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VELA AS THE MOST LIKELY SOURCE FOR THE PRIMARY ELECTRONS IN TEV REGION

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ABSTRACT

High-energy electrons lose energy by the synchrotron and inverse Compton processes during the passage in the Galaxy. By these raidative losses, the TeV electrons can propagate from the sources only within several hundred pc during their lifetimes of about 10^5 yr.
After the discovery of the evidence of electrons up to 100TeV in SN1006, the argument for supernova origin of high-energy cosmic-ray electrons has been strongly supported. Several candidates among nearby supernova remnants (SNRs) contributing to the high-energy electrons in the solar system have been investigated. The previous estimate of distance to Vela was 500pc, and too far to contribute effectively to TeV electrons in the solar system. However, the recent accurate estimate reduces this distance to 250 pc. Vela is now the most likely candidate contributing significantly to TeV electrons near the solar system. Comparing to the observed data, some consequences of Vela contribution to the spectrum of electrons in the TeV region, and the astrophysical significance are discussed in this paper.

INTRODUCTION

The supernova origin of high-energy electrons is strongly supported by the observations by ASCA and the Cangaroo group on the non-thermal X-ray spectrum and TeV gamma rays from SN1006 (Koyama et al., 1995, Tanimori et al., 1998). The Cangaroo group also detected TeV gamma-ray emission from Vela (Yoshikoshi et al. 1997). The output of electrons above 1GeV from SN1006 is estimated to be about 10^{48}erg. This is enough to explain the observed cosmic-ray electron flux, assuming each supernova accelerates a similar amount of electrons with explosion rate of 1/30yrs in the Galaxy.

The cosmic-ray electrons lose their energy by synchrotron and inverse Compton processes. The TeV electron loses its energy within a time of order of 10^5 yr., and can not travel far from the source.

The number of sources contributing to the electrons decreases progressively with electron energy, only a few supernova sources are expected to exist in this restricted area. Then one would expect la fluctuations in the spectrum at the high-energy end and the anisotropy of the electron flux.

As to the contribution of nearby sources, we have discussed in our previous paper that the contribu of Vela was minor in TeV region (Nishimura et al., 1997). The quoted distance of 500pc was too far electrons to arrive at the solar system within the age of Vela of about 10^4yrs. However, according to recent estimate, the Vela distance is most likely to be 250pc (Cha et al., 1999). It was estimated from spectroscopic identification of high velocity SNR gas by using Ca_{II} line of 68 OB stars. The location those OB stars was accurately determined by the Hipparcos satellite. By this change, Vela is likely contribute significantly to the high-energy electrons above 1TeV at the location of the solar system.

In this paper, we calculate the degree of contribution of each nearby SNRs, and describe that Vela the most likely source of electrons beyond 1TeV. If Vela is proved the main source of high-ener electrons, we can analyze propagation of TeV electrons by comparing with the observed spectrum and anisotropy towards Vela. It will bring us precise information about the acceleration and propagation cosmic rays.

PROPAGATION OF HIGH ENERGY ELECTRONS

High-energy electrons lose their energies by synchrotron and inverse Compton processes at the rate

$$dE/dt= -bE^2.$$

Thus the observed electrons of energy, E, should have been accelerated within a past duration $T=1/bE$. The lifetime, T, becomes progressively shorter with increasing energy. If we assume $\langle B^2\rangle^{1/2}=$ micro gauss (Webber, 1998), and are taking the Klein-Nishina formula for Compton process,

$$T\sim 1/bE = 2.1\mathrm{x}10^5(\mathrm{yr})/E(\mathrm{TeV}).$$

During this lifetime, electrons can diffuse within the distance of about $(2DT)^{1/2}$, where D is diffusion coefficient of electrons of that energy.

We can estimate the upper limit of D around TeV by the observed anisotropy ($<10^{-3}$) of the cos rays in this energy region. Putting the density of electrons as N and by using the relation (Berezinskii al., 1990, Ptuskin and Ormes, 1995);

$$\mathrm{Anisotropy} = \frac{3D}{c}\frac{\nabla N}{N},$$

the most probable upper limit of D is set as,

$$D=4\mathrm{x}10^{29}\ (E/\mathrm{TeV})^{0.3}\ \mathrm{cm}^2/\mathrm{s}.$$

by assuming a Kolomogorov spectrum of magnetic turbulence as a scattering center:

As a probable lower limit of the value of D, we put

$$D=10^{29}(E/\mathrm{TeV})^{0.3}\ \mathrm{cm}^2/\mathrm{s}.,$$

which is estimated by the diffusion coefficient at the low energy side of the 1-10GeV regions obtain from HEAO-C and Voyager data (Engelmann et al, 1990, Lukasiak et al., 1994).

Assuming these diffusion coefficients, an electron of 1TeV can travel from the sources on the average within about 500pc depending on when it was accelerated.

Then it is clear that only nearby sources contribute to the high-energy electrons in the solar system.

Contribution from nearby sources

As described in the preceding section One would expect large fluctuations of the spectrum in the TeV region as well as anisotropy towards the source. (Shen, 1960, Nishimura et al., 1979, 1980, 1997, Aharonian et al., 1995, Atoyan et al., 1995, Ptsukin & Ormes, 1995, Pohl et al., 1998).

