Proceedings of ICRC 2001: 2583 ⓒ Copernicus Gesellschaft 2001

ICRC 2001

Gamma-ray visibility of the ‘Single source’ of the knee

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Abstract. Recently Erlykin and Wolfendale (1997b) proposed ‘single source’ model of cosmic rays according to which explosion of a single, nearby and recent supernova is responsible for the `knee' structure of the primary cosmic ray energy spectrum. This source is also expected to emit high-energy gamma rays, which are produced as a result of nuclear interactions of high-energy particles with ambient matter. In this work we discuss some estimates of the flux of gamma rays to be observed at earth from the proposed ‘single source’ of the knee.

1. Introduction.

The existence of a ‘knee’ in the shower size spectrum of the cosmic ray extensive air showers (EAS) has been known for many years (Khristiansen and Kulikov, 1958). Such a feature wonders cosmic ray physicists and a great effort have been made in the quest for the origin of such interesting spectral behavior. But the mechanism of producing the knee is still not understood. Recently analyzing World's EAS data, Erlykin and Wolfendale demonstrated that shower size spectrum has a more complicated structure than just a steepening at a particular shower size (Erlykin and Wolfendale 1997a; 1997c; 1998; 2000; 2001). This structure includes presence of distinct bumps around the knee; *viz*, there are sequences of steepening (S) and flattening (F) as SFSF. Schatz (2001) has made a detail analysis of 28 size spectra from 7 different experiments for the fine structure of the knee spectrum. He also found some observational evidence for existence of the 2nd knee though the possibility of systematic errors as the cause of fine structure of knee cannot be ruled out. Erlykin and Wolfendale (1997b) explained the structure in terms of two or three peaks in the energy spectrum of the shower initiating cosmic particles. They further advocated (Erlykin and Wolfendale, 1997b) in favor of explosion of a single, nearby and recent supernova as the cause of this spectral structure. According to their model, the first (at lower energy) peak is due to the CNO group of nuclei whereas the peak at higher energy corresponds to iron group of nuclei. Such identification is in accordance with the theoretical model of non-linear acceleration of cosmic ray particles at supernova remnant (SNR) (Berezhko et al, 1996), which extend the accelerated particle spectrum to Z × 400 TeV. Observation of cosmic gamma radiation of appropriate flux from a supernova remnant may help to identify the ‘single source’ and thus provide an experimental support of this model.

Young supernova remnants are expected as sources of high-energy gamma rays (e.g. see Drury et al, 1994; Naito and Takahara, 1994; Mastichiadis, 1996; Gaisser et al., 1997; Baring, 1997, Berezhko and Völk, 2000; Elison, et al 2000). High-energy particles are accelerated at the diffusive shocks of SNRs. A fraction of accelerated particles interact with ambient matter and produce neutral pions. High-energy gamma rays are subsequently generated from decay of neutral pions. At high-energy range the gamma ray spectrum thus should reflect the cosmic ray characteristics at SNR. Gamma rays are also produced by accelerated electrons in bremsstrahlung interactions, via synchrotron radiation, and also in inverse Compton scattering on the cosmic background, diffusive galactic radiation and locally produced radiation fields. The intensity of π^o -decay gamma rays from a SNR depends mainly on the rate of injection of particles into the acceleration process and also on the density of swept up shell of dense gas. On the basis of simplified but reasonable model (Drury et al 1989) of injection scenario Drury et al. (1994) estimated π^o decay gamma ray flux from SNRs. Following their procedure in this work we compute π^o -decay gamma ray flux to be observed at Earth from the 'single source' of the knee.

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2. Cosmic ray flux from `Single source':

2.1. A simple estimate

SNRs are site of particle acceleration. Particles are accelerated at diffusive shocks of the SNR. The production spectrum of cosmic rays at the shower front is given by a power law (see e.g. Blandford and Eichler, 1987; Berezhko et al, 1996)

$$\frac{dN}{dE} = AE^{-\alpha} \qquad (1)$$

where the value of the spectral index α is close to 2. If ξ fraction of total energy of supernova explosion E_{SN} goes for creation of cosmic ray particles, then equation (1) yields

$$A = \frac{\xi E_{SN}}{\ln(E_{max}/m_p c^2)} \quad \text{GeV,} \qquad \text{for } \alpha = 2 \qquad (2)$$

$$= \frac{(2-\alpha)\xi E_{SN}}{E_{max}{}^{2-\alpha} - (m_p c^2)^{2-\alpha}} \quad \text{GeV,} \qquad \text{for } \alpha \neq 2 \qquad (3)$$

where E_{max} is the maximum energy attainable by a particle in the SNR. The propagation of cosmic rays from the source is obviously by diffusion. In a simplified model of diffusion (neglecting the effect of energy gained or loss during propagation, convection, losses of nuclei by collision and fragmentation) the transport equation takes the form

$$\frac{dN}{dt} = \nabla.(D\nabla N) + Q(r,t) \qquad (4)$$

where D is the diffusion coefficient of nuclei in the Galaxy and Q represents the source term. The Green's function for the above diffusion equation gives the probability density of finding a cosmic ray particle at a given radius r from the source which is given by (Gaisser, 1990)

$$P(r) = \frac{1}{8(\pi D\tau)^{3/2}} \exp\left[-r^2/(4D\tau)\right] \ \text{cm}^{-3} \qquad (5)$$

