TeV Gamma Ray observations and Origin of Cosmic Rays: Part II

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Abstract

Discussions are presented on Galactic TeV γ-ray sources from the veiw point of cosmic ray physics. Emission of TeV γ-rays from supernova remnants has been detected, providing a direct evidence of particle acceleration to energies higher than the TeV band and telling us that answer will be given, before long, to the long standing problem of origin of cosmic rays. On the other hand, the sky of TeV γ-rays is bright by radiation of electrons, implying that it is not straightforwardly easy to identify the site where hadronic cosmic rays are accelerated. Thus, extensive TeV γ-ray observations are to be done to fully solve the problem of origin of cosmic rays, and such further efforts in TeV γ-ray astronomy link cosmic ray physics closer to a variety of phenomena which take place in the Universe.

1. Introduction

After the break-through a decade of years ago by imaging air Čerenkov telescope (IACT), pont-like sources of Very High Energy(VHE) γ-rays are being uncovered against the overwhelming background of cosmic rays. Eighteen sources are listed in Table 1 in the first part by T.C. Weekes of the present papers entitled as “TeV Gamma Ray observations and Origin of Cosmic Rays”. The total number of sources is yet limited small, but there are already several various source classes. Among them, the supernova remnants (SNR) that emit VHE γ-rays present a direct clue to observationally clarify the origin of cosmic rays, which has remained as the question unanswered for more than half a century.

It has been believed from the energy budget of cosmic rays and the standard shock acceleration model that SNRs are the very site of accelerating cosmic rays up to $\sim 10^{15}$eV, the knee energy of the cosmic ray spectrum. SNRs exhibit a variety of observational features in angular size and morphological structure, depending on thier age, mass of the progenitor stars and the environmental conditions of the interstellar medium surrounding SNR. For instance, the emission from the Crab nebula, the first VHE γ-ray source established [33], is dominated by the centrally located pulsar, showing no evidence of hadronic γ-rays, *i.e.* γ-rays from

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the decay of π^0s produced by accelerated protons which will eventually constitute the main component of Galactic cosmic rays: VHE γ-rays from the Crab nebula are explained by inverse Compton radiation by electrons and positrons which are created and accelerated in the pulsar magnetosphere. Hadronic γ-rays, must be, if exist in the emission from Crab nebula, hidden below the observed energy spectrum of γ-rays radiated by electrons and positrons.

The IACT of the CANGAROO collaboration has been in operation for about 10 years and took the task of observing the southern sky where many candidate objects of accelerating cosmic rays are observable near the zenith. Two projects among the next generation IACTs of aperture $\sim$ 10m, the H.E.S.S.[12] and CANGAROO III telescopes[10], are located in the southern hemisphere and scheduled to commence full operation in the year of 2003. The inner Galaxy will be surveyed at the flux level by an order of magnitude weaker than the present sensitivity with angular and energy resolution improved to $\sim 1'$ and $15 \sim 20\%$ with the threshold energy of detecting γ-rays as low as 100 GeV, with detection area $\sim 10^4\mathrm{m}^2$ against $\sim 1\mathrm{m}^2$ of the instruments on board the satellites at GeV energies.

2. VHE γ-rays in relevance to the origin of cosmic rays

2.1. Purpose of cosmic ray physics

Cosmic rays are the particles accelerated beyond the thermal energy, by the processes enigmatic, to some extent, which are unlikely to take place in the stars like the sun. Cosmic ray propagation is not along a straight line, because of interactions with the interstellar medium. It is difficult from simple observation of arrival direction of cosmic rays to find the site of cosmic ray acceleration, however, in turn providing us with unique informations of the intersteller space. Thus, the study on the origin of cosmic rays can be put along three lines; (i) to find the site of acceleration, (ii) to study the propagation effect or equivalently to understand the interstellar medium, (iii) to clarify the acceleration mechamism and to uncover unknown physical laws if any emerge as related to the phenomena in study.

