ELSEVIER

Nuclear Physics B (Proc. Suppl.) 125 (2003) 222–229

NUCLEAR PHYSICS B
PROCEEDINGS
SUPPLEMENTS
www.elsevier.com/locate/npe

AGILE and Gamma-Ray Astrophysics

F. Longo[a,b], A. Argan[c], N. Auricchio[d], G.Barbiellini[a,b], A.Bulgarelli[d], P.Caraveo[c], E.Celesti[d], A.Chen[c,e], V.Cocco[e,f,g], E.Costa[h], G.Di Cocco[d], G.Fedel[a,b], M.Feroci[h], M.Fiorini[c], T.Froysland[e,g], M.Galli[i], F.Gianotti[d], A.Giuliani[c,e], C.Labanti[d], I.Lapshov[h], F.Lazzarotto[h], P.Lipari[j], A.Mauri[d], M.Marisaldi[d], S.Mereghetti[c], E.Morelli[c], A.Morselli[g], L.Pacciani[h], F.Paladin[b,e], A.Pellizzoni[c], F.Perotti[c], P.Picozza[f,g], C.Pittori[e,f,g], C.Pontoni[,e], J.Porrovecchio[h], B.Preger[e,h], M.Prest[b], M.Rapisarda[k], E.Rossi[d], A.Rubini[h], P.Soffitta[h], M.Tavani[h], A.Traci[d], M.Trifoglio[d], E.Vallazza[b], S.Vercellone[c], D.Zanello[j]

[a]Università di Trieste

[b]INFN, Sez. Trieste

[c]CNR-IASF (Istituto di Astrofisica), Sez. Milano

[d]CNR-IASF (Istituto di Astrofisica), Sez. Bologna

[e]CIFS, Torino

[f]Università "Tor Vergata"

[g]INFN Sez. Roma-2

[h]CNR-IASF (Istituto di Astrofisica), Sez. Roma

[i]ENEA, Bologna

[j]Università "La Sapienza" and INFN, Sez. Roma-1

[k]ENEA, Roma

The study of γ rays is fundamental for our understanding of the universe: γ rays probe the most energetic phenomena occurring in nature, and several signatures of new physics are associated with the emission of γ rays. The main science objectives and the status of the new generation high-energy gamma-ray astrophysics experiment AGILE are presented.

1. Introduction

Gamma-ray astronomy is a rapidly evolving field[1]. During the Nineties the Energetic Gamma-Ray Experiment Telescope (EGRET) aboard CGRO was very successful in detecting GeV γ-rays from around 70 AGN, 8 pulsars, and 170 sources not yet identified firmly with known objects [2]. EGRET has also measured the spectrum and the spatial distribution of the diffuse galactic γ-ray emission with unprecedented sensitivity and resolution [3]. Unfortunately since the de-orbiting of the Compton Gamma-Ray Observatory (CGRO) in June 2000 no space-based γ-ray detector has been operational.

The planned successor to EGRET, the Gamma-ray Large Area Space Telescope (GLAST), will not be launched before the year 2006. During the time before GLAST will become operational, the italian AGILE satellite (Astro-rivelatore Gamma a Immagini LEggero) will offer a sensitive area similar to that of EGRET and an angular resolution somewhat better than

doi:10.1016/S0920-5632(03)02250-3

EGRET [4]. All GeV gamma-ray experiments use pair production in thin foils of high-Z material to actually detect the γ-rays. Different techniques are used to track the e^+/e^--pairs and to measure their energy, though. In principle the gamma-ray energy threshold is around 10 MeV, but the short range of the pairs and small-angle scattering in the tracker significantly deteriorate the detector performance below 100 MeV. Towards high γ-ray energies self-vetoing and the finite thickness of the calorimeter can reduce the quality of measurement. The main problems with satellite-based γ-ray detectors, however, are the technical constraints which prohibit satellite payloads with an effective area of much more than a squaremeter. The flux of all cosmic γ-ray sources falls off with photon energy and therefore the scientific return of the γ-ray detectors at high photon energies is limited by statistics rather than inapplicability of the technique of measurement.

