Gamma ray astrophysics: the EGRET results

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Abstract
Cosmic gamma rays provide insight into some of the most dynamic processes in the Universe. At the dawn of a new generation of gamma-ray telescopes, this review summarizes results from the Energetic Gamma Ray Experiment Telescope (EGRET) on the Compton Gamma Ray Observatory, the principal predecessor mission studying high-energy photons in the 100 MeV energy range. EGRET viewed a gamma-ray sky dominated by prominent emission from the Milky Way, but featuring an array of other sources, including quasars, pulsars, gamma-ray bursts and many sources that remain unidentified. A central feature of the EGRET results was the high degree of variability seen in many gamma-ray sources, indicative of the powerful forces at work in objects visible to gamma-ray telescopes.

(Some figures in this article are in colour only in the electronic version)
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1. Introduction: gamma rays from the Universe
For most of history, humans have learned about the cosmos by viewing the light that our eyes can detect. Only in the twentieth century did it become clear that vast amounts of information arrive in different channels, most prominently the invisible forms of electromagnetic radiation. This information revolution started with radio, which can reach the Earth’s surface, and then exploded with the space age discoveries that essentially every part of the spectrum carries unique information about conditions and processes in distant parts of the Universe. Most of these forms of radiation are blocked by the Earth’s atmosphere and therefore require space observatories or some form of indirect detection.

Gamma rays represent the high-energy end of the electromagnetic spectrum, comprising photons with the highest frequencies or shortest wavelength. Because gamma rays are so energetic, they are usually defined by their energies, which are typically higher than 100 kilo electron volts (keV), although the line between x-rays and gamma rays is not a...
sharp one. Often x-rays are considered to be those photons produced by atomic or thermal processes, while gamma rays are those involving nuclear or nonthermal processes. Above $10^6$ eV (1 MeV), and with no upper limit to energy, all photons are gamma rays.

As might be imagined, gamma rays are produced by energetic phenomena. In fact, only the lowest-energy gamma rays, those associated with radioactivity, have natural sources on Earth. Cosmic sources of gamma rays extend to vastly higher energies, reflecting extreme physical conditions and powerful collisions. Astrophysical settings for gamma-ray production include supernovae, pulsars and quasars, as well as the interstellar and intergalactic medium. Although gamma rays are absorbed in the atmosphere, the Universe is largely transparent to these high-energy photons out to high redshift. Gamma rays thus provide a valuable probe of the largest energy transfers throughout much of the Universe. Such phenomena can be expected to be important in understanding the forces of change on the largest scale.

The present review is focused on one important segment of gamma-ray astrophysics: the results from the Energetic Gamma Ray Experiment Telescope (EGRET) that flew on the Compton Gamma Ray Observatory (CGRO) during its 1991–2000 life. EGRET provided the first detailed all-sky observations of high-energy gamma rays (with typical energies in the $100–1000$ MeV range). With the advent of two successors to EGRET, the Italian Astro-rivelatore Gamma e Immagini Leggero (AGILE) mission and the international Fermi Gamma-ray Space Telescope (formerly the Gamma-ray Large Area Space Telescope, GLAST) mission, the time seems appropriate to examine the observational foundation of these two current missions.

The outline of this review is as follows:

1. Introduction
2. EGRET in the context of other gamma-ray telescopes
   - Historical
   - CGRO
   - EGRET: Detecting high-energy gamma rays
3. An overview of the gamma-ray sky
4. Galactic diffuse
5. Gamma-ray sources: the third EGRET catalog
6. Galactic sources
   - Pulsars
   - Binary Sources
   - Other Sources
7. Extragalactic sources
   - Blazars
   - Other galaxies
   - Diffuse extragalactic radiation
   - Gamma-ray bursts
8. Local sources
   - The Moon
   - Solar flares
   - Primordial black holes
9. Open questions for AGILE and Fermi

2. EGRET in the context of other gamma-ray telescopes

2.1. Before the Compton Observatory

The potential for studying the sky with gamma rays was identified fifty years ago (e.g. Morrison 1958). A decade later the first definitive detections of gamma rays from space came with the OSO-3 discovery of gamma radiation from the plane of our Galaxy (Clark et al 1968). In the following years, a number of fairly small balloon-borne and satellite missions began to reveal aspects of the gamma-ray sky. Some examples are as follows.

- Browning, Ramsden and Wright (1971) found pulsed high-energy gamma radiation from the Crab Pulsar, using a gamma-ray telescope carried on a balloon.
- The US Small Astronomy Satellite 2 (SAS-2, Fichtel et al 1975) showed that high-energy gamma rays help trace the structure of our Galaxy, the Milky Way (Hartman et al 1979). It also discovered a second gamma-ray pulsar, the Vela Pulsar (Thompson et al 1975), and the first unidentified gamma-ray source, γ195 + 5 (Kniffen et al 1975), which was later called Geminga (Bignami et al 1983).
- The European COS-B satellite (Bignami et al 1975) produced the first catalog of high-energy gamma-ray sources, most of which were not identified with objects seen at other wavelengths (Hermesen et al 1977, Swanenburg et al 1981). In addition, it found the first extragalactic gamma-ray source, the nearby quasar 3C273 (Swanenburg et al 1978), and made the first gamma-ray observations of molecular clouds as spatially extended sources (Caraveo et al 1980).
- VELA satellites operated by the US military discovered short-duration cosmic gamma-ray bursts, a completely new phenomenon (Klebesadel et al 1973).
- The Third High Energy Astrophysical Observatory (HEAO-3) carried a low-energy gamma-ray telescope with high spectral resolution (Mahoney et al 1980) that detected the 0.5 MeV positron–electron annihilation line coming from the Galactic Center region (Riegler et al 1981), confirming previous reports from balloon instruments (e.g. Leventhal et al 1978).

During this same period, a parallel branch of gamma-ray astrophysics using ground-based detectors was developing. At gamma-ray energies above about $10^{11}$ eV (100 GeV), cosmic photons are too scarce to be detected by satellite detectors. The Earth’s atmosphere itself can be used, however, as a detector for these very high-energy (VHE) photons. When such photons collide with the material at the top of the atmosphere, they produce showers of particles moving faster than the local speed of light, thereby emitting Cherenkov radiation in the optical and ultraviolet. The flashes of light from these interactions can be detected with atmospheric Cherenkov telescopes (ACTs) on the ground, providing an indirect way to conduct gamma-ray astrophysics. A milestone in VHE gamma-ray astrophysics was reached in 1989 with the high-confidence detection of the Crab Nebula (but not the pulsar).
with the Whipple Observatory ACT (Weekes et al 1989). Although VHE studies are beyond the scope of the present review, this rapidly developing field is highly complementary to space-based gamma-ray studies. Weekes (2003) provides a broad review of gamma-ray astrophysics, with emphasis on the VHE field, while Chadwick et al (2008) and Aharonian et al (2008) present recent summaries of results.

Each of these programs provided a glimpse of the gamma-ray Universe, confirming the potential of this field for helping understand high-energy cosmic phenomena. None of them gave a comprehensive picture. Some viewed only portions of the sky. Some studied only a limited portion of the huge energy range falling under the gamma-ray banner. Most were operated for only limited durations. Figure 1 shows schematically the time frames and energy ranges of many of these space-based gamma-ray telescopes. NASA’s Great Observatories program offered the opportunity to make a major advance across much of the gamma ray portion of the spectrum.

