29th International Cosmic Ray Conference Pune (2005) **00**, 101–104

Cosmic Rays from nearby Pulsars

A. Bhadra

University of North Bengal, Siliguri, WB 734430 INDIA

Presenter: A. Bhadra (aru_bhadra@yahoo.com), ind-bhadra-A-abs1-og12-poster

Contribution of nearby gamma-ray pulsars to the cosmic rays observed at Earth has been studied respecting the observed isotropy of cosmic rays. It is found that energy spectrum of pulsar-originated cosmic rays to be observed at earth may differ significantly from the production spectrum, particularly for nearby and intermediate aged pulsars.

1. Introduction

Pulsars are widely considered to be natural sites for acceleration of charged particles. From the point of view of available energy, pulsars are very promising source of cosmic rays because the rotational energy at birth can be more than 10 times that of the supernova explosion. Observation of pulsed and/or steady flux of electromagnetic radiations from radio to gamma ray energies provides direct evidence that some pulsars are site of energetic particles of at least several TeV. Another important feature is the maximum energy (E_{max}) attainable by a particle in the acceleration process. For fast rotating pulsars E_{max} even could reach around 100 EeV [1], the highest energy cosmic ray particles observed so far. A significant fraction of the total cosmic ray flux at and above knee energy region may come from pulsars [2]. A point that usually raised is that the derived spectrum of cosmic rays from pulsars is much flatter than the observed spectrum. However, such derivation is based on the assumption that the production spectra from all pulsars have the same slope with same E_{max}. It has been shown recently [3,4] that the expected cosmic ray spectrum in the energy range from PeV to EeV coincides with the observation if the distribution of pulsar initial periods is similar to the Gamma distribution [3] or if the logs of initial pulsar periods and surface magnetic fields are given by the Gaussian distribution [4]. Observations show that cosmic rays are high isotropic; the amplitude of anisotropy is less then 10^{-2} at the knee energy region. While estimating contribution of a pulsar such isotropic nature of cosmic rays has to be respected. But this point is not considered in most analysis. In most of the recent efforts of estimating cosmic rays from pulsars collective contribution of all galactic pulsars rather than that from an individual pulsar are studied [2-7]. As a result the anisotropy that may arise due to contribution of a nearby pulsar is not revealed straightway. Thus, the individual contribution, particularly from nearby pulsars, is of high significance as it could provide important information on the pulsar parameters involved in the cosmic ray production process. In the context of single source model of the knee [8] contribution of nearby pulsars to the cosmic ray spectrum at knee region has been studied recently [9, 10] but in those studies parameters are chosen suitably so that the contribution of the pulsars becomes significant at the knee energy of the spectrum. In the present work we estimate cosmic ray flux from a nearby pulsar without any such bias and respecting the observed isotropy of cosmic rays.

2. Acceleration of nuclei by pulsars

Pulsars are generally believed to be rotating neutron stars. Since the moment of inertia of a neutron star is around 10^{45} $erg\ s^2$, a millisecond pulsar has a rotational energy $E = \frac{1}{2}I\Omega^2 \sim 10^{52}$ ergs. A fraction of such a huge rotational energy of a pulsar may be converted to the kinetic energy of the particles those present in the magnetosphere. The pulsar magnetosphere is usually considered to be composed of electron-positron pairs. However, hadronic component also may exist [1-7]. These nuclei can be accelerated by pulsars through large potential drop associated with strong electric field parallel to the pulsar magnetic field. Several detailed mechanisms have so far been suggested for accelerating particles by pulsars including the popular polar gap [6], and the outer gap [7] models. It has also been suggested that pulsars may accelerate protons/ heavy nuclei by converting their rotational energy to particle kinetic energy via a relativistic MHD winds near the light cylinder [1].

The energy spectrum of the particles accelerated by the electromagnetic field of the pulsar of angular speed $\Omega\ rad\ s^{-1}$, radius R and with the surface magnetic field $B_s = B_{12} \times 10^{12}$ Gauss is given by

$$\frac{dN}{dE} = \xi \frac{1.9 \times 10^{45}}{E} \left(fZB_{12} \left(\frac{R}{10^6\ cm} \right)^3 \right)^{-1} \left(\frac{\eta I}{10^{45}\ g\ cm^2} \right) GeV^{-1} \tag{1}$$

Here we assume that ξ fraction of total rotational energy loss of a pulsar goes to accelerate nuclei, f fraction of the the maximum possible electrostatic potential that can be generated due to the rotating magnetic dipole of the pulsar at time t is available for the acceleration process (in general f may depend on pulsar period and magnetic field), and η fraction of total rotational energy loss is due to the emission of magnetic dipole radiation. So apparently the energy spectrum of the produced accelerated particles has the E^{-1} dependence. But since the production times for particles of different energies are different, the observed spectrum may not have the simple E^{-1} dependence.

