29th International Cosmic Ray Conference Pune (2005) **3**, 121–124

Anisotropy of Cosmic Rays from the "Single Source "of the knee

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Single source model of cosmic rays advocates for an explosion of a single, nearby and recent supernova as the cause of the knee structure of the primary cosmic ray energy spectrum. In the present work we study the expected anisotropy of cosmic rays from the single source of the knee.

1. Introduction

The standard picture about the cosmic ray energy spectrum is that it has a power law behavior with a spectral break around 3×10^{15} eV which is referred to as the 'knee 'of the spectrum. Several attempts have so far been made to explain the knee feature but the problem remains controversial. A noticeable characteristic of the knee spectrum is its high degree of sharpness [1]. To account this feature of the knee along with its likely complicated structure, Erlykin and Wolfendale have proposed the 'single source 'model [1] of the knee in which the knee is the result of superposition of flux from a recent and nearby source over a smoothly steepening background.
A nearby supernova remnant (SNR) is usually supposed as the single source of the knee [1]. The energy condition to be satisfied by the source to produce the knee in the observed spectrum at the earth and non-observation of high energy gamma rays from any nearby SNR against the expectation [2, 3] constrain the position and age of the SNR single source within narrow ranges [3, 2]. But after determining the distance of the SNR Monogem Ring accurately, Thorsett *et al* [4] pointed out that the distance and age of the SNR remarkably coincide with the predicted location and age of the single source [3] and thus the remnant emerges as the most likely candidate for the single source. Theoretical investigations suggest [5, 6] that nearby gamma ray pulsars like Vela or Geminga also may contribute significantly at the knee energy.
Since the single source of the knee, whether a SNR or a pulsar, is a local one and contributes significantly to the observed cosmic ray spectrum at the knee region, it is important to examine whether the Rayleigh amplitude of anisotropy in the cosmic ray flux due to the source is within the experimental upper limits or not. In fact, the matter was discussed by Erlykin and Wolfendale [7] themselves shortly after introducing the single source model. However, the probable location and age of the source as well as the nature of the source are more specified now and the observable scenario of anisotropy has been improved during recent years. Hence it seems worthwhile to revisit the problem. In the present work we restrict our analysis on the estimation of Rayleigh amplitudes due to the single source and compare the results with the observations. We take slightly different approach for estimating amplitudes of anisotropy than that adopted in [7].

2. Amplitude of anisotropy

The anisotropy predicted for galactic cosmic ray sources relies on the model for the production of cosmic rays and for their propagation. The production of cosmic rays depends on the nature of the sources whereas the diffusion process due to scattering from minor irregularities in the field governs the propagation of accelerated charged nuclei from the source to Earth. The resultant amplitude of anisotropy is given by [8]

$$\delta = \frac{\lambda}{I(E)} \left| \frac{\partial I(E)}{\partial r} \right| \tag{1}$$

where λ is the scattering mean free path, I is local cosmic ray intensity and $\partial I/\partial r$ is the intensity gradient. The scattering mean free path λ is related with the diffusion coefficient $D(E)$ by $D(E) = \frac{1}{3}\lambda c$.
In a simplified model of diffusion (neglecting the effect of energy gained/losses during propagation, convection, losses of nuclei by collision and nuclear interactions) the transport equation is given by

$$\frac{dN}{dt} = \Delta.(D(E)\Delta N(r,t,E)) + Q(r',t',E) \tag{2}$$

where N is the density of particles at a position r at time t, D is the diffusion coefficient of nuclei in the Galaxy (in $cm^2 s^{-1}$) and $Q(r',t',E)$ represent s the source term. Thus cosmic ray density at r at time t after the release of total $n(E)$ particles by the source at $t = 0$ is given by

