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Cosmic ray acceleration search in Supernova Remnants

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Abstract

Galactic Supernova Remnants (SNRs) are among the best candidates as source of cosmic rays due to energetics, observed rate of explosion and as possible sites where the Fermi mechanisms naturally plays a key role. Evidence of hadronic acceleration processes taking place in SNRs are being collected with the Fermi-LAT, whose sensitivity in the range 100MeV-100GeV is crucial for disentangling possible hadronic contribution from inverse Compton or bremsstrahlung leptonic component. A survey of the detected SNRs will be given, focusing the attention on the role of the environment and the evolution stage of the SNR in the interpretation of the observed γ-ray spectra.

Keywords: Supernova Remnants, Cosmic rays, acceleration, gamma-rays

1. Introduction

After more than one hundred years from the discovery of cosmic rays (CRs) by Victor Hess [1] and Domenico Pacini in 1912 [2], the questions about the origin of these charged particles are still unsolved. Many observations have been performed since then, obtaining a great number of data which now have to be put in the right place to solve the *puzzle* of cosmic rays.

The measurements of the spectrum and composition of CRs revealed that this radiation consists of charged particles which reach incredibly high energies, up to 10^{20} eV. A detailed study gave much information about their propagation in the Galaxy and about the possible sources which can accelerate particles to such a high energy. In 1949, Enrico Fermi proposed a mechanism through which particles could be accelerated, requiring only the presence of a strong shock wave and producing a power-law spectrum for accelerated particles as required by he observations made on the Earth's surface.

In our Galaxy shock waves are very frequent, originating for example from the explosion of Supernovae. The observed explosion energy $E_{SN} \approx 10^{51}$erg and rate of explosion of Supernovae in the Galaxy $R_{SN} \approx 2-3$ SN/century are compatible with the observed cosmic ray density in the Galaxy $\rho_{CR} \approx 1$eV cm^{-3}, requiring an acceleration efficiency ϵ (fraction of the explosion energy to be transferred to accelerated particles in the form of kinetic energy) of approximately 10%:

$$\rho_{CR} = R_{SN} E_{SN}\, \epsilon\, \tau_{esc}, \tag{1}$$

where $\tau_{esc} \approx 10$ Myr is the confinement time of cosmic rays in the Galaxy.

For these reasons, Supernova Remnants (SNRs) are thought to be the most probable candidates of sources of galactic cosmic rays [3].

2. Cosmic rays

2.1. Cosmic ray spectrum

Figure 1 shows the energy spectrum of cosmic rays. The spectrum is well described by a power-law distribution over a wide energy range, from few hundreds MeV

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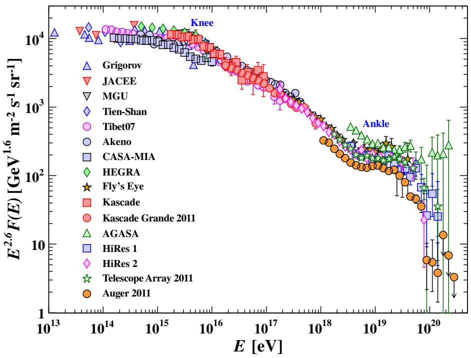

Figure 1: The all-particle spectrum as a function of energy-per-nucleus from air shower measurements. [4]

up to about a hundred EeV. The differential energy spectrum has been multiplied by $E^{2.6}$ in order to display the features of the steep spectrum that are otherwise difficult to discern.

For energy below 1 GeV, the spectrum presents a cut-off relative to the power-law distribution, due to the solar effects on charged particles. In fact, during the periods of high solar activity, the charged plasma emitted by the Sun, called *solar wind*, interacts with the incoming CRs, preventing their propagation to the Earth and reducing the observed flux. Conversely, the CR flux reaches its maximum during the periods of low solar activity. This phenomenon is known as *solar modulation* and has a cycle of about 11 years.

For energies above 10 GeV, particles are not affected by the solar wind and their spectrum follows a power-law:

$$F(E) = E^{-\alpha}, \tag{2}$$

where α represents the spectral index of the distribution. Its value changes significantly in two points of the spectrum. The first break, known as *knee*, occurs at an energy around 10^{15} eV, where the spectral index changes from a value of 2.7 to a value of 3. For energies above 10^{19} eV, which corresponds to the second break in the spectrum and is known as *ankle*, the spectral index becomes again 2.7.

The features observed in the spectrum may give information about the origin of cosmic rays. Particles with energy below 10^{18} eV are thought to be of galactic origin. In this picture, the knee could reflect the fact that most of cosmic ray accelerators in the Galaxy reach their maximum energy of acceleration between 10^{15} eV and 10^{18} eV, causing a break in the spectrum.

Concerning the *ankle*, it is thought to be the result of a higher energy population of particles overtaking a lower energy population, for example an extragalactic flux beginning to dominate over the galactic flux. In this case, the most probable candidates to accelerate cosmic rays up to these energies are the Active Galactic Nuclei (AGN), which are very far galaxies that emit a bright radiation in the entire electromagnetic spectrum.

Supernova remnants are considered good candidates for the acceleration of galactic cosmic rays, being able to accelerate particles through the Fermi acceleration mechanism, which predicts a power-law spectrum. The maximum energy of acceleration is related to the environment and the age of the SNR. At present there are some hints of acceleration up to energies close to the *knee*.

Due to the propagation of cosmic rays in the Galaxy, the expected spectrum at the source $Q(E)$ is related to the cosmic ray spectrum observed at the Earth's surface through the escape time of cosmic rays τ:

$$N(E) = Q(E)\tau(E). \tag{3}$$

Being $N(E) \propto E^{-2.7}$ and $\tau(E) \propto E^{-0.6\div-0.4}$, one obtains $Q(E) \propto E^{-2.1\div-2.3}$.

2.2. Fermi acceleration mechanisms

The *First order Fermi mechanism*, also known as *diffusive shock acceleration mechanism*, is based on the strong shock waves generated in the Galaxy, such as the ones originating from a Supernova explosion. The most important feature of this mechanism is that the energy gain for a particle crossing the shock wave is directly proportional to the velocity of the shock, resulting in a power-law spectrum with spectral index close to -2.

Be $\Delta E = \xi E$ the energy earned by a particle after a collision and P_{esc} the escape probability from the acceleration region after each collision. After n collisions, a particle with initial energy E_0 will have an energy $E_n = E_0(1+\xi)^n$, with a probability of being in the acceleration region equal to $(1-P_{esc})^n$. The number of collision necessary to reach an energy E is obtained inverting the first relation: $n = \ln(E/E_0)/\ln(1+\xi)$. The number of particles with energy greater than E will be proportional to the probability of having a particle with energy greater than E:

$$N(\geq E) \propto \sum_{m=n}^{\infty}(1-P_{esc})^m = \frac{(1-P_{esc})^n}{P_{esc}}. \tag{4}$$

Using the expression of n obtained previously:

$$N(\geq E) \propto \frac{1}{P_{esc}}\left(\frac{E}{E_0}\right)^{-\gamma}, \tag{5}$$