2.2. The Compton Gamma Ray Observatory

The Compton Gamma Ray Observatory (CGRO), shown in figure 2, was the second of NASA’s Great Observatories, following the Hubble Space Telescope. Although the original plan was to have all four operating simultaneously, circumstances delayed the launches of the Chandra X-ray Observatory (originally called AXAF) and the Spitzer Space Telescope (Infrared, originally called SIRTF) until the Compton Observatory mission was essentially complete. CGRO itself was launched on the Space Shuttle Atlantis on 5 April 1991 and operated successfully until it was de-orbited on 4 June 2000.

CGRO carried four gamma-ray telescopes, each with its own energy range, detection technique and scientific goals. Together these four instruments covered energies from less than 15 keV to more than 30 GeV, over six orders of magnitude in the electromagnetic spectrum. The three lower-energy telescopes were as follows.

- Burst and Transient Source Explorer (BATSE, Principal Investigator, G Fishman, NASA Marshall Space Flight Center). BATSE was the smallest of the CGRO instruments, consisting of one module located on each corner of the spacecraft. Each BATSE unit included a large flat NaI(Tl) scintillator pointed with its face away from the center of the observatory and a smaller thicker scintillator for spectral measurements, combining to cover an energy range from 15 keV to over 1 MeV. Important results from BATSE included the mapping of over 2700 gamma-ray bursts, showing an isotropic distribution on the sky. A summary of BATSE results is given by Fishman (1995).

- Oriented Scintillation Spectrometer Experiment (OSSE, Principal Investigator J Kurfess, Naval Research Laboratory). OSSE used four large, collimated scintillator detectors to study low-energy gamma-rays, 60 keV–10 MeV. OSSE mapped the 0.5 MeV line from positron annihilation and provided detailed measurements of many hard x-ray/soft-gamma-ray sources. Kurfess (1996) summarized many of the important results from OSSE.

- Imaging Compton Telescope (COMPTEL, Principal Investigator V Schönfelder, Max Planck Institute for Extraterrestrial Physics). COMPTEL detected medium-energy gamma rays using a Compton scattering technique, effective between 0.8 MeV and 30 MeV. Among its results, COMPTEL mapped the distribution of radioactive aluminium-26 in the Galaxy, showing the locations of newly formed material. The summary by Schönfelder et al (1996) describes many of the COMPTEL results.

This brief summary covers only a few of the many important results from these CGRO instruments. Schönfelder (2001) reviewed the entire field of gamma-ray astrophysics, with particular emphasis on this energy range.
2.3. EGRET: detecting high-energy gamma rays

In the energy range above 10 MeV, the principal interaction process for gamma rays is pair production, a direct example of the Einstein equation $E = mc^2$. The photon energy is converted into an electron and its antiparticle, a positron. This process can take place in the field of an atomic nucleus or in a strong magnetic field, but not in free space, in order to conserve energy and momentum. These high-energy gamma rays cannot be reflected or refracted; a gamma-ray telescope actually detects the electron and positron.

The Energetic Gamma Ray Experiment Telescope (EGRET) was the high-energy instrument on the Compton Observatory, covering the energy range 20 MeV–30 GeV (Hughes et al. 1980, Fichtel et al. 1983). The Co-Principal Investigators represented the three major contributors to the EGRET hardware: C Fichtel, NASA Goddard Space Flight Center (GSFC), R Hofstadter, Stanford University (SU), and K Pinkau, Max Planck Institute for Extraterrestrial Physics (MPE). The operational concept of EGRET, similar in most respects to the designs of other high-energy gamma-ray telescopes, is shown in figure 3. The two key challenges for any such telescope are (1) identifying the gamma-ray interaction in the presence of a huge background of charged particles (cosmic rays, solar particles and trapped radiation) and (2) measuring the gamma-ray arrival time, arrival direction and energy.

The process works as follows.

(i) A gamma ray enters EGRET. It first passes through the anticoincidence system without producing a signal.
(ii) The gamma ray interacts in one of 28 thin tantalum sheets. This interaction converts the gamma ray into an electron and a positron via pair production.
(iii) The spark chamber tracker records the paths of the electron and positron, allowing EGRET to see the pair interaction and to determine the arrival direction of the gamma ray.
(iv) The electron and positron pass through two scintillator detectors operated in a time-of-flight (TOF) configuration. The TOF signal confirms the direction of the particles and triggers the readout of the spark chambers.
(v) The electron and positron enter the calorimeter, producing an electromagnetic shower, which measures the energies of the particles and therefore the energy of the original gamma ray.
(vi) Unwanted cosmic ray particles produce signals in the anticoincidence system, which tell the electronics not to trigger the spark chamber. The anticoincidence system rejects nearly all unwanted signals produced by cosmic rays that enter EGRET.

Figure 4 shows EGRET as it appeared before integration onto the Compton Gamma Ray Observatory. Here is some information about the key subsystems.

- The anticoincidence system consists of a single dome of plastic scintillator, read out by 24 photomultiplier tubes mounted around the bottom. This subsystem was built by the MPE group.
- The tracker is made of 36 wire grid spark chambers, interleaved with the converter plates. The active area of the spark chambers is 81 cm × 81 cm. This subsystem was the work of the group at GSFC.
- The TOF trigger system, also from GSFC, has two 4 × 4 arrays of plastic scintillator tiles, each read out by a single photomultiplier tube.
- The calorimeter, called the total absorption shower counter (TASC), was made of 36 NaI crystals bonded together and read out by 16 photomultiplier tubes. The SU group built the TASC.

The primary EGRET calibration was carried out at the Stanford Linear Accelerator Center (SLAC), using a gamma-ray beam varying in energy from 15 MeV to 10 GeV. The beam scanned the active area of EGRET at a variety of angles.
out to 40° from the instrument axis. The calibration thus covered essentially the entire phase space to be observed in orbit (Thompson et al 1993). Analysis of both the calibration and flight data concentrated on recognizing and measuring the individual pair-production events. An initial selection of events was made in software, removing many triggers that did not produce tracks consistent with being electron–positron pairs. Events the software could not resolve were reviewed by data analysts and scientists, leading to a final data set almost entirely free of charged particle contamination.

The basic properties of EGRET are shown in table 1. The single-photon angular resolution or point spread function (PSF) is energy-dependent. The angle θ in degrees containing 67% of the gamma rays from a delta function source with energy E in MeV is given by $\theta = 5\cdot85E^{-0.534}$.

Observations of the Compton Gamma Ray Observatory ranged in duration from a few days to a few weeks, reflecting the paucity of cosmic gamma-ray photons. A listing of the observations, along with other information about CGRO, can be found at the CGRO Science Support Center Web site, http://cossc.gsfc.nasa.gov/docs/cgro/index.html.

Because the EGRET spark chambers were gas detectors, their performance deteriorated with time due to gas aging. The system carried enough replacement gas for four complete refills of the chamber, all of which were used. The performance of the instrument was recalibrated in flight, using constant sources such as the diffuse Galactic emission and bright pulsars as reference sources. The preliminary in-flight calibration was described by Esposito et al (1999), and the final performance analysis was described by Bertsch et al (2001).

3. An overview of the high-energy gamma-ray sky

In its nine-year lifetime, EGRET detected over 1,500,000 celestial gamma rays. One photon at a time, EGRET built up a picture of the entire high-energy gamma-ray sky. Figure 5 shows the summed map above 100 MeV, in Galactic coordinates. The Milky Way runs horizontally across the center of the figure, and the Galactic center lies at the center of the map.

This image provides a striking contrast to the view of the sky at visible wavelengths. Some of the key features that will be discussed in following sections are as follows.