2. Science Objectives

2.1. Galactic Diffuse Emission

Why is it interesting to study diffuse galactic γ-rays? This emission is produced in interactions of cosmic rays with gas and ambient photon fields and thus provides us with an indirect measurement of cosmic rays in various locations in the Galaxy. A significant fraction of the diffuse galactic γ-rays is supposedly produced in decays of neutral pions following inelastic collisions of cosmic ray nucleons. Leptonic emission is particularly important at γ-ray energies below 100 MeV, where bremsstrahlung is presumably the main emission mechanism. Inverse Compton scattering of relativistic electrons on soft ambient photons is expected to provide γ-rays with a hard spectrum, thus eventually dominating over the π^0-decay γ-rays at high energies [5]. The study of the diffuse Galactic γ-ray emission reveals a spectrum which is incompatible with the assumption that the cosmic ray spectra measured locally hold throughout the Galaxy [3]. The spectrum observed with EGRET below 1 GeV is in accord with, and supports, the assumption that the cosmic ray spectra and the electron-to-proton ratio observed locally are uniform, however, the spectrum above 1 GeV, where the emission is supposedly dominated by π^0-decay, is harder than that derived from the local cosmic ray proton spectrum. This is the well-known GeV excess.

2.2. Galactic sources

- **Supernova remnants**: SNR are considered the most likely sources of galactic cosmic rays. Observational evidence in favor of this scenario has been found only for cosmic ray electrons, not for the nucleons. The signal of π^0 decaying into $\gamma\gamma$ could indicate the dominant role of the acceleration of nuclei.

- **Unidentified EGRET sources**: EGRET has left a legacy of about 170 sources not yet identified firmly with known sources. Various population studies have been performed to search for correlations with classes of galactic objects. It has been suggested that some of the unidentified EGRET sources are SNR [6]. It is also possible that a number of unidentified γ-ray sources are actually pulsars born in the local star-forming region Gould's belt [7].

- **Pulsars**: To date eight pulsars have been identified in the EGRET data on account of pulsed emission. There are two competing models for the production of pulsed γ-rays: the polar cap model [8] and the outer gap model [9], which may be observationally distinguished in the energy range between 3 GeV and 30 GeV.

2.3. Extragalactic Sources

- **Active galactic nuclei** These sources show very intense emission, which in many cases is variable. The variability has been observed on all time scales accessible with the available measurement techniques down to about one hour. It should be noted that the AGN detected in the GeV to TeV range emit a significant, if not dominant, fraction of their luminosity in the form of γ-rays, indicating that with measuring γ-rays we actually study the main energy transfer processes in these objects. Simultaneous monitoring of a large number of AGNs per pointing will be possible with the new generation satellites. Several outstanding issues concerning the mechanism of AGN gamma-ray production and activity can be addressed in the near future including: (1) the study of transient vs. low-level gamma-ray emission and duty-cycles; (2) the relationship between the gamma-ray variability and the radio-optical-X-ray-TeV emission; (3) the correlation between relativistic radio plasmoid ejections and gamma-ray flares; (4) hard X-ray/gamma-ray correlations[10].

- **Gamma-ray bursts**: About ten GRBs were detected by the EGRET spark chamber during $\sim$ 7 years of operations [11]. This number was limited by the EGRET FOV and sensitivity and, from what we know today, not by the GRB emission mechanism normally producing gamma-rays above 100 MeV (Ref. [12]). The small deadtime of the new generation satellites allows a better study of the initial phase of GRB pulses (for which EGRET response was in many cases inadequate). The remarkable discovery of 'delayed' gamma-ray emission up to $\sim$ 20 GeV from GRB 940217 [13] is of great importance to model prompt and afterglow acceleration processes. Several models of Gamma-ray bursts (GRBs) predict GeV-TeV scale radiation from inverse Compton scattering or other processes with comparable fluence to the well measured MeV scale radiation. Measuring the HE component of GRBs may be critical to the understanding of the charged particle acceleration. It is usually presumed that the afterglow emission of GRBs is caused by the sweep-up of interstellar matter by the decelerating relativistic blast wave. If efficent proton acceleration to $\sim 10^{20}$ eV could be possible, which, if the protons would escape from the system without loosing their energy, could be one possible source of ultra-high energy cosmic rays [14,15].

2.4. Gamma-ray absorption by the infrared background

High energy γ-rays can interact with ambient radiation and form an electron/positron pair. The electrons would also be highly relativistic and would emit γ-rays at energies somewhat smaller than the energy of the primary γ-ray that has produced the pair. The secondary γ-rays would be emitted at a small angle with respect to the primary γ-ray, even if the electron was not significantly deflected by magnetic fields. Essentially, the γ-radiation cascades to lower energies and at the same time is scattered out of the line-of-sight. For the γ-ray flux from a point source this process corresponds to an absorption, with the radiation energy reappearing in the form of diffuse emission.