The subjects of VHE γ-ray astronomy, from a view point of using γ-rays as probe of detecting cosmic ray protons, can be organized, as illustrated in Fig. 1, in a way parallel to the cosmic ray studies. The three lines described above can be translated into VHE γ-ray astronomy as (i) to discover point-like sources of hadronic γ-rays, (ii) by observing diffuse emission from the Galactic disk, to understand the structure of the Galactic disk/interstellar medium which accelerate and confine cosmic rays, and (iii) to understand the acceleration of particles by using VHE γ-ray data such as energy spectrum and spatial distribution, and to constrain/uncover exotic/enigmatic processes such as the dark matter, quantum gravitational effects and so on.

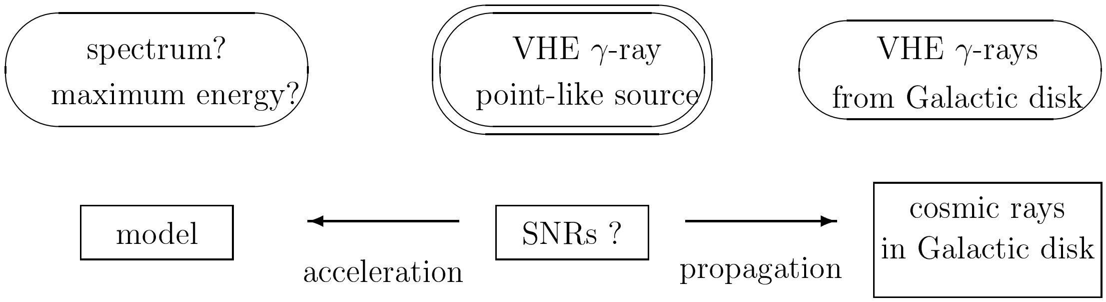

Fig. 1. Origin of cosmic rays in relevance to TeV γ-ray astronomy. Subjects of cosmic ray study (shown in the bottom line) correspond to VHE γ-ray topics indicated above. Point-like sources have been detected, but the diffuse emission from the Galactic disk is not yet in TeV band.

2.2. Acceleration site of cosmic rays

The energy spectrum of cosmic rays is a monotonous function of energy as $\propto E^{-\alpha_d}$, where $\alpha_d \approx 2.6$, implying that the acceleration sites of cosmic rays are to be discovered as both GeV and TeV γ-ray sources. The conventional theory of shock acceleration predicts a flatter energy spectrum of its power index $\alpha_0 \sim 2.0$, while the disk emission of γ-rays is expected to have a power index softer than α_0, probably as large as α_d of the local cosmic ray spectrum. Thus, point-like sources may be distinguished as dominant and prominent above the background emission of the Galactic disk, as γ-ray energy increases from GeV to TeV region [5].

However, the observations of TeV γ-rays in 1990's have indicated distinct dissimilarities between GeV and TeV sources; in the case of pulsars, the signal modulated by pulsar period in GeV band while non-modulated signal from pulsar nebula detected in TeV band; in active galactic nuclei, strong TeV blazars emitting weak GeV γ-rays. The dissimilarity, can be explained to some extent by the fact that TeV γ-ray sky is quite bright by energetic electrons. As illustrated in Fig.2, radiation from electrons is characterized by two peaked distributions of synchrotron and inverse Compton processes, when $E^2\, dN/dE$ are plotted where E and N are the energy and the number of photons, respectively. Thus, intense sources of TeV γ-rays, if due to electron radiation, are not likely found in bright GeV sources, but perhaps likely in bright x-ray sources.

The disk emission detected by the satellite borne instrument such as the EGRET in Compton Gamma Ray Observatory have provided the map of cosmic ray intensity as confined in the Galactic disk. However, identified Galactic sources of the EGRET catalogue consist so far only of pulsars. Evidence of hadronic γ-rays is still to be looked for in Galactic point-like GeV γ-ray sources. In the case of TeV γ-rays, the situation is reversed; emission from several known point-like sources such as SNR were reported as discovered, but diffuse γ-rays from the Galactic disk have not been detected yet in VHE energy band above 100GeV.

