mixed beam of energy from 0.5 up to 15 GeV. Particle identification was done with a Cherenkov detector (part of the T9 line) and a coincidence of scintillator tiles was used as trigger. The run program for the PS campaign included:

- electrons from 1 to 5 GeV: to provide a direct energy calibration of the calorimeter and to validate the electromagnetic interaction model in the simulation;
- protons at 6 and 10 GeV: to validate the low energy hadronic interaction models;
- tagged photons from 0.5 to 2.5 GeV of primary electron beam: for a direct measurement of angular response and energy resolution of the instrument;
- non tagged photons (primary beam energy 2.5 GeV): to verify the simulation of photon interactions and collect events with a higher rate, taking advantage of the full bremsstrahlung spectrum.

The photons in the T9 line were produced by bremsstrahlung of the electron beam. The photon energy was evaluated by measuring the electron momentum with a magnetic spectrometer (the tagger). Such a device was set up with the magnet in the T9 area and four SSD based tracking devices (for the two spectrometer arms) in a configuration already used by AGILE. A detailed description of the tagger detectors and their configuration can be found in [215]. The data from the tagger were synchronized and merged online with the CU data resulting in a more reliable monitoring of the beam and the instrument. In fact it was possible to correlate quantities regarding the CU, the beam and the tagger online. In September 2006 the CU was moved to the H4 beam line at the CERN SPS that provides particles with energy up to 400 GeV. The run program at SPS was mainly composed of:

- electrons from 10 to 280 GeV: to validate the electromagnetic interaction model in the simulation and improve the high energy reconstruction algorithm;
- hadrons from 20 to 150 GeV: to validate the high energy hadronic interaction models.
4.4 On flight calibration

On-orbit calibrations relate to all aspects of LAT measurements and data analysis results, from absolute timing to energy and direction measurements for individual events, to fluxes and positions of gamma-ray sources.

The accurate timestamps of the LAT are obtained using the Global Positioning System (GPS) of the Fermi spacecraft, which provides timing and position information. Those are needed for phase folding pulsars and correlating $\gamma$-ray observations with those at other wavelengths.

Source localization at GeV energies enables the LAT to resolve bright, adjacent sources previously labeled as unidentified and will help elucidate the origin of gamma-ray emissions from galactic cosmic rays accelerated in supernova remnants.

Operationally, calibration data are acquired in two distinct modes:

1. Dedicated, meaning that the trigger, detector and software filter settings are incompatible with nominal science data taking.

2. Continuous, meaning the trigger and software can, with only a small penalty in live time, acquire specialized data that is used to calibrate, or, more generally, monitor the performance of the LAT during nominal science data-taking.

Within a run the LAT acquires data with fixed instrument configurations. For the most part, the dedicated calibration runs are concerned with characterizing the electronics’ response to known stimuli while the continuous calibrations are aimed at calibrating the electronics with a known physics input. The stability of calibrations has been such that operations in dedicated-mode amount to approximately 2.5 hours every three months.

Sea-level cosmic ray muons were used to calibrate the low-energy scales and trigger thresholds. Instead, charge injection into the front-end electronics was used to calibrate the high-energy scales. Because of rise-time slewing effects, the optimal synchronization of trigger signals and optimal delays for data latching are energy dependent. Pre-launch tests was used to provide a best approximation of the optimal trigger timing, and verified and corrected the synchronization and delays with on-orbit data.

The on-orbit calibrations include synchronization of trigger signals, optimization of delays for latching data, determination of detector thresholds, gains and responses, evaluation of the perimeter of the South Atlantic Anomaly (SAA), measurements of live time and of absolute time and internal and spacecraft boresight alignments. Some results summarized in Table 4.4 were obtained using known astrophysical sources, galactic cosmic rays, and charge injection. There were only minor changes to calibration constants since launch and these quantities have been stable during the first eight months of operations.

4.4.1 Determination of SAA polygon

The orbit of Fermi intersects the Earth’s inner radiation belt in a region which is known as the South Atlantic Anomaly (SAA). This region features geomagnetically trapped protons with energies up to hundreds of MeV and electrons with energies up to tens of MeV. The flux of protons and electrons in the LAT energy range reach levels which are several orders
The Fermi LAT Instruments

