TeV Gamma Rays from Synchrotron X-ray SNR

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1. Abstract

Recent detections of both synchrotron X-ray and TeV gamma-ray emissions from several supernova remnants (SNR) are very exciting. SNR has been widely believed an unique candidate of cosmic-ray origin since the beginning of cosmic-ray physics, nevertheless little observational evidences have been reported so far. These detections are expected to be a clue of not only the galactic cosmic-ray origin but also the understanding of the particle acceleration by diffusive shock. Here we present a brief review about the recent observational results of CANGAROO project about two SNR in southern hemisphere. Also some understanding of the particle acceleration in such SNR based on multi-wave length observations is presented. In particular, we show the evidence of proton acceleration in SNR, RX J1713.7-3946, where a brief comment for the recently published counterarguments is added.

2. Introduction

High energy particles are well-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. In particular, 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 in accelerating 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 be accelerated in the galaxy since dominant part of cosmic rays are ions.

For a long time, supernova remnants (SNR) have been believed to be a fa-

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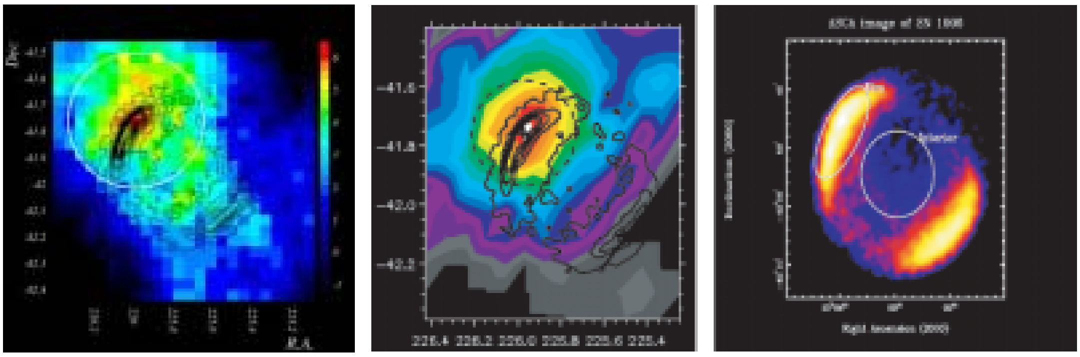

Fig. 1. SN1006 images of TeV gamma-ray observed by 10m telescope (right), same one by 3.8m telescope (center) and ASCA hard X-ray (left).

vored site for accelerating cosmic rays up to 10^{15}eV, because only they can satisfy the required energy input rate to the galaxy among several galactic objects[1]. 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[2]. SNR 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 a 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[3]. 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). From these reasons, lots of experiments looking for celestial TeV or more higher energy gamma rays had been extensively done more than last 40 years, but no reliable evidence were found. In particular EGRET detected GeV gamma rays from four SNR, but all observed spectra seemed to terminate around 1 GeV. Moreover in early 1990s Whipple group carried out the survey observation for the northern SNR, however they could not detect any TeV gamma-ray emission from observed six SNR. These six SNR are well-known young SNR, and then it had been quite expected to detect TeV gamma rays from several SNR in six ones. Those negative evidences had surely made scientists skeptical for the SNR origin of galactic cosmic rays. But the situation dramatically changed in 1995 as mentioned in the next section.

3. SN1006:first evidence of electron acceleration up to $\geq$ TeV

The first evidence for the very high-energy particle acceleration in a SNR was due to the observation of the strong synchrotron emission of SN1006 by the Japanese X-ray satellite ASCA in 1995[4]. Until that time, thermal X-ray emissions, which are known to be emitted from the heating plasma by a shock wave, had been observed from lots of SNR, whereas no synchrotron X-ray emission had been observed. Synchrotron X-rays are expected to be emitted from high energy elections accelerated by the same shock wave in SNR.