* The Milky Way is extremely bright, particularly toward the inner part of the Galaxy.
* The brightest persistent sources are pulsars.
Figure 5. The sky seen with EGRET, shown in Galactic coordinates. In this false color image, the Galactic Center lies in the middle of the image.

- Many of the bright sources away from the Galactic plane are highly variable types of active galactic nuclei in the blazar class.
- The Moon is visible and outshines the Sun most of the time.
- Many of the sources are not identified with known objects.

4. Galactic diffuse gamma-ray emission

The high-energy gamma-ray sky is dominated by the bright Galactic ridge. This component was the first one predicted and detected in gamma-ray astronomy, because our galaxy is known to be filled with high-energy particles, magnetic fields, photon fields and interstellar gas. The spatial distribution of the gamma radiation traces the galactic structure as determined from radio and other measurements. These basic features were known in the SAS-2 and COS-B era, along with the realization that the cosmic ray flux cannot be uniform throughout the Galaxy and still be consistent with these measurements. The EGRET data provided detailed information, but also introduced a puzzle that remains unresolved.

The physical processes that produce EGRET energy gamma rays are familiar ones to the particle physics community.

- Inelastic collisions of cosmic ray particles with the interstellar gas (mostly hydrogen) produce secondary particles, particularly charged and neutral $\pi$ mesons. The neutral pions decay almost immediately into two gamma rays. In the center of mass reference frame, each gamma ray has half the energy of the $\pi^0$, or about 67 MeV. Because the cosmic rays typically have a broad range of high energies, the energy spectrum of the gamma rays resulting from nucleon–nucleon collisions is spread out into a broad peak rather than a narrow line.
- Cosmic ray electrons colliding with photons can boost the photon energies into the gamma-ray band by inverse Compton scattering. The principal targets are the optical and infrared photons found throughout the Galaxy.
- Another cosmic ray electron process involves collisions with the interstellar gas, producing gamma rays through bremsstrahlung.
- Both nucleon and electron cosmic rays can in principle produce gamma rays through interactions with magnetic fields by synchrotron radiation. In practice, the fluxes expected from synchrotron radiation with known particles and magnetic fields are small compared with the other sources.

The EGRET energy spectrum of the gamma radiation from the Galactic Center region is shown in figure 6, along with the calculated source components (Hunter et al 1997). Below 100 MeV, electron bremsstrahlung is the principal component, while at higher energies the nucleon–nucleon $\pi^0$-decay source is the most important. The expected ‘bump’ compared with a power law spectrum is clearly visible.

Building on the work of Bertsch et al (1993), Hunter et al (1997) carried out detailed modeling of the Galactic radiation. Measured cosmic ray intensities were combined with a three-dimensional model of the photon and gas distribution, using 21 cm radio measurements to trace neutral hydrogen (H I) and carbon monoxide (CO) transition radio measurements as a tracer of molecular hydrogen (H2). Coupling between the matter and cosmic ray densities was assumed, based on arguments of dynamic balance between matter, magnetic fields and cosmic rays. This model reproduced most features of the observed gamma radiation.

Visible in figure 6 is one unexpected feature of the EGRET observations: the flux above 1 GeV exceeds the model prediction by a significant amount (well beyond any known measurement uncertainties). This discrepancy has become known as the ‘GeV excess.’

An alternative modeling approach, called GALPROP, has been developed by Strong et al (2000, 2004b). This model emphasizes cosmic ray propagation calculations and a larger inverse Compton contribution to the gamma radiation. Although the basic version of GALPROP does not reproduce the GeV excess, these authors have shown that plausible assumptions about cosmic ray densities in the Galaxy higher than the local values can reproduce the EGRET data.
De Boer (2005) has invoked a new component of the gamma radiation coming from annihilation of supersymmetric dark matter as the source of the GeV excess. Bergström et al (2006) conclude, however, that this dark matter model is inconsistent with measurements of antiprotons. Stecker et al (2008) argue in favor of a miscalibration of the EGRET detector at high energies as an explanation. No consensus exists. It is perhaps ironic that the one component of the gamma-ray sky that was thought to be understood has left a mystery at the end of the EGRET mission.

On a more local scale, Hunter et al (1994), Digel et al (1995), and Digel et al (1996) conducted gamma-ray studies of the nearby Ophiuchus, Orion, and Cepheus regions. By comparing the EGRET maps with maps of CO clouds, they were able to trace the ratio of molecular hydrogen column density to integrated CO intensity. The gamma-ray intensities were found consistent with models based on the local flux measurements of cosmic rays.

Another issue with the diffuse radiation is that the matter content of the Galaxy is not necessarily completely measured. Infrared data suggest the presence of unseen gas clouds that could require an additional component in the diffuse Galactic gamma-ray model (Grenier et al 2005).

5. Gamma-ray sources: the third EGRET catalog

Individual gamma-ray sources appear as excesses above the modeled diffuse emission. The EGRET analysis process used a maximum likelihood method to compare probabilities of fitting a given region of the sky with and without a source (Mattox et al 1996). The most complete analysis of the sky by the EGRET team was the third EGRET catalog (3EG; Hartman et al 1999). Starting from the Hunter et al (1997) diffuse model, the 3EG analysis examined each viewing period plus combinations of viewing periods, from the start of the mission up through the end of 1995, using multiple energy ranges. Because EGRET was operated only intermittently after this time, the total exposure added by later phases of the mission contributed little to the overall mapping of the sky.

Figure 7 summarizes the 3EG results on gamma-ray sources, with the source locations shown in Galactic coordinates. In this figure, the symbol size indicates the peak source brightness. The gamma-ray sky is highly variable, so not all sources were seen at all times. The census of the 271 3EG gamma-ray sources was as follows.

- 94 sources show a probable or possible association with the class of active galactic nuclei known as blazars.
- Five pulsars appear in the catalog.
- The Large Magellanic Cloud was detected as an extended gamma-ray source.
- One solar flare was bright enough to be seen in the source analysis
- 170 sources, well over half the total, had no identification with known astrophysical objects.

Following the publication of the 3EG catalog, extensive efforts were made to identify individual sources or source populations. A few of the 3EG sources appear to be artifacts of the analysis (Thompson et al 2001). The following sections describe the detected source classes and efforts at identification, as well as some sources that did not appear in the catalog.

Recently, Cassandjian and Grenier (2008) have developed a new catalog of EGRET sources, based on a new model of the diffuse emission (Grenier et al 2005). This catalog, which contains only 188 sources, incorporates many of the 3EG sources into the diffuse radiation as gas concentrations, particularly at intermediate Galactic latitudes. It does, however, remove a number of identified sources, some of which showed evidence of time variability. Changing the diffuse model would not be expected to eliminate time-variable sources. This catalog should probably be considered as an alternative analysis rather than a replacement for the 3EG catalog. Because it is so new, it has not received the same level of study as the 3EG catalog.
6. Galactic gamma-ray sources

Particularly along the Galactic plane, the modeling of the diffuse gamma radiation strongly affects the calculated properties, or even the existence, of sources. For this reason, the third EGRET catalog adopted different confidence levels for including sources as detections. Within $10^\circ$ of the Galactic plane, a statistical significance of $5\sigma$ was required; at higher latitudes the requirement was $4\sigma$. Even with this more stringent requirement, figure 7 shows a clear population of sources concentrated along the plane.