<table>
<thead>
<tr>
<th>Category</th>
<th>Title</th>
<th>Summary</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trigger</td>
<td>Time coincidence window</td>
<td>700 ns, settings within 50 ns</td>
</tr>
<tr>
<td>ACD</td>
<td>Pedestal</td>
<td>width &lt;4 digital counts or &lt; 0.01 MIP</td>
</tr>
<tr>
<td>ACD</td>
<td>Coherent noise</td>
<td>removed down to 0.005 MIP</td>
</tr>
<tr>
<td>ACD</td>
<td>MIP peak</td>
<td>stability &lt;10%</td>
</tr>
<tr>
<td>ACD</td>
<td>High range (CNO)</td>
<td>width of carbon peak~20% of peak</td>
</tr>
<tr>
<td>ACD</td>
<td>Veto threshold</td>
<td>turn-on at 0.4-0.5 MIP, set within ± 0.01 MIP</td>
</tr>
<tr>
<td>CAL</td>
<td>Pedestal</td>
<td>RMS within 0.1-0.2 MeV</td>
</tr>
<tr>
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<td>Electronics linearity</td>
<td>corrected to ≤1% of the measured energy</td>
</tr>
<tr>
<td>CAL</td>
<td>Energy scales</td>
<td>spread crystal-to-crystal ≤1%</td>
</tr>
<tr>
<td>CAL</td>
<td>Light asymmetry</td>
<td>2 mm (low energy), 9 mm (high energy) from 200-900 MeV</td>
</tr>
<tr>
<td>CAL</td>
<td>Zero-suppression threshold</td>
<td>set at 2 MeV, ~ 10 x electronics noise</td>
</tr>
<tr>
<td>CAL</td>
<td>Low-energy threshold</td>
<td>set at 100 MeV (± 1%)</td>
</tr>
<tr>
<td>CAL</td>
<td>High-energy threshold</td>
<td>set at 1 GeV (± 2%)</td>
</tr>
<tr>
<td>TKR</td>
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<td>avg strip occ. (10^{-5}), add ≤10% to the TKR data</td>
</tr>
<tr>
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<td>Trigger threshold</td>
<td>set at <del>0.28 MIP, spread channel-to-channel</del>5%</td>
</tr>
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<td>TKR</td>
<td>TeT conversion parameters</td>
<td>fitted to ~8% (statistical error)</td>
</tr>
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<td>TKR</td>
<td>MIP scale</td>
<td>RMS of correction factor (9%)</td>
</tr>
<tr>
<td>SAA</td>
<td>SAA polygon</td>
<td>in SAA for~13% of the orbit time</td>
</tr>
<tr>
<td>Timing</td>
<td>LAT timestamps</td>
<td>&lt; 0.3 μs with respect to a reference GPS</td>
</tr>
</tbody>
</table>

Table 4.4: Summary of the on-orbit Fermi LAT calibrations.
of magnitudes above those of primary cosmic rays. This extreme particle flux imposes constraints on LAT operations. The TKR electronics saturate due to the increase in the charge deposited per live time, leading to large dead time fractions, thereby hampering scientific observations. The continuous influx of particles generates high currents in the ACD photomultiplier tubes (PMT), thus exceeding safe operating limits, which leads to slow deterioration. Therefore, during SAA passages, triggering, recording and transmission of science data are stopped and the bias voltages of the PMTs are lowered from 900V to \(\sim\)400V. Only LAT housekeeping data are recorded and transmitted to the ground.

The position along the orbit defined by the GPS receiver aboard the Fermi spacecraft determines the transition between nominal science operations and the SAA transit mode. The latitude and longitude of the Fermi position are compared to the bounds of a polygon defined by 12 latitude-longitude vertices stored in the spacecraft memory. As the spacecraft position crosses this polygonal boundary it triggers the SAA transit mode. To avoid multiple entries and exits during a single orbit, a convex polygon is used to define the SAA region.

A conservative definition was chosen for this initial SAA boundary, with the expectation that the boundary based on particle rate measurements made with the LAT once it was on orbit would be updated.

After launch, diagnostic data of the LAT were used to refine the size of the polygon. Even though science triggers are disabled during SAA passages, fast trigger signals remain operational. Special TKR and ACD counters can sample the rate of fast trigger signals to determine position-dependent rates of the LAT along the orbit.

### 4.4.2 Live time

The live time is accumulated taking into account the variety of dead time effects. Science data taking is disabled during SAA passages (see Section 4.4.1). Instrumental dead time, during event latching and readout, is about 8% on average outside the SAA, although this fraction depends on the trigger rate (primarily background). The dependence on the geomagnetic latitude of Fermi is secondary. Other losses are caused by failures in transmission and ground processing and dedicated-mode calibrations.

Accurate accounting for live time is essential for obtaining calibrated fluxes and spectra for astrophysical sources of gamma rays. The live time relates the effective collecting area of the LAT to the overall exposure. Owing to the very large field of view of the LAT (>2 sr) and the relatively slow scanning rate (\(\sim\)4 deg min\(^{-1}\)) the accumulated live time typically is needed only coarsely (\(\sim\)30 s intervals) for accurate exposures to be calculated. For very bright transient sources, finer accounting for live time is used, owing to the high and variable rates of triggers. For example, a bright GRB in the field of view of the LAT, such as GRB080916C [107], can induce a dead time fraction of about 16% during the impulsive phase of the burst.