$$N(r,t,E) = \frac{n(E)}{8(\pi Dt)^{3/2}} exp[-r^2/(4Dt)] \; cm^{-3} \tag{3}$$

Employing the above equation in the Eq. (1) one gets

$$\delta = h(E)\frac{3r}{2ct(E)} \tag{4}$$

Here $h(E)$ denotes the ratio of the cosmic rays of energy E from the source to the total observed flux of cosmic rays at the same energy from all sources. The energy dependence of δ relies mainly on $h(E)$. But emission time and hence t also can be different for cosmic rays of different energies depending on the nature of source. A nice feature of the expression (4) is that it does not depend on the diffusion coefficient. However, if a different propagation scenario, such as the so-called anomalous diffusion [9], is adopted then the expression for anisotropy amplitude might depend on the diffusion coefficient. Here it should be mentioned that the numerical value of diffusion coefficient at concerned energy range is quite uncertain. Another important point is that once the contribution of the source to the total cosmic ray flux is fixed, there is no adjustable parameter left in the expression (4).

3. Expected amplitude of anisotropy due to the single source

The flux of particles from the single source is superimposed upon a background flux of particles from all other sources. To estimate the anisotropy due to the single source we take that the contribution of the source to the total cosmic ray flux at the knee energy is fifty percent *i.e.* $h(E_{knee}) = 1/2$.

3.1 Predicted anisotropy if the source is a supernova remnant

We first consider a supernova remnant as the source of the knee. In this case the slope of the production spectrum of cosmic rays is nearly the same to the over all cosmic ray spectrum (generated by all sources) up to the knee energy. Hence the source would contribute significantly not only at the knee position but also over an energy range below the knee. Consequently anisotropy due to the source over a wide energy range below the knee has to be considered. The energy conditions and the non-observation of high energy gamma rays suggest that the possible location of the source is around 250 to 350 pc from the Earth and its age should be around 80 to 100 kyr [3]. The expected amplitude of anisotropy due to the source as follows from the expression (4) are shown for its various possible positions and ages in table 1.

The anisotropy amplitude due to the SNR Monogem Ring is estimated as $\sim 6.2 \times 10^{-3}$ at the knee energy if the source is responsible for the knee. The contribution of the single source would remain substantial below the knee and accordingly the anisotropy amplitudes over an energy range below the knee should be of the same order to those given in the table 1.

Table 1. Expected amplitude of anisotropy at the knee energy due to the Single Source of the knee for its various locations and ages.

r (in pc)		250	300	350
δ	$t = 8 \times 10^4$ years	0.008	0.009	0.01
	$t = 10^5$ years	0.006	0.007	0.008

3.2 Predicted amplitude of anisotropy if the source is a gamma ray pulsar

The feasibility of a nearby gamma-ray pulsar as candidate for the single source of the knee has been explored in [5,6]. The investigations show that both the Geminga and Vela pulsars can satisfy the flux requirement for producing the knee. A point to be noted is that the contribution of a pulsar is significant only at the knee position (not over a wide energy region) if a pulsar is responsible for the knee. This is because of relatively flat spectrum of pulsar originated cosmic rays. Another important difference between the SNR and the pulsar originated cosmic ray scenario is that in the former case all cosmic rays are emitted within small duration after a certain period from the formation of the SNR whereas in the later case emission takes place continuously shortly after the formation of the pulsar. At any instant, however, pulsar emits nearly monenergetic particles. At the early stage of evolution, pulsar angular velocity is relatively large and it emits higher energy particles. However, as shown in [10], the cosmic ray spectrum to be observed at Earth due to a nearby pulsar can be significantly different than the production spectrum which simply goes as E^{-1}. It can be easily inferred from the relevant expressions given in [10], the Vela pulsar may contribute significantly at the knee position for suitable choices of the pulsar parameters involved in the generation process. The lower energy end of Geminga pulsar generated cosmic ray spectrum is also a possibility for producing the knee. The energy budget required to produce the knee can not be, however, satisfied by the higher energy end of the Geminga generated spectrum for realistic values of the pulsar parameters.

The expected amplitude of anisotropy for the Vela pulsar at the knee energy is estimated as $\delta \sim 0.16$ if the source is responsible for the knee. In a similar condition δ is around 0.35 if the Geminga pulsar is the source of the knee.

