Particle Acceleration and Cosmic-Ray Origin in the Galaxy

Toru Tanimori

Dept. of Physics, Graduate School of Science, Kyoto University, Kitashirakawa-Oiwakechou Sakyo-ku, Kyoto, 606-8502, Japan
tanimori@cr.scphys.kyoto-u.ac.jp

Abstract

In 1990’s Very High Energy Gamma-ray Astrophysics has dramatically advanced due to the Imaging Air Čerenkov Telescopes (IACTs). After the first detection of TeV gamma-ray emission from the Crab nebula in 1989, several type of TeV gamma-ray sources, Active Galactic Nuclei (AGN), young pulsar, and SuperNova Remnant (SNR), have been detected. In those discoveries, recent detections of both synchrotron X-rays and TeV gamma-ray emissions from several SNRs are very significant. SNR has been widely believed to be an unique candidate of galactic cosmic-ray origin since the beginning of cosmic-ray physics, whereas little observational evidences have been reported so far. Those are expected to be a clue of not only the galactic cosmic-ray origin but also the understanding of the particle acceleration due to a diffusive shock.

Here I present the recent results obtained by our group, CANGAROO, about the evidences of electron and proton acceleration in SNRs.

1 Introduction

As is well known, X-ray astronomy is an established field in astronomy, where several hundred thousands of X-rays sources have been found so far. On the other hands, the growth of gamma-ray astronomy had been relatively slow until the launch of the advanced gamma-ray satellite, Compton Gamma-Ray Observatory (CGRO), in 1991[1]. EGRET, a detector observing GeV gamma rays on-board CGRO, found more than 200 gamma-ray sources, whereas only 20 sources had been known before then. Emissions of high energy gamma rays were observed not only from galactic sources such as pulsar/nebulae and supernova remnants but also the more than hundred extragalactic sources. Figure 1 shows the GeV gamma-ray source catalog detected by EGRET in galactic coordinates. You see that hundreds of AGN were located out of the galactic plane, and moreover along the galactic plane there concentrated lots of unidentified sources.

Also several TeV gamma-ray sources have been recently established: Crab pulsar/nebula[2], Mrk421[3], Mrk501[4], PSR1706-44[5]. Celestial objects emitting very high energy gamma rays of energies greater than TeV had been expected as a natural consequence of the existence of cosmic rays, and they have been searched for since the middle of 20th century using the ground based detectors such as scintillation-counter arrays and air Čerenkov telescopes. Since huge background of hadron showers overwhelms the tiny signal of celestial gamma rays, no persistent TeV gamma-ray source had been found until the discovery of TeV gamma-ray
Figure 1: GeV gamma-ray source catalog detected by EGRET in galactic coordinates, where six TeV gamma-ray sources are also drawn by a circle.

emission from the Crab by the Whipple group in 1989\cite{2}. The Whipple group developed imaging Čerenkov technique\cite{6}, and hence the rejection power of hadron showers was greatly improved. In 1990’s several type of TeV gamma-ray sources have been detected with high statistics by adopting this imaging technique. In particular, successive discoveries of AGN emitting TeV gamma rays were astonishing\cite{3,4}.

Our group, CANGAROO, the collaboration of Japanese and Australian institutes, has observed TeV gamma-ray sources in the southern hemisphere since 1992 in South Australia\cite{7}. The southern hemisphere provides us a good chance to observe lots of galactic objects such as pulsar/nebulae, supernova remnants (SNRs), black holes, the galactic center, and so on. In fact we have found several galactic TeV gamma ray sources as listed in the review article of Weekes\cite{8}. In particular recent noteworthy discoveries are the several reports on the detection of TeV gamma-ray emissions from shell-type SNRs in both southern and northern skies\cite{9,11,12}, to which people have been eagerly looking forward ever since the beginning of cosmic-ray physics.

2 Cosmic-ray origin and shock acceleration

High energy particles are known to fill all over the galaxy and maybe over the surrounding halo, and play non-negligible roles on almost all phenomena in the universe. Moreover, high energy particles coming to the earth, “cosmic rays”, are surely affected on the circumstance of the earth. However, nobody know how and where such high energy particles are generated in the universe. These questions are unresolved yet, and always important issues in astrophysics in spite of the long history of the study of cosmic rays.

