On the Pulsar Origin of the Knee

Arunava Bhadra
High Energy and Cosmic Ray Research Centre, University of North Bengal, Siliguri 734430 India

Abstract

The high degree of sharpness of the knee in the cosmic ray energy spectrum favors for a single source origin of the knee. In the present work we explore the possibility that the knee is caused by a nearby pulsar. We also examine the candidature of the Geminga and the Vela pulsars as the single source of the knee.

1. Introduction

An important observation on the various size spectra of cosmic ray extensive air showers (EAS) is that the spectra of all components exhibit a very sharp knee [1]. It is difficult to explain [2] the high magnitude of the sharpness of the knee and its likely complicated structure [1,3] with the popular galactic modulation model (leakage from the galaxy due to reduced efficiency of galactic magnetic field to confine the cosmic ray particles within galaxy) [4] or with the other conversional models of the knee, such as a change in the high energy interaction scenario [5], nuclear photodisintegration at the sources [6] or a change in the particle acceleration efficiency [7]. To explain these important features of the knee spectrum Erlykin and Wolfendale proposed a single source model [1] of the knee in which the knee is the result of superposition of flux from a recent and nearby supernova over a smoothly steepening background component. The single source model thus adds an additional component in the form of contribution from a local single source to the spectra arisen from a conversional model of the astrophysical origin of the knee.

One problem, however, with the single source proposal is that in normal circumstances the source should be observed in high energy gamma rays [8] but no strong evidence for gamma ray emission from any nearby SNR exists. However, being local, there is a good probability that the source is in a lower density environment and as a result gamma ray flux from the source is too low to detect with the present gamma ray telescopes [9]. Still, upper limit of high energy π^o decay gamma rays from any nearby SNR imposed from observation and the energy condition that is required to produce the knee in the observed spectrum at the earth constrain the position and age of the single source in a narrow range which

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in turn reduces the probability of SNR as single source. Moreover, the model of cosmic ray origin in the SNR has not been observationally established yet. In fact some observational features are in contradiction with the model (see for example [10]). It is thus required to look for the alternatives.

As is well known pulsars are also regarded as possible sources of primary cosmic rays. It has been suggested that pulsars may accelerate protons and heavy nuclei by converting their rotational energy to particle kinetic energy via a relativistic MHD winds [11]. Heavy nuclei also could be accelerated in the outer gap of the pulsar magnetosphere [12]. Here we examine the possibility that the single source is a nearby pulsar rather than a supernova.

2. Energetic of the source

The main difference between a SNR and a pulsar as cosmic ray source is that in the later case the source energy spectrum is much flatter. As a result of the flat source spectrum, there may be a significant contribution in the flux of cosmic rays at earth at the knee region from a nearby pulsar whereas at lower energies its contribution will be rather negligible. On the other hand assuming the distribution of pulsar initial periods is similar to Gamma distribution, it has been shown [13] that expected cosmic ray spectrum coincide with the observation. Another important feature is the maximum energy (E_{max}) attainable by a particle in the acceleration process. In the case of SNR this is at most $Z \times 400$ TeV (Ze is the charge of the nuclei) if the SNR is in a low-density environment ($\rho \sim 3 \times 10^{-3}\ cm^{-3}$) [14] which gives E_{max} around 3 PeV for oxygen nuclei. On the other hand for pulsars E_{max} even could reach around 100 EeV [11], the highest energy cosmic ray particle observed so far. According to the Hillas condition [15], the maximum energy of a particle that can be contained near the light cylinder of a pulsar of angular speed $\Omega\ rad\ s^{-1}$ and with the surface magnetic field $B_s = B_{12} \times 10^{12}$ Gauss is

$$E_{max} = 3.4 \times 10^{11} Z B_{12} \Omega^2\ eV \tag{1}$$

Interestingly for Geminga pulsar ($B_{12} = 1.6, \Omega = 26.29\ rad\ s^{-1}$), $E_{max} \simeq 3$ PeV for oxygen nuclei as primary (coincidence!) and for Vela Pulsar it is around 5.6 PeV for protons.