Possible candidates of electron sources are listed in Table 1, located within 1 kpc with ages less than 4×10^5yrs. Note the distance to Vela changed to 250pc from 500pc in our old list.

Table. 1. List of Nearby SNRs and Pulsars

SNR	Pulsar	Distance (= r)	Age (= t)	Emax (= 1/bt)	Ref.
SN 185		0.95 kpc	$1.8{\cdot}10^3$ yr	116 TeV	(Strom, 1994)
S147		0.8	$4.6{\cdot}10^3$	46	(Braun, et al., 1989)
G65.3+5.7		0.8	$2.0{\cdot}10^4$	10	(Green, 1988)
Cygnus Loop		0.77	$2.0{\cdot}10^4$	10	(Miyata, et al., 1994)
Vela	B0833-45	0.25	$1.2\sim1.6{\cdot}10^4$	13~18	(Cha et al., 1999)
Monogem		0.3	$8.6{\cdot}10^4$	2.4	(Plucinsky, et al., 1996)
Loop 1		0.17	$2.0{\cdot}10^5$	1.1	(Eggar & Ashenbach, 1995)
Geminga	IE0630+178	0.4	$3.4{\cdot}10^5$	0.6	(Caraveo, et al., 1996)

We illustrate the degree of contribution of each source to electrons at 3TeV in Figure 1, assuming the output of electrons from each supernova is Qe (>1GeV) =10^{48} erg/ SN. Only a few SNRs contribute to the high-energy electron flux. As shown in the figure, the effect of the change of distance to Vela from 500pc to 250pc is quite sensitive. The flux of electrons around 1TeV is two orders of higher flux than the case of R=500pc. Significant contribution of Vela to the TeV electrons is now expected in case of R=250pc.

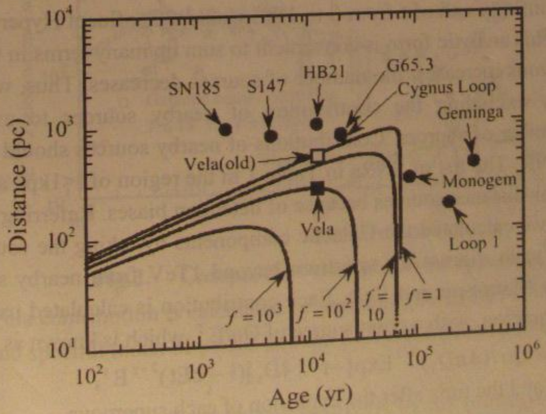

Fig.1. Contribution of each Supernova

Here we assume output of each SN for electrons beyond 1 GeV is 10^{48} erg, and $D=2\times10^{29}(E/TeV)^{0.3}$ cm^2/s. with spectral index of $\gamma=2.4$. Solid line shows equal intensity contour map for $f=(E/GeV)^3J$ (GeV^2/m^2.s.sr.), where J is the flux of electrons at 3TeV.

COMPARISON WITH THE OBSERVED DATA

Cosmic-ray electron spectrum has been observed by various instruments, in which only Emulsion Chamber was successful to observe the electrons beyond 1TeV. The flux of TeV electrons is low, and large SΩand high rejection power (~10^5) against to proton is required as a detector. Emulsion Chamber accords with these requirements (Nishimura et al., 1980, Kobayashi et al 1999), but is limited by a long exposure due to the accumulation of the background and has no timing information. Several upgraded instruments are being planned on board the space station to observe with long exposures.

Galactic component and the contribution of nearby sources.

Below 1TeV, many sources contribute to the spectrum. We need to take into account the halo thickness of the Galaxy, since the low-energy electrons can reach the halo boundary.

We calculate this galactic component with the following assumptions:

Supernovae distribute uniformly on the Galactic disc near the solar system, and

Explosion rate in the Galaxy = 1/30yrs.,

$Qe\ (>1GeV) = 10^{48}$ erg/ SNR, with Halo thickness of $h = 3$kpc.

At the low-energy side (<a few hundred GeV) (Engelmann et al 1990, Lukasiak et al. 1994).

$D = 10^{28}\ (E/GeV)^{0.6}\ cm^2/sec$ with spectral index of $\gamma = 2.2$.

At around 1TeV, we follow the estimate in the preceding section as:

$D = (1\text{-}4)10^{29}\ (E/TeV)^{0.3}\ cm^2/sec$, with spectral index of $\gamma = 2.4$.

The density of the electrons, Ne, from a point source with Qo/E^{γ} at a distance, r, and a time, t, after the ejection, is derived from the diffusion equation by the Fourier transform. Taking the boundary condition as Ne=0 at the halo boundary, the solution is given by, (Nishimura et al., 1979, Belezinskii et al, 1990).

$$Ne = \frac{Qo}{4\pi D_1 hE^{\gamma}} \sum_{n=0}^{\infty} (1 - bEt)^{\gamma-2} Exp[-D_1 kn^2 - r^2/(4D_1)],$$

where $D_1 = DoE^{\delta}(1-(1-bEt)^{1-\delta})/((1-\delta)bE)$, and $kn = (\pi/2h)(2n+1)$.

