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On the Origin of Cosmic Rays in the PeV - EeV Energy Range

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We consider a number of possibilities to explain the origin of cosmic rays above the knee: a variety of supernovae and hypernovae, pulsars, a Giant Galactic Halo and an extragalactic origin. We conclude that origin by way of shocks in the Galactic Halo, whatever their source, is most likely, with pulsars such as B0656+14 coming a close second.

1. Introduction

Below the knee at 3 PeV there is general agreement that supernova remnants (SNR) are responsible for the origin of the bulk of cosmic rays (CR). As for higher energies the situation is not clear. The problem is not with the total energy content, but rather with achieving single particle energies of the required magnitude.

2. Variety of supernovae and hypernovae

To our knowledge, it was P.L.Biermann who first suggested that another kind of supernovae coming from more massive and hot stars, such as Wolf-Rayet stars, can be responsible for the production of CR with energies above the knee [1]. This idea has been developed by Sveshnikova [2], who used the evidence that there are different classes of SN and even within a single class there is a spread of explosion energies. There is also a weak dependence of the maximum energy of accelerated particles E_{max} on the explosion energy within a single class, but the difference between E_{max} for different classes might be higher. With certain fractions of different SN classes and taking into account the mixed mass composition of accelerated particles, it is possible to reproduce the average shape of the CR energy spectrum above the knee. As would be expected, the dominant contribution to the spectrum comes from the most energetic classes: SNIbc and SNIIn.

We have made calculations for these two classes using a realistic Monte Carlo simulation of different SNR exploding sporadically in space and time in the Galactic Disk. The rates of explosion and the distribution of explosion energies have been taken from [2]. In Figure 1 we show 50 samples of energy spectra for protons accelerated by SNIbc and SNIIn. Although the mean spectrum (Figure 1b) extends up to EeV energies, the individual spectra demonstrate very strong irregularity, particularly in the region above PeV up to the EeV energies as a consequence of the rare and stochastic explosions of the very energetic SN. A mixed mass composition in the *energy* spectra can reduce the irregularity of the *rigidity* spectra, since it displaces the same rigidity spectra for different nuclei with respect to each other. However, this effect is small below the knee and only makes the cutoff in the energy spectrum less sharp compared with the cutoff in the rigidity spectrum. Since there is no such big irregularity in the observations of the spectrum beyond the knee the introduction of some smoothing mechanism is needed.

3. Pulsars

In [3, 4] we claimed that the SNR Monogem Ring is a good candidate for the Single Source responsible for the knee. It has been shown that the pulsar B0656+14 is associated with this SNR [5] and this is another

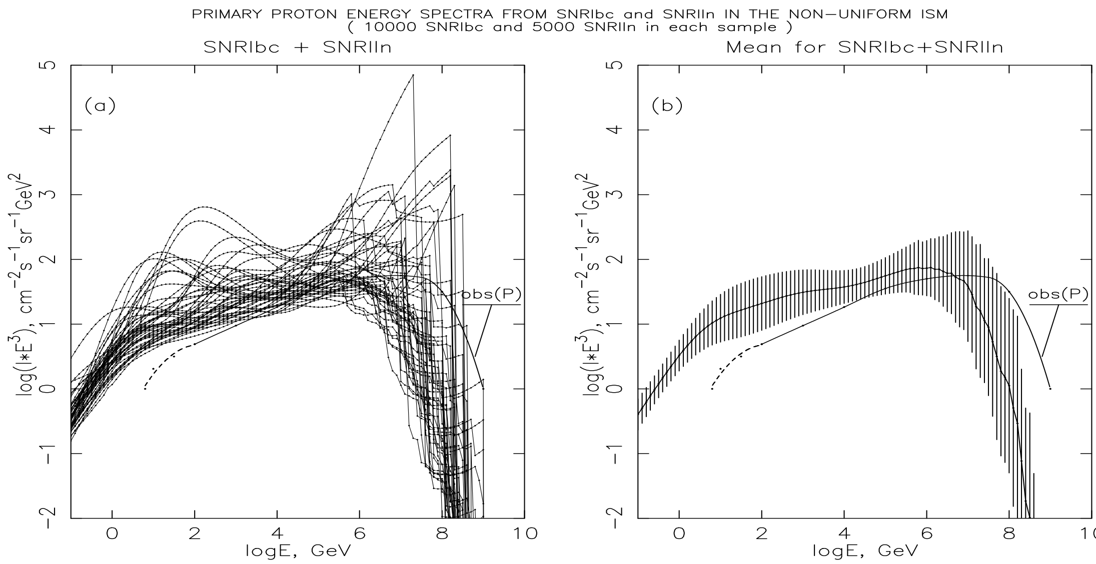

Figure 1. Energy spectra of CR accelerated by two types of SN - SNIbc and SNIIn (50 samples with the same distribution of explosion energies for both, but different distributions of $logE_{max}$ [2]: (a) the summed spectra of 10000 SNIbc and 5000 SNIIn; (b) the mean spectrum and its irregularity quantified by the standard deviation for the samples shown in (a). The curve *obs(P)* is our estimate of the proton spectrum needed to fit the experimental data.

