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EGRET Gamma-Ray Sources: Observations and Physics

R. Mukherjee

Dept. of Physics and Astronomy, Barnard College, Columbia University
New York, NY 10027, USA

Abstract. High energy astronomy above 30 MeV received a significant impetus from the observations of EGRET (Energetic Gamma-Ray Experiment Telescope) onboard the *Compton Gamma Ray Observatory* (CGRO). Until June 2000, when CGRO was de-orbitted, EGRET produced a wealth of important astrophysical results, and was responsible for the detection of more than 270 point sources of γ-rays. These sources include active galaxies, pulsars, the normal galaxy LMC, as well as the large majority of sources that remain unidentified. In addition, EGRET has detected the high energy emission from a few γ-ray bursts (GRBs). This article selectively reviews some of the important results from EGRET.

Key words: EGRET, Pair Telescope, Gamma rays, blazars, pulsars.

1. Introduction

High energy γ-rays are one of the most direct ways of studying the non-thermal Universe. Sources of very high energy radiation enable us to explore the highest energy accelerators in the cosmos, in situations with extreme gravitational and magnetic fields. Although high energy γ-rays have been studied for some time, rapid development in the field came only in the 1990s. The most significant thrust to high energy astronomy above 30 MeV came with the launch of the *Compton Gamma Ray Observatory* (CGRO) in 1991, which carried onboard the Energetic Gamma-Ray Experiment Telescope (EGRET), along with three other instruments. EGRET proved to be a highly successful γ-ray telescope, and this article selectively reviews some of the highlights from the mission.

Perhaps one of the most important results from EGRET has been the detection of high energy γ-ray emission from more than 67 active galaxies of the blazar class. One of the remarkable characteristics observed in blazars is that the γ-ray luminosity often dominates the bolometric power in these sources. The detection of blazars by EGRET has undoubtedly been one of the highlights of the mission, and has forever impacted upon our understanding of the emission mechanisms in these objects. This article summarizes some of the properties of the blazars detected by EGRET.

In addition to blazars, this article will review some recent work done in the field of EGRET unidentified sources, which constitutes the majority of the EGRET sources. A comprehensive review of all the exciting results from EGRET is not possible in just a few pages, and the reader is referred to some of the references mentioned in the article for further details.

2. The EGRET Instrument

EGRET was a pair production telescope that was sensitive to high energy γ-rays in the energy range $\sim$ 30 MeV to 30 GeV. The instrument had a lifetime of approximately 9 years, from 1991 April to 2000 June, and proved to be immensely successful. It had the standard components of a high-energy γ-ray instrument: an anticoincidence dome to discriminate against charged particles, a spark chamber particle track detector, a triggering telescope to detect the presence of the pair with the correct direction of motion, and an energy measurement system, which in the case of EGRET was constructed of NaI(Tl) crystals. The spark chamber was interspersed with high-Z material to convert the γ-rays into electron-positron pairs. EGRET's effective area was 1500 cm^2 in the energy range 0.2 GeV to 1 GeV, decreasing to about one-half the on-axis value at 18° off-axis. The threshold sensitivity of EGRET ($>$ 100 MeV) for a single 2-week observation was $\sim 3 \times 10^{-7}$ photons cm^{-2} s^{-1}. EGRET's angular resolution was energy dependent, varying from about 8° at 60 MeV to 0.4° above 3 GeV (68% containment). Further instrument details, as well as information on the preflight and postflight calibrations may be found elsewhere (e.g. Thompson et al. 1993; Esposito et al. 1999).

EGRET observations of a particular source region typically lasted for a period of 1 to 3 weeks, with some observations extending to 5.5 weeks. EGRET recorded the arrival times, directions and energies of the individual γ-rays. Using information from the exposure history maps, skymaps of counts and intensity were made for the entire field of view for each observation. The EGRET data was analyzed using a maximum likelihood technique in order to determine the significance of a source detection above the diffuse background. Details of EGRET data processing methods may be found in Bertsch et al. (1989) and Mattox et al. (1996).