6.1. Pulsars

The first high-energy gamma-ray source class was rotation-powered pulsars, starting with the Crab and Vela, seen by SAS-2 and COS-B. EGRET expanded the number of gamma-ray pulsars to at least 6, with several other good candidates. A summary of the EGRET results on pulsars is given by Thompson (2004). These rapidly rotating neutron stars, originally seen in the radio (Hewish et al. 1968), have strong magnetic, electric and gravitational fields. Particles accelerated to high energies in the magnetospheres of pulsars can interact near the pulsar to produce gamma rays through curvature radiation, synchrotron radiation or inverse Compton scattering.

The telescopes on the Compton Gamma Ray Observatory identified seven or more gamma-ray pulsars, some with very high confidence and others with less certainty. Figure 8 shows the light curves from the seven highest-confidence gamma-ray pulsars in five energy bands: radio, optical, soft x-ray ($<1$ keV), hard x-ray/soft gamma ray ($\sim 10$ keV–1 MeV) and hard gamma ray (above 100 MeV). Based on the detection of pulsations, all seven of these are positive detections in the gamma-ray band.

Some important features of these pulsar light curves are as follows.

- They are not the same at all wavelengths. Some combination of the geometry and the emission mechanism is energy-dependent. In soft x-rays, for example, the emission in some cases appears to be thermal, probably from the surface of the neutron star; thermal emission is not the origin of radio or gamma radiation.
- Not all seven are seen at the highest energies. PSR B1509−58 is seen up to 10 MeV by COMPTEL (Kuiper et al. 1999), but not at higher energies by EGRET.
- The six seen by EGRET all have a common feature—they show a double peak in their light curves. Because these high-energy gamma rays are associated with energetic particles, it seems likely that the particle acceleration and interactions are taking place along a large hollow cone or other surface. Models in which emission comes from both magnetic poles of the neutron star appear less probable in light of the prevalence of double pulses.

In addition to the six high-confidence pulsar detections above 100 MeV, three additional radio pulsars may have been seen by EGRET: PSR B1046−58, PSR B0656+14 and PSR J0218+4232, the only millisecond pulsar with evidence of gamma-ray emission (Kuiper et al. 2000, 2002).

Although the pulsations identify sources as rotating neutron stars, the observed energy spectra reflect the physical mechanisms that accelerate charged particles and help identify interaction processes that produce the pulsed radiation. Broadband spectra for the seven highest-confidence gamma-ray pulsars are shown in figure 9. The presentation in $\nu F_\nu$
format (or $E^2$ times the photon number spectrum) indicates the observed power per frequency interval across the spectrum. In all cases, the maximum power output is in the gamma-ray band. Other noteworthy features on this figure are as follows.

- The distinction between the radio emission (which originates from a coherent process) and the high-energy emission (probably from individual charged particles in an incoherent process) is visible for some of these pulsars, particularly Crab and Vela.
- Vela, Geminga, and B1055−52 all show evidence of a thermal component in x-rays, thought to be from the hot neutron star surface.
- The gamma-ray spectra of known pulsars are typically flat, with most having photon power-law indices of about 2 or less between 30 MeV and several GeV. Energy breaks are seen in the 1−4 GeV band for several of these pulsars. These changes in the spectral index may be related to the calculated surface magnetic field of the pulsar. The lowest-field pulsars have no visible break in the EGRET energy range; the existence of a spectral change is deduced from the absence of TeV detections of pulsed emission. The highest-field pulsar among these, B1509−58, is seen only up to the COMPTEL energy band.
- No pulsed emission is seen above 30 GeV, the upper limit of the EGRET observations, except for a recent detection of the Crab by the MAGIC telescope (Teshima, 2008). The nature of the high-energy cutoff is an important feature of pulsar models.
- Although figure 9 shows a single spectrum for each pulsar, the pulsed energy spectrum varies with pulsar phase. A study of the EGRET data by Fierro et al. (1998) of the phase-resolved emission of the three brightest gamma-ray pulsars (Vela, Geminga, Crab) showed no simple pattern of variation of the spectrum with phase that applied to all three pulsars. A broadband study of the Crab by Kuiper et al. (2001) indicated the presence of multiple emission components, including one that peaks in the 0.1−1 MeV range for the bridge emission between the two peaks in the light curve. Improved measurements and modeling of the phase-resolved spectra of pulsars can be expected to be a powerful tool for the study of the emission processes.

The measured spectra can be integrated to determine the energy flux of each pulsar. Except for the Crab and PSR B1509−58, whose luminosity peaks lie in the ~100 keV−1 MeV range, the energy flux for the other gamma-ray pulsars is dominated by the emission above 10 MeV. The energy flux can be converted to an estimated luminosity by using the measured distance to the pulsar and an assumed emission solid angle. For simplicity, I assume an emission into 1 sr. This value is unlikely to be the same for all pulsars but provides a simple reference point for comparison. A significant uncertainty in such calculations is introduced by the distance estimate. Table 2 summarizes these results for the ten pulsars. $P$ is the

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**Figure 8.** Light curves of seven gamma-ray pulsars in five energy bands. Each panel shows one full rotation of the neutron star. Adapted from Thompson (2004).
pulsar spin period in seconds. $\tau$ is the estimated age of the pulsar. $E$ is the rate the pulsar is losing energy as it slows down. $F_E$ is the energy flux seen at high energies (x-rays and gamma rays). The distance $d$ is given in kiloparsecs. $L_{\text{HE}}$ is the calculated high-energy luminosity of the pulsar. $\eta$ is the efficiency for conversion of spin-down energy loss into high-energy radiation.

One trend, first noted by Arons (1996), can be derived from this table. Figure 10 shows the efficiency of each pulsar as a function of the open field line voltage, the potential that can be developed by the rotating neutron star. The efficiency increases as the open field line voltage decreases. The implication of this figure is that there must be a limit where the open field line voltage must either turn off or reach some saturation value.

Despite trends such as the one shown in figure 10, each one of the nine high-confidence and lower-confidence pulsars seen by EGRET has at least one unique feature. Some examples are given below.

- The Crab is the only gamma-ray pulsar to have its light curve aligned with the light curves seen at all other wavelengths. This is the youngest gamma-ray pulsar and the one with the largest spin-down luminosity. It is also the least efficient of these in converting spin-down luminosity into high-energy radiation.
- PSR B1951+32 is the only one of these to have a spectrum extending to the limits of the EGRET energy range with no evidence of a spectral cutoff. Of the high-confidence pulsars, it is the only one not bright enough to appear as a source in the 3EG catalog.
- PSR B1706−44 is unique in having a gamma-ray spectrum with two power laws and a change in slope at about 1 GeV (compared with spectral cutoffs seen in others).
- Geminga is the only radio-quiet gamma-ray pulsar found by EGRET.
- PSR B1055−52 shows the highest efficiency of any of these pulsars for conversion of spin-down energy into gamma radiation.
- PSR B1046−58 is the only one of these with no pulsed x-ray counterpart.
- PSR J0218+4232 is the only millisecond pulsar with apparent gamma-ray emission. It is also the only one of these pulsars with another candidate gamma-ray source (a blazar) close enough spatially to cause source confusion.

Despite the wide range of information about these pulsars from their timing properties and their measured gamma-ray characteristics, the fact that a special feature can be found for each one limits our ability to draw broad conclusions.

Stimulated by these observations of gamma-ray pulsars, theorists have carried out extensive modeling of these high-energy neutron stars, but without reaching a consensus on where the particles are being accelerated in the star’s magnetosphere or how these particles interact to produce the gamma radiation. Some examples of theoretical high-energy pulsar modeling are Sturrock (1971), Ruderman and Sutherland (1975), Romani (1996), Harding and Muslimov (2005), Cheng and Zhang (1998) and Hirotani (2008). A useful overview of such theoretical work and the implications for pulsar population studies is given by Harding et al (2007).