Every time the LAT triggers, further data taking is disabled until the data from the event are read out. After the end of the time coincidence window the latency of the trigger system is 100 ns before the new time coincidence window is available, even if the previous event was not read out. Single front-end electronic channels can be dead for several microseconds while the pulse is above threshold.
4.4.3 Overall timing accuracy

Recording accurate arrival times of LAT photons is essential for studies of gamma-ray bursts and pulsar timing. Absolute timing tests were performed during pre- and post-launch activities. A discussion of LAT pulsar timing can be found elsewhere [216].

During pre-launch tests we recorded cosmic rays to measure the time difference between two GPS systems. The coincidence signal from these tiles triggered a VME-based GPS time system previously used by the ground γ-ray telescope CELESTE. Its absolute time accuracy was previously demonstrated by measuring the Crab optical pulsar [217]. Reconstructed muon tracks traversing the LAT detector were extrapolated to their impact point on the laboratory floor and their timestamps were measured with respect to the GPS of the Fermi satellite. If a muon passed through the pair of scintillators placed next to Fermi, a GPS timestamp from a standalone VME data acquisition system was also recorded. The LAT timestamps agreed with the reference GPS to within 0.3 μs.

4.5 Performance of the LAT

The performance of the LAT is basically determined by the design of the LAT hardware, the event reconstruction algorithms (i.e., the accuracy and efficiency with which the low-level event information is used to determine energy and direction), and event selection algorithms (i.e., the efficiency for identifying well reconstructed γ-ray events).

Figures 4.14 – 4.17 summarize the performance of the LAT. The performance parameters are subject to change as event selection algorithms are further optimized, particularly during the early part of on-orbit operations of Fermi. For the most up-to-date performance parameters go to http://www-glast.slac.stanford.edu/software/IS/glast_lat_performance.htm.

Figure 4.14 shows the on-axis effective area versus energy for each of the analysis classes defined in Table 4.3. Contributions from conversions in both the thin and thick sections of the tracker are included, with each contributing about 50% of the effective area. Note that the peak effective area, near 3 GeV, is nearly the same for all 3 analysis classes, while at energies below 300 MeV the effective area for the transient class is a factor of ∼1.5 larger than the for the diffuse class. Figure 4.15 shows the effective area for the source class on-axis and at 60° off-axis.

Figure 4.16 shows the energy dependence of the 68% containment radius (space angle) for γ-ray conversions in the thin section of the tracker that are incident either on-axis or at 60° off-axis for the source class. The PSF for γ-rays converting in the thick section of the tracker is about twice as wide.

Figure 4.17 shows the energy resolution of the LAT versus energy for the source class. With a diffuse γ-ray background model based on EGRET observations and the instrument performance summarized above, the source sensitivity of the LAT can be estimated. The source sensitivity of course depends not only on the flux of the source but it also depends on the spectrum of the source.
4.5 Performance of the LAT

Figure 4.14: Effective area versus energy at normal incidence for Diffuse (dashed curve), Source (solid curve), and Transient (dotted curve) analysis classes.

Figure 4.15: Effective area versus energy at normal incidence (solid curve) and at 60° off-axis (dashed curve) for Source analysis class.

Figure 4.16: 68% containment radius versus energy at normal incidence (solid curve) and at 60° off-axis (dashed curve) for conversions in the thin section of the tracker.
Figure 4.17: Energy resolution versus energy for normal incidence (solid curve) and at 60° off-axis (dashed curve).
Chapter 5

Upper Limit Statistical Method

Many GRBs happened inside the field of view of both AGILE and LAT, but were not detected by these instruments. To understand the GRB emission mechanisms, also a non-detection could be useful particularly to constrain the upper band of the GRB spectrum. In this chapter a method to compute upper limits will be discussed.

In the astrophysics community there are two common errors when an upper limit on the source flux is provided [218]. The first one, and the more common, is to confuse the sensitivity with the upper limit on the source flux. The $3\sigma$ fluctuation from the mean value of the background counts is taken as the count upper limit. Or if the background is thought to follow a Poisson distribution the upper limit is computed as the poissonian fluctuation from the background mean. This method does not take into account the presence of the source and its fluctuations so it could not be a good estimation of the source flux. The second method used is to subtract the number of the expected background counts $B$ from the received number of counts $N$. The counts from the source are then $N' = N - B$. This method fails to consider the Poisson fluctuation on the background counts.

More recently a method was implemented to taking into account both the source and the background counts and their Poisson fluctuation [219]. In this chapter is described an upper limit computational method which starts from the calculation of a Neyman confidence belt [220] for a signal $S$ given a number of counts $N$ and a number of expected background counts $B$. An extension of this paper include in the computation also the systematic error on the background expected counts [221]. This method proposed by Feldman and Cousins was widely used to provide upper limits values, but a study from Helene [222] shows that the coverage (the percentage of the times that the estimated upper limit lies above the true flux) of this method is not the chosen one: the upper limit is underestimated respect to the confidence level one wish to joint (see chapter §7 for the comparison of these two methods).