3. Escape from the nebula

Pulsar accelerated nuclei will inject into the nebula (most gamma ray pulsars have plerions as well as they have associated supernova remnants, only the oldest pulsars such as Geminga or PSR1055-52 show no sign of having plerions). Initially the accelerated nuclei will interact with the dense matter of the expanding nebula. The interactions become negligible when the column density is very much less than the interaction length of the energetic nuclei in the medium and the energetic nuclei can escape the remnant without significant losses shortly (within few years) after the explosion. However, outside the light cylinder the azimuthal component of the magnetic field dominates over the radial field and varies with radial distance as $B(r) \sim r^{-1}$. As a result a possibility is that energetic particles will be trapped in the nebula. However, it is known that several instabilities develop in the process of confinement of charged particles by magnetic fields and high energy nuclei will finally escape along the field lines of the irregular fields. The energetic nuclei will obviously propagate diffusively in the nebula before escaping into the interstellar medium. When the diffusive distance $\frac{cr_{neb}^2}{4D(E)}$ ($D(E)$ is the diffusion coefficient) traveled by the nuclei is greater than the radius of the nebula r_{neb}, the particle will escape from the nebula.

4. Cosmic ray flux to be observed at Earth

The diffusion process governs the propagation of accelerated charged nuclei from the source. Assuming Gaussian diffusion, the intensity of cosmic rays of energy E at a distance r from a pulsar would be

$$I_{cr}(r,E) = \frac{\xi 2.6 \times 10^{52}}{8(\pi D\tau)^{3/2}} exp[-r^2/(4D\tau)] \left(fZB_{12}\Omega(t) \left(\frac{R}{10^6\ cm} \right)^3 \right)^{-2} \left(\frac{\eta I}{10^{45}\ g\ cm^2} \right)\ cm^{-2}s^{-1}GeV^{-1} \tag{2}$$

where τ is the time passed after emission of a cosmic ray particle of energy E. Note that τ is different for different energetic particles.

5. Constraints from the directional isotropy of cosmic rays

The contribution of cosmic ray flux from a point source may be restricted by the observed high degree of isotropy of cosmic rays. In the diffusive propagation scenario mentioned above the amplitudes of anisotropy ($\delta = \frac{\lambda}{I(E)} | \frac{\partial I(E)}{\partial r} |$) resulting from a point source of cosmic rays reduces to

$$\delta = h(E) \frac{3r}{2c\tau(E)} \tag{3}$$

where $h(E)$ 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. A nice feature of the expression (4) is that it does not depend on the diffusion coefficient. 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). Observations show that cosmic rays are highly isotropic, δ is restricted to a small value. While estimating flux from a point source the constrain imposed by the observed anisotropy through the above equation has to be respected, which in turn could restrict the parameters f and ξ. Such restrictions rule out the possibility of a nearby pulsar as the single source of the knee which will be discussed elsewhere.

6. Application: Cosmic rays from two nearby gamma ray pulsars

We have calculated cosmic ray flux from the two nearby gamma ray pulsars, namely the Vela and the Geminga.

6.1 The Vela pulsar

Characteristic age of Vela pulsar is around $10,000$ years with periodicity 89.3 ms, slow down rate is 1.25×10^{-13} $/sec/sec$, and surface magnetic field is around 3.4×10^{12} Gauss [11]. The distance of the object from the Earth is around 500 pc though recent works suggest a smaller value of 300 pc. Both the observed pulsar period and slow down rate will be consistent with the adopted model only if $\left(\frac{R}{10^6\ cm}\right)^6 \left(\frac{\eta I}{10^{45}\ g\ cm^2}\right)^{-1} = 0.24$. For estimating the escape time from the nebula we use the model given in [12] for the evolution of the nebula. Using f as given by the self-sustained outer gap model [13], the spectra of cosmic rays from the pulsar to be observed at earth are shown in figure 1(a) for both proton and iron primaries assuming $\xi = 0.01$ and 0.001 respectively. The parameter ξ is so chosen to respect the observed isotropy of cosmic rays. The observed all particle cosmic ray (best fitted) spectrum is also given in the figure for comparison.