Prior to EGRET, two other successful satellite experiments, SAS-2 and COS-B, pioneered the field of high energy γ-rays. These experiments were responsible for making some of the first maps of the γ-ray sky and producing the first γ-ray source catalogs (Swanenburg et al. 1981).

3. EGRET Results

Diffuse Radiation

EGRET observations of the γ-ray sky have provided a unique view of the diffuse radiation above 30 MeV. Indeed, the diffuse radiation constitutes the bulk of the emission detected by EGRET. The diffuse emission is found to have a strong Galactic component arising from cosmic-ray interactions with the local interstellar gas and radiation (Hunter et al. 1997), as well as an almost uniformly distributed component believed to be of extragalactic origin (Sreekumar et al. 1998). The precise origin of the extragalactic diffuse emission is not well-known, and possibly includes both diffuse origin as well as contributions from unresolved point sources. Some models based on discrete source contributions have considered unresolved blazars as possible contributors. Recent estimates of blazar contribution based on a γ-ray evolution function derived from γ-ray data is roughly 25 to 30 percent (Chiang & Mukherjee 1998), although earlier estimations have found a larger contribution (Stecker et al. 1996). A review on the Galactic and extragalactic diffuse γ-ray emission as detected by EGRET is given elsewhere in these proceedings (Sreekumar et al. 2001).

Blazars

Figure 1 shows the 271 point sources detected by EGRET above 100 MeV, as presented in the Third EGRET (3EG) catalog (Hartman et al. 1999). Active galactic nuclei of the "blazar" class constitute the largest fraction of the identified EGRET sources, and are marked as red circles in the figure. EGRET has detected high energy emission from more than 65 blazars, and this has indeed been one of the highlights of the mission. One notes that prior to the launch of EGRET, 3C 273 was the only extragalactic source known to emit γ-rays.

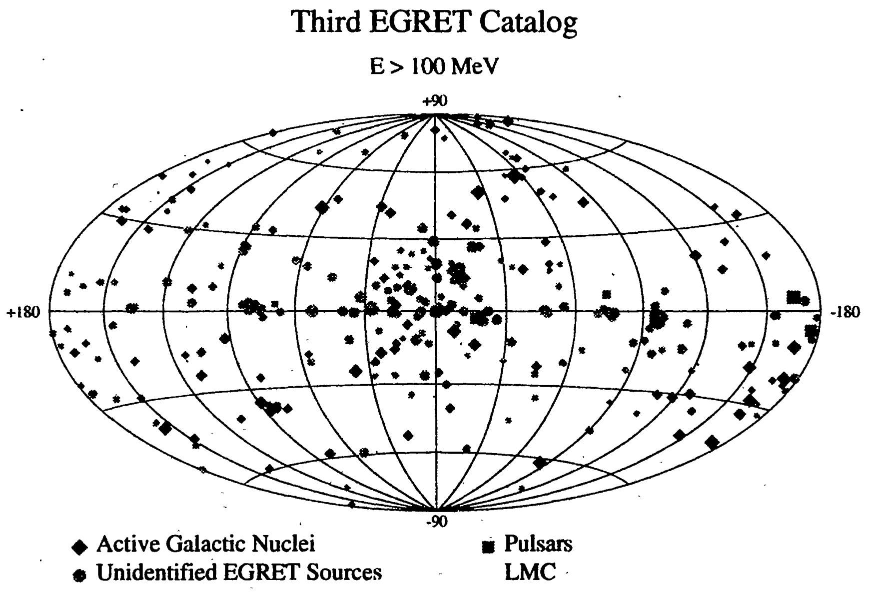

Figure 1: Point sources detected by EGRET at energies greater than 100 MeV listed in the Third EGRET Catalog (Hartman et al. 1999). The colours of the symbols correspond to the different kinds of sources detected by EGRET, as indicated in the key.

