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High Energy Cosmic-Ray Electrons Beyond 100 GeV

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Abstract

We report and discuss the new measurements of high energy electrons observed with emulsion chambers exposed by balloons in 1996 and 1998. By the improvement of the sensitivity of X-ray films, it is now possible to detect the electron showers down to 300GeV by naked eye scanning. The statistical precision of electron spectrum beyond a few hundred GeV was much improved.
As to the contribution of nearby sources at high energy electron spectrum, the latest estimate of the distance of 250pc to Vela, which is much smaller than the previous estimate of 500pc, leads to a possible significant contribution of Vela to the observed electrons in TeV region. The astrophysical significance of this consequence is presented.

1 Introduction:

High energy cosmic-ray electrons cannot travel far from their sources, because of their rapid energy losses through the synchrotron and inverse Compton processes, Thus the observations of electrons are believed to bring us a unique information of nearby sources and propagation of electrons. Beyond 100GeV, however, only few measurements were successful to measure the absolute flux of electrons. Series of long duration balloon observations were performed with emulsion chambers of 0.4m^2 sr. each in 1996 and 1998 at Sanriku Balloon Center. The sensitivity of X-ray films are improved, and it is now possible to detect the electron showers down to 300GeV by naked eye scanning. About 50 electrons beyond 300GeV were detected. Our previous spectrum is still consistent with these new data. However, statistical precision of electron spectrum beyond a few hundred GeV was much improved which will make more precise analysis of the spectrum in this energy region.

As to the contribution of nearby sources, we have discussed in our past paper that the contribution of Vela is not important in TeV region (Nishimura et al., 1997). The adopted distance of 500pc was too large for electrons to arrive at the solar systems within the age of 10^4 yrs. There should be other sources of SNRs or Pulsars contributing to electrons in TeV region. However, according to the recent estimate by the spectroscopic identification of high velocity SNR gas using OB stars and the location measurements by Hipparocos, the distance to Vela is most likely to be 250pc (Cha et al., 1999). By this change, Vela is likely to contribute significantly to the high energy electrons at the location of the solar system, and we discuss its astrophysical significance of this contribution.

2 Experiments:

Two emulsion chambers of 40cm$\times$50cm each were exposed to the balloon altitude above 36km at Sanriku Balloon Center in 1996 and 1998. Each exposure time was 37h52m and 19h34m. Emulsion chamber is a detector consisting of a stack of emulsion plates and lead plates. Nuclear emulsions of Fuji ET7B of 60 μm thickness are coated on both sides of a methacrylate plate of 800 μm thickness. We put also screen type X-ray films (phosphoric plates with high sensitive photographic films) to locate the electron showers by naked eye scanning. Because of a large acceptance angle of the emulsion chamber compared with other detectors, we have a large $S\Omega$ of about 0.4m^2 sr. for each chamber of 40cm$\times$50cm. This large $S\Omega$ means that the chamber has a capability to measure the low flux of high energy electrons. The energy of the electron is determined by analyzing the transition curve of shower electrons within a circle of 100μm from the shower axis in the nuclear emulsion plates. The accuracy of the energy determination is about 10%, which was calibrated by an accelerator beam of electrons of fixed energy (Nishimura et al., 1980). The emulsion chamber also has the ability of identifying the electrons among the abundant proton initiated showers by detailed inspection of the starting point of showers through a microscope. We can discriminate a proton initiated diffraction dissociation event with a few prongs that is confusing with an electron accompanying an electron pair at the beginning of electron shower. Most of them were identified by the differences of angular spreads of those events (Abduzhamilov et al., 1988, Boos et al., 1978). The rejection power against protons is thus estimated as high as about 10^5, including the effect of the difference of the interaction m.f.p. between electron and proton, and the energy shift of proton.

In the exposure of 1996 and 1998, we improved the sensitivity of X-ray films for naked eye scanning. Full analysis was completed beyond 400GeV. We found 8 electrons beyond 800GeV, 13 beyond 600GeV, and 30 beyond 400GeV, being consistent with the spectrum so far obtained. The identification of electrons from 300 GeV to 400 GeV (~20) are in progress and will be completed by the time of Conference. The statistical precision of electron spectrum beyond a few hundred GeV was much improved to make more precise analysis of the spectrum in this energy region. Our energy spectrum including these new data is shown in the Table 1, Fig.1, and Fig.2.