After the sieve of all these methods a Bayesian method was chosen: it was proposed from Helene in [223] and [5]. This Bayesian method was selected, instead of the frequentist one (Feldman & Cousins), because of the studies on the coverage and because in the frequentist approach the physical limits of the flux are irrelevant [224] (for example a source flux could be negative in the computation but then the lower limit of the interval is placed on the lower physical bound), while this physical information is used in the Helene calculation.
5.1 The Helene method

If $S$ is the mean counts received from a source in the observation time $t_{ob}$ and $N$ the photons detected in the same time interval, $N$ follow the Poisson distribution:

$$P(N) = e^{-S}S^N/N!.$$  \hfill (5.1)

In the case that on top of the source photons there is an average background $B$, the new Poisson distribution is:

$$P(N) = \sum_{N_s,N_b} \frac{e^{-S}S^{N_s}e^{-B}B^{N_b}}{N_s!N_b!} = \frac{e^{-(S+B)(S+B)^N}}{N!} \hfill (5.2)$$

with $N_b$ and $N_s$ counts from background and source respectively and, as before, $S$ and $B$ are the mean counts in the time interval $t_{ob}$. In the case of the analysis presented in chapter §6 the mean of background counts $B$ is assumed known to a high degree of precision and its error is negligible. For this purpose the background is sampled in an off-source time interval at least ten times longer than $t_{ob}$.

From the Bayes theorem the posterior probability for the parameter $S$ as a function of the observables $N$ and $B$ is:

$$f_{N,B}(S) \propto p(S)P_S(N).$$  \hfill (5.3)

$P_S(N)$ is, in this case, the Poisson distribution (5.2) for $S + B$. The function $p(S)$ is the, so called, prior that contains all the prior knowledge on $S$ one wants to put into the estimate.

The subjective information the prior is not always accepted by the physicists because the final evaluated probability is thought not objective. In the Helene method the prior contains the only physical bound of nonnegative flux from the source. In this case the prior probability distribution function is a constant defined in $[0, +\infty]$ that means that all the fluxes in the definition range have the same probability. As shown in fig. 5.1 the result depends weakly from this prior information and that other priors that disfavour large received counts give similar upper limits. In fig. 5.1 the constant prior (a) is compared with other two priors, one of those (b) is an exponential prior ($e^{-\lambda S}$ with $\lambda = 0.005$) while the other (c) is a Lorentzian prior ($((\lambda^2 + S^2)^{-1}$ with $\lambda = 20$).

The posterior probability in the Helene method is:

$$f_{N,B}(S) = Ce^{-(S+B)(S+B)^N}/N! \hfill (5.4)$$

where $C$ is the constant that contains the prior constant and the normalization of the Poisson distribution of $S + B$ respect to $S$:

$$C = \left[ \int_{0}^{\infty} dSe^{-(S+B)(S+B)^N}/N! \right]^{-1} = \left( \sum_{n=0}^{N} e^{-B}B^n/n! \right)^{-1} \hfill (5.5)$$
5.1 The Helene method

Figure 5.1: In [218] a study on the influence of the chosen prior on the upper limit value is presented. Because a constant prior is though to be not realistic a comparison is done between the upper limits resulting with other priors that do not extend to infinity. The resulting upper limit on the source as a function of the detected counts is shown in the plot: the tree curves refers to (a) a constant prior, (b) an exponential prior ($e^{-\lambda S}$ with $\lambda = 0.005$) and (c) a Lorentzian prior ($((\lambda^2 + S^2)^{-1}$ with $\lambda = 20$).

Eqq. (5.2) and (5.4) reflect the difference among the frequentist and the Bayesian approach. In fact eq. (5.2) describes the probability to have $N$ counts given $S$ and $B$ (frequentist approach). While the eq. (5.4) gives the probability for a source to have a flux $S$ given $B$ and the observed $N$ counts (Bayesian approach).

The definition of the confidence level is now simply the integral of $f_{N,B}(S)$ in the interval $[S_{\text{min}}, S_{\text{max}}]$:

$$\int_{S_{\text{min}}}^{S_{\text{max}}} dS f_{N,B}(S) = CL.$$ (5.6)

The interval $S_{\text{max}} - S_{\text{min}}$ is minimized for a given confidence level as showed in [218]. This mean that among all the intervals that covers the 95% of the total probability function the integral 5.6 is the smallest one.