In addition to the gamma-ray pulsars identified by their periodic emission, there are several potential associations of known pulsars with EGRET sources. Some radio pulsars discovered after the end of the CGRO mission are positionally consistent with 3EG sources and have enough energy to power the observed gamma radiation (e.g. Kramer et al 2003, Halpern et al 2001). A related case is 3EG J1835+5918, with properties suggesting an association with the isolated neutron star RX J1836.2+5925 (Mirabal and Halpern 2001, Reimer et al 2001, Halpern et al 2002). Because gamma-ray pulsars appear to have significant timing noise, searching for pulsations in the EGRET data by extrapolating timing solutions back in time involves too many trials to produce high-confidence results, as illustrated by the unsuccessful search for PSR J2229+6114, found in the error box of 3EG J2227+6122 (Thompson et al 2002).
of variability at the 4.8 s spin period of the neutron star flare during an EGRET observation, including some evidence X-3, an accretion-powered x-ray binary, may have shown a from binary sources, although the case is far from certain. Cen The EGRET data showed some indication of gamma radiation 6.2. Binary sources

The EGRET data showed some indication of gamma radiation from binary sources, although the case is far from certain. Cen X-3, an accretion-powered x-ray binary, may have shown a flare during an EGRET observation, including some evidence of variability at the 4.8 s spin period of the neutron star (Vestrand et al 1997). Two sources in the 3EG catalog, 3EG J0241+6103 and 3EG J1824−1514, are positionally consistent with high-mass x-ray binary systems (HMXB) often placed in the microquasar class, LSI +61°303 (Kniffen et al 1997, Tavani et al 1998) and LS 5039 (Paredes et al 2000) respectively. The detection of TeV radiation from both these HMXBs, showing orbitally modulated emission for LSI +61°303 (Albert et al 2006) and periodic emission for LS 5039 (Aharonian et al 2006), indicates that such sources can accelerate particles to energies well beyond those needed to produce gamma rays in the EGRET energy band. The evidence that the EGRET sources are actually these binary systems remains largely circumstantial, however, and searches for other binaries in the EGRET data have been unsuccessful.

6.3. Other Galactic sources

Most of the 3EG sources along the Galactic plane remain unidentified, including one that flared up to be the second brightest source in the gamma-ray sky for less than one month (Tavani et al 1997). Two general approaches have been followed in order to shed light on the possible nature of these sources.

- The characteristics of the Galactic EGRET sources as a class, based on their spatial and spectral properties, were investigated by several authors. Starting with the earlier 2EG catalog (Thompson et al 1995), Mukherjee et al (1995), Kanbach et al (1996) and Merck et al (1996) compared the characteristics of unidentified sources with Galactic tracers. McLaughlin et al (1996) developed a method for characterizing gamma-ray source variability and found that some of the catalog Galactic sources appear to be variable. Özel and Thompson (1996) constructed log N−log S distributions for 2EG sources, showing that the number of unidentified sources N with flux greater than S at high Galactic latitudes had an isotropic distribution, consistent with being either quite local or extragalactic. Similar analyses were carried out for the 3EG catalog. Reimer and Thompson (2001) and Bhattacharya et al (2003) studied the log N−log S distributions. Spatial-statistical considerations and variability studies suggest that there is a population of Galactic and variable GeV gamma-ray emitters among the unidentified EGRET sources (Nolan et al 2003). A population of steady gamma-ray sources with different properties from those close to the Galactic plane, possibly associated with the nearby Gould Belt complex of gas and stars, was suggested by Gehrels et al (2000). As noted by Cassandjian and Grenier (2008), many of these may be gas clouds that were not modeled in the EGRET analysis. A valuable summary of 3EG source characteristics, along with some cautions about limitations, is given by Reimer (2001). The strongest conclusion from these many studies was that the EGRET Galactic sources comprise more than one population.
Correlations of known Galactic populations with the positions of the EGRET sources offered another approach to trying to discern their nature. Using various statistical techniques, various authors found indications of associations of EGRET sources with star forming regions or groups of hot and massive stars (e.g. Kaaret and Cottam 1996, Romero et al 1999), supernova remnants (e.g. Sturmer and Dermer 1995, Esposito et al 1996) or pulsar wind nebulae (e.g. Roberts et al 2001). Torres et al (2003) provide an excellent summary of the observational and theoretical possibilities for supernova remnants as EGRET sources. Pulsar populations may also explain a fraction of the Galactic unidentified sources (Yadigaroglu and Romani 1997). All these classes of sources are plausible, because they have the potential to accelerate particles to high energies in an environment in which the particles can interact to produce gamma rays. There are several issues with these analyses.

- All these sources tend to be located in the same regions. Particularly considering the possibility that more than one type of gamma-ray source may be present, separating the classes is difficult.
- There is no unique spectral or timing signature for most of these sources, in the absence of pulsations or orbital periods (which have not been found).
- The EGRET error boxes are too large to make unique associations possible. In fact, none of these approaches found a clear example of one source that would serve as a prototype for the class.

Ultimately, all these efforts proved valuable in pointing to young, active Galactic objects as likely gamma-ray sources.

7. Extragalactic gamma-ray sources

As seen in figure 7, EGRET sources are seen in all directions in the sky. The detection of the nearby quasar 3C273 by COS-B (Swanenburg et al 1978) had long suggested that extragalactic sources would be a significant component of the high-energy sky (e.g. Bignami et al 1979).

7.1. Blazars

Just three months after the launch of the Compton Observatory, a Target of Opportunity pointing (requested by the OSSE team in search of emission from a supernova in the Virgo cluster) produced the first big surprise in the EGRET data. The observation that was expected to produce an observation of 3C273 was instead dominated by a very bright source about 10° away, positionally consistent with a more distant quasar, 3C279, with a redshift \( z = 0.536 \) (Hartman et al 1992). This detection had two immediate implications.

- The gamma-ray sky is variable, at least on long time scales, because COS-B had not seen this source.
- The idea of nearby AGN as candidate gamma-ray sources was at best incomplete. The fact that 3C279 was part of the blazar subclass of AGN, thought to be powered by supermassive black holes and having powerful jets of particles and radiation pointed toward the Solar System (Blandford and Rees 1978, Blandford and Königl 1979), suggested that gamma rays might be a valuable probe of jet sources.

The recognition of short-term variability of 3C279 (on a scale of days, Kniffen et al (1993)) reinforced the idea that jets were a likely source of the EGRET-detected gamma rays. The rapid variability required a compact emitting region, and such a region should be opaque to gamma rays due to gamma–gamma pair production, the interaction of a high-energy gamma ray with a lower-energy photon to produce an electron–positron pair, \( \gamma + \gamma = e^+ + e^- \), unless most of the photons are moving in the same direction, as in a jet. Some example calculations of this process are those of Mattox et al (1993) and Sikora et al (1994). The ultimate confirmation of such gamma-ray sources as blazars came with multiwavelength campaigns that found correlated variability of gamma-ray flares with flares seen at other wavelengths. The first example was a flare seen in PKS 1406–076 in January 1993, shown in figure 11, where an optical flare was seen nearly simultaneous with the gamma-ray flare (Wagner et al 1995). Such correlated variability is a valuable source of information about how such jets are formed, how they are collimated and how they carry energy.