EGRET-detected blazars include OVV quasars, BL Lac objects, and high polarization quasars (HPQs). These sources are characterized by emissions that include high radio and optical polarizations, strong variability at all wavelengths, and non-thermal, continuum spectra. Blazars detected by EGRET are radio-loud, flat-spectrum radio sources, with radio spectral indices $\alpha_r \geq -0.6$ for a flux density of $S_r \propto \nu_r^{\alpha_r}$. In the majority of the blazars, the γ-ray emission dominates the bolometric power in the spectral energy distributions of these objects. The γ-ray luminosity of the EGRET blazars (assuming isotropic emission) ranges from 10^{45} to 10^{49} erg s^{-1}. Most of the blazars detected by EGRET belong to the category of flat-spectrum radio quasars (FSRQs), with about 17 being BL Lac objects. In addition, EGRET has also detected γ-ray emission from Cen A, a radio galaxy, the only one seen to emit γ-rays (Sreekumar et al. 1999). Several blazars detected by EGRET have been observed to exhibit apparent superluminal motion (e.g. 3C 279, 3C 273, 3C 454.3, PKS 0528+134), as evidenced from VLBI radio observations (Vermeulen & Cohen 1994).

Another characteristic of EGRET blazars is that they exhibit flux variability on time scales on the order of days to months. Long term flux variability for EGRET blazars have been discussed earlier by several authors (e.g. von Montigny et al. 1995; Mukherjee et al. 1997a). Figure 2 is an example of variability seen in EGRET blazars on the time scale of months, for the specific case of the blazar PKS 0528+134 over a period of six years. The data points correspond to the time averaged flux from the source during a particular observation, with the non-detections shown as upper limits at the 95% confidence level. PKS 0528+134 is one of the most variable sources detected by EGRET and exhibited a dramatic flare in 1993 March when its flux was several times greater than that of the Crab (Mukherjee et al. 1999).

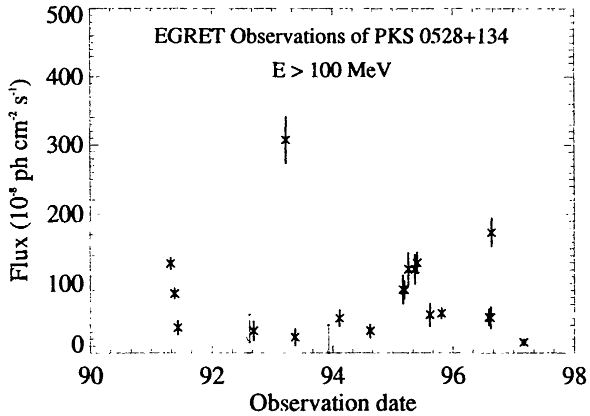

Figure 2: Flux history of the blazar PKS 0528+134 for the time period 1991 - 1998. The downward arrows correspond to 2σ upper limits (Mukherjee et al. 1999).

In general, the study of short time scale variability of blazars by EGRET is limited by the small number of photons detected by EGRET during a single observation. However, some EGRET-detected blazars have been observed to flare dramatically on much shorter time scales. A recent example of this is 3C 279 which demonstrated substantial flux variations on time scales as short as a day during the 1999 Jan-Feb and 2000 Jan-Mar observations. Figure 3 shows the light curves in the EGRET, optical (R-band) and X-ray (RXTE/PCA) bands for 3C 279 (Hartman et al. 2001). Other examples include PKS 1622-297 which exhibited a major flare during the observation in 1995. A flux increase by a factor of at least 3.6 was observed in a period of less than 7 hours (Mattox et al. 1997). The peak flux observed was $(17 \pm 3) \times 10^{-6}$ cm^{-2} s^{-1} ($E > 100$ MeV), which corresponded to an isotropic luminosity of 2.9×10^{49} ergs s^{-1} (Mattox et al. 1997). Other blazars that have shown strong variability on timescales of 1 to 3 days in the past are PKS 0528+134, 3C 454.3, 3C 279, PKS 1633+382, 1406-076, and CTA26. Studies of fast variations of γ-ray emission in blazars using structure function analysis techniques have also been carried out for a few selected sources (Nandikotkur et al. 1997; Wagner et al. 1997).