potential source of CR beyond the knee. However, it might happen only if the SNR shell or the termination shock of the pulsar wind nebula confined the high energy CR emitted by the pulsar for a long time after the SN explosion and released them quite recently. In Figure 2a we show the energy spectrum of protons and nuclei created by this pulsar if its confinement time is 0.9 of its age. It is seen that emitted iron nuclei can contribute at an energy above 10^8 GeV. If this contribution is dominant over other sources the problem of the irregularity disappears since the pulsar is a part of the Single Source in this energy region. In Figure 2b we show the result of the processing of 46 available EAS size spectra by an 'excess over the running mean' method. It is seen that at $log(N_e/N_e^{knee}) > 1.5$, which corresponds to primary energies above 10^8 GeV, the spectrum has an excess, which lends support to the assumption about the pulsar contribution in this region. The recent muon size spectrum from the MSU EAS array [6] also has an excess in this region.

4. A Giant Galactic Halo

If CR in the PeV-EeV energy range are of Galactic origin, then there has to be a mechanism which reduces the irregularity shown in Figure 1. The most natural way is to introduce a long term accumulation of CR within a confinement volume, similar to the well known 'leaky box' for the Galaxy, but with a much larger size and longer lifetime in it. Such an accumulation can be achieved with the help of a Giant Galactic Halo [7, 8, 9]. To ensure the accumulation of the particles we assumed the existence of a Galactic Wind similar to the solar wind with the termination shock at a distance of about 100 kpc, which works as a Giant Leaky Box [10]. It can be that acceleration of particles beyond PeV energies occurs also at this termination shock, but we imply that its main role is to reflect particles back into the Halo interior. Extragalactic CR (EG) appear in this scenario as the leakage from halos of various galaxies populating the Universe.

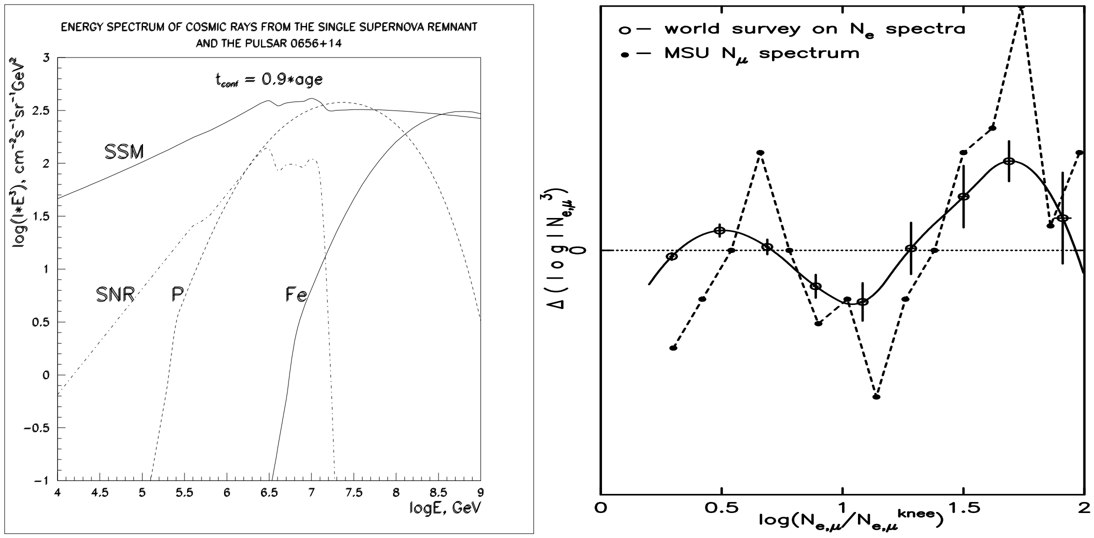

Figure 2. (a) Energy spectra of CR from the pulsar B0656+14, observed at the Earth. The CR nuclei are protons (P) and iron-nuclei (Fe). The CR energy spectrum in the Single Source Model is shown by the full line denoted as 'SSM' with the contribution of the SNR shown by the dash-dotted line denoted as 'SNR'. (b) The mean excess over the running means for 46 available EAS size spectra (full line) and the MSU muon size spectrum [6] (dashed line).