4. Discussion

Cosmic rays are highly isotropic as revealed from the observations, particularly up to around the ankle of the spectrum above which the measurements suffer from low statistics. Harmonic analysis of the right ascension distribution of cosmic rays suggests that the Rayleigh amplitudes in the knee region are much less than 10^{-2} [11-14]. The recent KASCADE measurements [11] give upper limit of δ around 5×10^{-3} at the knee position whereas observation by the EAS-TOP experiment [12] obtains that δ is less than 10^{-3} at 1 PeV. Beyond the knee at present observational upper limits of Rayleigh amplitudes is, however, less constrained, $\delta \sim 10^{-2}$ [11, 13, 14].

The present measured upper limit of anisotropy at the knee energy does not rule out the possibility that the single source is a SNR, as evident from table 1. The predicted anisotropy for the Monogem Ring SNR, if it is the single source, is very close to the measured upper limit of anisotropy at the knee range. However, at slightly lower energies the situation is critical as the measured upper limits of amplitudes, particularly those obtained by the EAS-TOP experiment [12], is much less then 10^{-3} against the expectation. On the other hand if pulsar is considered as single source the situation is even worse. The Vela pulsar is only $\sim 10^4$ years old and hence if it contributes significantly at the knee the expected anisotropy is large ($\delta \sim 0.16$) which runs contradictory to

the observation. The same is true for the Geminga pulsar also. However, the anisotropy amplitudes predicted for pulsars lie on a very narrow energy window at the knee. Since cosmic rays at this energy region have been studied indirectly using extensive air shower technique, a detailed simulation is required to examine whether such anisotropy can be reproduced from the measurements of secondary components.
The anisotropy of cosmic rays due to the single source is likely to be closed to the present direction of the source and should be revealed from phase analysis. However, observations [12, 13] do not point to any known local source. But it is possible that the anisotropy phase is directed by the local magnetic field rather than the single source. Energy dependence of anisotropy amplitudes and phase around the knee can provide important signature for the model. But the observational situation in these regards are not rich enough for any meaningful conclusion.

References

[1] A. D. Erlykin, A. W. Wolfendale, *J. Phys. G: Nucl. Part. Phys.* **23**, 979 (1997); *Astropart. Phys.* **8**, 265 (1998)
[2] A. Bhadra, *J.Phys. G: Nucl. Part. Phys.* **28**, 397 (2002)
[3] A. D. Erlykin, A. W. Wolfendale, *J. Phys. G: Nucl. Part. Phys.* **29**, 709 (2003)
[4] S. E. Thorsett *et al*, *ApJ Letters,* **592**, L71 (2003)
[5] A. Bhadra, Proc. 28th Int. Cosmic Ray Conf., (Tsukuba, Japan) 1, 303 (2003)
[6] A. D. Erlykin, A. W. Wolfendale, *Astrpart. Phys.* **22**, 47 (2004)
[7] A. D. Erlykin, M. Lipski, A. W. Wolfendale, *Astrpart. Phys.* **8**, 283 (1998)
[8] G. J. Dickinson, J. L. Osborne *J. Phys. A: Math., Nucl. Gen.* **7**, 728 (1974); J. L. Osborne, J. Wdowczyk, A. W. Wolfendale, *J. Phys. A: Math., Nucl. Gen.* **9**, 1399 (1976)
[9] A. A. Lagutin *et al.*, *Nucl. Phys. B (Proc. Suppl.)* **97**, 267 (2001)
[10] A. Bhadra, Proc. 29th Int. Cosmic Ray Conf., (Pune, India) (2005)
[11] T. Antoni *at al.*, *Astrophys. J.* **604**, 627 (2004)
[12] M. Aglietta *at al.*, Proc. 28th Int. Cosmic Ray Conf., (Tsukuba, Japan) 1, 183 (2003)
[13] R. W. Clay *at al.*, Proc. 25th Int. Cosmic Ray Conf., (Durban, SA) 4, 185 (1997)
[14] T. Kiffune *et al.*, *J.Phys. G: Nucl. Part. Phys.* **12**, 129 (1986)