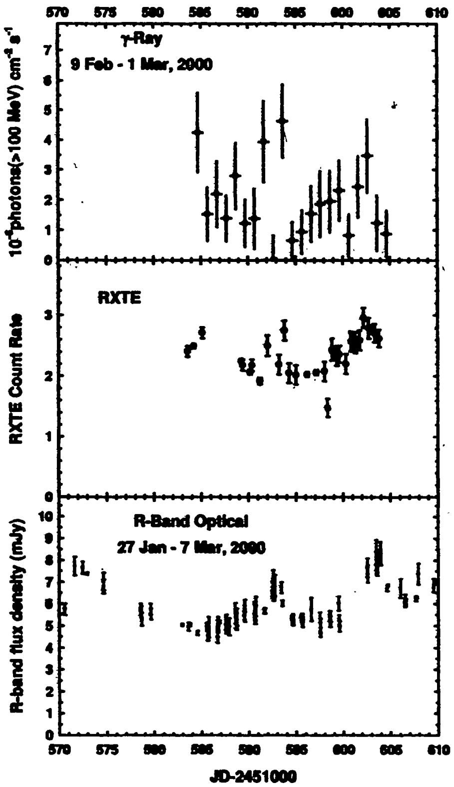

Figure 3: Gamma-ray, X-ray and optical (R-band) light curves for 3C 279, as observed in early 2000. Figure taken from Hartman et al. (2001), which also discusses a correlation analysis of the data.

The study of short time scale variability in blazars is important as they help to constrain the size of emission regions in these objects. A flux variation by a factor of two on an observed time scale δt_{obs} limits the size r of the emitting region to roughly $r \leq c\delta t_{obs}/(1+z)$ using simple light travel time arguments. When combined with the large values of the inferred isotropic γ-ray luminosity, this implies that the blazar emission region is very compact.

The spectra of blazars detected by EGRET cover the energy range from 30 MeV to 10 GeV and are well-described by a simple power-law model. Details of the EGRET spectral analysis techniques for blazars may be found elsewhere (e.g. Montigny et al 1995). The average photon spectral index of blazars in the EGRET energy band is ~ 2.2. Figure 4 shows the spectra of two blazars detected by EGRET, one an FSRQ and the other a BL Lac object (Hartman et al. 1999). There is no evidence of a spectral cutoff for energies below 10 GeV for the blazars detected by EGRET.

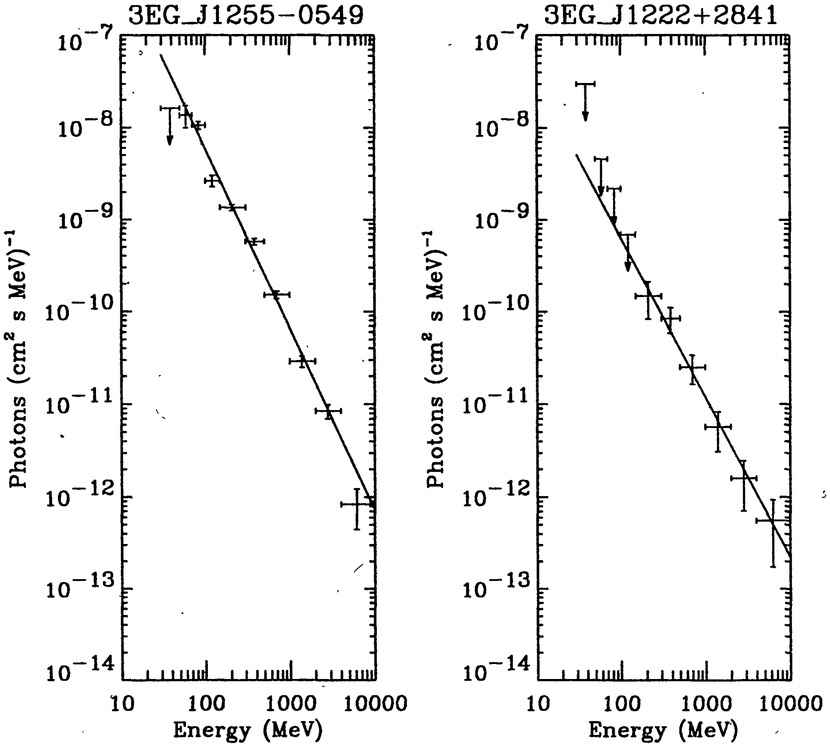

Figure 4: Photon spectra of the FSRQ 3C 279 (left) and the BL Lac object 1219+285 (right) in the energy range 30 MeV to 10 GeV. The solid lines are the best fit to a power law. 2σ upper limits are shown as downward arrows.