Table 1. Electron Spectrum observed in the Chambers up to 1998

Energy bin (GeV)	$<E>$ (GeV)	$S\Omega T$ ($\mathrm{m^2 \cdot sr \cdot s}$)	N^{*}_{ob}	N^{**}_{prim}	Flux(J) $(\mathrm{m^2 \cdot sr \cdot s \cdot GeV})^{-1}$	$E^3 J$ ($\mathrm{GeV^2/m^2 \cdot sr \cdot s}$)
1500−3000	2068	6.648×10^5	10	5.2	$(5.21 \pm 3.32) \times 10^{-9}$	46±29
1000−1500	1214	6.648×10^5	17	10.1	$(3.04 \pm 1.29) \times 10^{-8}$	54±23
800−1000	892	5.463×10^5	20	14.2	$(1.30 \pm 0.42) \times 10^{-7}$	92±30
600−800	690	1.288×10^5	13	10.4	$(3.33 \pm 1.18) \times 10^{-7}$	109±39
400−600	486	7.133×10^4	24	19.6	$(9.94 \pm 2.53) \times 10^{-6}$	114±29
300−400	345	2.358×10^4	9	6.4	$(2.71 \pm 1.31) \times 10^{-6}$	111±54
200−300	243	9.726×10^3	7	5.4	$(5.55 \pm 2.78) \times 10^{-6}$	80±40
150−200	172	2.665×10^3	4	3.6	$(2.70 \pm 1.52) \times 10^{-5}$	138±77
100−150	121	1.679×10^3	8	7.2	$(8.55 \pm 3.38) \times 10^{-5}$	152±60
60−100	75.8	6.82×10^2	9	9.0	$(3.30 \pm 1.10) \times 10^{-4}$	144±48
30−50	37.9	6.98×10^1	6	6.0	$(4.30 \pm 1.76) \times 10^{-3}$	234±96

* N_{ob}: Observed number of electrons.

** N_{pr}: Number of electrons after correcting the energy loss and atmospheric secondary electrons.

3 Astrophysical Significance of High Energy Electrons:

The supernova origin of high energy electrons is strongly supported by the observations of ASCA and Cangaroo group on non thermal X-rays and TeV gamma-rays from SN1006 (Koyama et al., 1995, Tanimori et al., 1998). TeV gamma rays from Vela are also detected by Cangaroo group (Yoshikoshi et al., 1997). The output of electrons beyond 1GeV from SN1006 is estimated as about 10^{48} erg. This is enough to explain the electron flux observed in cosmic-rays, assuming each SN accelerates similar amount of electrons with explosion rate of 1/30yrs (Ginzburg, et al. 1990).

High energy electrons lose energy by synchrotron and inverse Compton processes, which are proportional to the square of energy as: $-bE^2$. Thus the observed electrons of energy, E, should have been accelerated within a past duration of $T = 1/bE$. Their life time, T, becomes progressively shorter with increasing energy.

If we assume $< B^2 >^{1/2} = 7\ \mu$G (Zweibel et al., 1997, Webber, 1997, 1998),

$T \sim 1/bE = 2.1 \times 10^5 \mathrm{yr}/E(\mathrm{TeV})$, with Klein-Nishina formula for Compton Process.

During this time, they can propagate the distance of r from the source,

$$r \sim 2(DT)^{1/2} = 2(D/bE)^{1/2},$$

where D is the diffusion coefficient of propagation of electrons.

We can estimate the value of D around TeV by the observed anisotropy ($\leq 10^{-3}$)of the cosmic-rays in this energy region. The most probable upper limit of D is set as follows:

$$D = 4 \times 10^{29}(E/\mathrm{TeV})^{0.3}\mathrm{cm}^2/\mathrm{sec}$$

by using the relation of

$$\mathrm{Anisotropy} = 3D/c \cdot \nabla N/N$$ (Ginzburg et al., 1990, Ptuskin and Ormes, 1995).

Also as a probable lower limit of the value of D, we have

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

which is estimated by low energy side values in 1-10GeV regions from HEAO-C and Voyager data. The electrons of 1 TeV can propagate within the average distance from the sources between 500 pc and 1 kpc, depending on when it was accelerated.

4 Spectrum of Electrons from Nearby Sources:

Because the electrons should have been accelerated within limited ranges of location and time, the numbers of sources become progressively fewer with increasing energy of electrons. One would expect anisotropy and large fluctuations of the spectrum in this energy region (Shen, 1960, Nishimura et al., 1980, 1997, Aharonian et al., 1995, Atoyan et al., 1995, Ptsukin & Ormes, 1995).

Possible candidates of electron sources are listed in Table 2, locating within 1 kpc with ages less than 4×10^5 yrs. Note the distance to Vela changed to 250pc from 500pc in our previous list.