Radio and X-ray observations have revealed lots of high energy phenomena in the universe, where huge amount of energy is consumed to accelerate particles up to more than GeV energies, since high energy electrons in the magnetic field emit synchrotron radiation of radio to X-ray. Also high energy ions (mainly proton) must surely exist in the galaxy since almost cosmic rays are ions.
For a long time, supernova remnants (SNRs) have been believed to be a favored site for accelerating cosmic rays up to $10^{15}\text{eV}$, because only they can satisfy the required energy input rate to the galaxy among several galactic objects\cite{13}. In addition, a shock acceleration theory was established around 1980s, in which particles are accelerated with the collisions between particles and plasma gas moving at a supersonic velocity in the space\cite{14}. SNRs are a just extended and heated gas system accompanied by very strong shocks. Shocks are very common phenomena in the universe, and hence the shock acceleration has been widely applied for high energy phenomena in the universe. Thus shock-acceleration mechanism has been a standard theory for particle acceleration in astrophysics. Although this theory looks very simple and reliable, an observational evidence is still very sparse.

In order to investigate the shock-acceleration mechanism, SNR is an unique and ideal laboratory because it is quite simple and a well-understood astronomical object. The evolution of SNR can be fairly explained with several observables such as explosion energy of the SNR, total mass of the ejecta, density of the inter stellar medium (ISM) around the SNR and the age after the explosion\cite{15}. In addition, the resoluble size of a SNR enables us to directly observe the geometrical structure of the shock front accelerating particles, which provides lots of significant physical parameters quantitatively (absolute value of the magnetic field, index of power law, maximum energy of particle acceleration, and so on).

### 2.1 SN1006: first evidence of electron acceleration up to $\geq \text{TeV}$

The first evidence for the very high-energy particle acceleration in a SNR was presented by the observation of the strong synchrotron emission of SN1006 by the Japanese X-ray satellite ASCA in 1995\cite{16}. By assuming the magnetic field of several $\mu$ gauss, observed synchrotron X-ray emission strongly supported the existence of high energy electrons of tens or hundreds of TeV. Those high energy electrons must emit not only synchrotron radiation but also high-energy gamma rays due to Inverse Compton (IC) process by the hard collision with 2.7K Cosmic Microwave Background (CMB). Scattered photons acquire the energy of about one tenth of primary electrons, and hence their energies reach near 10 TeV in SN1006. They could be detected by the CANGAROO telescope in the TeV region \cite{17, 18, 19, 20}. In 1996
and 1997, CANGAROO succeeded in detecting the TeV gamma-ray emission from the north rim of SN1006\cite{9} as shown in Fig.2.

There exists a simple but useful formula connecting among relativistic electrons, high energy photons scattered by IC process, synchrotron photons and soft seed photons. The emission powers of synchrotron radiation and IC scattering, $P_{\text{sync}}$ and $P_{\text{IC}}$ are respectively expressed as follows,

$$P_{\text{sync}} = \frac{4}{3} \sigma_T c \gamma^2 \beta^2 U_B, \quad P_{\text{IC}} = \frac{4}{3} \sigma_T c \gamma^2 \beta^2 U_{\text{soft}},$$ \hspace{1cm} (1)

where $\sigma_T$ is the Thomson cross section, $\sigma_T = 6.7 \times 10^{-25} \text{cm}^2$, and $c\beta$ and $\gamma$ are the velocity and Lorentz factor of the electron. $U_B$ and $U_{\text{soft}}$ are energy densities of the magnetic field and the soft seed photons, respectively. Since the energy density of soft seed photons (CMB) is well-known, an observed gamma-ray flux provides a good estimation of the magnetic field strength at the acceleration site in SN1006. Figure 2.1a shows the wide band energy spectrum at the north rim of SN1006 from radio to TeV, and also the fitting result based on the IC model\cite{21}. All data are fitted very well, and several significant parameters, magnetic field($B$), power index($a$), maximum energy ($E_{\text{max}}$) were determined independently: $B = 4.3\mu$ gauss, $a = 2.2$, and $E_{\text{max}} = 60$ TeV.

Here we assumed that the detected TeV gamma-ray emission is mainly due to IC process with very high energy electrons considering the tenuous shell of ($\leq \sim 0.4$ cm$^{-3}$)\cite{10}. In fact the expected spectrum from $\pi^0$ decay generated by high energy proton conflicts with the upper limit in the GeV (Fig.2.1a).