2.5. Fundamental Physics

Recent quantum gravity models predict that the speed of photons depends on their energy[16]; this effect could cause delays of O(100ms) in the arrival time of photons from GRBs, and thus be detectable. The new generation gamma-ray experiments are suited for Quantum Gravity studies. The existence of sub-millisecond GRB pulses lasting hundreds of microseconds [17] opens the way to study QG delay propagation effects. If these ultra-short GRB pulses originate at cosmological distances, sensitivity to the Planck's mass can be reached.

3. EGRET

The Energetic Gamma Ray Experiment Telescope was the highest energy instrument on board the Compton Gamma Ray Observatory, and covered the broadest energy range, from 20 MeV to 30 GeV [18]. It had a large field of view, good angular resolution and very low background. Because it was designed for high-energy studies, the detector was optimized to detect gamma rays when they interact by the dominant high-energy pair-production process which forms an electron and a positron pair within the EGRET spark chamber. EGRET was sensitive to gamma rays in the energy range from about 30 MeV to 30 GeV. In the mode used for most of the observations, the effective area of the telescope is about 1000 cm^2 at 150 MeV, 1500 cm^2 around 0.5-1 GeV, decreasing gradually at high energies to about 700 cm^2 at 10 GeV for targets near the center of the field of view. EGRET's effective area is maximum when the target is on axis and falls to approximately 50% of this value when the angular offset reaches 18°.

The instrument had components typically used in the high energy gamma-ray telescopes until the 1990's; an anticoincidence system to discriminate against charged particle radiation, a multilevel thin-plate spark chamber system to convert gamma rays and determine the trajectories of the secondary electron-positron pair, a triggering telescope that detects the presence of the pair with the correct direction of the motion, and an energy measuring calorimeter, which in the case of EGRET is a NaI(Tl) crystal. Descriptions of the instrument and details of the instrument calibration, both before and after launch, could be found in [19,20]. The instrument was carefully designed to be essentially free of internal background, and calibration tests verified that the internal background was at least an order of magnitude below the extragalactic diffuse gamma radiation.

The scientific goals of the mission included the study of the high energy transfers in neutron stars, other galactic objects, and active galaxies, the galactic and extragalactic high-energy gamma-ray diffuse radiation, energetic solar phenomena, cosmic rays and supernovae, and the high-energy gamma-ray emission of the gamma ray bursts.

4. AGILE

The AGILE scientific instrument is based on an innovative design based on three detecting systems: (1) a Silicon Tracker, (2) a Mini-Calorimeter (MC), and (3) an ultralight coded mask system with Si-detectors (Super-AGILE). AGILE is designed to provide: (1) excellent imaging in the energy bands 30 MeV–50 GeV (5–10 arcmin for intense sources) and 10-40 keV (1–3 arcmin); (2) optimal timing capabilities, with independent readout systems and minimal deadtimes for the Silicon tracker, Super-AGILE and Mini-Calorimeter; (3) large fields of view for the gamma-ray imaging detector (GRID) (~3 sr) and Super-AGILE (~1 sr).

Despite of its smaller dimensions AGILE will have comparable performances to EGRET on axis and substantially better off axis. The innovative technology will allow AGILE to achieve the smallest deadtime in high-energy astrophysics

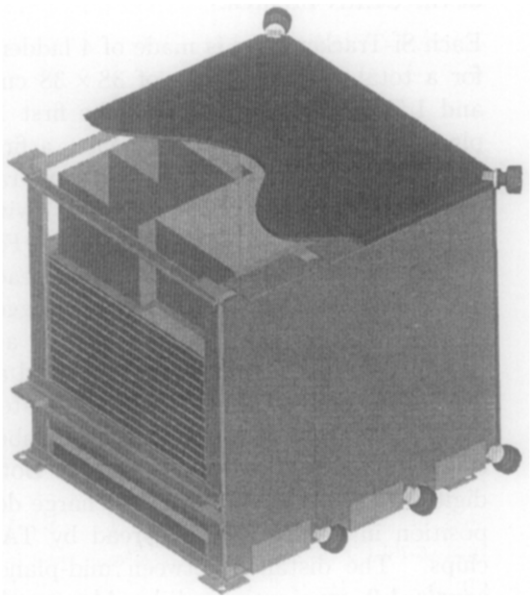

Figure 1. Schematic view of the AGILE instrument

Fig. 1 shows the AGILE instrument configuration of total weight of ~ 80 kg including the Si-Tracker, Super-AGILE, Mini-Calorimeter, the Anticoincidence system and electronics. The baseline AGILE instrument is made of the following elements.