We now estimate the rotational energy of a pulsar required for producing the knee spectrum at the earth. The energy spectrum of the accelerated particles during the lifetime of the pulsar is given by [11]

$$\frac{dN}{dE} = \frac{\xi E^{rot}}{E_{max}} E^{-1}\ , \tag{2}$$

where ξ is the fraction of the total rotational energy E^{rot} of the pulsar creates the cosmic ray particles. We assume that the source (pulsar) is emitting continuously from time t_{on} until now at a constant spectral rate

$$\frac{dN}{dEdt} = \frac{\xi \dot{E}^{rot}}{E_{max}} E^{-1} \ . \tag{3}$$

Although a young pulsar is usually encircled by the remnant of the pre supernova star still, accelerated nuclei can escape the remnant without significant losses shortly after the explosion [11]. So we assume $t - t_{on}$ as the age of the pulsar. The diffusion process governs the propagation of accelerated charged nuclei from the source. Usually the diffusion scenario is considered as Gaussian. However, there is strong indication that the interstellar medium is highly non-homogenous [4] and as a result the simple homogeneous diffusion approximation is no longer valid. Instead one may approach with the so-called anomalous diffusion scenario, which considers the interstellar medium as fractal like. Using the Green function obtained by Lagutin it et al [16] for anomalous diffusion process with $\alpha = 1$ (the parameter α indicates the fractal nature of the interstellar medium [4]), the intensity of the cosmic ray from the source is

$$I_{cr}(r) = \frac{\xi c \dot{E}^{rot} E^{-1}}{8\pi^3 E_{max} r^2 D(E,\alpha) \left(1 + \frac{r^2}{D^2(E,\alpha)\tau^2}\right)} \ cm^{-2} s^{-1} GeV^{-1} \ , \tag{4}$$

where c is the speed of light, τ is the age of the pulsar and $D(E,\alpha) \left(\equiv D_o^{(\alpha)} \left(\frac{E}{Z}\right)^{\delta} \right)$ is the anomalous diffusivity. If η fraction of the total cosmic ray flux ($\sim 1 \times 10^{-17}\ cm^{-2} s^{-1} GeV^{-1}$) at knee (3 PeV) is due to the single source then Eq. (4) gives the energetic of the source *viz.*

$$\xi \dot{E}^{rot} = \eta \ 6.5 \times 10^{32} \left(\frac{r}{1\ pc}\right)^2 \left(1 + 9.2 \times 10^5 \left(\frac{r}{1\ pc}\right)^2 \left(\frac{\tau}{1\ year}\right)^{-2}\right) \ GeV \tag{5}$$

Here we have taken $D_o = 2.5 \times 10^{-5}$ pc/year [17] and $\delta = .25$ [16]. Table 1 shows the rotational energy required for a nearby pulsar to contribute about fifty percent cosmic ray (assuming proton) flux at knee (at earth) for its various position and age. According to Eq. (8) the flux of cosmic ray particles from Geminga Pulsar ($r \simeq 150$ pc, $\tau \simeq 4 \times 10^5$ years and for oxygen nuclei as primary) at the knee energy (3 PeV) is around $\xi \ 1.65 \times 10^{-17}\ cm^{-2} s^{-1} GeV^{-1}$ whereas for the Vela Pulsar ($r \simeq 500$ pc, $\tau \simeq 1.1 \times 10^4$ years, proton as primary and knee is at 5.6 PeV) this is about $\xi \ 6 \times 10^{-20}\ cm^{-2} s^{-1} GeV^{-1}$.

3. Discussion

We explore the possibility that the single source of knee is a nearby pulsar rather than a SNR. The rotational energy of a pulsar required for its various positions and age to produce the knee spectrum at earth is obtained. We also

Table 1. Required rotational energy of a pulsar to produce the knee for its various age and positions.

r (in pc)		100	200	300	500
$\xi \dot{E}^{rot}/10^{37}(inGeV)$	$\tau = 10^4$ years	30	490	2500	19250
	$\tau = 10^5$ years	0.64	6	28	200

estimate the flux of cosmic ray particles from the Geminga and the Vela pulsars at knee region. The result show that the Geminga pulsar is a possible candidate for the single source of the knee.

One possible way to test the single source hypothesis is through observation of high-energy gamma rays of appropriate flux. The flux of gamma rays expected from the pulsar responsible for the knee will be estimated in a future work.

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4. References

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