By assuming the magnetic field of several μ 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 [5] [6] [7] [8]. In 1996 and 1997, CANGAROO succeeded in detecting the TeV gamma-ray emission from the north rim of SN1006[9] as shown in Fig.1.. 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[10] using a 3.8m imaging telescope. The southern hemisphere provides us a good chance to observe lots of galactic objects such as pulsar/nebulae, SNR, 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[11]. In 2000 we costructed a new 10m telescope to exploit the sub-TeV energy region, and as a first taget of this SN1006 was observed as shown in Fig.1..

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_{sync} and P_{IC} are respectively expressed as follows,

$$P_{sync} = \frac{4}{3}\sigma_T c\gamma^2\beta^2 U_B, \ \ P_{IC} = \frac{4}{3}\sigma_T c\gamma^2\beta^2 U_{soft}, \tag{1}$$

where σ_T is the Thomson cross section, $\sigma_T = 6.7 \times 10^{-25} cm^2$, and $c\beta$ and γ are the velocity and Lorentz factor of the electron. U_B and U_{soft} are energy densities of the

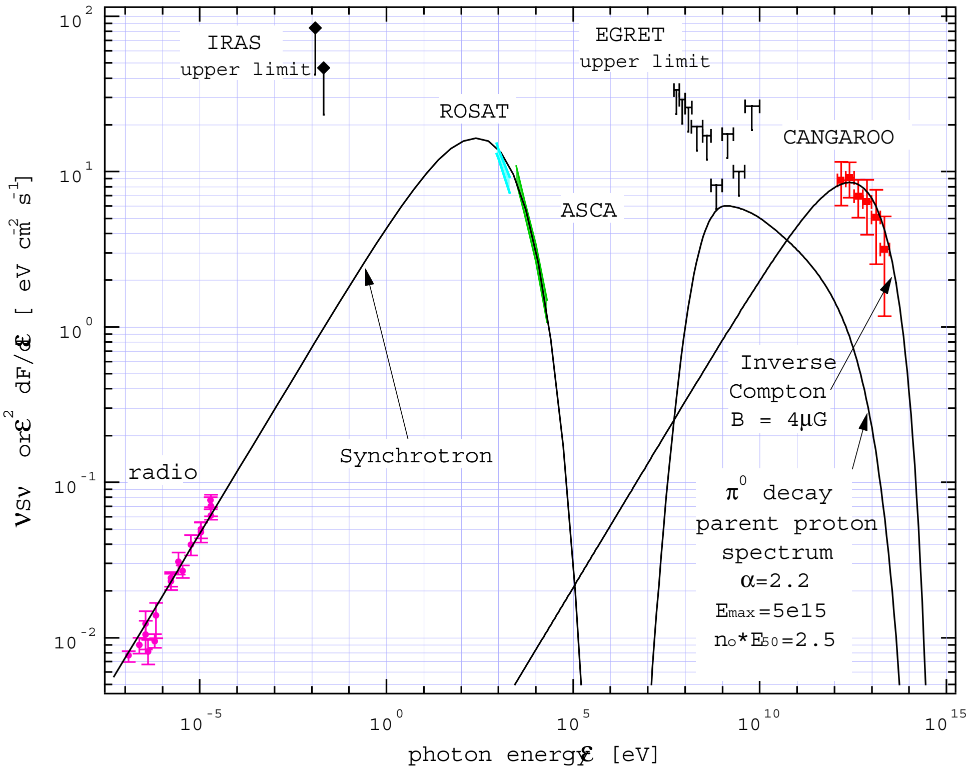

Fig. 2. Energy spectrum at the north rim of SN1006 from radio to TeV, and also fitting results based on the shock model.

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. 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[12]. All data are fitted very well, and several significant parameters, magnetic field(B), power index(a), maximum energy (E_{max}) were determined independently: $B = 4.3\mu$ gauss, a = 2.2, and $E_{max} = 60$ 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 (≤∼0.4 cm^{-3})[13]. In fact the expected spectrum from π° decay generated by high energy proton conflicts with the upper limit in the GeV (Fig.2.).