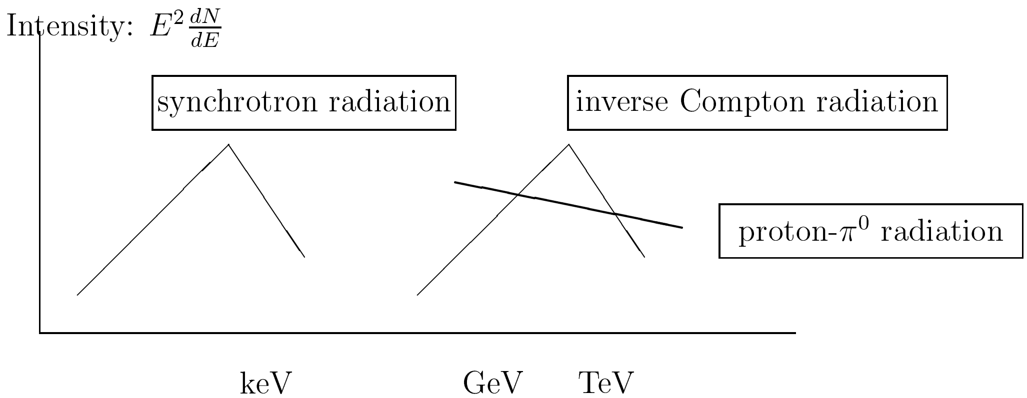

Fig. 2. Schematic view of spectral energy distribution of TeV γ-ray sources. Hadronic γ-rays are expected to have a monotonous spectrum from GeV to TeV energy in contrast to the case of synchrotron and inverse Compton emission by electrons.

2.3. Energy spectrum of cosmic rays and VHE γ-rays : Problem of the knee

The slope of cosmic ray spectrum changes at the "knee" $\sim 10^{15}$eV and the softening of spectrum above the knee, *i.e.* an increase of power index by about 0.5, are usually interpreted as due to less efficient acceleration of cosmic rays above 10^{15}eV, and/or to difficulty of confining cosmic rays of energies higher than 10^{15}eV. The slope, or the power index $\alpha_d \approx 2.6$ below the knee of cosmic ray spectrum, is explained by multiplying the spectrum $\propto E^{-\alpha_0}$ of shock acceleration by the confinement time $\propto E^{-\beta}$ of cosmic rays into the Galactic disk.

The general understanding is consistent with the strong shock in supernova, which accelerates particles up to the knee energy. The maximum acceleration energy E_{max} is $\sim 10^{15}$eV [20] in SNRs and the energy spectrum of VHE γ-rays from SNRs should extend to energies as high as $\sim 10^{14}$eV.

3. SNRs and VHE γ-rays

Several EGRET unidentified sources are accompanied by SNR within in its positional error circle and the emission from these sources show a hard energy spectrum of power exponent consistent with the value $\alpha_0 \sim 2.0$ [11] as predicted for the strong shock acceleration, and their flux extrapolated to TeV energy is sufficiently high to be detectable by IACT [8,23]. Attempts are made by using early IACTs of the Whipple, HEGRA and CANGAROO groups to detect VHE γ-rays from these unidentified sources, presuming that the GeV γ-ray emission is from the accompanied SNR, however failing to detect TeV γ-ray signal [*e.g.*25]. The γ-ray energy spectra $\propto E_\gamma^{-2}$ of the EGRET unidentified sources must have a cut off somewhere between 10GeV and several hundred GeV, which is hardly consistent with what is expected for the energy spectrum from cosmic ray sources.

A shell-type SNR, SN 1006, emits nonthermal x-rays from bright spots in the supernova shell, of which energy spectrum is well explained by synchrotron radiation, presenting evidence of electrons accelerated at least up to 100TeV [18]. The intensity of TeV γ-rays from SN 1006 detected by CANGAROO group [27] appears, if magnetic field is $\sim 6\mu$G, consistent with inverse Compton radiation by the same electrons responsible for the x-ray emission colliding the 2.7K MWB (microwave background) photons. Three SNRs are so far reported as TeV γ-ray sources; in addition to SN 1006, RXJ1713.7-3946 [22], which was discovered by the Rosat All-Sky Survey, and Cas A [2] reported by the HEGRA collaboration.

In the case of the latter two SNRs, it is claimed that the detected TeV signal is due to π^0 decay γ-rays and presents evidence of acceleration site of cosmic ray protons. The spectral energy distribution of RXJ1713.7-3946 from x-ray to TeV γ-rays of radiation, when magnetic field of $\sim 10\mu$G is used to fit the x-ray spectrum with synchrotron radiation, appears difficult to fit the TeV flux with inverse Compton radiation, thus suggesting hadronic γ-rays to be the likely case [9]. A model calculation for Cas A indicates that observed TeV γ-ray intensity can be made consisitent with π^0 decay γ-rays but too high to be explained by inverse Compton radiation [2].

