Cosmic-Ray accelerators in Milky Way studied with the Fermi Gamma-ray Space Telescope

Tuneyoshi Kamae
SLAC and KIPAC, Stanford University, 2575 Sand Hill Road, Menlo Park, CA 94025, USA
E-mail: kamae@slac.stanford.edu

Abstract. High-energy gamma-ray astrophysics is now situated at a confluence of particle physics, plasma physics and traditional astrophysics. Fermi Gamma-ray Space Telescope (FGST) and upgraded Imaging Atmospheric Cherenkov Telescopes (IACTs) have been invigorating this interdisciplinary area of research. Among many new developments, I focus on two types of cosmic accelerators in the Milky-Way galaxy (pulsar, pulsar wind nebula, and supernova remnants) and explain discoveries related to cosmic-ray acceleration.

1. Introduction

Fermi Gamma-ray Space Telescope (Fermi) [1,2] and Imaging Atmospheric Cherenkov Telescopes (IACTs) [3] have been invigorating the interdisciplinary research area at the confluence of particle physics, plasma physics and traditional astrophysics. Among them are particle acceleration mechanisms at work in cosmic environment. Most cosmic accelerators have been discovered in gamma-ray observations so far including Supernova remnants (SNR), Pulsars (PSR), and Pulsar wind nebulae (PWN) in the Galactic sky, and, Active Galactic Nuclei (AGN) and Gamma-Ray Bursts (GRB) in the Extra-Galactic Sky [4].

Particles are accelerated in similar mechanisms both in cosmic and man-made accelerators. Gamma-rays are emitted via synchrotron radiation ($e^-/e^+$ in B-field), inverse Compton scattering (between $e^-/e^+$ and seed photons), pion production (interaction of $p/\alpha$ with gas), and bremsstrahlung (interaction between $e^-/e^+$ and gas).

We explain how and where particles ($e^-/e^+$ in this case) are accelerated and how and where gamma-
rays are emitted, taking the pulsars and the pulsar wind nebulae as examples.

Here, the pulsar is a fast-rotating (a few to ~500 times per second), highly-magnetized (10^6-10^{14} Gauss on the surface), neutron star with a radius of ~10km and mass of ~1.5 solar-mass). Particles are accelerated by magnetic induction to a few 10^{12} eV (TeV) in the pulsar. The pulsar wind nebula (PWN) is a plasma cloud filled with energetic e^-/e^+ extending around a pulsar where particles coming out of the pulsar are accelerated further to >10^{15} eV (PeV) [4].

2. Fermi Gamma-ray Space Telescope and Imaging Atmospheric Cherenkov Telescopes

In this presentation we use gamma-ray data taken by the Large Area telescope (LAT) onboard Fermi Gamma-ray Space Telescope (FGST) for 10^9 eV (GeV) energy range [1,2] and Imaging Atmospheric Cherenkov Telescopes (IACTs) for the TeV energy range [3]. Performance of the former and that of a typical IACT, High Energy Stereoscopic System (H.E.S.S.) [5] are given below and in Table 1.

2.1 Large Area Telescope on Fermi Gamma-ray Space Telescope

FGST-LAT was built by an international space program funded by USA (NASA, DOE), Japan, Italy (INFN, ASI), France, and Sweden. The collaboration was formed in 1995 and Japan officially joined in 1997. The LAT collaboration’s proposal was selected in the NASA Announcement of Opportunity in 2001. The instrument was assembled and tested in 2006 at SLAC, integrated with the satellite in 2007, and launched to a Low-Earth Orbit on June 11, 2008 (Fig.1). Science operation started on August 4, 2008 after a month verification period. A catalog of ~1400 point sources detected by the instrument was published in March 2010 [6]. The instrument has been surveying the entire sky since the August 4, 2008 making 144k orbits and recording 474M gamma-rays by Jan 20, 2011. The key performance parameters are given in Table 1.