Here τ is the age of the supernova explosion. For the production spectrum of cosmic rays represented by equation (1), the intensity of cosmic rays at a distance r from the source will be (Johnson, 1994)

$$I_{CR}(r) = \frac{cAP(r)E^{-\alpha}}{4\pi} \quad \text{cm}^{-2}\text{s}^{-1}\text{GeV}^{-1}\text{Sr}^{-1} \qquad (6)$$

Here it is assumed that cosmic rays are propagated from a point source. Any trapping of the cosmic ray particles at the shock will lead to an enhancement of the flux (Johnson and Dawson. 1995). Thus eq. (6) should be considered as a lower limit to the expected flux from the remnant.

2.2 Intensity in 'single source' model.

According to the 'single source' model, the observed cosmic ray spectrum is due to superposition of the contribution from the 'single source' of the knee over a smoothly steepening background spectrum caused by many distant sources (Erlykin and Wolfendale, 1997b). The source component has three different parts corresponding to three different types of nuclei, each with a differential spectral form E^{-2} before the peak and a sharp cut-off afterwards. The most prominent part is attributed to the CNO group (mainly Oxygen). Alternatively Helium nuclei could be associated with the main peak. The rest two parts are due to medium heavy nuclei and heavy nuclei (iron and nickel). The condition of smoothly steepening of background component and observed flux well above and below the knee puts a constraint on the intensity of the cosmic rays coming from the `single source'. The resultant intensity of cosmic rays from the 'single source' in the form of flux of oxygen nuclei, as taken in the model, is ~7.9×10^{-5} E^{-2} cm^{-2}s^{-1}GeV^{-1}Sr^{-1}. The intensity of iron nuclei is ~ 2.5×10^{-5} E^{-2} cm^{-2}s^{-1}GeV^{-1}Sr^{-1} and that for the all particle spectrum from the source is ~ 1.26×10^{-4} E^{-2} cm^{-2}s^{-1}GeV^{-1} Sr^{-1}. The maximum energy attainable by a nuclei in the SNR is also available from the experimental data, which is around 3×10^{15} eV for oxygen nuclei. Comparison of these observed (as interpreted in the model) spectrums with eq. (6) is, however, not possible when α=2 because of the energy dependence of diffusion coefficient. The diffusion coefficient depends on the rigidity as D ~ $R^{1/3}$ (Berezinsky, 1990). To match the energy dependence of the observed intensity from the single source, the production spectrum have to be much flatter than the canonical value of α=2, particularly at higher energies. The non-linear acceleration process provides such scenario (Berezhko et al., 1996). In this preliminary work we are only making a rough estimate and hence we assume that the average value of D (>E) is energy independent. With such assumption comparing equation (6) with the observed intensity from the 'single source', we get

$$\xi_i \frac{E_{SN}}{10^{51}\text{erg}} = \frac{B}{P(r)} \qquad (7)$$

where ξ_i is the fraction of total energy of supernova explosion goes to create i-th type of nuclei. B~ 8×10^{-67} and ~1.2×10^{-66} for oxygen component and all particle spectrum respectively. The eq. (7) gives correlation between energetic of the source and the position of the source. So one could get information about the energetic of the source provided the distance and age τ of the source is known from other considerations or vise versa.

3. π^o -decay Gamma-ray flux from the `Single source'

If the cosmic ray nuclei have a power law differential energy spectrum

$$F(E) \sim E^{-\alpha+1}, \qquad (8)$$

the production rate of π^o decay γ-rays from collisions of cosmic ray nuclei with ambient matter (mostly proton) may be written as

$$Q_\gamma(E) = Z_\gamma^\beta \sigma_{pA} cnF(E) \qquad (9)$$

where Z_γ^β is the so-called spectrum weighted moment of the inelastic p-A cross-section, σ_{pA} is the inelastic proton-nuclei cross section, c is the velocity of light, and n is the density of the ambient matter. The above relation is obtained by extending the expression of emissivity of γ-rays in p-p collision (Drury et al, 1994). The spectrum-weighted moment is defined as

