Gamma Ray Astronomy

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ABSTRACT. The energy domain between 10 MeV and hundreds of GeV is an essential one for the multifrequency study of extreme astrophysical sources. The understanding of spectra of detected gamma rays is necessary for developing models for acceleration, emission, absorption and propagation of very high energy particles at their sources and in space. After the end of EGRET on board the Compton Gamma Ray Observatory this energy region is not covered by any other experiment, at least up to 50 GeV where ground Čerenkov telescopes are beginning to take data. Here we will review the status of the space experiments that will fill this energy region: AGILE and GLAST, with particular emphasis at the connection with all the other ground planned experiments and at the contribution of these experiments to particle physics.

1. The AGILE detector

The techniques for the detection of gamma-rays in the pair production regime energy range are very different from the X-ray detection ones. For X-rays detection focusing is possible and this permits large effective area, excellent energy resolution, very low background. For gamma-rays no focusing is possible and this means limited effective area, moderate energy resolution, high background but a wide field of view (see figure 1). This possibility to have a wide field of view is enhanced now, in respect to EGRET, with the use of silicon detectors, that allows a further increase of the ratio between height and width (see fig.2), essentially for two reasons: a) an increase of the position resolution that allow a decrease of the distance between the planes of the tracker without affect the angular resolution, b) the possibility to use the silicon detectors themselves for the trigger of an events, with the elimination of the Time of Flight system, that requires some height. In figure 4 is shown the basic principle and main elements of a pair conversion telescope.

The AGILE design was derived from a refined study of the GILDA project (A.Morselli 1994),(G.Barbiellini et al. 1995),(A.Morselli et al. 1995) that was based on the techniques developed for the WiZard silicon calorimeter (R.L.Golden et al. 1990), already successful flown in balloon experiments.

In fig.3 there is a comparison between AGILE and the most famous previous gamma-ray satellites. The dimensions of AGILE are comparable to those of SAS-2 and Cos-B, but thanks to the advance of the techniques the performances of AGILE are better than that of EGRET.

AGILE is done by a collaboration between the Universities and INFN sections of Roma 2 and Trieste and the CNR Institutes IFC of Milano, IAS of Roma, Tesre of
Fig. 1. Detector Technology: X-ray versus Gamma-ray.

Fig. 2. EGRET (Spark Chamber) versus GLAST (Silicon Strip Detector).
Fig. 3. Comparison between the pasto gamma ray experiments (SAS-2, Cos-B, EGRET) and AGILE.

Fig. 4. Main elements of a pair conversion telescope and principle of detection.
Bologna. The name of the people involved in the collaboration together with the on-line status of the project is available at http://www.roma2.infn.it/infn/agile. A description of the capabilities of AGILE can be found in (A.Morselli et al. 1999b),(S.Mereghetti et al. 1999),(A.Morselli et al. 1999c),(A.Morselli et al. 2000a),(G.Barbiellini et al. 2000).

Here we want to stress the capabilities of AGILE for fundamental physics, because the existence of sub-millisecond GRB pulses lasting hundreds of microseconds opens the way to study quantum gravity delay propagation effects by AGILE.

The candidate effect would be induced by a deformed dispersion relation for photons of the form(G.Amelino-Camelia et al. 1998):

$$c^2 P^2 = E^2 (1 + f(E/E_{QG}))$$

where $E$ is the photon energy, $E_{QG}$ is the effective quantum gravity energy scale and $f$ is a model-dependent function of the dimensionless ratio $E/E_{QG}$.

At small energies $E \ll E_{QG}$, we expect that a series expansion of the dispersion relation should be applicable:

$$c^2 P^2 = E^2 (1 + a(E/E_{QG}) + O(E/E_{QG})^2)$$

and

$$v = dE/dP \sim c(1 + a(E/E_{QG}))$$

This type of velocity dispersion results from a picture of the vacuum as a quantum-gravitational ‘medium’, which responds differently to the propagation of particles of different energies and hence velocities. This is analogous to propagation through a conventional medium, such as an electromagnetic plasma. Medium fluctuation are at a scale of the order of $L_p \sim 10^{-33}$ cm and time delay are of the order of $\Delta t \sim \alpha E/E_{QG} D/c$.