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

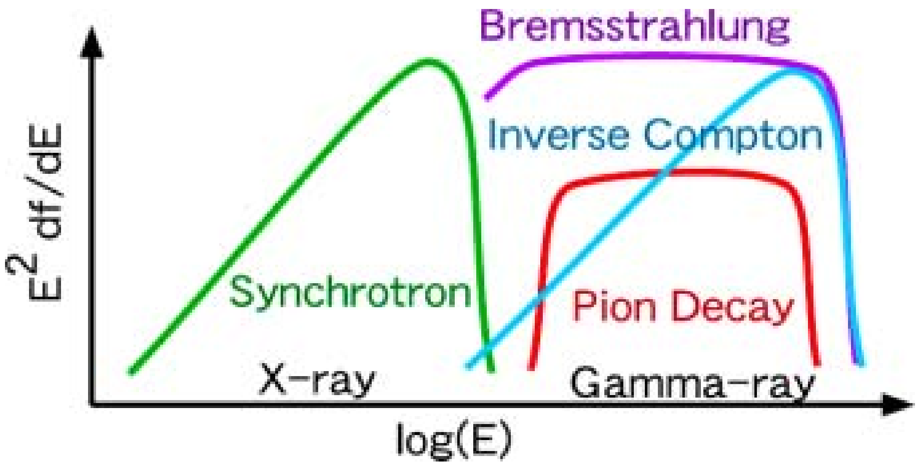

Fig. 3. Schematic image of expected energy spectra from both IC process and π° decay with synchrotron spectrum.

gamma rays (electron or proton) will be possible by observing the wide spectrum from sub to multi TeV region as shown in Fig.3.. Gamma-ray spectrum flatter than $E^{-2.0}$ in this region is surely due to IC process, while that due to π° decay generated by collision between interstellar matter (ISM) and high energy protons is expected to be steeper than $E^{--2.0}$.

4. RX J1713.7-3946: first evidence of proton acceleration up to the TeV region

After the discovery of synchrotron X-ray emission, several SNR emitting synchrotron X-rays were found. RXJ1713.7-3946 was observed as the strongest synchrotron X-ray emitter among SNR by ASCA in 1997 [14], and subsequently TeV emission was detected from the maximum X-ray emission point[15]. Although this SNR emits an intense synchrotron X-ray similar to SN1006, those two SNR 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[16]. Therefore this TeV emission might be ascribed to the π° 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 10m telescope[17], and the result has been recently published[18]. Here summary is presented.

The differential fluxes of TeV gamma-rays from RX J1713.7-3946 are plotted in Fig.5.a with previous data[15], and the best fit is

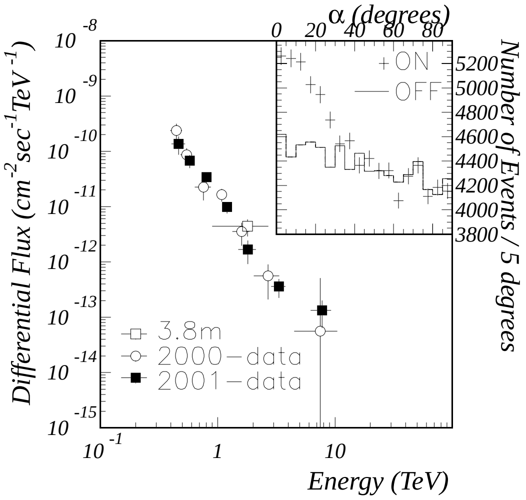

Fig. 4. **a:** Differential fluxes obtained by this experiment together with that of CANGAROO-I. Inserted graph is the excess events determined from the plots of image orientation angle.