Integration of r from 0 to infinity and of t from 0 to 1/bE yields a Confluent Hypergeometric Function for each term in the series. This analytic form is convenient to sum up many terms in the series.

As the energy of the electrons increases, the number of sources decreases. Thus, we need to calculate the galactic component by excluding the contribution of nearby sources to avoid the effect of fluctuations by the small number of sources. Contributions of nearby sources should be calculated from the observed data of each SNR. The list of SNRs in Table 1 in the region of $r<1$kpc and $T<4\times10^5$yr may be missing longer-age and far-distance sources because of detection biases. Referring to the contribution of each source in Figure 1, we calculated the Galactic components by taking the sources excluding the area of $r<0.5$kpc and $T<10^5$yr to discuss the spectrum beyond 1TeV from nearby sources. The SNRs existing in this area are only Monogem and Vela. Each contribution is calculated using the solution of the 3-dimesional diffusion equation: with a point source of Qo/E^{γ}, which is known as

$$Ne = Qo/(4\pi D_1)^{3/2} Exp[-r^2/4D_1](1 - bEt)^{2-\gamma} E^{\gamma},$$

where r and t is the distance and the time after the explosion of each supernova.

Some examples of the calculated results are shown in Figures 2 and 3 for galactic component and the contribution of individual sources within a region of $r<0.5$kpc and $<10^5$yr. together with observed data.

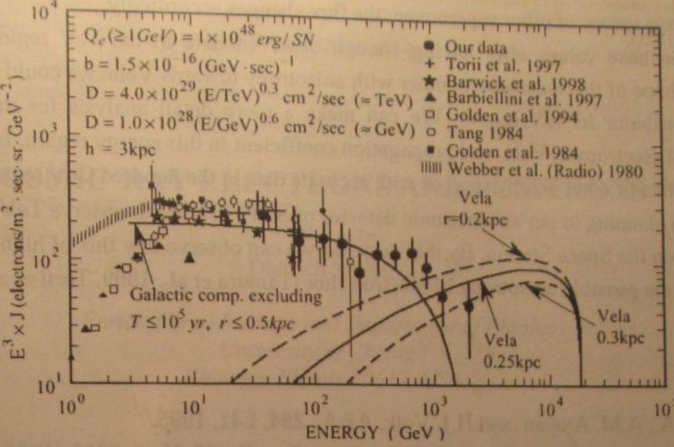

Fig.2. Comparison with observed spectrum.

Vela contribution is calculated by assuming $D=4x10^{29}(E/TeV)^{0.3}$ cm^2/s., around TeV and spectral index of γ=2.2 (around GeV), 2.4 (around TeV), see text

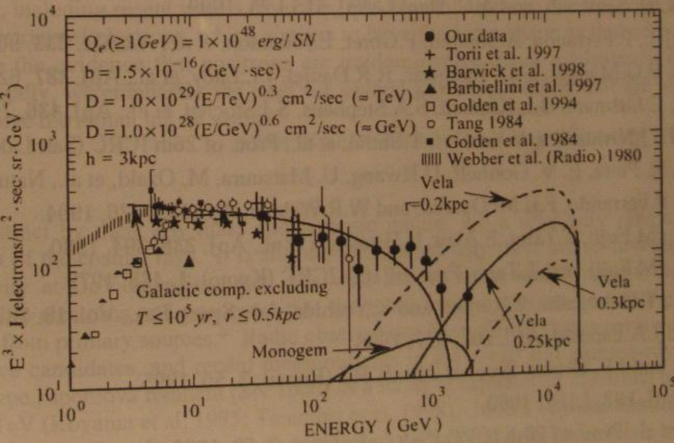

Fig.3. Comparison with observed spectrum.

Vela contribution is calculated by assuming $D=10^{29}(E/TeV)^{0.3}$ cm^2/s. around TeV, and spectral index of γ =2.2 (around GeV), 2.4 (around TeV), see text

The spectral shape and absolute flux change sensitively by the propagation parameters, distance and age (r, t), and electron output of each source. The diffusion coefficient around TeV region is not exactly known, and we adopted the most likely value estimated in the preceding section. The sensitivity of those values to the flux is shown in the Figures 2 and 3, and we see some combinations of the parameters are already not acceptable even in the present observed data.

Electron flux is proportional to the electron output of each source. If electron output of Vela deviates from the average values of other supernovae, the flux changes accordingly.

We can fix those values after having enough observed data in the TeV region. If we observe pronounced shape of the spectrum together with anisotropy towards Vela, we could identify that Vela the main contributor in TeV region. We can make a more detail analysis for the distance to Vela acceleration of electrons at Vela, and propagation coefficient in this energy region. In addition, we could identify the effect of other nearby sources with accurate data in the hundred GeV region.

We are also planning to put an electronic detector of SciFi (BETS) to observe TeV electrons for a very long duration on the Space Station. By this detector, we can observe low flux of high-energy electrons well as detect the possible anisotropy of electron flux (Tamura et al., 1999, Torii et al., 1999, Yoshida al., 2000).

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