- **Silicon-Tracker**, a gamma-ray pair-converter and imager made of 12 planes, with two Si-layers per plane providing the X and Y coordinates of interacting charged particles. The fundamental Silicon detector unit is a tile of area 9.5×9.5 cm^2, microstrip pitch equal to 121 μm, and thickness 410 μm. The adopted "floating readout strip" system has a total of 384 readout channels (readout pitch equal to 242 μm) and three readout TA1 chips per Si-tile. Four silicon detectors are connected together through wire bonding to obtain a "ladder" 38 cm long. Fig. 2 is a picture of the ladder built for the May 2000 testbeam at the CERN PS area.

Each Si-Tracker layer is made of 4 ladders, for a total geometric area of 38×38 cm^2 and 1,536 readout channels. The first 10 planes are made of three elements: a first layer of Tungsten (0.07 X_0) for gamma-ray conversion, and two Si-layers (views) with microstrips orthogonally positioned. For each plane there are then $2 \times 1,536$ readout microstrips. Since the GRID trigger requires at least three Si-planes to be activated, two more Si-planes are inserted at the bottom of the Tracker without Tungsten layers. The total readout channel number of for the GRID Tracker is $\sim 43,000$. Both digital and analog information (charge deposition in Si-microstrip) is read by TA1 chips. The distance between mid-planes equals 1.9 cm (optimized by Montecarlo simulations). The GRID has an *on-axis* total radiation length near ~ 0.8 X_0. Special algorithms applied off-line to telemetered data will allow optimal background subtraction and reconstruction of the photon incidence angle. Both digital and analog information are crucial for this task. The positional resolution obtained by these detectors in recent beam tests at CERN is excellent, being below 40 μm for a large range of photon incidence angles [21].

- **Super-AGILE**, made of four square Silicon detectors ($19 \times 19\,\text{cm}^2$ each) and associated FEE placed on the first GRID tray plus an ultra-light coded mask system supporting a Tungsten mask placed at a distance of 14 cm from the Silicon detectors. Super-AGILE tasks are: *(i)* photon-by-photon detection and imaging of sources in the energy range 10-40 keV, with a field-of-view (FOV) of ~ 0.8 sr, good angular resolution (1-3 arcmins, depending on source intensity and geometry), and good sensitivity (~ 5 mCrab for 50 ksec integration, and < 1 Crab for a few seconds integration); *(ii)* simultaneous X-ray and gamma-ray spectral studies of high-energy sources; *(iii)* excellent timing ($\sim 4\,\mu$s); *(iv)* burst trigger for the GRID and MC; *(v)* GRB alert and quick on-board positioning capability. Ref. [22] describes the Super-AGILE structure and scientific capabilities.

- **Mini-Calorimeter** (MC), made of two planes of Cesium Iodide (CsI) bars, for a total (on-axis) radiation length of 1.5 X_0. The signal from each CsI bar is collected by two photodiodes placed at both ends. The MC tasks are: *(i)* obtaining additional information on the energy of particles produced in the Si-Tracker; *(ii)* detecting GRBs and other impulsive events with spectral and intensity information in the energy band $\sim 0.3 - 100$ MeV. We note that the problem of "particle backsplash" for AGILE is much less severe than in the case of EGRET. AGILE allows a relatively efficient detection of (inclined) photons near 10 GeV and above also because the AC-veto can be disabled for events with more than $\sim$ 100 MeV total energy collected in the MC. Ref. [23] describes the MC characteristics.

- **Anticoincidence System**, aimed at both charged particle background rejection and preliminary direction reconstruction for triggered photon events. The AC system surrounds all AGILE detectors (Super-AGILE, Si-Tracker and MC). Each lateral face is segmented with three plastic scintillator layers (0.6 cm thick) connected to photomultipliers placed at their bottom. The signal from each scintillator layer is collected laterally by optical fibers attached to photomultipliers at the