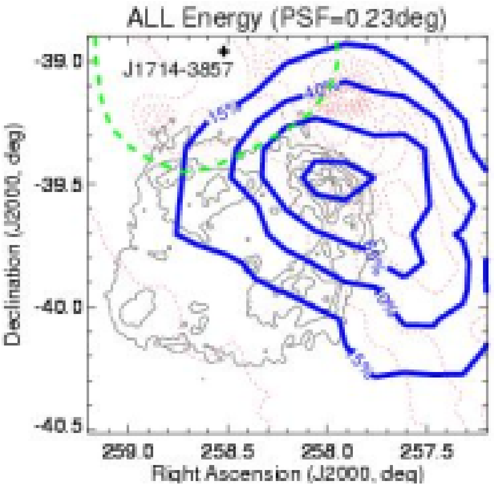

Fig. 5. **b:** Revised profile of emission of TeV gamma rays around the NW-rim of RX J1713.7-3946 (solid thick contour), intensity profile of hard X-ray emission by ASCA (solid thin contour) and infra red ones from IRAS (dotted contour).

$$dF/dE = (1.63 \pm 0.15 \pm 0.32) \times 10^{-11} (E/1TeV)^{-2.84 \pm 0.5 \pm 0.20}\ \mathrm{TeV}^{-1}\mathrm{cm}^{-2}\mathrm{s}^{-1}, \quad (2)$$

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[19], and is well consistent with synchrotron/Inverse Compton (IC) models [5] [6] [7] [8] [12]. While both SNR 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.5.b, together with the synchrotron X-ray ($\geq$ 2keV) contours by ASCA[20] and infrared ones from IRAS 100μm results[21] which possibly indicates the density distribution of the inter stellar matter. This figure has been recently modified after the publication since the small bag in the software calculating the direction of observed gamma rays was found. In this figure, the observed TeV gamma-ray intensity peak coincides with the maximum point NW- rim observed

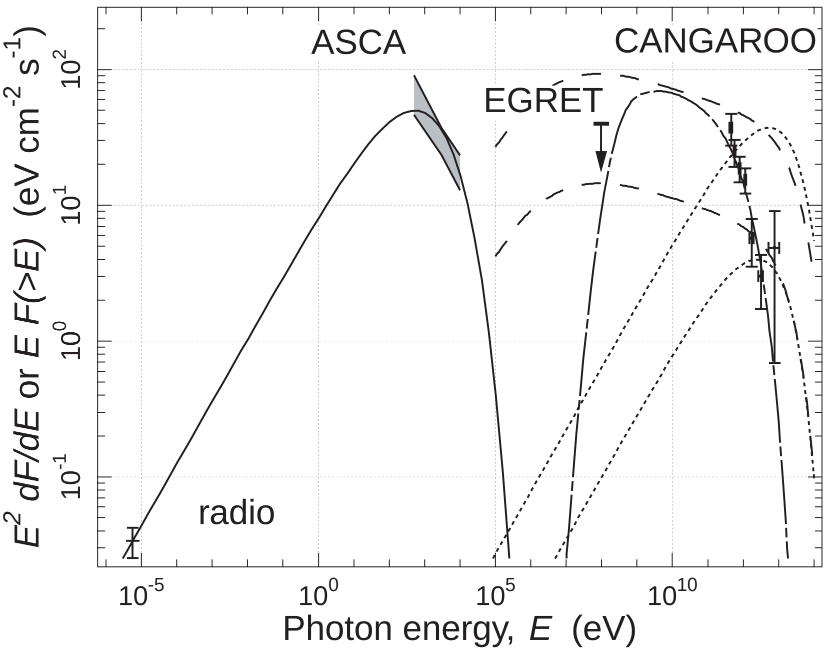

Fig. 6. Multi-band emission with models. TeV gamma-ray points are from this work. Lines show model calculations: synchrotron emission (solid line), Inverse Compton emission (dotted lines), bremsstrahlung (dashed lines) and emission from π°decay (dot-dashed line).