However, the case of electron progenitor and mutual cosistency among the multi wavelength data of RXJ1713.7-3946 are argued against the interpretation by the hadronic γ-rays [7,24]. Wide agreement on the interpretation is thus left to further continuing investigations. The situation is twisted also in the case of SN 1006; hadronic γ-rays are argued as *a physically plausible* model with magnetic field as strong as $\sim 100\mu$G [6]. Observationally on the other hand, Hegra group reported signal consistent with the CANGAROO flux at higher energies [31], while confirmation has been not yet presented from the multi IACTs of stereoscopic observation recently made by H.E.S.S.

4. Perspectives for clarifying the origin of cosmic rays

4.1. VHE γ-ray Sources of hadronic γ-rays: Acceleration site

If the observed spectral energy distribution from radio to γ-rays can not be fit with the spectra expected from synchrotron and inverse Compton emission of electrons, the source is then regarded as the acceleration site of hadronic cosmic rays. However, the fitting of the energy spectrum with models is not straight-foward and simple. The energy spectrum of TeV γ-rays from SNRs is affected by a number of conditions; strength of magnetic field, multiple populations of old and young electrons, age of SNR, *i.e.* the evolutional effect, environmental conditions of SNRs such as association of molecular clouds of dense matter, and so on.

It is to be noted that the spectral energy distribution over muti wavelengths of TeV γ-ray sources are still not covered sufficiently well: the Crab nebula, among the known pulsar nebulae and SNRs, is the only case that is detected with not a mere upper limit but with definite fluxes of both GeV and TeV γ-rays. At least, upper limits of a sufficiently small value are necessary for obtaining firm conclusion on the emission mechanism, since the GeV band is located in the midway between the two peaks of synchrotron and inverse Compton radiation spectra. A similar situation was noted also in the case of pulsar nebula PSR 1706-44 [1,15]. Recent data of the Chandra x-ray satellite indicate that the pulsar nebula emits x-rays with a spectrum softer and weaker than the result of Rosat satellite, enhancing the difficulty in adjusting the observed flux and model prediction [19].

4.2. Maximum energy of cosmic rays accelerated in SNR

The maximum acceleration energy E_{max} is presumed to take an almost same value $\sim 10^{15}$eV among many SNRs. However, the γ-ray spectrum of RX J1713.7-3946 [9] appears to have a steepening at about 5 TeV much lower than the γ-ray energy corresponding to the knee energy of cosmic rays, and E_{max} is yet not observed for Cas A. The SNR RX J1713.7-3946, as well as the SNRs within the error circle of the EGRET unidentified sources, if GeV emission is due to SNR, can be thus regarded as not the standard but exceptional ones of E_{max} much lower than the canonical or the average value which is presumably $\sim 10^{15}$eV of SNRs. The number of TeV γ-ray SNRs currently known is, of course, too small to argue about the statistics on E_{max}. Nevertheless, it is interesting and would be worthwhile to consider about consequences of low E_{max}, in order to draw a view of further investigation of SNRs by observing TeV γ-rays.

The first case is that a number of SNRs of higher E_{max} and possibly of weaker TeV γ-ray intensities still remain undetected. A hint of signal from Monoceros SNR was reported by Hegra group [21] and recent Cangaroo observation may suggest signals from RCW 86 [32] and RXJ0852.0-4622 [14]. It is expected that hundreds of SNRs are accelerating cosmic ray protons, since the strong shock of supernova remnant continues for $10^{4\sim5}$ years to accelerate protons while the rate of supernova explosion is about one per 100 years. Ideally, we need to observe the maximum energy E_{max} of γ-ray energy spectra over a hundred of SNRs and to add those energy spectra of TeV γ-rays over many SNRs to examine/confirm if the averaged spectrum is consistent with the cosmic ray spectrum and γ-ray spectrum from the Galactic disk, as well as to understand shock acceleration in SNR.