Some arguments favoring the existence of the big halos in our and other galaxies and even for clusters of galaxies have been put forward in [11–14]. In [15] we showed that anomalous diffusion can help to create such a Giant Halo with a long tail of CR above and below the Galactic Disk.

Figure 3 shows a version of the CR energy spectrum which comprises four major components: CR from SNR in the Galactic Disk, Giant Halo, Single Source at the knee and EG. The Giant Halo has the spectrum of accelerated particles $\propto E^{-2.7}$, the lifetime in the Halo $\tau = 10^{17}/E(GeV)$ years and an accumulation time equal to the age of the Galaxy of 10^{10} years. Integration of the CR emitted by SNR in the Galactic Disk during such a long time and large space gives a regular energy spectrum with no fluctuations of its shape. If the contribution of the Giant Halo spectrum is such as shown in Figure 3, then the irregularity of the total spectrum caused by sporadic SNR explosions in the Disk is substantially reduced.

5. Conclusion

Independently of the source of CR particles between PeV and EeV energies (young SNR, young pulsars, 'cannonballs', re-acceleration in the Halo or others) the existence of a Giant Galactic Halo can help to reduce the irregularity of the total spectrum caused by sporadic SN explosions. We remember that such a Halo can also help us to understand the small radial gradient of CR in the Galaxy and their small anisotropy.

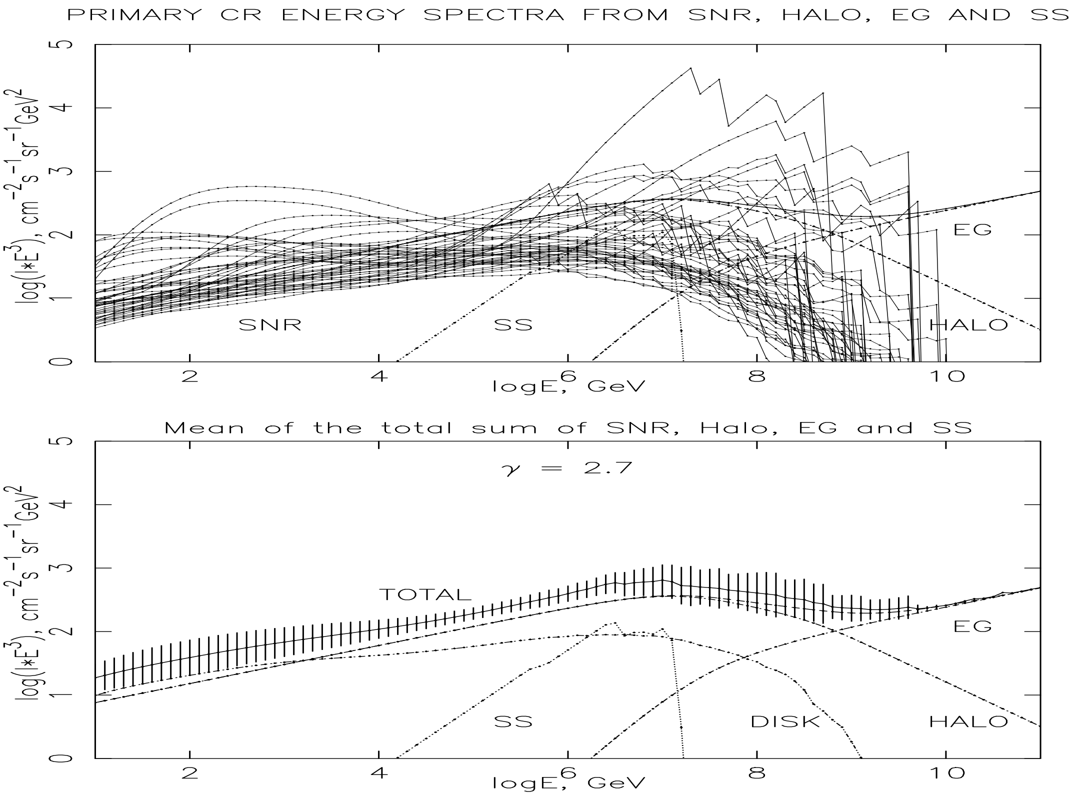

Figure 3. (a) Four major components of the CR spectrum: SNR in the Galactic Disk, Giant Halo, Extragalactic CR (EG) and the Single Source (SS). (b) The all particle CR spectrum is the sum of the four components shown in (a). The irregularity of the spectrum is substantially reduced due to the smoothing effect of the Halo.

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