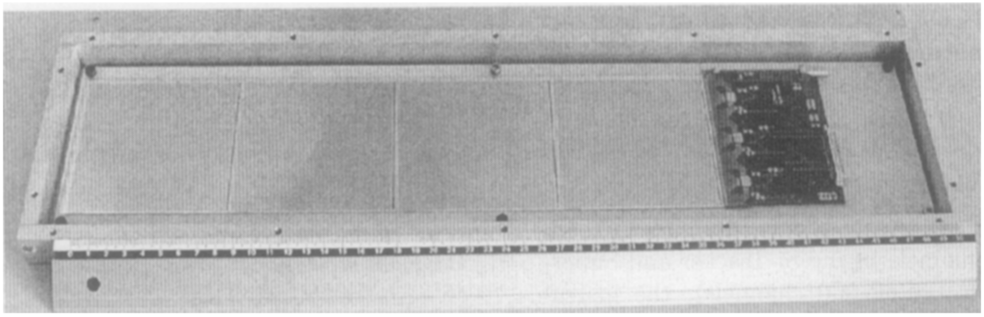

Figure 2. Prototype ladder tested during the May 2000 testbeam

bottom. A single square plastic scintillator layer (0.5 cm thick) constitutes the top-AC layer whose signal is read by four photomultipliers placed at the four corners.

- **Data Handling System**, for fast processing of the GRID, Mini-Calorimeter and Super-AGILE events. The GRID trigger logic for the acquisition of gamma-ray photon data and background rejection is structured in two main levels: Level-1 and Level-2 trigger stages. The Level-1 trigger is fast ($\sim 5\mu$s) and requires a signal in at least three out of four contiguous tracker planes, and a proper combination of fired TA1 chip number signals and AC signals. An intermediate Level-1.5 stage is also envisioned (lasting $\sim 20\ \mu$s), with the acquisition of the event topology based on the identification of fired TA1 chips. Both Level-1 and Level-1.5 have a hardware-oriented veto logic providing a first cut of background events. Level-2 data processing includes a GRID readout and pre-processing, "cluster data acquisition" (analog and digital information), and processing by a dedicated CPU. The Level-2 processing is asynchronous (estimated duration $\sim$ a few ms) with the actual GRID event processing. The GRID deadtime turns out to be $\sim 100\ \mu$s and is dominated by the Tracker readout.

The charged particle and albedo-photon background passing the Level-1+1.5 trigger level of processing is simulated to be < 100 events/sec for the nominal equatorial orbit of AGILE [24]. The on-board Level-2 processing has the task of reducing this background by a factor between 3 and 5. Off-line processing of the GRID data with both digital and analog information is being developed with the goal to reduce the particle and albedo-photon background rate above 100 MeV to ~ 0.01 events/sec.

In order to maximize the GRID FOV and detection efficiency for large-angle incident gamma-rays (and minimize the effects of particle backsplash from the MC and of "Earth albedo" background photons), the data acquisition logic uses proper combinations of top and lateral AC signals and a coarse on-line direction reconstruction in the Si-Tracker. For events depositing more than ~ 100 MeV in the MC, the AC veto can be disabled to allow the acquisition of gamma-ray photon events with energies larger than 1 GeV.

Appropriate data buffers and burst search algorithms are envisioned to maximize data acquisition for transient gamma-ray events (e.g., GRBs) in the Si-Tracker, Super-AGILE and Mini-Calorimeter, respectively.

The Super-AGILE event acquisition is conceptually simple. After a first "filtering" based on AC-veto signals and pulse-height discrimination in the dedicated FEE

(XAA1 chips), the events are buffered and transmitted to the CPU for burst searching and final data formatting. The 4 Si-detectors of Super-AGILE are organized in 16 independent readout units, of $\sim 5\,\mu s$ deadtime each.

Given the relatively large number of readable channels in the Si-Tracker and Super-AGILE ($\sim 50,000$ channels), the instrument requires a very efficient readout system. In order to maximize the detecting area and minimize the instrument weight and absorbed power, the GRID and Super-AGILE front-end-electronics is partly accommodated in special boards placed externally on the Tracker lateral faces. Electronic boxes, P/L memory (and buffer) units will be accommodated at the bottom of the instrument.

Table 1 summarizes the main characteristics of the AGILE gamma-ray instrument and its performance compared to that of EGRET. We assumed a typical 2-week pointing duration and a $\sim 50\%$ exposure efficiency.