6.2 The Geminga pulsar

Geminga pulsar is about 150 pc away from the Earth with period $P = 0.237$ s, $\dot{P} = 1.0975 \times 10^{-14}$ and surface magnetic field $B = 1.6 \times 10^{12}$ G [14]. Since Geminga is a relatively old pulsar, presence of ions in its magnetosphere is questionable. However, observation of high energy gamma rays from this pulsar indicates the presence of high energy particles in its atmosphere. Besides the non- observation of radio waves from the pulsar suggests that these high energy particles may not be electrons. Hence it is likely that ions are present in its magnetosphere. Observations suggest that the pulsar does not have any nebula, probably due to its age. Taking $\xi = 0.1$ (so that observed isotropy is obeyed) we estimate the spectra of cosmic rays from the pulsar to be observed at earth for proton and iron primaries which are shown in figure 1(b). Here also $\left(\frac{R}{10^6\ cm}\right)^6 \left(\frac{\eta I}{10^{45}\ g\ cm^2}\right)^{-1} = 0.24$ is adopted for consistent pulsar period and slow down rate.

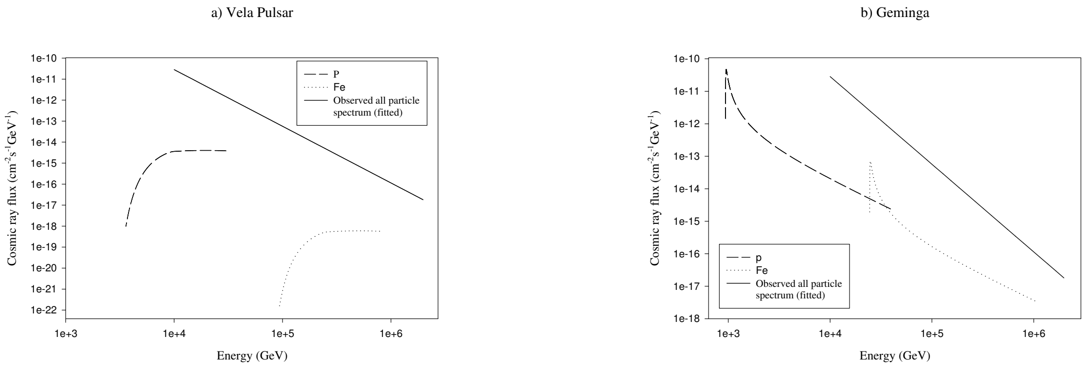

Figure 1. Cosmic Rays from nearby gamma ray pulsars

7. Discussion

In the present work we have studied the contribution of a nearby pulsar to cosmic rays observed at earth. We make use of the widely employed general electromagnetic acceleration process for production of high energy particles. In this scenario particles of different energies emit at different times. Further observed isotropy of cosmic rays has been exploited to constrain parameters involved in the cosmic ray generation process. The analysis shows that both the Vela and the Geminga may contribute at most 1 % of the observed cosmic rays below the knee. The cosmic ray spectrum to be observed at Earth from Geminga pulsar is found noticeably different than the production spectrum.

References

[1] P. Goldreich, and W. J. Julian, *ApJ* **157**, 869 (1969); P. Blasi, R. I. Epstein, and A. V. Olinto, *ApJ Letts.* **533**, L123 (2000)
[2] W. Bednarek, and R. J. Protheroe, *Astropart. Phys.* **16**, 397 (2002)
[3] M. Giller, and M. Lipski *J. Phys. G: Nucl. Part. Phys.* **28**, 1275 (2002)
[4] W. Bednarek and M. Bartosik *Astron. AstroPhys.* **423**, 405 (2004)
[5] V. S. Berezinsky *et al* Astrophysics of Cosmic Rays (North Holland, Amsterdam) (1990) and references therein.
[6] M. Ruderman, P. G. Sutherland *ApJ* **196** 51 (1975); J. Arons, E. T. Scharlemann, *ApJ* **231**, 854 (1979); A. K. Harding, A. G. Muslinov, *ApJ* **508**, 328 (1998)
[7] K. S. Cheng, C. Ho, M. Ruderman, *ApJ* **300**, 500 (1986); *ApJ* **300**, 525 (1986)
[8] A. D. Erlykin, A. W. Wolfendale, *J. Phys. G: Nucl. Part. Phys.* **23**, 979 (1997)
[9] A. Bhadra, Proc. 28 Int. Cosmic Ray Conf., (Tsukuba, Japan) (2003) 1 , 303
[10] A. D. Erlykin, A. W. Wolfendale, *Astrpart. Phys.* **22**, 47 (2004)
[11] V. A. Dogiel, *IL Nuovo Cim.* **19C**, 671 (1996)
[12] J. P. Ostriker, J.E. Gunn, *ApJ* **164**, L95 (1971); M. J. Rees, J.E. Gunn, *MNRAS* **167**,1 (1974)
[13] L. Zhang, and K. S. Cheng, *ApJ* **487**, 370 (1997)
[14] J. H. Taylor, R. N. Manchester, A. G. Lyne, *ApJS* **88**, 529 (1993)