Continuing EGRET observations revealed a series of bright, well-localized sources positionally consistent with prominent blazars. Many of these were known as optically violently variable (OVV) quasars or BL Lacertae (BL Lac) objects. Although the term ‘blazar’ is not uniquely defined, it typically encompasses those active galactic nuclei with the following characteristics: radio-loud, with flat radio spectrum, significant polarization in optical and/or radio and significant variability. Blazars are seen across the electromagnetic spectrum, with a characteristic two-peak spectral energy distribution (SED), as illustrated in figure 12 (Hartman et al 2001a). At lower frequencies, from radio to optical or sometimes x-rays, the emission is thought to be dominated by synchrotron radiation of high-energy electrons in the jet. The upper peak, extending from x-rays upward, is thought to be primarily inverse Compton scattering of low-energy photons by the same population of high-energy electrons that produces the lower-energy synchrotron radiation. The source of the photons to be upscattered can be the synchrotron radiation itself (synchrotron self-Compton) or some outside source of photons (external Compton). Extensive modeling of blazars has evolved following the EGRET discoveries. An example of such modeling is shown in figure 12. In many cases, the gamma-ray emission is the dominant observable output of these blazars.

Some of the EGRET blazars of particular interest are as follows.

- **3C279.** This first blazar recognized by EGRET was prominent many times during the CGRO mission. It was the first to be involved in a concentrated multiwavelength campaign (Maraschi et al 1994). A later multiwavelength campaign in January-February 1996, shown in figure 13, captured a dramatic flare, seen at multiple wavelengths...
Figure 11. Optical and gamma-ray flare in PKS 1406−076 (Wagner et al 1995).

Figure 12. Spectral energy distribution for 3C279 during a bright state in January 1996 (just before a large flare) with models (Hartman et al 2001a). Modeled components, from left to right in the figure: synchrotron radiation, thermal radiation from the accretion disk, synchrotron-self-Compton radiation, Compton radiation from scattering of accretion disk photons and Compton radiation from scattering of photons from gas clouds. (Wehrle et al 1998). The gamma-ray flux increased by over a factor of 10 during this flare. As a point of interest, the limited optical coverage of this flare came about because most of the optical astronomers who monitor this source were attending a blazar workshop at the time and were not at their telescopes.

• PKS 1622−297. Located not far from the Galactic Center region, this lesser-known blazar was not seen in any of the first 17 EGRET observations of this region, then flared up in the Summer of 1995 to be the brightest gamma-ray source seen by EGRET to that time and the one showing the fastest time variability, doubling in flux in less than 8h, with the limitation being just the photon statistics (Mattox et al 1997).
Some examples are given below. Offered opportunities for multiwavelength comparisons and most numerous class of identified gamma-ray sources, they peaked BLLac objects (HBLs). With blazars as the classified as flat-spectrum radio quasars (FSRQs), low-
in this field has also evolved, and blazars are now usually and to other studies of active galactic nuclei. Terminology
gamma-ray blazar provided a stimulus to this field of study
A number of prominent blazars were not seen by EGRET
electron or by protons. A comparison of spectral energy distributions led Fossati
• Mkn 421. This well-known BL Lac object appeared in an early EGRET observation (Lin et al 1992). Its detection helped stimulate the TeV gamma-ray astronomy community, and it became the first blazar detected at TeV energies (Punch et al 1992).
• PKS 0528+134. This blazar, actually the first one that appeared in the EGRET data although not identified until later, is one of at least five seen by EGRET with redshift z > 2.0 (Hunter et al 1993). Although it underwent a strong flare during one 1993 observation (figure 14, Mukherjee et al (1999)), it was also seen to be quite stable during other observations, even in short-timescale investigations (Wallace et al 2000).
• PKS 2255−282. After the completion of the third EGRET catalog, this blazar was the only new one to appear with high significance in the EGRET data (Macomb et al 1999). The bright gamma-ray flare appeared in early 1998 following a period of rising flux in the submillimetre band (Tornikoski et al 1999).

The EGRET discoveries of numerous highly variable gamma-ray blazars provided a stimulus to this field of study and to other studies of active galactic nuclei. Terminology in this field has also evolved, and blazars are now usually classified as flat-spectrum radio quasars (FSRQs), low-frequency peaked BLLac objects (LBLs) and high-frequency peaked BL Lac objects (HBLs). With blazars as the most numerous class of identified gamma-ray sources, they offered opportunities for multiwavelength comparisons and classifications. Some examples are given below.

• A number of prominent blazars were not seen by EGRET despite significant exposures (von Montigny et al 1995a).
• An effort was made to find a unified model for AGN based on geometry: the orientation of the black-hole/accretion disk/torus/jet system relative to the viewing direction (Urry and Padovani 1995). The beamed nature of the EGRET gamma radiation, associated with apparent superluminal motion seen in the radio, is an important aspect of this scheme, because it emphasizes that blazars must have jets aligned close to our line of sight.

- A comparison of spectral energy distributions led Fossati et al (1998) to suggest that the ‘blazar sequence’ in which higher-luminosity blazars (usually FSRQs) have their synchrotron and Compton peaks at lower energies while lower-luminosity blazars (LBLs and HBLs) have peaks at increasingly higher energies as their luminosity decreases (see figure 15).
- Very long baseline interferometry (VLBI) radio studies have been used to construct time-resolved images of the jets associated with the EGRET blazars. In addition to finding that many of these blazars have apparent superluminal motions (a relativistic illusion produced by the fact that the jet is directed close to our line of sight), a study of a sample of bright blazars suggests that those blazars seen in gamma-rays tend to have higher jet Lorentz factors than those blazars not seen by EGRET (figure 16, Kellerman et al (2004)).
- Another important result from VLBI studies is an indication that gamma-ray flares seen with EGRET occur at approximately the same time that new components of radio emission (‘knots’) emerge from the core of the AGN (Jorstad et al 2001). This result suggests that the gamma radiation is produced in the parsec-scale region of the jet rather than closer to the black hole at the center of the AGN.

Summaries of the observational properties of the EGRET blazars were given by von Montigny et al (1995b) and Mukherjee et al (1997). Mukherjee (2001) reviewed the EGRET blazar results after the end of the CGRO mission. Efforts to search the third EGRET catalog systematically for blazar-like counterparts were carried out by Mattox et al (2001) and by Sowards-Emmerd et al (2004). A number of plausible associations were added to the ones shown in the catalog. Figure 17 shows a map of such associations.

Although many studies of these blazars provided useful insights into jets and other AGN features, others found puzzling results. The Sowards-Emmerd et al results concluded that some of the high-Galactic-latitude EGRET sources did not have clear identifications with blazar-like sources. Nandikotkur et al (2007) carried out a detailed study of gamma-ray blazar variability using the entire EGRET data set and found a variety of relationships between flux and spectral hardening, without a simple pattern. Hartman et al (2001b) concluded that at least one episode of variability of 3C279 was not correlated with optical or x-ray variation. No consensus has emerged about whether the jets are primarily dominated by electrons or by protons.

### 7.2. Other galaxies

As noted in the previous section, not all EGRET sources at high Galactic latitudes are identified as blazars. Other potential extragalactic sources are discussed below.

#### 7.2.1. Local galaxies

The same type of cosmic ray interaction processes that operate in our Galaxy are likely to operate in other normal galaxies, although most of these are too far away to be detectable. EGRET was able to set only
upper limits on gamma radiation from the Andromeda Galaxy, M31, for example (Sreekumar et al 1994). One exception is the Large Magellanic Cloud (LMC), reported as an extended gamma-ray source by Sreekumar et al (1992). Based on radio and optical observations, the LMC is thought to have a cosmic ray population similar to that of the Milky Way. The source seen by EGRET was consistent in flux and spatial extent resulting from cosmic ray interactions in the LMC. A map of the EGRET emission and a comparison with the radio emission that traces the gas content of the LMC is shown in figure 18.