The confidence interval defined in eq. 5.6 can be obtained numerically integrating in both directions from the most probable value of eq. 5.4 and always choosing to sum the side with the higher probability until the wanted confidence level is reached as fig 5.2 shows. If the lower limit of this interval is 0 the source flux is compatible with 0 and an upper limit is provided otherwise the source is detected with the desired confidence level. For example if the background expected counts are 4 there is a detection at 95% confidence level with at least 9 received counts.
Figure 5.2: The minimal 95% confidence interval for $S$ if $N = 6$ and $B = 0$ is the shaded region in the posterior distribution function of $S$. See [218].

This method was implemented in a C++ program to use it in any case and with any number of counts. Before adopting it for the real analysis the code was tested for $N$ that ranges from 0 to 9 and for each $N$ the $B$ counts vary from 0.0 to 10.0. The result of the test, in the case of 95% of confidence level required, are shown in tab. 5.1: in each row the lower limit and the upper limit are listed. Similar tables were compiled for the cases of 68% and 99.7% confidence level required. All these tables were compared with the tables in [218].
Table 5.1: Test table for the C++ implemented Helene method in the case of 95% required confidence level.
Chapter 6

Analysis and results from AGILE

After two years of operations three GRBs were detected by AGILE-GRID: 080514B [225], 090401B [135] and 090510 [226]. This is contrast with the rough expectation of 1 GRB/month that AGILE could have detected in one year of operation, based on the previous EGRET detections [227]. The prelaunch expectations for AGILE were derived using the ratio of the field of view of EGRET and AGILE/GRID and estimating simply that since EGRET detected almost 1 GRB per year then AGILE/GRID should have detected almost 1 GRB per month[227]. The AGILE results show that this rate was not correctly estimated. To provide a better estimation, the BATSE detected rate and the ratio of the EGRET and BATSE fields of view were considered: EGRET detected only 1 GRB out of 10 in its field of view. In the AGILE sample, there are respectively 25 and 35 GRB per year in the two years of the AGILE mission and since AGILE detected with high significance three of them, there is a small disagreement with the rate of 1/10 in its field of view that it should have detected. Moreover the vast majority of the GRB occurred in the AGILE field of view were triggered by Swift/BAT with lower peak flux and softer spectrum. Fermi/LAT is detecting almost a similar fraction of high energy GRB (see chapter §7).

6.1 Selected Sample

The studied GRBs in this analysis were selected based on these two simple criteria, location of the GRB in the Field of view, distance of the GRB from the Earth center greater than 80° to avoid earth occultation of the detected events.

The list of all GRB is shown in table 6.1, with the corresponding GCN reporting the trigger and location and/or the GRB spectral information. The table reports also the GCN issued already by AGILE/GRID reporting the results of the quick look analysis.
### Analysis and results from AGILE

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<tr>
<th>Name</th>
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<th>DEC</th>
<th>Theta</th>
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<th>Spectral Info</th>
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</table>
6.2 Background evaluation and Upper Limit calculation

In the upper limit evaluation, the most crucial important analysis is the background evaluation. A precise background investigation is important to predict, with a good precision, the estimated counts mean value $B$ in the observation time $t_{ob}$.

To calculate the background rate correctly some requirements were made (see fig. 6.1 green distribution), first of all the satellite on-flight and data-taken parameters have to be in the correct range (i.e. GPS information, star sensor and pointing information), and the chosen event must be completely reconstructed from the off-line software for the reconstruction and filtering (in the fig.6.1 all the events discarded are in the distributions light blue and red). All the background studies were made before the GRB trigger, to avoid the contamination of the background data with signal data, in fact it is ignored for how long lasts the GRB emission in this energy range. Besides the spatial region of the GRB search is selected: 15 deg of radius from the GRB position (grey distribution in fig 6.1). More than the orbit, the AGILE data are modeled by the earth occultation and the passage through the SAA phase (see green distribution in fig. 6.1), both these situations were excluded in the background sampling (in the fig. 6.1 the time intervals when the signal region is occulted by the earth are indicated with the blue bars on the bottom). The last condition, for the requirement that the mean $B$ must have negligible error, is the time interval, where the background rate is calculated, is asked to be at least ten time longer than the $t_{ob}$. Moreover the interval is selected to be the nearest to the trigger time with these characteristics.

The research of the signal has similar requirements: the selected events must be com-

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<th>Duration</th>
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<th>Counts Mean</th>
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Table 6.1: Information on the sample selected for the upper limit calculation. The spectral information are provided by Konus/WIND (KW) Wide-band All-sky Monitor (WAM) on board of the Suzaku satellite, Gamma-Ray Burst Monitor (GBM) on board of the Fermi satellite and Burst Alert Telescope (BAT) on board of the Swift satellite.
Figure 6.1: The selection of events (as explained in the text) to model the background expectation in the signal region.

The table 6.2 shows the results from the application of the Helene method to the GRBs analyzed. The confidence level of the upper limit given in counts and in flux is 99.7% (corresponding to a 3 Gaussian σ).

