Abstract

The energy range between 10 and 50 MeV is an experimentally very difficult range and remained uncovered since the time of COMPTEL. Here we propose a possible mission to cover this energy range.

1. Introduction

High-energy phenomena in the cosmos, and in particular processes leading to the emission of gamma-rays in the energy range 10 MeV - 100 GeV, play a very special role in the understanding of our Universe. This energy range is indeed associated with non-thermal phenomena and challenging particle acceleration processes. The Universe can be thought as a context where fundamental
physics, relativistic processes, strong gravity regimes, and plasma instabilities can be explored in a way that is not possible to reproduce in our laboratories. High-energy astrophysics and atmospheric plasma physics are indeed not esoteric subjects but are strongly linked with our daily life. Understanding cosmic high-energy processes have a large impact on our theories and laboratories applications. The technology involved in detecting gamma-rays is challenging and drives our ability to develop improved instruments for a large variety of applications. GAMMA-LIGHT is a Small Mission which aims at an unprecedented advance of our knowledge in many sectors of astrophysical and Earth studies research. The Mission will open a new observational window in the low-energy gamma-ray range 10-50 MeV, and is configured to make substantial advances compared with the previous and current gamma-ray experiments (AGILE [1] and Fermi [2]). The improvement is based on an excellent angular resolution achieved by GAMMA-LIGHT using state-of-the-art Silicon technology with innovative data acquisition. Despite the recent important results and progress, AGILE and Fermi are leaving crucial unresolved issues because of their sensitivities, angular resolutions, and limited monitoring capability. GAMMA-LIGHT will address all astrophysics issues left open by the current generation of instruments. In particular, the breakthrough angular resolution in the energy range 100 MeV - 10 GeV is crucial to resolve patchy and complex features of diffuse sources in the Galaxy as well as increasing the point source sensitivity. This proposal addresses scientific topics of great interest to the community, with particular emphasis on multifrequency correlation studies involving radio, optical, IR, X-ray, soft gamma-ray and TeV emission. At the end of this decade several new observatories will be operational including LOFAR, SKA, ALMA, HAWK, CTA. GAMMA-LIGHT will ”fill the vacuum” in the 10 MeV-10 GeV band, and will provide invaluable data for the understanding of cosmic and terrestrial high-energy sources.

2. Astrophysics Objectives of GAMMA-LIGHT

Many crucial scientific issues are left unsolved by the current generation of gamma-ray instruments (AGILE, Fermi). They constitute the main GAMMA-LIGHT scientific objectives:

1. the definitive search of Dark Matter gamma-ray signatures in the Galaxy and in particular in the Galactic Center region;
2. completely resolving the Galactic Center region in gamma-rays: the central BH region, GeV and TeV sources, nebulae, compact sources, SNRs;
3. resolving the diffuse emission in the Galactic plane, relation with cosmic-ray propagation, star forming regions in the Galactic plane; extending the cosmic-ray propagation and emission properties of the “Fermi bubbles” to the lowest energies below 100 MeV;
4. resolving spatially and spectrally SNRs and addressing the origin and propagation of cosmic-rays with unprecedented accuracy;
5. polarization studies of gamma-ray sources;
6. detection of soft gamma-ray pulsars in the range 10-100 MeV, and pulsar wind nebulae studies;
7. detection of compact objects, microquasars, relativistic jets in the range 10 MeV - 1 GeV resolving the issue of hadronic vs. leptonic jets for a variety of sources (e.g., Cyg X-3);
8. detection and localization of transients and exotic sources with much improved sensitivity; detection of Crab Nebula gamma-ray flares with excellent sensitivity down to 10 MeV;
9. blazar studies down to 10 MeV, excellent positioning resolving source confusion;
10. GRB excellent capability in the range 10 MeV - 5 GeV; sub-millisecond timing capability in the range 0.3-100 MeV.

3. The instrument

A scheme of GAMMA-LIGHT can be seen in figure 1. The gamma-ray Tracker is the heart of the payload and it is made of 40 planes of silicon strip detectors organized in 41 trays without tungsten converter. Each tray is configured as follows: two layers of 25 Silicon tiles each (except trays 1 and 41 which have a single
Figure 2: Point Spread Function (PSF, 68% containment radius) of the GAMMA-LIGHT gamma-ray (GRID) imager (in red color) obtained by extensive GEANT-4 simulations which assume an incidence angle of $30^\circ$, Silicon strip analog readout, and Kalman filter analysis of particle tracks. For comparison, we show the Fermi-LAT Pass7V6 PSF (total LAT: blue curve; front-LAT: black color) and the AGILE PSF (in gray color).

layer) organized in 5 ladders composed of 5 tiles bonded together. Each tray is made of a 1 cm core of aluminum honeycomb covered on both sides by a 0.5 mm thick Carbon fiber layer. The resulting tray height is 1.1 cm and the total Tracker height is slightly above 50 cm. The Tracker is a compact, low-power 153,600 channel detector with self-triggering capability, fast timing possibility and full analog readout. The active element is a single-sided, AC-coupled, 410 $\mu$m thick, 9.5x9.5 cm$^2$ Silicon strip detector with microstrips of 121 $\mu$m pitch, alternate strip readout pitch of 242 $\mu$m with one floating strip, and polysilicon resistors for the bias.