If a considerable number of SNRs having $E_{max} \ll 10^{15}$eV are found to exist, our standard picture on cosmic rays around the knee should be revised: The distribution of $E_{max} \ll 10^{15}$eV over a number of SNRs in this case will result in, after integrated over the SNRs, the source spectrum of cosmic rays effectively steeper than $E^{-\alpha_0}$. Further multiplication by $E^{-\beta}$ of confinement time would become incosistent with the observed spectrum $\propto E^{-2.6}$ of cosmic rays, possibly requiring contrubution from reacceleration of cosmic rays in the interstellar space.

4.3. Propagation of cosmic rays

The softening of energy spectrum at higher energy does not exclusively mean the limit of acceleration energy E_{max}. Protons of higher energies generally tend to escape faster from confined regions; acceleration as well as radiation site. Propagation effects may thus affect the energy spectrum, and also increase the angular size of TeV γ-ray sources at higher γ-ray energy, making it relatively difficult to detect γ-rays from SNRs.

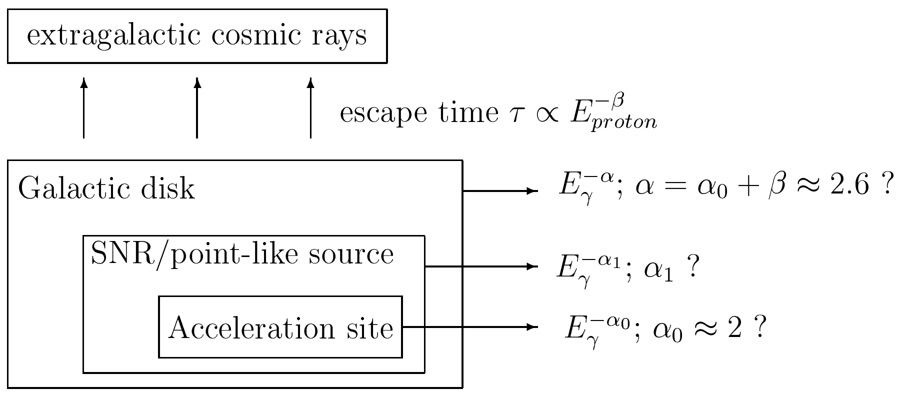

Fig. 3. Propagation of cosmic rays. Cosmic ray transportion and its effects are to be studied through the morphology of γ-ray sources in detail, for example, energy spectrum as a function of place.

A high resolution mapping of SNRs, SN1006 and RXJ1713.7-3946, of the Chandra x-ray satellite has revealed regions of sharply edged, narrow filamentary x-ray emission, enabling deep and detailed studies about the structure and emission mechanism of SNR [*e.g.* 29]. The bright region of non-thermal x-rays should correspond to the region where N_e the number of high energy electrons is high, in other word, the acceleration site of electrons, and the modulation, such as $N_e B^2$ or $N_e n_H$, by magnetic field B and/or the matter density n_H is likely to cause radiation region deviated from the acceleration site, depending on the radiation mechanism, synchrotron radiation or bremsstrahlung. If γ-rays are due to inverse Compton process by the same electrons for x-rays and the universal 2.7K MWB as target photons, the distribution of γ-ray intensity N_γ represents N_e solely and then the distribution of B could be separately solved. Better angular resolution by the stereoscopic observation of the next generation IACT system is awaited for to compare x-ray and γ-ray morphology data.

In the case of hadronic γ-rays, N_γ is proportional to the product of the number of protons N_p and n_H, and the comparison of x- and γ-ray data becomes more complicated. In addition, the energy loss mechanisms different between electrons and protons affect their propagation differently likely to give different energy spectra of electrons and protons varying from place to place.

Protons are transported from acceleration site to radiation region where n_H is high, then propagate out to fill the Galactic disc to constitute cosmic rays, as illistrated in Fig. 3. Each of the propagation and radiation process modifies the energy spectrum of electrons and protons. Finally, cosmic ray protons escape from the Galactic disk with time $\propto E^{-\beta}$ where $\beta \approx 0.5$. The energy spectra corresponding to these processes need to be observationally investigated near at high energy $\sim 10^{12}$ to 10^{15}eV.