Table 1. Performance of FGST-Large Area Telescope\(^a\) and HESS\(^b\)

| Parameters               | Fermi-LAT                  | H.E.S.S.                  |
|-------------------------|----------------------------|---------------------------|
| Energy range            | 100MeV-300GeV              | 100GeV-3TeV               |
| Effective area          | ~7000cm\(^2\) (E>1GeV)    | ~10^5m\(^2\) per mirror  |
| Field of view           | ~2.4 sr                   | ~3 deg in radius         |
| Angular resolution      | 0.8(E[GeV])^{-0.8}deg     | 1-5 arcmin               |
| Sensitivity (E\(^2\)dN/dE) | ~10^{-12} erg/cm\(^2\)/s (2yrs) | ~3x10^{-13} erg/cm\(^2\)/s |
| Sky coverage            | ~all sky (every ~3hrs)     | selected pointing         |

\(^a\) http://www-glast.slac.stanford.edu/software/IS/glast_lat_performance.htm and [1,2]  
\(^b\)[3,5]

2.2 High Energy Stereoscopic System (HESS)

HESS has been a most productive Imaging Atmospheric Cherenkov Telescope. The current version (HESS-I) has been completed in 2003 in Namibia and has been operational ever since [3,5]. It consists of 4 nearly identical telescopes and has been observing astronomical objects accessible from the southern hemisphere. The key performance parameters are summarized in Table 1.

3. Acceleration Mechanisms: Man-made accelerators vs Cosmic Accelerators

There are 4 acceleration mechanisms known to operate in cosmos: they have a counter part in the man-made accelerator or in the plasma experiment as shown in Figs.2a-2d.
These acceleration mechanisms are believed to be accelerating particles to TeV to PeV energy range. As particle energies increase synchrotron radiation loss becomes non-negligible [4,7]. Even if the accelerator has capability to reach beyond PeV energy range, B-field inherent to the accelerator site limit the maximum energy as listed in the second row of Fig.2. Here m=mass, q=charge, B=mag field.

\[ \varepsilon_a = \sqrt{\frac{3}{2} \frac{m^2}{q^{3/2}}} B^{-1/2} \]
\[ \varepsilon_d \approx \frac{3}{2} \frac{m^3}{q^4} B^{-2} R^{-1} \]
\[ \varepsilon_c = \frac{3^{1/4}}{2} \frac{m}{q^{1/4}} B^{1/4} R^{1/2} \]

Fig.2a. Shock fronts formed within Lorentz-boosted plasma in jets of AGNs and GRBs.

Fig.2b. Particles recycle through the shock front made of turbulent B-field and reach to high energy.

Fig.2c. Electric field induced by the rapidly rotating dipole B-field of a neutron star.

Fig. 2d. Energy stored in B-field is released as kinetic energy of particles.

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Fig.3a. A cosmic one-shot linear accelerator in a near-by AGN, Cen A. Faint linear structure is extending to up-left and down-right.

Fig.3b. A cosmic recycling accelerator in an SNR, Cas A. The shock accelerator is at the thin blue broken ring in the outer periphery.

Fig. 3c. A cartoon of Crab Pulsar. The neutron star has a magnetic dipole pointing at B and rotates about an axis \( \Omega \) at \( \sim 30 \text{Hz} \). Particles are accelerated in the blue stripes.

Shown in Fig.3 are 3 types of cosmic accelerators: (a) galaxies hosting a super-massive black-hole, Active Galactic Nuclei (AGN), where energetic particles stream out along jets; (b) supernova remnants (SNR) with a ring-like shock front expands into interstellar space; (c) a fast-rotating magnetized neutron star where induction generate high potential drop near the boundary of its magnetosphere [4].

4. Gamma-ray Emission from the Pulsar and the Pulsar Wind Nebula

We present new discoveries by Fermi about particle acceleration in the pulsar and the PWN taking the Vela pulsar [8] and the Crab nebula [9] as examples, respectively.

4.1 Fermi-LAT narrows down the \( \gamma \)-ray emitting region in the pulsar
Spectrum of pulsed gamma-ray emission has been measured for several pulsars including that from the Vela pulsar and the Crab pulsar. We show the gamma-ray pulse profile of the Vela pulsar in 3 energy bands in Fig.4a. If the pulsed gamma-rays are emitted near the neutron star surface (the polar cap model) where B-field is extremely strong, they will be converted to an $e^-/e^+$ shower and will not reach to us [10]. The predicted spectrum is shown by the dashed line in Fig.4c contradicting the Fermi observation. We conclude that the emission region is away from the neutron star by least 3 times its radius as has been predicted by the outer gap model [11].