Particularly important is the AGILE Mini-Calorimeter with the independent readout for each of the 32 CsI bars of small deadtime ($\sim 20\mu$s). Energy dependent time delays near 100 $\mu$s for ultra-short GRB pulses in the energy range 0.3 - 3 MeV can be detected (requiring the detection of a minimum of 5 photons). If these GRB ultra-short pulses originate at cosmological distances, sensitivity to the Planck’s mass can be reached. Also the tracker deadtime will be of $\sim 100\mu$s, improving by three orders of magnitude the performance of previous spark-chamber detectors such as EGRET, and this will open a new window in the determination of the high energy (>20 MeV) gamma-ray burst time profile.

2. GLAST

The Gamma-ray Large Area Space Telescope (W.Atwood et al. 1994), (A.Morselli 1997), (A.Morselli 1999a) has been selected by NASA as a mission involving an international collaboration of particle physics and astrophysics communities from the United States, Italy, Japan, France and Germany for a launch in the first half of 2006.

The main scientific objects are the study of all gamma ray sources such as blazars, gamma-ray bursts, supernova remnants, pulsars, diffuse radiation, and unidentified high-energy sources.
Fig. 5. The GLAST instrument, exploded to show the detector layers in a tower, the stacking of the CsI logs in the calorimeter, and the integration of the subsystems.
Fig. 6. Instrument performance, including all background and track quality cuts.

Fig. 7. Estimate of the number of AGNs that GLAST will detect at high latitude in a 2 year sky survey compared to EGRET’s approximate detection limit.
Many years of refinement has led to the configuration of the apparatus shown in figure 5, where one can see the 4x4 array of identical towers each formed by: • Si-strip Tracker Detectors and converters arranged in 18 XY tracking planes for the measurement of the photon direction. • Segmented array of CsI(Tl) crystals for the measurement the photon energy. • Segmented Anticoincidence Detector (ACD). The main characteristics, shown in figure 6, are an energy range between 20 MeV and 300 GeV, a field of view of ~ 3 sr, an energy resolution of ~ 5% at 1 GeV, a point source sensitivity of 2x10^{-9} (ph cm^{-2} s^{-1}) at 0.1 GeV, an event deadtime of 20 μs and a peak effective area of 10000 cm^2, for a required power of 600 W and a payload weight of 3000 Kg.

The list of the people and the Institution involved in the collaboration together with the on-line status of the project is available at http://www-glast.stanford.edu.

2.1. Active Galactic Nuclei

GLAST will dramatically extend the number of observed AGN, as well as the energy range over which they can be observed. Indeed, GLAST might be called the "Hubble Telescope" of gamma-ray astronomy as it will be able to observe AGN sources to z ~ 4 and beyond, if such objects actually existed at such early times in the universe. Figure 7 shows the so called Log N versus Log S distribution, where N is the number of sources and S is source flux for E_γ > 100 MeV, for AGN. The curve is extrapolated from EGRET data and an AGN model of the diffuse gamma-ray background based on the assumption that AGN sources follow a luminosity function similar to flat spectrum radio
quasars. Extrapolation from EGRET AGN detections projects that about 5,000 AGN sources will be detected in a 2 year cumulative scanning mode observation by GLAST, as compared to the 85 that have been observed by EGRET in a similar time interval. This large number of AGN’s covering a redshift range from $z \sim 0.03$ up to $z \sim 4$ will allow to disentangle an intrinsic cutoff effect, i.e., intrinsic to the source, from a cutoff derived from the interaction with the extra galactic background light, or EBL. Only by observing many examples of AGN, and over a wide range of redshifts, one can hope to untangle these two possible sources of cutoff. In figure 8 is shown the number of photons detected by EGRET from 3C279 and the number expected with GLAST in the case of extragalactic background light attenuation and without attenuation. Determination of the EBL can provide unique information on the formation of galaxies at early epochs, and will test models for structure formation in the Universe.

2.2. Gamma-ray burst

Gamma-ray bursts (GRBs) are intermittently the most intense and most distant known sources of high-energy gamma rays; at GeV energies, the brightest GRBs are 1000-10,000 times brighter than the brightest AGN. The unparalleled luminosities and cosmic distances of GRBs, combined with their extremely fast temporal variability, make GRBs an extremely powerful tool for probing fundamental physical processes and cosmic history.