in X-ray, but the TeV gamma-ray emission extends over the ASCA contours. In particular modified emission region of TeV gamma rays shows the extension toward the north-west, which is a opposite direction of the extension of hard X-ray emission. Thus the distribution of TeV gamma rays seems to extend towards the CO cloud in the north-west. Nearby GeV gamma-ray source EG H1716 reported in EGRET 3rd Catalogue is also plotted. Recent paper pointed out the possible coincidence of this source to RX J1713[22]. Here we stress that observed TeV gamma rays obviously emits not from this GeV source point but from the maximum point of the hard X-ray emission, considering the uncertainty of the point spread function of our telescope with 0°.2 and the distance of $\sim$ 0°.8 between those two points.

The broad band energy spectrum is plotted in Fig.6. with theoretical predictions (described below). Also in this figure, other data has been shown using data from the ATCA (Australia Telescope Compact Array)[23], ASCA [14] [20], and EGRET. The upper limit of GeV gamma rays at the maximum flux point of TeV gamma rays was obtained from the EGRET archived data[24].

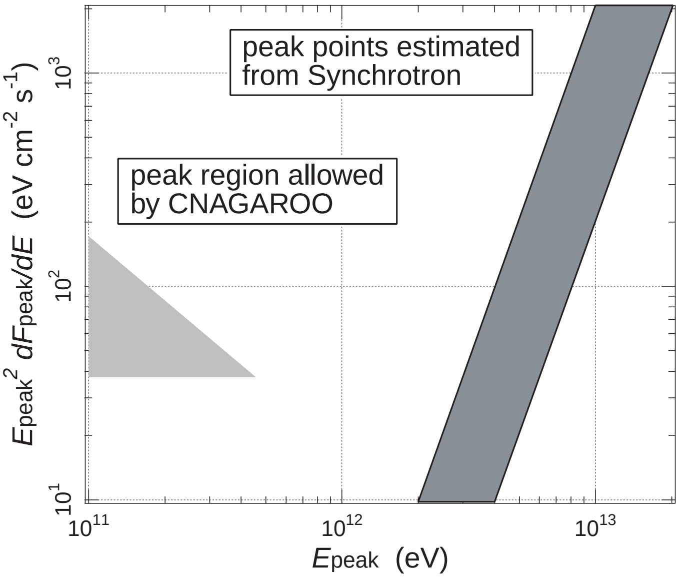

Fig. 7. Allowed regions in parameter space (peak flux versus peak energy). The peak energies and fluxes for IC processes are allowed in the above parameter space, and also the allowed region from experimental flux corresponds to the lower-right corner of the shaded area.

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

$$\frac{dN}{dp} = N_0 \left(\frac{p}{mc}\right)^{-\alpha} \exp\left(-\frac{p}{pmax}\right) [cm^{-2}eV^{-1}c] \quad . \tag{3}$$

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. The resultant best fit is plotted in Fig.6. (the solid line), of which detail are mentioned in Ref.[18]. 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 Fig.6. for two typical magnetic field strengths, 3 and 20μG. 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 hatched area in Fig.7. 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 $\sim 300 protons/cm^3$ was assumed. The dashed lines in Fig.6., for magnetic fields of 3 and 20μG, are both inconsistent with our observation. In the bremsstrahlung process, high energy electrons also ionize a neutral atom in the plasma, and hence 6.4 keV line emission of neutral ion are expected to be observed simultaneously. However observed X-ray spectra from any position of this SNR shows no peaks around 6.4 keV, which indicates that bremsstrahlung is not dominant in gamma-ray emission.