The Calorimeter (CAL) is made of CsI elements each of dimensions: height = 4.5 cm, square size of 1 cm. Total lateral length of 50 cm (48x48 pixels).

The Anticoincidence (AC) system is made of a top plastic scintillator layer of thickness of 0.6 cm and lateral panels surrounding all four sides (3 panels for each side). All panels are coupled to PMTs by scintillating optical fibers.

The Point Spread Function is shown in figure 2, the effective area is shown in figure 3 and the sensitivity for 48 hr (solar time) observation is shown in figure 4. For a 2-day observation, sensitivities up to GeV energies are background dominated. At higher energies, sensitivities are photon limited: here we show the limit sensitivities assuming at least $N=5$ high-energy photons detected within the 99% confidence radius. GAMMA-LIGHT is assumed to be pointing in a LEO orbit with an overall exposure efficiency of 0.6 similar to AGILE’s (checked with real data). Fermi-LAT is assumed to be in sky-scanning mode with an overall exposure efficiency per single source of 0.16 (as checked with real data). Final data acquisition efficiencies are assumed to be equal to 0.6; they take into account background rejection in a LEO orbit and on-board trigger logic and ground data processing as deduced from Fermi and AGILE.

4. Dark Matter in our Galaxy

The nature of Dark Matter (DM) is still a mystery. Gamma-ray emission from our Galaxy may reveal the existence of certain types of DM, by means of the production of secondary $\gamma$-rays after the annihilation (or decay) of the DM particle candidates [3].
The importance of GAMMA-LIGHT for Dark Matter searches can be seen in figures 5 and 6 where the differential γ-ray energy spectra per annihilation of Weakly Interacting Massive Particle (WIMP) are plotted [4]. As one can see the bulk of the emission even for high WIMP masses is in the energy range 5 MeV - 100 MeV.

In the Fermi-LAT analysis of the galactic center the diffuse γ-ray backgrounds and discrete sources, as we model them today, can account for the large majority of the detected γ-ray emission from the Galactic Center. Nevertheless a residual emission is left, not accounted for by the above models of standard astrophysical phenomena [5], [6], [7].

So in the inner region of the Milky Way a better angular resolution in respect to AGILE and Fermi is needed in the 5 MeV - 100 MeV energy range in order to disentangle the possible DM contribution from the diffuse background and the point sources contribution (see for example [8]).

Let us finally remark that decaying DM can produce a detectable line in the Gamma-Light energy range [9]. In principle, detectability is expected to be large in the very galactic center since hadronic emission models for this region are predicting a fall down about 100 MeV (see Fig. 2 of [10]).

GAMMA-LIGHT can resolve the Galactic Center (GC) region and similar complex regions of the plane.

The GC is indeed one of the most difficult regions to observe in high-energy gamma-rays. Optical emission is heavily obscured by dust, and both the concentration of point sources and the concentration of clouds and diffuse emission enhancements is very high, a fact that complicates both the analysis and source identifications. Towards the GC (and the anti-center) the rotational velocity of the Galaxy is entirely transverse, no longer allowing the distance of the interstellar gas to be determined through radio line shifts. In addition, the column density of atomic hydrogen can be very large. Nevertheless, important progress has been made by AGILE and Fermi. The most surprising discovery has been the observation of large, well-defined bubbles/lobes above and below the Galactic plane extending 50° above and below the GC with a width of about 40 degrees in longitude [11]. These lobes have a uniform surface brightness with sharp edges, neither limb-brightened nor centrally-brightened, and are nearly coincident with a similar haze seen by WMAP, suggesting a common origin, most likely inverse Compton emission of high-energy electrons scattering off the microwave photons producing gamma-rays or escaping hadrons. The leptonic or hadronic hypotheses would imply an injection of high-energy particles in the past ~10 Myr. Possible mechanisms include an accretion event onto the central black hole, a nuclear starburst, or the accumulation of events from a precessing jet. Each of these scenarios poses a number of problems. GAMMA-LIGHT will de-
termine the morphology and spectral properties below 1 GeV of the GC region and Fermi-bubbles with unprecedented accuracy, and will contribute to resolving the issue of the nature of this emission.

An example of the difficulty in the analysis of the GC region is the search for the gamma-ray counterpart to the super-massive black hole at the center of the galaxy, Sgr A*. At TeV energies, HESS has found a strong point source within 10 arcminutes of Sgr A*. However, source of the TeV emission may be either Sgr A* itself, or a nearby plerion discovered within the central few arcseconds, or a putative "black hole plerion" produced by the wind from Sgr A*, or the diffuse 10 pc region surrounding Sgr A*. An analysis of 25 months of Fermi data by [12] found 4 new sources within a 10°x10° region around Sgr A* in addition to the 19 already listed in the first Fermi Source Catalog (1FGL). The source coincident with both the HESS source and the position of Sgr A*, 1FGL J1745.62900, shows no variability in either GeV or TeV energies, while the GeV spectrum indicates that the emission mechanism must be distinct from that of the TeV emission. Much higher angular resolution is needed to distinguish among the various scenarios, and GAMMA-LIGHT is the ideal instrument to resolve these issues.

