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Recent Development of Galactic γ-ray Observation and The Origin of Cosmic Rays

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Abstract

The origin of the cosmic ray still remains unsolved problem since cosmic ray was discovered. Recent observation of Galactic γ-ray emission suggests that supernova remnants (SNRs) have prime candidates for production sites of Galactic cosmic rays. Here I report on the results of γ-ray observation and the origin of cosmic rays.

Keywords: Galactic γ-ray observation, cosmic ray, cosmic ray origin

1. Introduction

The origin of the cosmic ray is one of the unsolved problems since cosmic ray has been discovered by Victor Hess in 1912.

In 1949, E. Fermi proposed the Fermi acceleration process of cosmic rays[1]. In his theory, cosmic rays are accelerated in the galaxy by collisions against the moving molecular clouds having magnetic field . And it has a feature that the theory shows naturally an inverse power law of cosmic ray energy spectrum. But, it has the difficulty to explain that cosmic rays get enough energy while moving in the galaxy.

Early 1950s, Hayakawa and Morrison suggested the Supernova Remnant (SNR) as the origin of cosmic rays and expected that they emit high energy γ-rays via decay of π^0 meson produced by a collision of originated cosmic ray with ambient matter. And accelerated cosmic rays quickly diffuse out of their sources, mix with those from other sources. While the cosmic rays transport from their sources to the Earth, they interact with interstellar matter and create γ rays. Therefore, the galactic diffuse γ-ray is the standard tracer of cosmic-ray propagation.

Recent γ-ray observation of the Large Area Telescope (LAT) on the Fermi Gamma-ray Space Telescope gives us advancing knowledge in astrophysics, cosmic ray physics and particle physics.

In the report, I describe the recent development of γ-ray observation and the origin of cosmic rays .

2. Energy Spectrum of Cosmic Ray

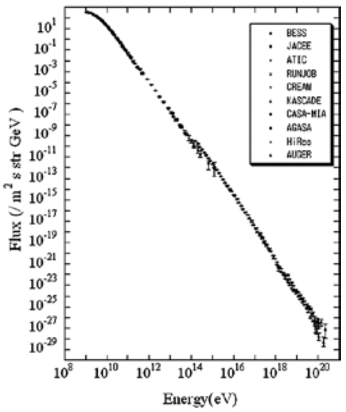

Figure 1. The Differential energy spectrum of cosmic rays as observed at the Earth.

The cosmic ray particles are mostly charged nuclei, mainly proton, that arrive isotropically at Earth. An over view of cosmic ray energy spectrum is shown in Fig.1 [2]-[11] which is observed in the Earth.

The spectrum is so steep that about 10^{14} eV is the highest energy at which cosmic rays can be observed directly at the top of the atmosphere. To study cosmic rays with higher energy requires to overcome the problem of low flux. Ground-based air shower detectors are used to detect atmospheric cascade shower particles initiated by the incident cosmic ray.

Cosmic rays have a power law like, $I(E)=K\ E^{-\gamma}$ energy spectrum that extends beyond 10^{20} eV and seems to have at least two features in the whole spectrum. At energy above $10^{15.5}$ eV, the power index γ steepens from 2.7 to about 3.1. This is called the knee of the cosmic ray spectrum. At energy above $10^{18.5}$ eV, the spectrum flattens again called ankle.

In the Galaxy, mean galactic magnetic field is 1 ∼ 3 μ G and at the energy of $10^{18.5}$ eV, the gyro radii of protons is order of 1∼3 kpc. Protons of higher energy would easily escape from galaxy. Therefore, it is generally believed that the cosmic rays of energies up to $10^{18.5}$ eV are of galactic origin.

3. γ ray Observation

The SAS2[12] and COS-B[13] missions were the first stage of galactic γ-ray observation in space. They led to the next stage of observation by EGRET[14] on Compton Gamma-Ray Observatory. EGRET detected γ-rays of energy from 30 MeV to 30 GeV and gave us the first all-sky survey above 100 MeV in figure 2. It shows the brightest diffuse emission along with the Galactic plane, which is due to cosmic ray interactions with the interstellar matter. The typical SNR such as Vela, Geminga and Crab are clearly found as the bright knots of emission. EGRET found many high energy sources, which identified as astronomical objects, but unidentified high energy sources are remained. EGRET observation changed our view of the high energy Universe through high energy emission