4.4. Sources other than SNR and Terra Incognita

The HEGRA group conducted a scan of covering 1/4 of the Galctic plane, and detected an unidentified TeV source [3,26], which has a hard emission spectrum, with $> 5\sigma$ significance at a position of 0.5° north of Cyg X-3. Extensive efforts of such scan over whole the sky may uncover more sources of peculiar emission of γ-rays peaked at TeV energies and hidden as unknown to other bands, and some of them representing new classes of objects other than SNRs and pulsar nebulae.

Observation of VHE γ-rays by IACT is limited below $\sim$ 10TeV, lower than the knee energy by about an order of magnitudes. It still remain unchallenged to clarify the origin of cosmic rays above 10^{15}eV as well as extragalctic cosmic rays and transient sources such as γ-ray burst (GRB) and x-ray binaries like Cen X-3.

Evidences are reported that the Galactic center is quite likely to be a TeV γ-ray source [17,28]. A special interest has been put since early days of IACTs made available [30] on the annihilation of the dark matter in the Galactic center to produce TeV γ-rays. In order to distinguish from various other conventional emission mechanisms, careful investigations on the energy spectrum and morphorgy of emission region are to be done. The exotic emission of VHE γ-rays is not a result of particle acceleration and thus not related to the origin of cosmic rays, but presents new insights on the nonthermal high energy processes, *i.e.* the final goal that cosmic ray physics aims at.

4.5. Cosmic rays viewed from outside

VHE γ-rays from the whole of the other galaxies, emitted by cosmic rays interacting with interstellar matter of the galaxies, have a reasonably small angular size and enable us to observe the full structure of cosmic ray confinement in galaxy, with an importance no less than observing the Galactic disk emission and by avoiding the difficulty of detecting TeV diffuse γ-rays. VHE γ-rays from a nearby starburst galaxy NGC 253 at a distance of $\sim$ 2.5Mpc [13] was discovered with a significance over 10σ, and also a giant elliptic galaxy M87 [4] as VHE γ-ray source. The production mechanism is not clear yet, but the emission seems extended to represent propagation and confinement of cosmic rays in the galaxy.

The TeV flux observed is above the extrapolation from the EGRET upper limit when the cosmic ray spectrum in the galaxy is assumed to have a slope similar to the Galactic case. The two galaxies have undoubtedly much higher fluxes than the Galactic cosmic rays, and the behaviour of the cosmic rays is likely very far from those in the Milky Way Galaxy. Nontheless, it has opened a way to understand the confinement of Galactic cosmic rays by looking from outside of the galaxy and to study cosmic rays in other galaxies.

5. Conclusions

The number of Galactic VHE γ-ray sources is increasing. The problem of origin of cosmic rays is just beginning to be answered by using TeV γ-rays. The current status is summarized as:

1. Point-like source of hadronic γ-rays, the site of accelerating hadronic cosmic rays, are (almost) found. The difficulty of identifying hadronic γ-rays is partly because VHE γ-ray sky is bright due to high activities of electrons, and probably because there exist a wide variety of particle acceleration processes.

2. The maximum acceleration energy E_{max} in SNR is not yet observationally clear. It is necessary to collect data over many SNRs and to study in detail the morphology of γ-rays with better angular accuracy with wider field of view to know the transport/propagation effects of cosmic rays.

3. VHE γ-rays from other galaxies have been discovered, which expands the field of studying cosmic rays into extragalactic space and other galaxies, enriching our understandings of Galactic cosmic rays.

The next generation of IACTs will soon provide us with new knowledges and insights for clarifying the origin of cosmic rays. Many questions are still left for further efforts in future; observation of the maximum energy E_{max} of shock acceleration in SNR up to $\sim 10^{15}$eV, to uncover hidden VHE sources, cosmic ray sources above the knee energy. Objects of transient, extended nature and 10∼100 TeV energy γ-rays have not been explored yet. Observation with a wide field of view is necessary to extend/enrich the study of origin of cosmic rays [16]. In parallel with these investigations, to uncover new/exotic phenomena is also an important and unique task that is imposed on VHE γ-ray astronomy as well as cosmic ray physics.

This research is supported by a Grant-in-Aid in Scientific Research of the Japan Ministy of Education, Culture, Sports, Science and Technology.

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