In order to decipher the underlying physics of the emission mechanisms in blazars, it is essential to study the broad band spectral energy distributions (SEDs) of these sources. Since EGRET first started detecting blazars, several multiwavelength campaigns have been organized to simultaneously observe these sources at different wavelengths (e.g. see Shrader & Wehrle 1997 for a review). Although these campaigns have proven difficult to organize, and the SEDs of blazars are often non-simultaneous or under-sampled, they have helped constrain blazars models.

Figure 5 shows the SED of the blazar 3C 279 from radio to γ-ray energies over 15 decades in energy for two different epochs (Wehrle et al. 1998). The overall SEDs of both FSRQs and BL Lac objects show two distinct parts: the synchrotron component and the inverse Compton (IC) component. In the case of FSRQs, as shown in figure 5 the first peak is in the optical-IR band, while the second peak is in the MeV-GeV energy range. The figure demonstrates the dominance of the γ-ray luminosity over that at other wavebands. 3C 279 also shows considerable spectral variability, particularly in the γ-ray band, between different epochs. This has been found to be a characteristic feature of the FSRQs observed by EGRET.

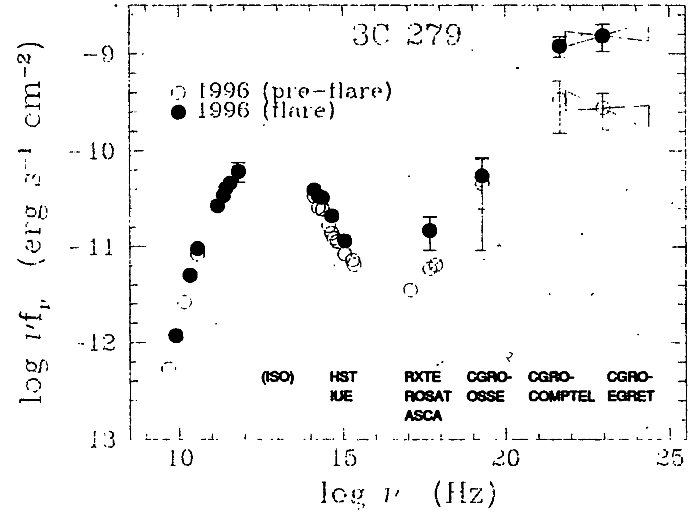

Figure 5: SED of 3C 279 from radio to γ-ray energies for different epochs. The figure demonstrates the considerable variability that is often seen in the broad band spectra of blazars (Wehrle et al. 1998).

Of the blazars detected by EGRET only three have been seen at TeV energies (> 250 GeV), all three being X-ray selected BL Lac (XBL) objects. These are Mrk 421, Mrk 501, and PKS 2155-304 (e.g. Weekes 2000). The SED of these X-ray selected BL Lac objects is different from that of FSRQs. Unlike in FSRQs, the γ-ray peak in the SED of these high-frequency-peaked BL Lacs (HBLs) no longer dominates the spectrum, although it plays a very important part. SEDs of the FSRQs and BL Lac objects detected by EGRET have been studied by many researchers, both for individual sources as well as for source classes, and the reader is pointed to some of the following references for further information (e.g. Sambruna 1999; Fossatti et al. 1999; Ghisellini et al. 1998; Urry 1999).

SEDs of EGRET blazars have been used to constrain γ-ray emission models. Most blazar models assume that blazars are powered by accretion of matter on to a supermassive black hole, and that γ-ray emission originates in strongly beamed jets. The absence of intrinsic $\gamma - \gamma$ pair absorption in the observed blazar spectra strongly points to the fact that γ-ray emission is beamed radiation from the jet. A review of the constraints placed on AGN models from the γ-ray observations may be found in Schlickeiser (1996). Current blazar models are roughly divided into leptonic or hadronic models. A detailed description of the differences between these models is beyond the scope of this article, but may be found elsewhere (e.g., Boettcher 1999a; Aharonian 2000). Leptonic jet models are often used to explain SEDs of EGRET-detected blazars. Two recent examples of this may be found for the cases of the blazars PKS 0528+134 (Mukherjee et al. 1999; Boettcher 1999b) and 3C 279 (Hartman et al. 2001), in which multi-epoch, broadband SEDs of the two sources were studied. A review of the physics inputs from multiwavelength observation of AGN is given elsewhere in these proceedings (Boettcher 2001).