GLAST, in concert with the Gamma-ray Burst Monitor, will measure the energy spectra of GRBs from a few keV to hundreds of GeV during the short time after onset when the vast majority of the energy is released. GLAST will also promptly alert other observers, thus allowing the observations of GLAST to be placed in the context of multiwavelength afterglow observations, which are the focus of HETE-2 and the upcoming Swift missions. The additional information available from GLAST’s spectral variability observations will be key to understanding the central engine.

Figure 9 illustrates a very intense, short GRB. The true EGRET time profile is very uncertain because the ~ two hundred milliseconds EGRET dead time per photon is comparable to GRB pulse widths; hence, many more photons may have been incident on EGRET during the extremely intense initial pulse. The GLAST dead time will be ~ 10,000 times smaller, thus allowing a precise measurement of the gamma-ray flux during the peak. This characteristic together with its larger field of view and larger effective area, should permit to detect virtually all GRBs in its field of view reaching the “the edge” of the GRB distribution, as does BATSE. Figure 10 shows another intense burst with very different temporal character which occurred in EGRET’s field of view on 1994 Feb 17. At BATSE energies (25-1000 keV), this event persisted for ~160 s; however, at EGRET energies, it apparently continued at a relatively high flux level past an Earth occultation, for at least 5000 s, to deliver a delayed ~18 GeV photon. GLAST, with negligible self veto, will have good efficiency above 10 GeV and it will be able to localize GRBs with sufficiently high accuracy to enable rapid searches at all longer wavelengths. About half of the 200 bursts per year detected by GLAST will be localized to better than 10 arc minute radius, an easily imaged field for large-aperture optical telescopes.
Fig. 9. EGRET and BATSE light curves of the Superbowl burst, GRB930131. The burst consisted of an extremely intense spike, followed by low-level emission for several seconds. The true temporal development at energies $>100$ MeV is uncertain since EGRET dead time is comparable to GRB pulse widths.

Fig. 10. EGRET and BATSE light curves of GRB940217. Burst cessation at BATSE energies occurs at 160 s. Extended emission at EGRET energies persist beyond an intervening earth occultation, up to 5000 seconds after the BATSE event.
2.3. Pulsars

GLAST will discover many gamma-ray pulsars, potentially 50 or more, and will provide definitive spectral measurements that will distinguish between the two primary models proposed to explain particle acceleration and gamma-ray generation: the outer gap (R. Romani, 1996) and polar cap models (J. Daugherty, and A. Harding, 1996) (see figure 11). From observations made with gamma ray experiments through the EGRET era, seven gamma-ray pulsars are known. GLAST will detect more than 100 pulsars and will be able to directly search for periodicities in all EGRET unidentified sources. Because the gamma-ray beams of pulsars are apparently broader than their radio beams, many radio-quiet, Geminga-like pulsars likely remain to be discovered.

2.4. Search for supersymmetric dark matter

GLAST is particularly interesting for the supersymmetric particle search because, if neutralinos make up the dark matter of our galaxy, they would have non-relativistic velocities, hence the neutralino annihilation into the gamma gamma and gamma Z final states.
can give rise to gamma rays with unique energies $E_\gamma = M_\chi$ and $E'_\gamma = M_\chi (1 - m_\chi^2/4M_\chi^2)$.

In figure 12 is shown how strong can be the signal (L. Bergström et al. 1998) in the case of a cuspy dark matter halo profiles distribution (J. Navarro et al. 1996).

Figure 13 shows the GLAST capability to probe the supersymmetric dark matter hypothesis (L. Bergström et al. 1998). The various zone sample the MSSM with different values of the parameters space for the three classes of neutralinos defined in the previous section. The previous galaxy dark matter halo profile (J. Navarro et al. 1996) that gives the maximal flux has been assumed. The solid line shows the number of events needed to obtain a 5 $\sigma$ detection over the galactic diffuse $\gamma$-ray background as estimated from EGRET data. As the figures show, a significant portion of the MSSM phase space is explored, particularly for the higgsino-like neutralino case.

This effort will be complementary to a similar search for LSP looking with cosmic-ray experiments at the distortion of the secondary positron fraction and secondary antiproton flux induced by a signal from a heavy neutralino.

In figure 14 (on the left) there are the experimental data (M. Boezio et al. 2000) for the positron fraction together with the distortion of the secondary positron fraction (dashed line) due to one possible contribution from neutralino annihilation (dotted line, from (E. Baltz and J. Edsjö 1999)).