5. Conclusions

The AGILE scientific instrument is innovative in many ways, and is designed to obtain an optimal gamma-ray detection performance despite its relatively small mass and absorbed power. The refined readout of the Silicon Tracker allows to reach an excellent spatial resolution ($\sim 40\,\mu m$) that is crucial for gamma-ray imaging. The combination of hard X-ray (Super-AGILE) and gamma-ray imaging capabilities in a single integrated instrument is unique to AGILE. We anticipate a crucial role of Super-AGILE for studies of AGNs, GRBs, and Galactic sources. Positioning better than ~ 6 arcmin can be obtained for sources detectable in the hard X-ray range. Instrumental deadtimes for the different detectors are unprecedently small for gamma-ray instruments, and microsecond photon timing can be achieved. An optimal Burst Search Procedure is implemented in the on-board Data Handling System allowing a GRB search for a broad dynamic range of durations from milliseconds to hundreds of seconds. AGILE will provide an important step forward in γ astronomy. We are confident that the partnership between High Energy Physics and High Energy Astrophysics will be the source of new discoveries over a wide range of subjects.

REFERENCES

1. For a review, see for example C.M. Hoffman, C. Sinnis, P. Fleury and M. Punch, Rev. Mod. Phys, 71, 897, 1999 or M.Pohl astro-ph/0111552
2. Hartman R.C. et al., ApJS, 123, 79, 1999
3. Hunter S.D. et al., ApJ, 481, 205, 1997
4. Mereghetti S. et al., Proc. of *The nature of unidentified galactic high energy gamma-ray sources*, Eds. Carraminana, Reimer and Thompson, Astrophysics and Space Science Library, Kluwer Academic Press, 331, 2001
5. Porter T.A., Protheroe R.J., J. Phys. G, 23, 1765, 1997
6. Esposito J.A. et al., ApJ, 461, 820, 1996
7. Perrot C.A., Grenier I.A., Proc. 27th ICRC, Copernicus Gesellschaft, 2419, 2001
8. Daugherty J.K., Harding A.K., ApJ, 458, 278, 1996
9. Hirotani K., ApJ, 549, 495, 2001
10. Tavani M. et al., *Proceedings of Gamma2001 Conference*, AIP Conf. Proceedings, eds. Ritz S., Gehrels N. and Shrader C.R., 2001, Vol. 587, p. 729
11. Schneid E.J. et al., in AIP Conf. Proc., Vol. 384, p.253, 1996
12. Tavani M., PRL, 76, 3478, 1996
13. Hurley K. et al., Nature, 372, 652, 1994
14. Vietri M., ApJ, 453, 883, 1995
15. Waxman E., PRL, 75, 386, 1995
16. G. Amelino-Camelia, et al., Nature 393, 763, 1998
17. Bhat C.L. et al., Nature, 359, 217, 1992
18. See http://cossc.gsfc.nasa.gov/cossc/egret/ and references therein.
19. Thompson D.J. et al., ApJS, 86, 629, 1993
20. Nolan P.L. et al., IEEE Transactions Nucl. Sci., 39, 993, 1992
21. Barbiellini G. et al., NIM-A, 490, 146, 2002
22. Lapshov I. et al., *Proceedings of Gamma2001*

	EGRET	AGILE
Mass	1830 kg	80 kg
Gamma-ray energy band	30 MeV–30 GeV	30 MeV–50 GeV
Field of View	~ 0.5 sr	~ 3 sr
PSF	5.5°	4.7° (@ 0.1 GeV)
(68% containment radius)	1.3°	0.6° (@ 1 GeV)
	0.5°	0.2° (@ 10 GeV)
Deadtime for γ-ray detection	$\gtrsim 100$ ms	$\lesssim 100\,\mu$s
Sensitivity	8×10^{-9}	6×10^{-9} (@ 0.1 GeV)
(ph cm^{-2} s^{-1} MeV^{-1})	1×10^{-10}	4×10^{-11} (@ 1 GeV)
	1×10^{-11}	3×10^{-12} (@ 10 GeV)

Table 1
A comparison between EGRET and AGILE

Conference, AIP Conf. Proceedings, eds. Ritz S., Gehrels N. and Shrader C.R., Vol. 587, p. 769, 2001
23. Auricchio N. et al., *Proceedings of Gamma2001 Conference*, AIP Conf. Proceedings, eds. Ritz S., Gehrels N. and Shrader C.R., Vol. 587, p. 749, 2001
24. Cocco V., Longo F. & Tavani M., *Proceedings of Gamma2001 Conference*, AIP Conf. Proceedings, eds. Ritz S., Gehrels N. and Shrader C.R., Vol. 587, p. 744, 2001