Thus, electron-based models fail to explain the observational results and so we examined π° decay models. The π°s are produced in collisions of accelerated protons with the interstellar matter. A model[25] adopting Δ-resonance and scaling was used. We adopted parameters for Equation (2) of $\alpha = 2.08$ and p_{max} = 10 TeV, considering plausible parameter regions of typical shock acceleration theory. The result is shown by the dot-dashed curve in Fig.6.. The best fit parameters for the total energy of accelerated protons E_0 and matter density n_0 must satisfy $(E_0/10^{50}[ergs]) \cdot (n_0[protons/cm^3]) \cdot (d/6[kpc])^{-2} = 300$, where d is the distance to RX J1713.7-3946. A value of $E_0 \sim 10^{50}[ergs]$ 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 π° 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 $E_0 \sim 10^{50} erg$, assuming the distance of 6 kpc and target molecular cloud density of several times of $10^2 protons/cm^3$. 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 $1 \times 10^{40} erg/sec$ for the luminosity of galactic cosmic-rays.

After this publication several counterarguments have been presented; all of those argued that the gamma-ray spectrum calculated from our data using the proton acceleration model conflicts with the upper limit of EGRET in GeV region[27] [28]. Figure8. shows the several possible gamma-ray spectra expected from the proton acceleration model by varying the index of the power law of

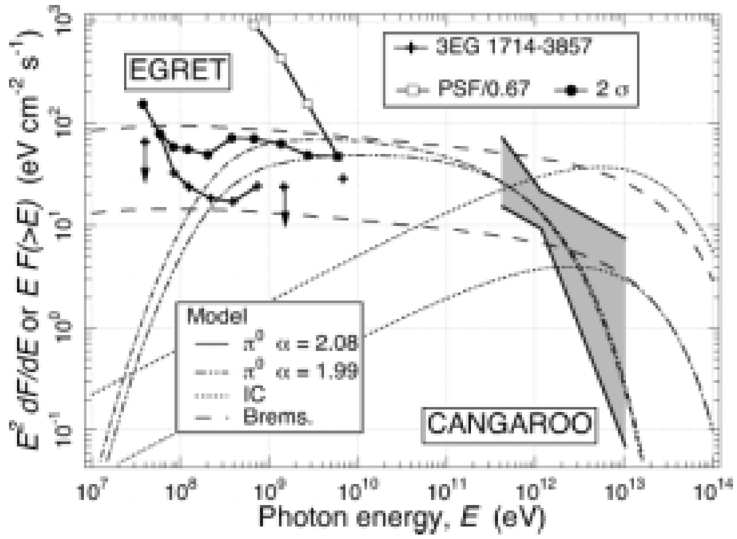

Fig. 8. Reviesed gamma-ray spectra. Observed TeV gamma-ray points are same to the publication, while the error band is added. Differential upper limits in the GeV region was estimated using the EGRET archived data. Lines show model calculations: synchrotron emission (solid line), Inverse Compton emission (dotted lines), bremsstrahlung (dashed lines) and emission from π°decay (dot-dashed lines) which were calculated for two resonable power indeics of accelerated protons.

accelerated protons within a reasonable range. In addition an error region of our data is plotted. Taking into account those points, there obviously remains the possibility of the proton acceleration model. What we pointed out here is that Synchrotron IC model is very difficult to explain both X-ray and TeV gamma-ray spectra, and then inductively our data strongly support the proton acceleration model. Recently Uchiyama et al, analyzed the Chandla data, and their result also support the our conclusion[29].

5. Summary

In northern hemisphere, HEGRA group reported the detection of TeV gamma-ray emission from famous young SNR, Cassiopeia A in 2001[26]. Thus recent detections of TeV gamma rays from SNR will obviously advance the studies of the galactic cosmic-ray origin and the shock acceleration mechanism by stimulating multi-wave length observations for SNR. In particular combination of the morphological studies in both X-ray and gamma rays will be a key for the identification of accelerated particles. Advanced X-ray telescope satellites, Chandla 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 ≤ 0.1 degree. In southern hemisphere, CANGAROO and H.E.S.S groups will begin the stereo observations using 10m-class IACTs in 2002.

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