4.1 Discovery of giant flares in the Crab nebula by Fermi

Crab nebula (see Figs.5a and b) has been the best studied astronomical object and considered to be a stable standard candle on which almost all X/$\gamma$-ray telescopes have been calibrated. Two unexpected surprises came in 2009 and 2010: it is neither stable in the X-ray band [12] nor in the $\gamma$-ray band [13]. The nebula consists of the Crab Pulsar at the center, a ring-like termination shock where the wind of high energy particles stalls outside of the pulsar light cylinder, the cocoon-like structure housing the particles diffusing out of the pulsar and termination shock (Fig.5b). The finger-like structure in Fig.5a is believed to be created by the Rayleigh-Taylor instability as shown in the cartoon (Fig.5b).

Crab Nebula has been found, in the X-ray band, to be “flickering” at ~0.5-1 year time-scale at ~5% flux-level in the past ~10 years [12]. Even more surprising is two big flares (Fig.6a) Fermi found in 100MeV-GeV gamma-rays [13]. The $\gamma$-ray spectrum during the two flares is consistent with the synchrotron emission (Fig.6b). The flare #2 is particularly interesting because the maximum electron
energy inferred from the spectrum is ~PeV. The rise time of flare #2 is less than 1 day or less than the
time the accelerated particle making one circle: the diffusive shock acceleration would not work and
non-standard mechanism has to be invoked [13].

Fig.6a. Time profiles of flares #1 (top) and #2 (bottom) seen by Fermi [13]

Fig.6b. The γ-ray spectra for flares #1 (lower dashed) and #2 (upper dashed) compared with that during the non-flaring period (solid line) [13].

5. Gamma-ray Emission from Supernova Remnants

1.1. Fermi finds middle-aged SNRs interacting with dense interstellar clouds

Fermi LAT observed nearly 10 SNRs of which about a half are found to be very bright in the GeV γ-
ray band. They are found to be middle-aged ones where the shock front is impinging into dense clouds [14,15]. The standard diffusive shock acceleration theory does not apply to such environment and some new development is called for.

Fig.7a γ-ray spectrum from SNR W44 by Fermi and IACT [14]

Fig.7b.Distr of γ-rays (color) and gas (green) in W44 [14]

Fig.7c γ-ray spectrum from SNR IC443 by Fermi and IACTs [15]

Fig.7d. 68% containment circles (circles) and centers (crosses) of γ-ray distr by Fermi and IACTs and gas (contours) for IC443 [15]

The broad-band γ-ray spectra obtained by combining Fermi and IACTs observations are compatible that the γ-rays are decay products of π⁰ produced in nuclear interactions of p/α accelerated in the SNRs, presumably at the shock front [14,15]. The spectral shapes of p/α deduced from γ-rays spectra are power-law with a break ranging from ~1GeV to 70GeV as tabulated in Table 2.

| SNR   | Age  | Distance | Gas dens × CR | PL or Broken-PL | Eγ, [GeV] | αLE | αHE |
|-------|------|----------|---------------|-----------------|-----------|------|------|
| Name  | kyr  | kpc      | n × W_p [erg cm⁻³] |                 |           |      |      |
| W49B  | 4.0  | 7.5      | 1.1 × 10¹²     | 4.0             | 2.0       | 2.7  |
| W49U  | 20   | 3.0      | 6 × 10¹¹       | 8.0             | 1.74      | 3.7  |
| W51C  | 39   | 6.0      | 5.2 × 10¹²     | 15              | 1.5       | 2.9  |
| IC 443| 39   | 1.5      | 6.7 × 10²⁰     | 69              | 2.09      | 2.87 |
| W28 (North) | 40 | 2.0      | 1.3 × 10²¹     | 1.0             | 2.09      | 2.74 |
6. Conclusions

The new generation of astronomical $\gamma$-ray experiments are discovering many cosmic accelerators with their much-improved sensitivity and sky-coverage. Some of them seems to behave as expected but some show unexpected behaviour. These new behaviours call for physics processes which are new to astrophysics but have been well studied in other disciplines of physics. High energy $\gamma$-ray astrophysics is located at a confluence of disciplines and congruous with the spirit of this symposium. To be specific, collaboration with plasma physicists simulating the particle-turbulence interaction will be most appreciated.

The $\gamma$-ray data obtained by Fermi are publically available at Fermi Science Support Centre with science analysis tools [16]. The support centre offers assistance to users and posts many FAQs.

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