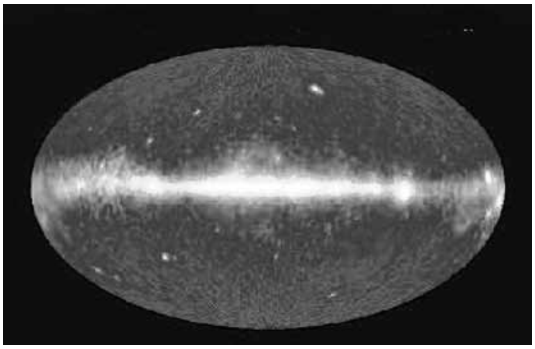

Figure 2. The whole sky map of high energy γ ray observed by EGRET. EGRET team http://heasarc.gsfc.nasa.gov/docs/cgro/egret/

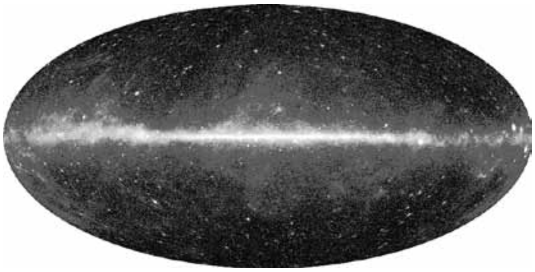

Figure 3. All-sky view from Fermi, bright emission in the plane of the Milky Way. Credit: NASA/DOE/International LAT Team. http://fermi.gsfc.nasa.gov/ssc/

from our Galaxy and beyond.

After EGRET, the Large Area Telescope (LAT) on the Fermi Gamma-ray Space Telescope (Fermi)[15] was launched on 2008 for determining the nature of these sources and advancing knowledge in astronomy, astrophysics, and particle physics. The Fermi LAT is a pair-conversion telescope using silicon strip detectors instead of spark chamber which was using EGRET and has wide field-of-view, high performance for high-energy γ-rays, covering the energy from below 20 MeV to more than 300 GeV, also precision of position.

Figure 3 shows the all-sky map for γ-ray emission observed by Fermi LAT which is much resolved rather than EGRET.

More than several 100 GeV, the ground-based imaging Cherenkov telescopes such as VERITAS, MAGIC and H.E.S.S. etc are deployed to observe the very high energy γ rays up to several 100 TeV. These telescopes are operating effectively as the complements of the γ rays observation mission in space.

4. γ-ray Observation and Cosmic Ray Origin

The energy density in cosmic rays is estimated ∼ 10^{-12} erg/cm^3 from the cosmic ray observation. The power required to maintain cosmic ray energy density in steady state is to be 10^{41} erg/s, assuming the observed energy density is the typical value of entire galactic disk. In supernova explosion, the kinetic energy of supernova ejecta is about 10^{51} erg and the frequency of supernova in the Galaxy is estimated ∼ 1/30 year^{-1}. Therefore, the power available in supernova explosion is sufficient to maintain the energy carried by the galactic cosmic ray, which is one of the strong prediction that the supernova explosions might be the powerful sources of the cosmic ray.

The acceleration process was assumed to be stochastic. They believe the mechanism of particle acceleration in expanding SNR shocks well understanding in theoretical. The diffusive shock acceleration in supernova explosion blast wave is the most plausible theory of the origin of cosmic ray acceleration. As SNRs are the sources of galactic cosmic rays, accelerated cosmic rays may interact to the ambient matter and produce γ -rays. It is expected that SNRs are a source of high energy γ-rays. The observation of X ray and γ-ray emission from SNR reveal the existence of energetic electrons, but evidence of accelerated hadrons did not confirm yet.

The Galactic shell-type SNR RX J1713.7-3946 was discovered by ROSAT satellite in the X-ray spectrum. H.E.S.S. observed SNR RX J1713.7-3946 and detected γ-ray emission throughout the whole SNR[16]. They measured the differential γ-ray spectrum from 190 GeV to 40 TeV and the energy spectrum of the whole remnant is well described by a power law with photon index 2.19. That is consistent with the picture of an SNR origin of cosmic rays in which an index of production spectrum is expected about 2.0. They discussed about observed spectrum based on the two models, one is a γ-ray production of inverse Compton scattering of very high energy electrons and the other is due to π^0 decay from proton-proton interaction. And they lead the conclusion that π^0 decay model is favored from the multi-wavelength consideration.