Unidentified Sources

It is interesting to note that more than 60% of the EGRET sources are unidentified, with no firmly established counterparts at other wavelengths. Some of these sources have remained unidentified since the first surveys of the γ-ray sky with the COS-B satellite (Swanenburg et al. 1981). The identification of the EGRET sources, particularly those close to the Galactic plane has proved to be challenging. About 40% of the EGRET sources lie within $|b| \leq 10^\circ$ of the Galactic plane. Identification on the basis of position alone has been difficult because the size of the EGRET error contours is typically large, $\sim 0.5^\circ - 1^\circ$. In addition, the presence of strong Galactic diffuse emission along the plane, and a lack of tight correlation between the γ-ray flux and other properties, like X-ray flux, core radio flux, etc., allows only the strongest sources to be identified on the basis of position alone.

Comprehensive surveys of the fields associated with the EGRET unidentified sources have met with limited success (see Mukherjee, Grenier & Thompson 1997b for a review). Several researchers have considered the possibility that rotation-powered pulsars are likely identifications for the unidentified 3EG sources (e.g. Halpern & Ruderman 1993; Helfand 1994). It has been noted previously that the unidentified EGRET sources in the Galactic plane lie in proximity to star formation sites and supernova remnants (Yadigaroglu & Romani 1997, Sturner & Dermer 1995, Esposito et al. 1996), or are correlated with OB associations and massive stars (Montmerle 1979; Kaaret & Cottam 1996; Kaul & Mitra 1997; Romero et al. 1999). Recently, it has been noted that the mid-latitude unidentified EGRET sources form a population distinctly different from the sources along the Galactic plane (Gehrels et al. 2000; Grenier 2000). Further, it has been suggested that these mid-latitude sources are probably associated with the Gould Belt of massive stars and gas clouds, about 600 light years away (Gehrels et al. 2000).

Studying multiwavelength data in the fields of EGRET unidentified sources has recently been used as an approach to aid in the identification of some of the high energy 3EG sources. For instance, using archival X-ray imaging data from *ROSAT* (PSPC and HRI) and *ASCA* GIS, as well optical observations, Mukherjee et al. (2000) have concluded that 3EG J2016+57 in the Cygnus region, is most likely the blazar-like radio source B2013+370 (G74.87+1.22). This identification was later confirmed by Halpern et al. (2001a) who found optical spectroscopic identifications of all soft and hard X-ray sources in the error circle of the EGRET source, leaving B2013+370 as the most likely counterpart of 3EG J2016+3657. Figure 6 shows the X-ray image of the field of 3EG J2016+3657, with the position of B2013+370 marked as source # 3.

3EG J2227+6122 is another source in the Galactic plane that was the subject of recent multiwavelength study (Halpern et al. 2001b). *ROSAT* and *ASCA* observations of the EGRET field showed the presence of a point source RX/AX J2229.0+6114, which had no optical counterpart. Using X-ray and radio data Halpern et al. (2001b) concluded that 3EG J2227+6122 is a young pulsar (Halpern et al. 2001c). An image from