By contrast, Ginzburg (1972) predicted that the Small Magellanic Cloud (SMC) would not be detectable at the sensitivity of EGRET, because that galaxy is thought to be unable to sustain a local cosmic ray population. The absence of significant gamma radiation from the SMC was a critical test of whether cosmic rays are confined to galaxies. The upper limit from EGRET (Sreekumar et al 1993) provided the evidence to prove Ginzburg’s hypothesis that cosmic rays are confined to galaxies.

7.2.2. Radio galaxies and others. Evidence for gamma-ray emission from other extragalactic sources is less secure. The nearest large radio galaxy, Cen A, may have been seen by EGRET. There is a catalog EGRET source positionally consistent with Cen A, and the energy spectrum appears to be a continuation of the spectrum seen at lower energies (Sreekumar et al 1999). In the absence of any variability correlated with other wavelengths, however, this identification is not certain. A similar situation exists for two other radio galaxies. NGC 6251 is located in an EGRET source error box and is a plausible, but not definite, identification (Mukherjee et al 2002), and 3C111 has been suggested as a possible counterpart to another EGRET source (Squera et al 2005).

Searches for other extragalactic populations include the following.

- Upper limits on some starburst galaxies were given by Sreekumar et al (1994).
- Searches for EGRET gamma rays from clusters of galaxies were reported by Reimer et al (2003), who also provide a critical analysis of some suggestions of cluster emission in the EGRET data.
- Stacking analyses gave upper limits in examining possible low-level contributions from radio galaxies (Cillis et al 2004) and luminous infrared galaxies (Cillis et al 2005).

7.3. Diffuse extragalactic radiation

Finding a signal of diffuse extragalactic gamma radiation, sometimes called the extragalactic gamma-ray background, is probably the most difficult analysis challenge for a gamma-ray telescope, because this emission is what remains after...
Figure 17. New candidate identifications for EGRET sources (Sowards-Emmerd et al 2004). The sources are the same as the 3EG catalog (figure 7). The filled circles show potential blazar associations. The sources shown by open circles do not have blazar counterparts. This analysis did not extend to declinations south of $-40^\circ$, shown by a solid contour. Crosses show sources that were not classified.

Figure 18. EGRET gamma radiation from the Large Magellanic Cloud region (Sreekumar et al 1992). The contours of gamma-ray intensity show an extent consistent with that seen at radio frequencies.

all foreground constituents of the radiation are subtracted. For the EGRET analysis, the foreground included three principal components, dealt with in separate steps by Sreekumar et al (1998).

• Individual sources, as identified for the EGRET catalog work, were removed from the analysis.
• A residual contribution from the bright Earth limb was eliminated by removing all photons whose arrival directions were within 4 times the point spread function from the limb (for a given energy), enlarged from the standard EGRET cut of 2.5 times the PSF from the limb.
• The Galactic diffuse component was taken into account, based on the standard model developed for EGRET analysis (see section 4).

The third of these steps was the most critical, because the Galactic diffuse emission exceeds any extragalactic diffuse radiation everywhere on the sky, including the Galactic poles. The basic approach was to compare the observed radiation with that expected from the Galactic model and then to extrapolate to a condition of no Galactic emission. Figure 19 shows such a fit for the standard EGRET energy bands.

This analysis produced a non-zero residual for all energies. The resulting extragalactic diffuse spectrum was consistent with a power law with an index of $-2.10 \pm 0.03$.

The unresolved gamma radiation after removal of foreground contributions is certainly not all truly diffuse emission. As with the x-ray background, some or all of this radiation results from individual sources that are too faint to be recognized by EGRET. Primary candidates those from the known extragalactic gamma-ray source classes are as follows.

• Normal galaxies like the Milky Way must contribute. Pavlidou and Fields (2002) estimate that up to 30% of the emission at 1 GeV may result from such galaxies, with a lesser contribution at other energies. With a sample of only the Milky Way and the LMC, however, any extrapolation must be considered highly uncertain.
• Blazars are strong candidates to be the origin of much of the unresolved emission. Many authors have estimated this contribution, and the results range from about 25% to 100% of the total (e.g. Stecker and Salamon 1996, Mukherjee and Chiang 1999, Chiang and Mukherjee 1998, Mücke and Pohl 2000). The principal challenges for this calculation are twofold: (1) blazars seen by EGRET were almost always in a flaring state, and the duty cycle for such flaring remains highly uncertain; and (2) the evolution of blazar gamma-ray emission must be estimated. The wide range of potential contributions to the diffuse radiation reflects the sensitivity of the calculation to the input assumptions.

Beyond the contributions from known but unresolved sources, there is no shortage of other candidate mechanisms for
Figure 19. Observed gamma ray flux in many high-latitude locations, comparing that observed (Y-axis) with the flux expected from the EGRET model of the Galactic diffuse emission (Sreekumar et al. 1998). The correlation is strong, and the offset from zero represents the diffuse emission.
producing a largely isotropic gamma-ray background on the scale observed by EGRET. Dermer (2007) presents a recent summary. Some possibilities that have been discussed in recent years include unresolved emission from galaxy clusters (Ensslin et al 1997), starburst galaxies (Thompson et al 2007), shock waves associated with large scale cosmological structure formation (Loeb and Waxman 2000, Miniati 2002), distant gamma-ray burst events (Casanova et al 2007), annihilation of weakly interacting massive particles (WIMPs) (e.g. Ullio et al 2002) and cosmic strings (Berezinsky et al 2001).

Strong et al (2000) and Moskalenko and Strong (2000) have argued for a larger component of the Galactic diffuse emission from inverse Compton scattering of the Galactic plane photons and the cosmic microwave background. Because the calculation of the extragalactic emission depends on correct subtraction of the Galactic contribution, this alternate approach would change the result on any determination of the extragalactic diffuse emission. A new model of the Galactic diffuse emission (Strong et al 2004a) has provided a new estimate of the extragalactic diffuse gamma radiation that is lower in flux and steeper than that found by Sreekumar et al (1998). The revised spectrum is not consistent with a power law and shows some positive curvature. Both results are shown in figure 20.

7.4. Gamma ray bursts

Gamma-ray bursts (GRBs) have been described as the brightest explosions in the Universe, radiating more energy in a few seconds than our sun will emit during its entire 10 billion year lifetime. Much of this energy is seen as low-energy gamma rays, with typical energies in a range around 100 keV. GRBs are thought to be caused by unusually powerful supernovae (collapsars) or possibly an effect of the merger of two neutron stars or a neutron star and a black hole (for a recent review, see Meszaros (2006)). During the Compton Observatory mission, BATSE recorded more than 2700 GRBs, averaging nearly one per day. A small fraction of these bursts were also seen by EGRET, revealing important characteristics of GRBs.

EGRET photons above 30 MeV were seen coincident with BATSE low-energy gamma-ray emission for at least 4 bursts (for a summary, see Dingus (2003)). Because these were the brightest BATSE bursts in the EGRET field of view and EGRET upper limits from other bursts do not constrain the results, it is possible that all GRBs have a high-energy component. The combined energy spectrum shows no break up to 10 GeV, suggesting that the spectrum may extend to even higher energies. Having a spectrum extend to such high energies assures that GRBs are nonthermal phenomena.

The importance of these detections is that high-energy gamma rays should not escape easily from the environment of a GRB due to the high flux of lower-energy photons. The process of photon–photon pair production, $\gamma + \gamma = e^+ + e^-$, would effectively remove all the high-energy gamma rays, unless all the photons are moving in the same direction, i.e. beamed, with high bulk Lorentz factor (e.g. Baring 1994). Lithwick and Sari (2001) calculate that Lorentz factors of several hundreds are needed.