In order to verify the origin of cosmic rays, we have to obtain a clear evidence of proton acceleration. The identification of the parent particles of TeV gamma-rays (electron or proton) will be possible by observing the wide spectrum from sub to multi TeV region as shown in Fig.2.1b. Gamma-ray spectrum flatter than $E^{-2.0}$ in this region is surely due to IC process, while that due to $\pi^0$ decay generated by collision between interstellar matter (ISM) and high energy proton is expected to be steeper than $E^{-2.0}$.  

Figure 3: a: Energy spectrum at the north rim of SN1006 from radio to TeV, and also fitting results based on the shock model. 

Figure 4: b: Expected energy spectra from both IC process and $\pi^0$ decay with synchrotron spectrum.
3 RX J1713.7-3946: first evidence of proton acceleration up to the TeV region

RXJ1713.7-3946 was observed as the strongest synchrotron X-ray emitter among SNRs by ASCA in 1997\textsuperscript{22}, and subsequently TeV emission was detected from the maximum X-ray emission point\textsuperscript{11}. Although this SNR emits an intense synchrotron X-ray similar to SN1006, those two SNRs looks different. Its morphology is obviously more complex than that of SN1006, of which north parts might interact with the molecular cloud observed by the radio telescope\textsuperscript{23}. Therefore this TeV emission might be ascribed to the $\pi^0$ decay generated by the collision of accelerated protons with the molecular cloud.

To clarify the nature of accelerated particles, we have observed this point again in 2000 and 2001 using the new CANGAROO 10m telescope\textsuperscript{24}, and the result has been recently published\textsuperscript{25}. Here summary is presented.

The differential fluxes of TeV gamma-rays from RX J1713.7-3946 are plotted in Fig.6a with previous data\textsuperscript{11}, and the best fit is

\begin{equation}
\frac{dF}{dE} = (1.63 \pm 0.15 \pm 0.32) \times 10^{-11} (E/1\text{TeV})^{-2.84\pm0.5\pm0.20} \text{ TeV}^{-1}\text{cm}^{-2}\text{s}^{-1},
\end{equation}

where the first errors are statistical and the second are systematic. You note that RX J1713.7-3946 is one of the brightest galactic TeV gamma-ray sources discovered so far, and the power-law spectrum increases monotonically in a single power law as energy decreases. This feature is in contrast to the Tev gamma-ray spectrum of SN 1006, which flattens below 1 TeV\textsuperscript{26}, and is well consistent with synchrotron/Inverse Compton (IC) models\textsuperscript{17, 18, 19, 20, 27}. While both SNRs emit intense X-rays via the synchrotron process, different TeV spectra suggest that different emission mechanisms may act respectively.

Morphology of the gamma-ray emitting region is shown by the thick-solid contours in Fig.6b, together with the synchrotron X-ray ($\geq 2\text{keV}$) contours by ASCA\textsuperscript{28} and infrared ones from IRAS 100\textmu m results\textsuperscript{29} which possibly indicates the density distribution of the interstellar matter. The observed TeV gamma-ray intensity peak coincides with the maximum point NW-rim observed in X-ray, but the TeV gamma ray emission extends over the ASCA contours. A possible extension towards the CO cloud in the north-east\textsuperscript{30} can also be seen.

The broad band energy spectrum is plotted in Fig.8a with theoretical predictions (described below). Also in this figure, other data has been shown using data from the ATCA (Australia Telescope Compact Array)\textsuperscript{31}, ASCA\textsuperscript{22, 28}, and EGRET\textsuperscript{32}.

In order to explain the broad-band spectrum, three mechanisms, the synchrotron/IC process, bremsstrahlung, and $\pi^0$ decay produced by proton-nucleon collisions are considered, where the momentum spectra of incident particles (electrons and protons) are assumed to be

\begin{equation}
\frac{dN}{dp} = N_0 \left( \frac{p}{m c} \right)^{-\alpha} \exp \left( -\frac{p}{p_{\text{max}}} \right) \left[ \text{cm}^{-2}\text{eV}^{-1}\text{c} \right],
\end{equation}

based on the shock acceleration model. The effects of acceleration limits from the age and size of the SNR and energy losses of particles are included in the exponential term. Best-fit values of free parameters in (2) for the radio and X-ray fluxes due to synchrotron radiation from
Figure 5: **a:** Differential fluxes obtained by this experiment together with that of CANGAROO-I. Inserted graph is the excess events determined from the plots of image orientation angle.