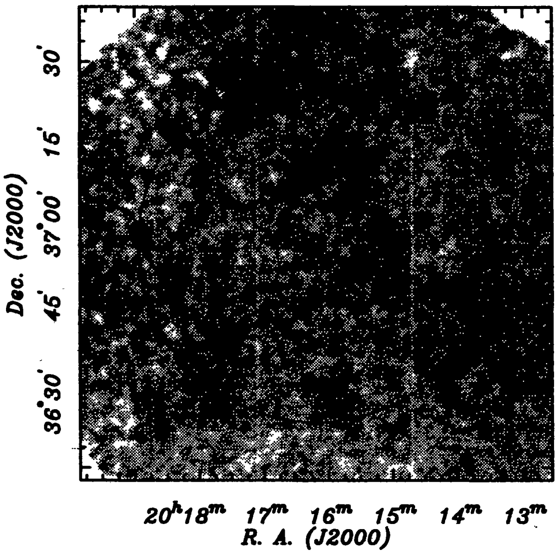

Figure 6: *ROSAT* PSPC image and 95% confidence error circle of 3EG J2016+3657, taken from Mukherjee et al. (2000). The individually-numbered X-ray sources are described in that paper and in Halpern et al. (2001a). Source # 3 is the blazar-like radio source B2013+370.

the *Chandra* X-ray Observatory showed a point source surrounded by diffuse emission, contained within the incomplete radio shell, at the location of RX/AX J2229.0+6114. Halpern et al. (2001c) suggested that this is a new supernova remnant, G106.6+2.9, with the radio shell likely to be a shock between the pulsar wind nebula and the surrounding medium.

Other efforts to identify the γ-ray sources using X-ray imaging studies are described elsewhere (e.g., Brazier et al. 1998; Mirabal & Halpern 2001; Reimer et al. 2000; Roberts, Romani & Kawai 2001).

Other Sources

In addition to blazars, EGRET has detected γ-rays from 6 pulsars. These are the Crab, Vela, PSR 1706-44, B1951+31, B1055-58, and Geminga. Soft γ-rays have also been seen from the pulsar B1509-58, although no pulse was detected in the EGRET energy range. A few other pulsars have been marginally identified. All strongly-detected γ-ray pulsars are double-pulsed, although the light curves exhibit a wide variety of patterns. Unlike blazars, the flux history of pulsars show relatively constant emission over time. The γ-ray spectra of these sources have power-law indices in the range -1.39 to -2.07. An up-to-date review on EGRET pulsars and how they impact upon models of pulsar γ-ray emission is given elsewhere (Thompson 2000).

EGRET has also detected high energy emission from 5 γ-ray bursts (GRBs). A review on the EGRET-detected bursts is given by Dingus et al. 1998.

Summary

The exciting results from EGRET, during this past decade, have been instrumental in opening a new chapter in high energy γ-ray astrophysics. The EGRET results were complemented by results from ground-based atmospheric Cherenkov telescopes (ACTs), which detected γ-rays with energies above 250 GeV from a few of the same sources (see Catanese & Weekes 1999 for a review). In the future, it is clear that one needs more sensitive instruments, both satellite-borne as well as ground-based to study the high energy γ-ray sky. Currently, two next-generation space experiments, GLAST and AGILE are planned. GLAST, which is expected to be launched in 2005, is projected to be a state-of-the art detector which will use a Si-strip tracker and a CsI calorimeter (Gehrels & Michelson 1999). GLAST's sensitivity will be a factor of > 30 better than EGRET, and is expected to detect two orders of magnitude more sources than EGRET. GLAST will have some overlap with ground-based instruments in the 30-300 GeV regime. A smaller EGRET-sized experiment, the Italian AGILE (Tavani et al. 1999), sensitive in 30 MeV to 50 GeV energy range, is expected to be launched in 2002 and bridge the gap before GLAST.

The space-based experiments will be complemented by several next generation ground-based experiments. It is particularly important to study the energy region between 20 and 250 GeV, which has been unexplored until now. Recently, two experiments STACEE and CELESTE have demonstrated that lower energy thresholds can be achieved by using existing large arrays of solar heliostat mirrors to collect Cherenkov light (Oser et al. 1999; de Naurois et al. 1999). In addition, experiments that will be built in the future include MAGIC in Spain, HESS in Namibia, VERITAS in Arizona, and Super-CANGAROO in Australia (see Catanese & Weekes 1999, and references therein). The project GRACE in India will involve four independent experimental systems that will span nearly ten decades of photon energy ($\sim$ 10 keV - 100 TeV) and do coordinated studies of γ-ray sources (Bhat 2001). These experiments will complement each other and together span the energy range from 20 GeV to 10 TeV.

In summary, the future of high energy γ-ray astronomy looks very promising.

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