A second aspect of the EGRET GRB observations offers a different challenge to models of these explosions. In addition to the prompt high-energy emission, delayed emission from some GRBs was detected by EGRET. One example is shown in figure 21, probably the best-known EGRET GRB detection. In this burst, high-energy emission, including the highest-energy photon associated with a GRB at 18 GeV, was seen nearly 90 min after the initial burst (Hurley et al 1994).

An example of shorter-term delayed emission was found by Gonzalez et al (2003) by comparing BATSE data with data from the EGRET TASC calorimeter (see section 2.3). Unlike the primary EGRET gamma-ray telescope, the TASC was an omnidirectional detector for gamma rays up to energies of nearly 200 MeV. For GRB941017, shown in figure 22, the GRB spectrum was seen to evolve from the one dominated by the low-energy BATSE data to the one dominated by the higher-energy EGRET emission over the course of about 200 s. The fact that the spectrum is still rising at the upper limit of the TASC readout suggests that the delayed emission probably extended to yet higher energies. This burst was not in the field of view of the EGRET spark chamber, precluding measurements at higher energies. The relationship of these delayed gamma-ray components of bursts may be related to afterglows seen at longer wavelengths, but such burst afterglows were not known for most of the EGRET era, so no measurements were made.

8. Local gamma-ray sources

Although most objects energetic enough to produce gamma rays detectable by EGRET are distant, there are two sources visible within the Solar System (in addition to the Earth itself, since the Earth’s atmosphere is gamma-ray bright due to...
Figure 21. The long-duration high-energy emission from the gamma-ray burst of 17 February 1994 (Hurley et al 1994). Upper panel: energies and arrival times of individual EGRET photons from the direction of the burst. The horizontal lines show periods with no data. Lower panel: Ulysses 25–150 keV counts rates during the same time period. Inset: expanded plot of the early time of the burst, showing the EGRET photons compared with the BATSE light curve. (Reprinted by permission from Macmillan Publishers Ltd: Nature (Hurley et al 1994), copyright 1994.)

cosmic ray interactions, e.g. Petry (2005)). These two local sources are the Moon and the Sun.

8.1. The Moon

A remarkable, yet well-understood, curiosity of gamma-ray astrophysics is that in this part of the electromagnetic spectrum the Moon is brighter than the quiet Sun (when no solar flares are present). Morris (1984) predicted the Moon to be a gamma-ray source, using a calculation extrapolated from modeling of the Earth’s atmospheric gamma radiation. The same types of interactions of cosmic rays with matter that produce the diffuse Galactic gamma radiation (meson production, Compton scattering, and bremsstrahlung; see section 4) take place in the lunar surface. Thompson et al (1997) analyzed relevant portions of the EGRET data in a moving, Moon-centered coordinate system to verify the prediction, including evidence of the expected variation of the lunar gamma radiation with the solar cycle of cosmic ray modulation. Figure 23 shows the calculated and measured spectra for the Moon.

The same processes that produce the lunar radiation also operate in the atmosphere of the Sun. All other factors being equal, the fact that the Sun and Moon subtend the same solid angle from the Earth might suggest that they would be equally bright in gamma rays. The solar magnetic field, however, excludes some of the Galactic cosmic rays from hitting the solar atmosphere, making the expected gamma-ray flux from the quiet Sun lower (Hudson 1989, Seckel et al 1991). The original EGRET analysis found only an upper limit for the Sun, consistent with these calculations, although a more recent calculation and analysis of the EGRET data provides some evidence for a weak detection of the non-flare solar gamma radiation (Orlando and Strong 2008).

8.2. Solar flares

Although the quiet Sun is not a bright gamma-ray source, solar flares can accelerate particles to high enough energies to produce strong gamma-ray emission. The Compton Observatory was launched near solar maximum, and in early June of 1991 a number of solar flares were detected by all the
instruments on CGRO, including EGRET (Schneid et al. 1996). On 1991 June 11 EGRET observed gamma-ray emission up to energies above 1 GeV for over 8 h (Kanbach et al. 1993) following a large solar flare. This flare represented the most energetic radiation ever seen from the Sun. The energy spectrum confirmed evidence seen from previous missions that solar flares could accelerate protons (which collide with ambient solar material to produce neutral pions that decay into high-energy gamma rays). That spectrum is shown in figure 24. Modeling of the particle acceleration and interactions provided the first evidence for long-term trapping of particles in solar flare regions (Mandzhavidze and Ramaty 1992).

8.3. Microsecond bursts—the search for Hawking radiation from near-Earth black holes

Hawking (1974) and Page and Hawking (1976) calculated that tiny black holes that had formed in the early Universe might be detectable as flashes of high-energy gamma rays. The process of black hole evaporation, called Hawking radiation, is negligible for solar mass black holes or larger, but those that formed with mass about $10^{14}$ g would have lost enough mass that their final evaporation might be seen if they were close enough to the Earth. Search for the EGRET data for multiple gamma rays occurring within the 1 $\mu$s live time of the spark chamber was able to set a new limit on such black holes, although not extremely restrictive (Fichtel et al. 1994).

9. Summary—open questions for AGILE and Fermi

The Energetic Gamma Ray Experiment Telescope (EGRET) on the Compton Gamma Ray Observatory provided a dramatic new view of the high-energy Universe, including the first all-sky mapping of the sky at energies above 30 MeV. The EGRET observations revealed a wealth of information about Galactic and extragalactic gamma radiation from both individual and diffuse sources. Perhaps the single most striking characteristic of the EGRET gamma-ray sky is its variability, ranging from the extremely rapid flaring of gamma-ray bursts to the long-term variations seen in some sources such as blazars. As with many successful missions, however, the questions that were answered led to new questions for future missions. With AGILE and Fermi now in operation, the time has come to seek out the solutions to some of these mysteries left behind by EGRET.

- What is the nature of the diffuse Galactic gamma radiation, and in particular the GeV excess? Does this unexpected finding indicate some exotic new physics or a more mundane origin such as calibration?
Does the gamma radiation from the Milky Way or its surroundings contain clues to unseen forms of matter, such as cold dark gas or dark matter? Mapping the gamma-ray emission with higher precision and comparing those measurements with information about gas derived from other types of observations is a highly promising avenue for this research.

What will a larger sample of gamma-ray pulsars reveal about the location of the particle acceleration and the particle interaction processes under extreme conditions? How many more radio-quiet pulsars will be found, and what will those pulsars say about the neutron star population of our Galaxy?

Which binary systems produce gamma rays, and how do those systems work?

What other classes of Galactic objects have enough energy to produce gamma rays detectable by the new generation of telescopes?

Will including new, high-quality gamma-ray measurements of blazar spectra and time variability in multi-wavelength studies provide the clues to jet properties such as composition and possibly to jet formation and collimation?

What will the new gamma-ray measurements of other galaxies tell us about cosmic rays and matter densities in these systems?

What other types of extragalactic objects are capable of generating detectable gamma ray fluxes?

Will the new data resolve the diffuse extragalactic radiation as a collection of discrete sources, or will there be some residual diffuse emission that demands a new and possibly exotic explanation?

Do most or all gamma-ray bursts have high-energy emission, and what does that radiation say about the forces at work in these explosive phenomena?

Can high-energy gamma-ray measurements of solar flares shed new light on solar activity?

What surprises will be found in the gamma-ray sky?

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