The SNR W44 is a middle-aged ($\sim 2.0 \times 10^4$ year) supernova known to be interacting with ambient molecular cloud. EGRET instrument detected a γ-ray source vicinity of the SNR, but its association with W44 was not clear. Recently, Fermi LAT data were analyzed by morphological study and found the γ-ray emission from the shell of SNR W44[17]. Fermi LAT is observed γ-ray of energy from 200 MeV to 300 GeV. The observed spectral energy distribution is steepen toward high energies, at lower energy photon index is $\sim$2.06 and at higher energy it has $\sim$ 3.02 with a break energy of $\sim$1.9 GeV. Most of the γ-ray emission comes from the SNR shell, which is interacting with molecular clouds. When a accelerated high energy cosmic ray interacts with ambient gas, π^0 decays and electron bremsstrahlung become important for γ-ray emission. And Fermi LAT spectral energy distribution of SNR W44 shows that most detected emission is attributed to π^0 decays, but γ-ray emission of bremsstrahlung is not excluded completely.

The Crab Nebula is a young supernova remnant, recorded in 1054 A.D.. The SN explosion left a young neutron star, which is the pulsar of the Crab Nebula. In almost all energies, emission has been detected, ranging from radio to very high energy γ-rays.

Crab pulsar emits a wind of magnetized plasma and pulsar wind is expected to make a shock, in which particles may undergo shock acceleration. The broad-band spectral energy distribution of the Crab Nebula is composed of two broad nonthermal components. A low-energy emission from radio to γ-ray frequency is thought to be from synchrotron radiation. The high-energy component above ~ 400 MeV is thought to be emitted via inverse Compton scattering. The unexpected γ-ray flares greater than 100 MeV were discovered by the Fermi LAT from Crab Nebula[18]. The first flare occurred in February 2009 and lasted ~16 days, the second one is in September 2010 and lasted ~4 days. During the flares, γ-ray flux from the nebula increased by factors of 4 and 6, respectively. And the brevity of flares implies that the γ-rays were emitted via synchrotron radiation from $\sim 10^{15}$ eV electrons in a small region of $\sim 1.4 \times 10^{-2}$ pc. The discovery of γ-ray flares in Crab Nebula by Fermi LAT is very surprise, which has the difficulties to explain widely discussed acceleration mechanism of diffusive shock acceleration.

For the galactic diffuse γ-rays, the EGRET[19] data fits the general picture well with expected, however, the exception that the spectral index above a GeV is harder than expected. It is usually assumed that these γ-rays are from the interaction of with ambient matter. The production spectrum of the γ-rays from decay of π^0 production by cosmic-ray interactions in the ISM should have the same spectral index as the parent particle. The γ-ray spectrum index is expected same as the cosmic ray spectrum about 2.7, because the γ-rays propagate directly in the Galaxy. But it is more likely harder of 2.4. It may suggest that interstellar proton or electron spectra rather hard compared with local direct measurements.

The OB association is a group of massive stars with spectral types of O and early B. A typical OB association might have about 20 stars. The average mass of OB stars is about 20 times of solar mass, and finally explodes as the supernova. Their average lifetime is rather short as $\sim 10^7$ years. Massive O stars have strong stellar winds, and the strong stellar winds have totally more than 10^{51} erg in kinetic energy. The winds expand over dozen of light years. OB association stars are unbounded gravitationally, but moving at speeds of about 20 km/s. Then, most of their supernovae explosions occur within the cavity of stellar wind bubble. Supernova explosion produces the forward moving shock wave, which sweep up ambient matter and expands as like the shell. In the shock, stellar wind matter accelerated by the diffusive acceleration mechanism as the cosmic ray. In the OB association, successive supernova explosions release massive matter and energy into the space. Successive shock waves, produced by the successive SNR, expand approaching each other. The cosmic rays, accelerated and gained enough energy, leak from the shock and diffuse in the space. And they collide head-on against approaching another shock wave and get scattering as well as acceleration. The repetition of collision induces the reaccelerating of cosmic rays getting much higher energy. The distribution of OB association is not uniform but to the Galactic center. The Galactic diffuse γ-ray observation may relate to the distribution of OB association.

5. Summary

The origin of cosmic ray is unsolved problem for long time. Recent observation of cosmic γ-ray emission reveals the SNR is the most plausible site for Galactic cosmic ray origin, but some different kinds of acceleration mechanism are working with. And it might be expected that the high precision γ-ray observations and detailed theoretical calculations are confirming the origin and the acceleration of Galactic cosmic ray.

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