From the count upper limit to a flux upper limit the AGILE effective area is introduced. This area is measured on-flight from a known flux: the Vela spectrum from 35 MeV to 20 GeV is divided into 15 energy bins and for each bin the received photons are divided for the relative Vela flux to obtain the instrument effective area in that energy range.
6.2 Background evaluation and Upper Limit calculation

Figure 6.2: The count map of the selected signal region of 15 deg in the case of the GRB090410 (colored squares) in its T90=150s. To see if there are features in the background spatial distribution also the background events are plotted (black dots).

Figure 6.3: Lightcurve in T90 interval of GRB090410. The vertical blue line is the time of the trigger, while the horizontal blue line indicates the expected background counts. The times are referred to the trigger time.
The total effective area must be calculated convolving the spectrum with different areas. The source spectrum is used to weight the areas with the photons that the instrument could receive from the source. If the GRB spectrum is $E^{-2.5}$ the total effective area is:

$$A_{GRB} = \frac{\sum_i A_{Vela} E_i^{-2.5} \Delta E_i}{\sum_i E_i^{-2.5} \Delta E_i}$$  \hspace{1cm} (6.1)$$

where $E_i$ is the mean energy in each interval where the effective area is measured, and the $\Delta E_i$ is the width of the energy bin. The flux is then corrected for the occulted fraction of the region.

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6.3 Analysis of GRB with spectral information

For those GRB with available public spectral information, a comparison of the estimated upper limit with the estimated flux in the AGILE/GRID band was performed (as shown in fig.6.4 for GRB090410) and listed in table 6.3. For the GRB with exponential cutoff spectral shape, the derivation of the upper limit was done using a tentative high energy power law value of -2.5. From the public GCN the value of the spectrum normalization

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Table 6.2: Upper limits table. The spectral index assumed is -2.5 and the energy range is 30 MeV - 3 GeV

6.3 Analysis of GRB with spectral information

For those GRB with available public spectral information, a comparison of the estimated upper limit with the estimated flux in the AGILE/GRID band was performed (as shown in fig.6.4 for GRB090410) and listed in table 6.3. For the GRB with exponential cutoff spectral shape, the derivation of the upper limit was done using a tentative high energy power law value of -2.5. From the public GCN the value of the spectrum normalization
was calculated and then the flux extrapolated up to the GRID band of 30 MeV - 3 GeV. Figure 6.4 shows spectrum for the GRB090410, the extrapolated flux value is indicated with the blue horizontal line, while the estimated upper limit is the horizontal red line; similar behavior is present in most of the GRBs. In two cases 090219 and 090904B the upper limit is lower than the expected flux. But in the first case the spectrum measured by the Fermi/GBM was fitted with a power low and there should be a cut off at energies >1 MeV. Instead in the second case the upper limit is not far from the extrapolated, from a band function, flux and there could be a cut off at some energy. Or the spectrum was not enough well measured to be fitted, indeed not a unique spectral fit function was proposed for this burst: both a band and a power law with an exponential high energy cutoff functions gave good results from fit.

Figure 6.4: Spectral extrapolation at high energy of the GRB090410. The blue horizontal line shows the derived expectation for the GRB flux in the band 30MeV - 3GeV, while the red line is the UL flux estimated with the Helene method.
6.3 Analysis of GRB with spectral information

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Table 6.3: Comparison of the derived upper limit with the estimated count rate derived using the available spectral information
Chapter 7

Analysis and results from Fermi/LAT

The upper limit analysis performed within the AGILE collaboration were done also with the LAT data. Estimating the significance of non-detections of GRB emission by the LAT, as by AGILE, may play an important role in understanding the intrinsic GRB spectra. The relatively low LAT detection rate of high energy emission from GRBs may be an hint of a deviation from the pure extrapolated power law predicted by a simple "Band" function.

As presented in chapter §4 the LAT effective area is $\sim 10$ times larger than the AGILE effective area, so LAT is more sensitive to the fainter $\gamma$-ray sources; indeed Fermi detected 12 GRBs so far, instead AGILE only 3 (with an year data more than Fermi/LAT). A contribution to this higher number of detected GRBs is the presence of the Gamma-ray Burst Monitor (GBM) on board of the Fermi satellite.

The primary objective of GBM is to extend the energy range over which bursts are observed downward from the energy range of the LAT into the hard X-ray range where extensive previous data exist. A secondary objective is to compute burst locations onboard to allow re-orienting the spacecraft so that the LAT can observe delayed emission from bright bursts. GBM uses an array of twelve sodium iodide scintillators and two bismuth germanate scintillators to detect $\gamma$-rays from $\sim 8$ keV to $\sim 40$ MeV over the full unocculted sky [4].

From the beginning of the science operations to the end of October 2009 LAT detected 12 out of the 166 GRBs in its field of view triggered by the GBM. As can be seen from fig. 7.1 there are no preferred sky direction for the detection.