$$Z_\gamma^\beta = \int_0^1 x^\beta g(x)dx \qquad (10)$$

where x is the Feynman variable and g(x) is the inclusive cross section. For β = 1, the spectrum weighted moment represents the fraction of interaction energy that goes into creation of π^o particles (partial elasticity). One can estimate this from the results of p-p interaction using theoretical models (e.g. Frichter et al., 1997). Recent results from emulsion chamber experiments (Augusto et al, 1999; Wilk and Wlodarczyk, 1998) or analysis of cosmic ray results also provide (Bhadra, 1999) information about the elasticity parameter in high-energy proton-nuclei cross interactions. σ_{pA} can be estimated either using Glauber method (Glauber and Matthiae, 1970) or from cosmic ray results (Baltrusatis *et al*, 1984; Block, M.M. et al, 1999; Honda et al, 1993; Aglietta *et al*, 1997). Thus one can estimate $Q_\gamma(E)$ for p-A collisions from corresponding $Q_\gamma(E)$ in p-p collision.

If the production spectra of cosmic rays in the SNR is given by equation (1) with α=2 and for cosmic ray particles are proton, the integral flux of gamma rays above 1 TeV from an SNR at a distance r from the source is (Drury et al, 1994)

$$F(>E\ \text{TeV}) \approx 9 \times 10^{-11} \left(\frac{E}{1\text{TeV}}\right)^{-1} \xi \left(\frac{E_{SN}}{10^{51}\text{erg}}\right)\left(\frac{r}{1\text{kpc}}\right)^{-2}\left(\frac{n}{1\text{cm}^{-3}}\right) \text{cm}^{-2}\text{s}^{-1} \qquad (11)$$

For the same consideration the flux of gamma rays with energies above 100 MeV (close to the EGRET threshold energy) is given by

$$F(\geq 100\ \text{MeV}) \approx 4.4 \times 10^{-7} \xi \left(\frac{E_{SN}}{10^{51}\text{erg}}\right)\left(\frac{r}{1\text{kpc}}\right)^{-2}\left(\frac{n}{1\text{cm}^{-3}}\right) \text{cm}^{-2}\text{s}^{-1} \qquad (12)$$

Using equations (7), (9), (11) and (12) we compute the gamma ray flux to be observed at Earth from the 'single source' for various distances and different ages of the SNR which are given in table 1. Here we have taken n =1, D = 10^{29} cm^2s^{-1}.

Table 1. Expected gamma-ray flux from a SNR of different ages at various distances, which may serve as single source of the knee.

Age of SNRS in years	Distance of the source in pc	F(>100 MeV) $cm^{-2}s^{-1} \times 10^{-7}$	F(>1 TeV) $cm^{-2}s^{-1} \times 10^{-11}$
10^3	100	16	35
10^4	100	0.9	1.8
10^4	200	19	3.8
10^5	100	15	30
10^5	200	4.6	9.5
10^5	500	3.3	6.7

Clayton's SN and SN/Pulsars, Loop I are among the possible candidates of the 'single source'. We estimate gamma ray flux for each of these sources (assuming all of these sources are SNRs), which are given in Table 2.

Table 2. Expected gamma-ray fluxes from the possible candidates of 'single source'.

Source	Age of the Source in years	Distance of the Source in pc	F(>100 MeV) $cm^{-2}s^{-1} \times 10^{-7}$	F(>1 TeV) $cm^{-2}s^{-1} \times 10^{-11}$
Clayton's SN	10^5	40	85	180
SN/Pulsar Loop 1	10^5	130	9	19

4. Discussion.

We make some estimates of the gamma ray flux from the possible candidates of the 'single source' of the knee. We take cosmic ray flux from the source, as interpreted in the model, as input, since it is necessary to have a consistent relation between cosmic ray flux and gamma ray flux from the source. In the calculations, we make some assumptions. As a result our estimated flux only represents the lower limit of the gamma-ray flux to be observed from the 'single source'. For example if we take energy spectrum of cosmic ray particles at the source is harder than E^{-2}, then energy requirement of the source will increase and so is the gamma ray flux from the source. Since the 'single source' is regarded as a recent and nearby supernova remnant, the observation of gamma ray luminosity and spectrum from SNRs may be helpful to identify the source. The present estimates show that the expected TeV gamma-ray flux (and also 100 MeV flux) should be detectable by present experiments. But no strong evidence for gamma ray emission from isolated SNRs exists. Esposito et al. (1996) presented some association between unidentified EGRET sources (at above 100 MeV) with some SNRs. IC443 and γ-Cygni are the prominent among them. But the energy requirement of these sources to produce the knee rules out their candidature as the 'single source' of the knee. It seems if 'single source' exists then it may be a pulsar rather than a SNR.

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