The Origin of High Energy Cosmic-Ray Electrons and Nearby Supernova Remnants

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Abstract

We calculated the energy spectrum of cosmic-ray electrons in a semi-analityc approach by separating the contributions of distant and nearby sources, using the observed local SNRs in the neighborhood of the solar system. In this calculation, we considered the case that the accelerated electrons are liberated from the SNR after $\sim 10^3 - 10^5$yr from the explosion. The electron spectrum from the source is assumed to be a power-law with an exponential cut-off. From this calculation, we found that some observed nearby SNRs leave unique signatures in the form of identifiable structure in the energy spectrum of TeV electrons. This suggests that, in addition to providing information on the mechanisms of acceleration and propagation of cosmic-rays, specific cosmic-ray sources can be identified through the precise observation of electrons in the TeV region.

1. Introduction

Evidences of non-thermal X-ray emission and TeV gamma-rays from the supernova remnants (SNRs) reveal that high energy cosmic-ray electrons are accelerated in supernovae [6,8]. These accelerated electrons would be suppressed in the spectrum while still being trapped in and escaping from the remnant. Then, it is important to include this change of the injection spectrum from the source to calculate the cosmic-ray electron spectrum in the Galaxy. As discussed in Erlykin & Wolfendale [2], another important parameter is when the accelerated electrons are liberated from the remnant after the explosion.

In this paper, we show how the spectral change and release time of electrons from the remnant affect in the cosmic-ray electron spectrum. As a result, our calculations indicate the possibility that some known nearby SNRs are the most likely candidates for the sources of cosmic-ray electrons in the TeV region.

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2. Acceleration in SNRs and Propagation in the Galaxy

According to shock-acceleration models, maximum energies of accelerated electrons are limited, by the SNR age, a free escape energy of $\sim 10-100$TeV, or synchrotron losses [7]. Analysis of the observed radio and X-ray spectra also suggests that the typical electron spectrum produced in a remnant is a power-law with a cut-off of $10-100$TeV [4]. Therefore, we took an electron injection spectrum of a power-law with an exponential cut-off of the form of $\exp(-E/E_{\rm c})$. As for the release time, we assume that electrons are liberated burst-likely from SNRs in the release time of $\tau = 0-10^5$yr. We also take the following parameters; the output energy of electrons over 1 GeV in a supernova explosion is $W = 1\times10^{48}$erg/SN, and the spectral index is $\gamma = 2.4$ in the TeV region.

Since high energy electrons lose energy by synchrotron and inverse Compton processes during propagation in the Galaxy at the rate of $dE/dt = -bE^2$, electrons lose almost all of their energy E after time $T = 1/bE$. Therefore, electrons observed with energy E must have been accelerated within $T = 1/bE$ from the present. The lifetime T becomes progressively shorter with increasing energy. Assuming $B = 5\mu$G [3] and taking the Klein-Nishina formula for Compton process, the lifetime is $T = 1/bE = 2.5\times10^5({\rm yr})/E({\rm TeV})$. We calculate the case of the diffusion coefficient of $D({\rm cm^2s^{-1}}) = D_0(E/{\rm TeV})^{0.3}$ with $D_0 = (1-4)\times10^{29}({\rm cm^2s^{-1}})$ in the TeV region. During this time, electrons at 1 TeV can diffuse an average distance of $R = (2DT)^{1/2}$; i.e. $0.4-0.8$kpc at 1 TeV.

In the diffusion model for the propagation of electrons in the Galaxy, the electron density $N_{\rm e}$ is represented by the equation

$$\frac{dN_{\rm e}}{dt} - \nabla(D\nabla N_{\rm e}) - \frac{\partial}{\partial E}(bE^2N_{\rm e}) = Q(E,r,z,t), \qquad (1)$$

where Q is the electron source strength, and r is the distance to sources from the solar system. Taking the boundary condition $N_{\rm e} = 0$ at the boundary of the Galactic halo $z = \pm h$, one can get the general solution of the equation (1) [5]. We separately calculated the contributions to the electron energy spectrum from nearby and distant sources [1]. For this purpose, we defined "nearby" to mean SNRs with distances $r \leq 1$kpc and times $T \leq 1\times10^5$yr, referring to the properties of SNRs in Table 1. In this calculation, we assumed that supernovae occur uniformly on the Galactic disk at the rate of 1/30 yr, and took the halo thickness to be $h = 3$kpc.