This rate is similar to the EGRET detection rate within the respective fields of view in agreement with the pre-launch predictions [228] of 1 burst every 2/1 months. These predictions were made assuming that the emission component observed in the 10-1000 MeV band in the BATSE bright population, continues unbroken into the LAT energy band.

The upper limit LAT analysis is still on an early stage. Here its status will be presented with some preliminary results. The spatial event selection is done according with the energy dependent Region Of Interest (ROI) as it is shown in fig. 4.16: for higher energies the radius on the ROI decreases because a better resolution of the direction of the incoming
photons is expected. The minimum energy of the events is chosen to be 100 MeV, because the instrument response function is not well known under this energy. To avoid the contamination from the albedo photons a cut on the incoming photon zenith angle is set to 105°. The class of events from the reconstruction algorithm dedicated to the GRB is the so called “Transient” (see §4.2.3), this class of events provide a large effective area (shown in fig. 4.14), but the residual background rate is higher than in the other classes. The fraction of background events does not dominate the signal events if small time intervals around the trigger time are analyzed, but becomes more important when larger time intervals are selected because the signal rate decreases.

To take into account properly the background rate a collaboration tool is used. This tool provides the expected background for the ROI and the time interval analyzed. The background is estimated for any part of the celestial sphere, and in 30 energy bins from 100 MeV to 300 GeV logarithmically spaced. The estimation is based solely on properties of the LAT backgrounds extracted from real data and it is the sum of a cosmic-ray and a gamma-ray component:

- the first component estimation initially involves the calculation of the all-sky cosmic-ray rate, for each second of an observation, and for the location of the spacecraft at that second. Then, the amount of cosmic-rays from each direction of the celestial sphere is estimated using the theta and phi distributions of cosmic rays (calculated from real data) as probability distribution functions.

- The second gamma-ray component is estimated by multiplying a pre-calculated map that contains the amount of gamma-ray background per unit of exposure by the exposure of the observation under consideration.
At this stage of the analysis, four methods are under evaluation to finally derive the
upper limits. They are divided into two groups: unbinned likelihood analysis and counting
analysis. The former methods will give more constraining upper limits, but these will only
be reliable for cases where the burst localization is very accurate. The latter methods will
be less constraining in general, but they will also be less sensitive to errors in the burst
location. One of the two counting methods is the Helene method explained in chapter §5
and developed in this thesis while the other is the Feldman and Cousins method [219].

In the unbinned likelihood analysis, the burst is treated as a point source at the
best location. The expected distribution of counts is modeled using the energy-dependent
LAT PSF and a power-law function for the underlying spectrum. An isotropic background
component is included in the model, and the spectral properties of this component are
derived using the background estimator tool. For maximum likelihood fits, confidence
intervals can be determined using the profile likelihood method [229]. This entails scanning
in the parameter of interest, in this case the flux, while maximizing the log-likelihood,
\( \log(L) \), with respect to the other free parameters of the model. The two methods that
uses the unbinned likelihood analysis differ one from the other for the treatment of the
low fluxes: one use a Bayesian approach with the insertion of a prior knowledge function,
instead the other has a fully frequentist approach and no limits on the source flux are
imposed. Since there are cases where the burst flux in the LAT band will be weak or
zero, the maximum likelihood value of the source flux may actually be negative owing
to downward statistical fluctuations in the background counts. Because the unbinned
likelihood function is based on Poisson probabilities, in the Bayesian approach a prior
is imposed that requires the source flux to be non-negative. This is necessary to avoid
negative probability densities that may arise for measured counts that are found very
close to the GRB point-source location because of the sharpness of the PSF. Given the
prior of the non-negative source flux, the resulting likelihood function can be treated as
the posterior distribution for the flux parameter. In this case, an upper limit may
be obtained by finding the flux value at which the integral of the normalized likelihood
function is: 
\[
\Delta \chi^2 = 1 \quad \text{or} \quad \Delta (\log(L)) = 0.5
\]

5 is taken.

These four methods must be tested to understand their coverage and their sensitivity:
the method which provide the deepest upper limit guaranteeing the chosen 95% of coverage
will be used to give the final results. Some simulations are produced to compare different
UL methods at different source flux level in terms of coverage (the percent number of times
that the true flux is below the upper limit) and shape of the overall UL distributions. The
simulations have do not have the purpose to test the background model used and how this
affects the UL computation; in these simulations the background component is perfectly
known. Four cases with different relative fluxes are simulated: the background flux could
be 1,2,3 or 5 times the burst flux, then for each case two time intervals are simulated:
100s and 1000s. The set of the simulated burst characteristics are the following:

- sky position: 350.0, -63.0 (RA, DEC) which corresponds to 319.25, -51.13 (L, B);
- location respect the spacecraft: on-axis;
- assumed index for the source spectrum: -2.2
Some results from the simulations are shown in figs. 7.2, 7.3. In these figures the calculated upper limits are plotted for each of the 5000 simulations done. In the case the computed 95% interval is not compatible with zero also the lower limit is plotted. The red dash-dotted line is the simulated true flux of the burst.