The expected data from the experiment PAMELA (P. Picozza et al. 2001) in the annihilation scenario for one year of operation are shown by grey circles.
Fig. 13. Number of photons expected in GLAST for $\chi \chi \rightarrow \gamma \gamma$ from a 1-sr cone near the galactic center as a function of the possible neutralino mass. The solid line shows the number of events needed to obtain a five sigma signal detection over the galactic diffuse gamma-ray background as estimated by EGRET data.

Fig. 14. Distortion of the secondary positron fraction (on the left) and secondary antiproton flux (on the right) induced by a signal from a heavy neutralino.
In the same figure (on the right) there are the experimental data for the antiproton flux (D. Bergström et al. 2000) together with the distortion on the antiproton flux (dashed line) due to one possible contribution from neutralino annihilation (dotted line, from (P. Ullio 1999)). Total expected flux is shown by solid line. The antiproton data that PAMELA would obtain in a single year of observation for one of the Higgsino annihilation models are shown by grey circles.

3. **Ground-based Gamma-ray Experiments:**

High-energy gamma rays can be observed from the ground by experiments that detect the air showers produced in the upper atmosphere. Air shower arrays directly detect the particles (electrons, muons, and photons) in air showers, and atmospheric Cherenkov telescopes detect the Cherenkov radiation created in the atmosphere and beamed to the ground (see figure 15). Detectors based on the atmospheric Cherenkov technique consist of one or more mirrors that concentrate the Cherenkov photons onto fast optical detectors. Photomultiplier tubes (PMTs) placed in the focal plane are generally used to detect the Cherenkov photons. Two problems in using atmospheric Cherenkov telescopes (ACT) are the night-sky background and the large isotropic background from cosmic-ray showers. The energy threshold of an atmospheric Cherenkov telescope is determined by the number of Cherenkov photons needed to observe a signal above the level of the night-sky background.
In the last decade, ground-based instruments have made great progress, both in technical and scientific terms. (For a recent review, see (C.Hoffman et al. 1999).) On the technical side, atmospheric Cherenkov telescopes have demonstrated that a high degree of gamma/hadron discrimination and a source pointing accuracy of 10-30 arc minutes (depending on the source strength) can be achieved based on the detected Cherenkov image.

The Crab nebula, which has been shown to be a standard candle source at very high energies, can be detected with high statistical confidence in under twenty minutes of observation. The single-photon angular resolution achieved by the state-of-the-art Cherenkov telescopes such as Whipple, CANGAROO, CAT, or HEGRA approaches 0.1 degrees above 500 GeV. As one goes to lower energies with advanced telescopes, like the proposed MAGIC telescope shown in figure 16, this measurement is expected to broaden by about a factor of two. For individual point sources, ground-based instruments have unparalleled sensitivity at very high energies (above 50-250 GeV). For many objects, full multi-wave-length coverage over as wide an energy range as possible will be needed.
to understand the acceleration and gamma-ray production mechanisms. In addition, at high energies above 10 GeV the spectra from distant AGNs may be cut off due to absorption by interstellar radiation fields. Spectral measurements by both GLAST and ground-based instruments will be needed to measure these absorptive effects accurately.

4. Conclusion

Two gamma-ray space experiments, AGILE and GLAST, are under construction. Their time of operation and energy range are shown together with the other space X-ray satellite and gamma-ray experiments in figure 17. Note that they will cover an interval not covered by any other experiments. Note also the number of other experiments in other frequencies that will allow extensive multifrequency studies.
In figure 18 the AGILE and GLAST sensitivities compared with the others present and future detectors in the gamma-ray astrophysics range are shown. The predicted sensitivity of a number of operational and proposed Ground based Cherenkov telescopes, CELESTE, STACEE, VERITAS, Whipple is for a 50 hour exposure on a single source. EGRET, GLAST and AGILE sensitivity is shown for one year of all sky survey. MILAGRO sensitivity is for one year of sky survey. Note that on ground only MILAGRO and ARGO will observe more than one source simultaneously. The Home Pages of the various instruments are at http://www-hfm.mpi-hd.mpg.de/CosmicRay/CosmicRaySites.html.

5. Acknowledgments

The author wishes to thanks the organizing committee for the possibility to present this paper in honour of J.Tran Thanh Van, who dedicated so much effort to improve friendship between physicists from all over the world.
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