3. Results and Discussions

Figure 1 shows contours of the expected electron flux at 3TeV (with flux values scaled by E^3) as a function of age and distance of the SNR in the case of $D_0 = 2\times10^{29}({\rm cm^2s^{-1}})$. As shown in Fig. 1, the electron flux is strongly dependent on source age and distance.

Table 1. List of nearby SNRs [5].

SNR	R(kpc)	T(yr)
SN185	0.95	1.8×10^3
S147	0.80	4.6×10^3
HB 21	0.80	1.9×10^4
G65.3+5.7	0.80	2.0×10^4
Cygnus Loop	0.44	2.0×10^4
Vela	0.30	1.1×10^4
Monogem	0.30	8.6×10^4
Loop1	0.17	2.0×10^5
Geminga	0.4	3.4×10^5

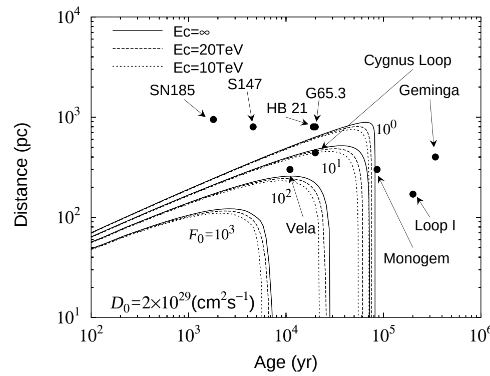

Fig. 1. Contours of the electron flux E^3J at 3TeV between T and R.

Figure 2 shows the calculated energy spectra of electrons without a cut-off and with a cut-off of $E_\mathrm{c} = 20$ TeV in the injected electron spectrum from the remnant, assuming the promptly release after the explosion. We can find that these spectra are similar with each other, in spite of the cut-off energies.

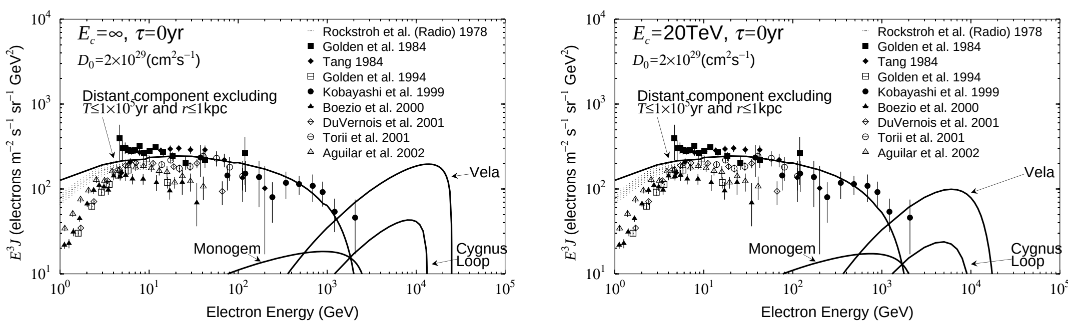

Fig. 2. Calculated Spectra without a cut-off (left) and with a cut-off of $E_\mathrm{c} = 20$TeV (right) in the promptly release of electrons after the explosion ($\tau = 0$), comparing with presently available data (references in [5]).

Figure 3 shows the calculated energy spectra with a cut-off of $E_\mathrm{c} = 20$TeV, in which electrons are released burst-likely after the explosion in the release time of $\tau = 5 \times 10^3$yr, 1×10^4yr, 5×10^4yr, and 1×10^5yr, respectively. As shown in Fig. 3, the delay of the release time from SNRs have a large impact on the flux in the TeV region for $\tau > 10^4$yr.