Figure 7.2: Results for the Helene and the Feldman and Cousins methods from the 5000 simulations in the case of 100s and background flux 3 times the source flux.

Figure 7.4 shows the coverage for the four method as a function of the background flux for all the simulations with 100s. As a preliminary discussion on the coverage it seems that the Profile method largely undercover the required confidence level. But other studies are on-going on these methods and any decision is not taken yet.

As a preliminary result from this analysis the upper limits for a sample of burst are computed. The sample is called the “Golden Sample”, because is compiled with some of the brightest GBM bursts, the requirements for these bursts are to have a registered rate in the BGO detectors of at least 70 counts/s and be within the LAT field of view. These events, which were bright in the BGO bandpass but nonetheless went undetected by the LAT, comprise likely candidates for evidence of spectral curvature above $\sim 40$ MeV. A subsample of the “Golden Sample” is listed in table 7.1 which reports also their spectral parameters: normalization, peak energy, alpha and beta. This subsample comprises the bursts of the “Golden Sample” that have a complete spectral analysis of the GBM data.

In figures 7.5, 7.6 for each burst listed above, except the ones without $\beta$, the GBM flux and the LAT expected flux (extrapolating the spectrum from the GMB energies to the LAT energies) are plotted (black dots) with their errors (grey triangles). For comparison
Figure 7.3: Results for the likelihood methods (Bayesian and Profile) from 5000 simulations in the case of 100s and background flux 3 times the source flux.

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<th>GRB Name</th>
<th>Normalization</th>
<th>$E_p$ (keV)</th>
<th>$\alpha$</th>
<th>$\beta$</th>
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Conclusions

The Gamma Ray Bursts were first discovered by the Vela satellites in 1969. Since then many discoveries were made, but still there is no solution on the GRB progenitors and the emission mechanisms that can produce high energy photons up to tens of GeV. The BATSE detector on board of the CGRO satellite was dedicated to the deep study of the GRBs. Because of the high number of GRB detected by BATSE, population studies were possible. One of the major discoveries was the bimodal distribution of the time duration of the prompt. GRBs are classified as short if their prompt duration is less than 2s and long otherwise. The high energy detector EGRET was also on board of the CGRO satellite. It detected 5 GRBs with energy > 50MeV together with BATSE. Two important discoveries were made: a very late emission of high energy photons (up to 90mins) in the GRB 940217 [97] and a spectral extra component at energies > 100MeV lasted for more than 200s in the GRB 941017 [100]. Both these properties are inconsistent with a pure electron synchrotron model.

More recently, also the Astro-rivelatore Gamma ad Immagini LEggero (AGILE) detected three GRBs with energy > 30MeV: 080514B [134] with a high energy delayed component, 090401B [135] and 090510 [136] which shows an extended high energy emission.

The Fermi/LAT instrument has an effective area 10 times larger than the EGRET one and together with a larger field of view and a smaller dead time it collects more statistics to perform a detailed temporal-spectral analysis [3]. The possibility to re-point itself autonomously when a bright GRB happens and the synergy with the GBM instruments dedicated to the GRBs monitoring, make the LAT a perfect instrument to investigate the problems opened by EGRET on the GRB high energy emission. In the first 15 months of science operations more than 300 bursts were detected with the Gamma-ray Burst Monitor also on board of the Fermi satellite. Among those, 12 were detected also by the LAT instrument, both long and short with at least 10 photons > 100MeV, but only few GRBs have also photons at energies > 1GeV.

Many GRBs happened inside the field of view of both AGILE and LAT, but there were not detected by these instruments. To understand the GRB emission mechanisms, also a non detection could be useful particularly to constrain the upper band of the GRB spectrum. After the sieve of some methods a Bayesian method was chosen and tested: it was proposed from Helene in [223] and [5]. This Bayesian method was selected, instead of the frequentist one (Feldman & Cousins), because of the studies on the coverage and because in the frequentist approach the physical limits of the flux are irrelevant, while this physical information is used in the Helene calculation.

In the AGILE energy range above 30 MeV and till 3 GeV, the estimated GRB flux
upper limits using the method proposed range between $1 \times 10^{-3}$ and $1 \times 10^{-2}$ ph s$^{-1}$ cm$^{-2}$. Instead the Fermi/LAT preliminary flux upper limit derived in this thesis in the energy range 100 MeV - 300 GeV is roughly $5 \times 10^{-5}$ ph s$^{-1}$ cm$^{-2}$. These values put some strong constraints in the high energy emission models.
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