Figure 6: **b:** Profile of emission of TeV gamma rays around the NW-rim of RX J1713.7-3946 (solid thick contours).

Figure 7: **a:** Multi-band emission with models. TeV gamma-ray points are from this work. Lines show model calculations: synchrotron emission (solid line), Inverse Compton emission (dotted lines), bremsstrahlung (dashed lines) and emission from $\pi^0$ decay (dot-dashed line).

Figure 8: **b:** Allowed regions in parameter space (peak flux versus peak energy). The peak energies and fluxes for IC processes are allowed in the above parameter space, and also the allowed region from experimental flux corresponds to the lower-right corner of the shaded area.
electrons are obtained 2.08 for $\alpha$, 126 for $(p_{\text{max}}/\text{TeV})(B/\mu G)^{0.5}$, where $c$ is the speed of light, and 2.00 for $N_{\circ}(V/4\pi d^2)(B/\mu G)^{(\alpha+1)/2}$, where $V$ is the volume of the radiation region and $d$ is the distance from the Earth.

Thus the resultant best fit is plotted in Fig.8a (the solid line). We initially assumed the 2.7 K CMB as the seed photons for IC scattering. Calculated inverse Compton Spectra are plotted with dotted lines in Figure 2 for two typical magnetic field strengths, 3 and 20 $\mu G$. Note that these models are far from consistent with the observed sub-TeV spectrum. In general synchrotron/IC process gives a clear correlation between the peak fluxes and its energies of synchrotron and IC emissions as a function of the strength of the magnetic field. We investigated the allowed region of peak flux of IC emission taking into account the uncertainties of IR emission for the IC seed photons. The calculation was carried out both with and without this IR maximum energy emission in the IC process, assuming various incident-electron spectra. The hatched area in Fig.8b is the resulting theoretically allowed region of the peak flux, and also the experimentally allowed region are plotted by the shaded area. The predictions of synchrotron/IC models are obviously inconsistent with our experimental data by an order of magnitude. The bremsstrahlung spectrum was calculated assuming that it occurs in the same region as the synchrotron radiation. A material density of $\sim 300 \text{protons/cm}^3$ was assumed. The dashed lines in Fig.8a, for magnetic fields of 3 and 20 $\mu G$, are both inconsistent with our observation.

Thus, electron-based models fail to explain the observational results and so we examined $\pi^o$ decay models. The $\pi^o$'s are produced in collisions of accelerated protons with interstellar matter. A model adopting $\Delta$-resonance and scaling was used. We adopted parameters for Equation (2) of $\alpha = 2.08$ and $p_{\text{max}} = 10 \text{ TeV}$, considering the plausible parameter regions of typical shock acceleration theory. The result is shown by the dot-dashed curve in Fig.8a. The best fit parameters for the total energy of accelerated protons $E_0$ and matter density $n_0$ must satisfy $(E_0/10^{50}\text{[ergs]}) \cdot (n_0[\text{protons/cm}^3]) \cdot (d/6\text{kpc})^{-2} = 300$, where $d$ is the distance to RX J1713.7-3946. A value of $E_0 \sim 10^{50}\text{[ergs]}$ gives $n_0$ of the order of 10 or 100[protons/cm$^3$] for distances of 1 or 6 kpc, respectively. Both cases are consistent with the molecular column density estimated from Fig. 7 of ref.6. Thus the $\pi^o$ decay model alone readily explains our results, which provide the first observational evidence that protons are accelerated in SNR to at least TeV energies.

We can guess more about the galactic cosmic-ray origin. Using observed TeV gamma-ray flux, total energy of protons in the SNR was estimated to be $E_0 \sim 10^{50}\text{erg},$ assuming the distance of 6 kpc and target molecular cloud density of several times of $10^2\text{protons/cm}^3$. The energy input rate for proton acceleration estimated from this observation can represent the energetics of cosmic rays in the Galaxy. In other words, if such SNR are born every 100 years and accelerate protons, the SNR can provide all the energy of cosmic rays inside the Galaxy, where we adopt $1 \times 10^{40}\text{erg/sec}$ for the luminosity of galactic cosmic-rays.