Table 2. List of Nearby SNR and Pulsars

SNR	Pulsar	Distance	Age	$E_{\max}$	Ref
SN 185		0.95 kpc	1.8×10^3 yr	116 TeV	(Strom,1994)
S 147		0.8	4.6×10^3	46	(Braun, et al.,1989)
G65.3+5.7		0.8	2.0×10^4	10	(Green, 1988)
Cygnus Loop		0.77	2.0×10^4	10	(Miyata, et al., 1994)
Vela	B0833-45	0.25	$1.2 \sim 1.6 \times 10^4$	$13 \sim 18$	(Cha etal., 1999)
Monogem		0.3	8.6×10^4	2.4	(Plucinsky, et al., 1996)
Loop 1		0.17	2.0×10^5	1.0	(Eggar & Ashenbach, 1995)
Geminga	IE0630+178	0.4	3.4×10^5	0.6	(Caraveo, et al., 1996)

We calculate the electron spectrum from these nearby sources by assuming the parameters as;

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

$D = (10^{29} - 10^{30})(E/\mathrm{TeV})^{\delta}\mathrm{cm}^2/\mathrm{sec}$ with δ=0.3, spectral index: γ = 2.4, 2.2

SN explosion rate in the Galaxy: 1/30yrs.

For low energy side, the diffusion coefficient was estimated from the data of HEAO-C and Voyager (Webber et al.,1992, Engelmann et al.,1990, Lukasiak et al., 1996). Some examples of calculated results together with observed data are shown in Fig.1 and Fig.2.

The distance to Vela changed from 500pc to 250pc is based on the latest estimate (Cha et.al., 1999). The effect of this change is quite sensitive to the flux of electrons around 1 TeV, giving two orders of higher flux than that in the case of r = 500pc. Significant contribution of Vela to the TeV electrons is now expected as illustrated in Fig.1 and Fig.2. One could also observe the anisotropy of about 10% for TeV electrons from Vela in the case of r=250pc (Ptuskin & Ormes 1995).

As shown in the figures the spectral shape and absolute flux changes sensitively by the values of the diffusion coefficient D and distance r. Some combinations of the parameters are already not acceptable even in the present observed data. If the spectrum has a pronounced shape together with anisotropy as we expected, we could identify Vela is the main contributor in TeV region. Then we can make more precise analysis on the distance, the acceleration of electrons in Vela, and propagation parameters in this energy region. If we observe cut-off energy in the spectrum beyond a few TeV, we need to find a reason why Vela does not contribute. Also with more accurate data in hundred GeV regions, we could identify the effect of other nearby sources.

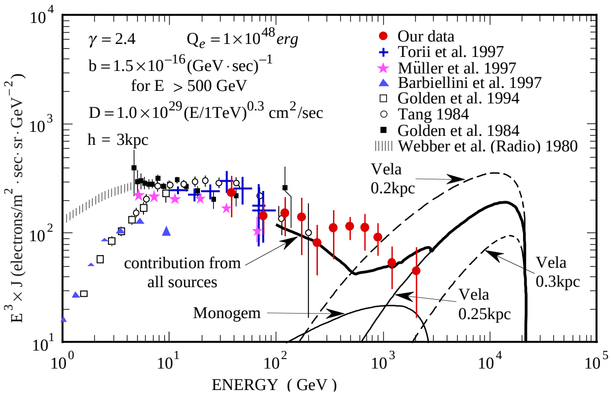

Figure 1: Calculated Spectrum and Observed data with $D = 10^{29}(\frac{E}{\text{TeV}})^{0.3}\text{cm}^2/\text{sec}$, γ= 2.4

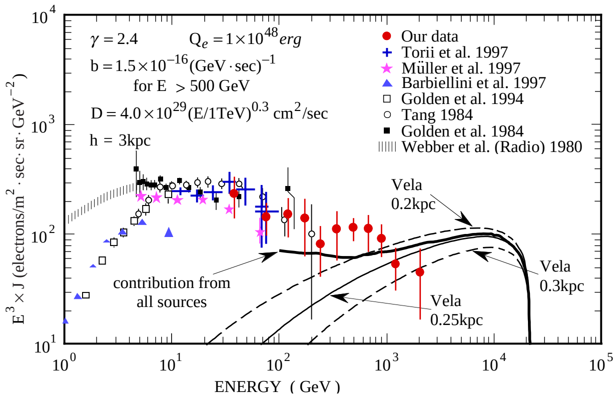

Figure 2: Calculated Spectrum and Observed data with $D = 4 \times 10^{29}(\frac{E}{\text{TeV}})^{0.3}\text{cm}^2/\text{sec}$, γ= 2.4

In this respect, the emulsion chamber seems to be the most efficient and reliable detector to observe the spectrum of electrons from a few hundred GeV to TeV region. We continue the long duration exposure of the chambers, but the duration of one exposure is probably limited to 10days, because of increasing of the background tracks in the emulsions. We are also planning to put an electronic detector of SciFi (BETS) on the Space Station to observe electrons for a very long duration. By this detector, we can measure the low flux of high energy electrons and detect the possible anisotropy of electron flux (Torii et al., 1997, Tamura et al., 1999).

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