The results of our calculation by separating distant and nearby components are consistent with the observed data for the local primary electron spectra in the energy range from 10GeV to 2TeV. Our model also predicts that some nearby SNRs present unique, identifiable structures in the electron spectrum from 1TeV to 10TeV. For $\tau = 0$ and $\tau = 5 \times 10^3$yr, the energy spectra are similar with each other and the Vela SNR is the most dominant source in the TeV region. For $\tau = 1 \times 10^4$yr and $\tau = 5 \times 10^4$yr, the Cygnus Loop and the Monogem SNR are

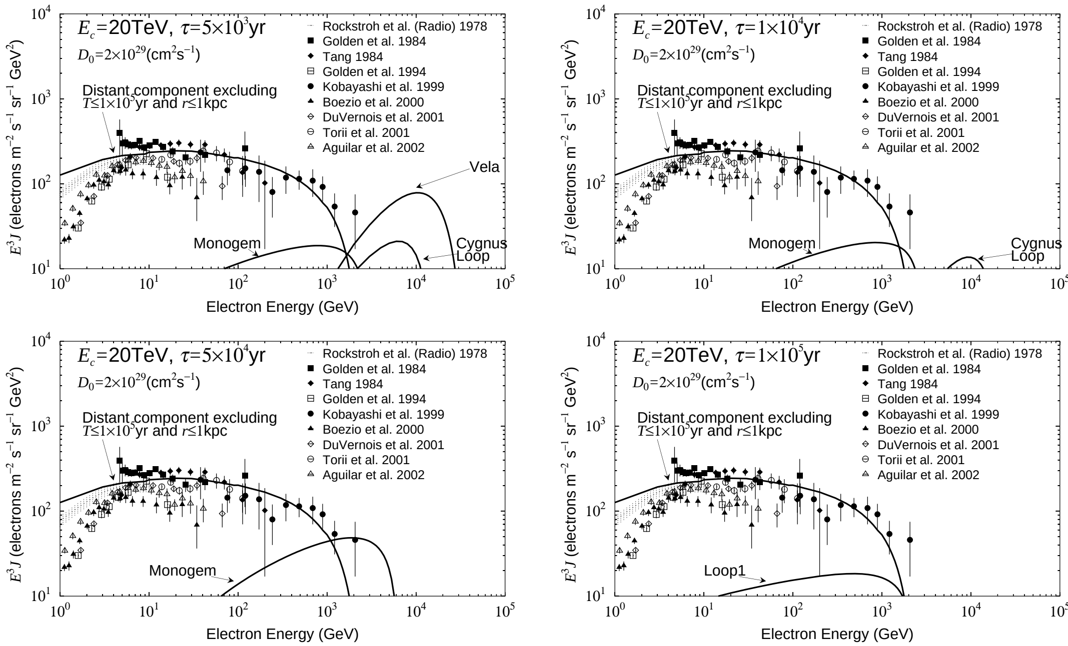

Fig. 3. Calculated Spectra with a cut-off of $E_c = 20$TeV at $\tau = 5 \times 10^3$yr, 1×10^4yr, 5×10^4yr, and 1×10^5yr, respectively.

dominant, and for $\tau = 1 \times 10^5$yr there are no dominant known sources in the TeV region. We also checked the case of the continuous release, and found that the spectrum is well represented by that of the burst-like release with a mean value of the continuous release time.

In this paper, it is demonstrated that measurements of the energy spectrum of electrons in the TeV region are crucial to detect the unique effects of nearby sources. Direct observations with such detectors as CALET[9], emulsion chambers[5], and other future experiments will reveal the origin of cosmic-ray electrons in this energy region, and also bring us important information on the sources, acceleration, and propagation of cosmic-ray electrons.

4. References

1. Atoyan A.M., Aharonian F.A., Völk H.J. 1995, Phys.Rev.D 52, 3265
2. Erlykin A.D., Wolfendale A.W. 2002, J.Phys.G: Nucl.Part.Phys. 28, 359
3. Ferriere K.M. 2001, Rev. Modern Phys. 73, 1031
4. Hendrick S.P., Reynolds S.P. 2001, ApJ 559, 903
5. Kobayashi T. et al. 2001, Adv. Space Res. 27, 653
6. Koyama K. et al. 1995, Nature 378, 255
7. Sturner S.J. et al. 1997, ApJ 490, 619
8. Tanimori T. et al. 1998, ApJ 497, L25
9. Torii S. 2003, in this volume.