Figure 7: The gamma-ray spectrum of one of the most prominent gamma-ray emitting SNRs showing a clear signature of neutral pion decay, W44. The Fermi (green triangles) and AGILE (red diamonds) data are shown. The spectral modeling involves a component due to the neutral pion decay (yellow line) plus a component due to Bremsstrahlung (blue line). The red curve shows the expected GAMMA-LIGHT sensitivity for a 1-year effective time integration.

5. SNRs and Diffuse "Cocoons" in the Galaxy: Origin and Propagation of CRs

Although a fair number of Supernova Remnants (SNRs) have been detected and recently studied by AGILE and Fermi, a number of outstanding issues regarding the origin of cosmic-rays (CRs) remain to be addressed. Today a few dozen SNRs are known to emit gamma rays: the study of these objects together with their non-thermal properties (e.g., radio and X-ray emission) is the topic of many investigations in CR physics and particle acceleration mechanisms (e.g., [13], [14], [15]). However it is often quite difficult to distinguish, for these objects, the different components that contribute to the gamma-ray spectrum (for energies greater than ~10 MeV up to tens of TeV, the only emission processes expected to produce emission are the decay of neutral pions produced in p-p scattering, inverse Compton on low energy photons and Bremsstrahlung). The models so far produced to explain the SNR gamma-ray emission show that the knowledge of the spectrum at low energies (below 100 MeV) is crucial for this purpose. In fact, the rapid fall of the gamma-ray spectrum at energies less than 100 MeV is the most significant feature in the spectrum which may allow to discriminate hadronic vs. leptonic emission. Electron Bremsstrahlung can provide an opposite behavior. Until now, this analysis was possible only for very few SNRs (e.g., [16], [17]). GAMMA-LIGHT will be able to resolve the complex morphology of the SNR gamma-ray emission. It will provide invaluable information for a detailed modelling of CR acceleration and propagation.

6. Polarization Studies

GAMMA-LIGHT can greatly contribute to determine gamma-ray polarization for intense sources. The absence of high-Z converters in the gamma-ray Tracker makes possible the measurement of the pair production plane and angles with good accuracy. A method to determine the polarization direction of high energy (50 MeV-30 GeV) linearly polarized gamma-rays was analyzed and discussed in [18]. The polarization information is contained in the azimuthal distribution of the created pair. The GAMMA-LIGHT Tracker will have an excellent angular resolution above a few hundreds of MeV to determine the aperture angle of positrons and electrons. This is an exciting possibility in the study of intense gamma-ray sources.

7. Terrestrial Gamma-Ray Flashes

Terrestrial Gamma-Ray Flashes (TGFs) (see [19] for a recent review) are one of the most intriguing phenomena in the geophysical sciences and the manifestation of the highest energy natural particle accelerators on Earth. TGFs are millisecond time-scale bursts...
of gamma-rays produced above thunderstorms and associated to lightning activity. Although several observations are available and a general picture of this phenomenon based on Bremsstrahlung by relativistic runaway electrons produced in thunderstorms strong electric field is commonly accepted, there are many points which remain obscure. Among the outstanding issues, we mention here the highest achievable energies (which translates into the maximum voltage drop that can be established within thunderclouds) the connection with lightning and cloud microphysics, and the global and local TGF occurrence rate. There are currently three active space instruments capable of TGF detection: AGILE, RHESSI, and Fermi GBM. AGILE in particular have shown that the TGF energy spectrum extends well above 40 MeV ([20] up to 100 MeV [21] with a spectral shape which is difficult to reconcile with current production models. TGFs are now established as one of the coupling mechanisms between lower and upper atmosphere. Since TGFs appear to be a much more common phenomenon than previously expected [22], it is important to assess the impact of these phenomena on the physical/chemical state of the atmosphere, and on the climate. This is especially true if a large fraction is emitted at high energy, as suggested by the recent AGILE observations, since high-energy particles can have a significant role in aerosol nucleation and ultimately in cloud formation [23]. The study of TGFs and energetic radiation from thunderstorms has now entered a golden age. Future observational breakthrough will come with the Atmosphere-Space Interaction Monitor (ASIM), the ESA mission for the study of TGFs and Transient Luminous Events (TLEs), and by the CNES micro-satellite TARANIS, expected to be launched in 2014 and 2015 respectively. However, none of the forthcoming missions have detection capabilities above 40 MeV or imaging capabilities above 10 MeV, where the memory of the electric field orientation at the source region is carried off by gamma-ray photons.

8. Conclusion

For X-ray and gamma-ray experiments the time of operation versus energy range is shown in figure 8. Note that GAMMA-LIGHT will cover an interval not covered by any other experiments. Note also the number of other experiments at other frequencies that will allow extensive multifrequency studies.


Figure 8: Timeline schedule versus the energy range covered by present and future detectors in X and gamma-ray astrophysics.