4 Summary

Recent detections of TeV gamma rays from SNRs will obviously advance the studies of the galactic cosmic-ray origin and the shock acceleration mechanism by stimulating multi-wave length observations for SNRs. In particular combination of the morphological studies in both
X-ray and gamma-rays will be a key for these studies; advanced X-ray telescope satellites, Chandra and Newton, are now providing excellent images and spectroscopy, also the stereo observation by the 10m-class IACTs will soon provide good quality TeV gamma-ray images with the angular resolution of $\leq 0.1$ degree. In southern hemisphere, CANGAROO and H.E.S.S groups will begin the stereo observations using 10m-class IACTs in 2002.

References

[1] R.C. Hartmann, et al., Astrophys. J. Suppl.,123,79, (1999)
[2] G. Vacanti, et al., Astrophys. J.,377,467, (1991)
[3] M. Punch, et al., Nature,358, 477, (1992)
[4] J. Quinn, et al., Astrophys. J.,456, L85, (1996)
[5] T. Kifune , et al., Astrophys. J.,438, L91, (1995)
[6] A.M. Hillas, Proc. 19th Int. Cosmic-Ray Con.(La Jolla), 3, 445, (1985)
[7] T. Hara, et al., Nucl. Instrum. Methods Phys. Rev., A332, 300, (1993)
[8] T.C. Weekes, Proc. of GeV-TeV Gamma Ray Astrophysics Workshop (Snowbird), ed B. Dingus, 3

[9] T. Tanimori , et al., Astrophys. J.,497, L25, (1998)
[10] R. Willingale et al., Mon. Not. R. Astron. Soc.,278, 749, (1996)
[11] H. Muraishi , et al., Astron. Astrophys.,354, L57, (2000)
[12] F. Aharonian et al., Astron. Astrophys.,370, L12, (2001)
[13] L.O’C. Drury, W.J. Markiewicz and W.J. Volk, Astron. Astrophys.,225, 179, (1989)
[14] R.D. Blandford and D. Eichler, Phys. Rep.,154, 1, (1987)
[15] L.I. Sedov, LaTeX: Similarity and Dimensional Methods in Mechanics (Academic Press, 1959).
[16] K. Koyama, et al., Nature,376, 255, (1995)
[17] M. Pohl, Astron. Astrophys.,307, L57, (1996)
[18] A. Mastichiadis, Astron. Astrophys.,305, L53, (1996)
[19] A. Mastichiadis and O.C. Jager, Astron. Astrophys.,311, L5, (1996)
[20] T. Yoshida and S. Yanagita, Proc. 2nd INTEGRAL Workshop, ESA SP382, 85, (1997)
[21] T. Naito, et al., Astron. Nachr.,320, 205, (1999)
[22] K. Koyama et al, *Publ. Astron. Soc. Japan*, 49, L7, (1997)

[23] P. Slane et al., *Astrophys. J.*, 525, 357, (1999)

[24] T. Tanimori, *Prog. of Theoretical Phys. Suppl.*, 143, 78, (2001)

[25] R. Enomoto, et al., *Nature*, 416, 823, (2002)

[26] T. Tanimori, et al., *Proc. on 27th ICRC2001*, 6, 2465, (2001)

[27] T. Naito, T. Yoshida, M. Mori, and T. Tanimori, *Astron. Nachr.*, 320, 205 (1999)

[28] H. Tomida, Synchrotron Emission from the Shell-like Supernova Remnants and the Cosmic-Ray Origin, Ph. D. thesis, Kyoto Univ. (1999).

[29] Skyview, NASA, at [http://skyview.gsfc.nasa.gov](http://skyview.gsfc.nasa.gov).

[30] Y. M. Butt, et al., *Astrophys. J.*, 562, L167, (2001)

[31] D. C. Ellison, P. Slane, and B. M. Gaensler, Preprint astro-ph/0106257 (2001)

[32] R. C. Hartman et al., *Astrophys. J. Suppl.*, 123, 79, (1999)

[33] T. Naito, and F. Takahara, F., *J. Phys. G*, 20, 477, (1994)

[34] G. B. Rybichi, and A. P. Lightman, Radiation Processes in Astrophysics, John Wiley and Sons (1979), and references therein.