VERY HIGH ENERGY GAMMA RAY ASTRONOMY

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Abstract

Copious electrons and positrons appear to produce gamma ray emission while protons are apparently "silent". The wide band radiation of electrons provides a link of gamma ray data to the other bands of radio to X-rays, encouraging the data analysis over "multi-wavelengths". The study of the "origin of cosmic rays" is now "expanding" beyond our Galaxy and a new light is shed on the long-standing puzzle.

1. Introduction

High Energy (HE; at 100 MeV - 10GeV energies) and Very High Energy (VHE; in the region of 100 GeV to TeV energies) gamma rays are linked to energetic particles. They are produced through the non-thermal mechanism of those elementary particles as progenitor. The particle interaction includes also absorption of gamma rays through the process of pair creation of electron and positron, $\gamma + \varepsilon \rightarrow e^- + e^+$, where ε stands for the photon of background radiation field. The gamma ray reactions characterize VHE gamma ray astronomy. The Universe, through the high temperatures of the big bang, experienced processes of much higher energies than the present time. Detection of the relics of the earlier Universe, such as gamma rays from anti-matter annihilation on matter or from primordial black holes, acted, to some extent, as impetus for promoting gamma ray astronomy. Although the upper limits on those give important constraints, presented in this paper will be what are related to the "present Universe". We also restrict ourselves in VHE results mainly by using the results by CANGAROO (Collaboration of Australia and Nippon for a GAmma Ray Observatory in the Outback).

The observation window in gamma rays at the shortest wavelengths of electromagnetic radiation was established by Compton Gamma Ray Observatory

(CGRO) launched in 1991, simultaneously with the success of ground-based technique to detect TeV gamma rays. The current status of gamma ray astronomy in its growing stage is demonstrated in Fig. 1, the plot of the number of point sources discovered in the gamma ray bands compared with those in X-rays. The number of the discovered sources is similar to what was at 1970's years in X-ray astronomy.

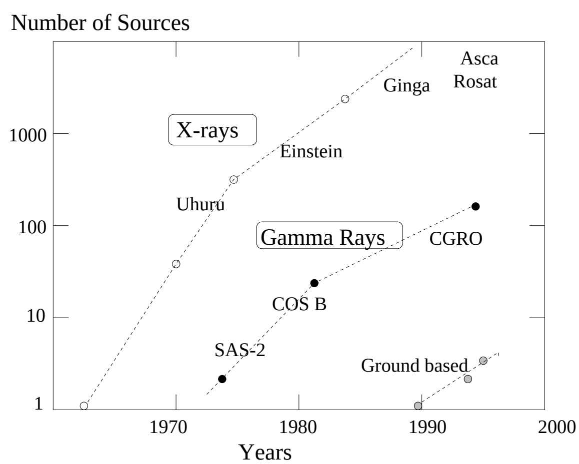

Fig. 1. The number of point souces plotted against the year of observation

2. Ground-based detection of VHE gamma rays from SN 1006 and Markaraina 501

The review of gamma ray astronomy covering almost all the relevant topics will be found in the Proceedings of the 4th CGRO Symposium. In particular, the results and prospect of VHE gamma ray astronomy are described in Weekes et al. 1997 in the Proceedings and references are therein, as well as the CANGAROO results in Kifune et al. 1997. In the present paper, we discuss about VHE gamma ray astronomy, by taking as example the two observations that took place in the last year, 1997, the outburst of Markarian 501 and VHE gamma rays from Supernova SN 1006.

Electromagnetic radiation beyond GeV appears to have non-thermal spectrum, and must be related to cosmic rays which are the typical example of non-thermal high energy phenomena known since a long time ago. Supernova remnants are the most likely site of shock-acceleration of cosmic ray protons. Koyama et al. (1995) detected non-thermal X-rays from the shell of supernova SN 1006 and argued that shock acceleration takes place to produce up to $\sim$100 TeV electrons in the object. This lead CANGAROO to observe and find evidence of VHE gamma ray emission from SN 1006 (Tanimori et al. 1998). As for extragalactic sources of VHE gamma rays, patient monitoring by the Whipple group was blessed by the detection of outbursts of VHE gamma rays from AGN (Active Galactic Nuclei) Markarian 501, also providing the other air Črenkov telescopes with the opportunity of observing the intense beam of VHE gamma rays. The high state intermittently continued for several months, and the emission spectrum appeared to extend up to 10 TeV and higher.

In the detections of SN 1006 and Markarian 501 as well as in the case of pulsar nebula, VHE gamma rays are consistent with emission from electrons; through the inverse Compton process, while the progenitor electrons also produce synchrotron radiation into the bands at longer wavelengths of radio to X-ray bands. The luminosities L_{sync} and L_{ic} of synchrotron and inverse Compton radiation, respectively, are proportional to the energy density of magnetic field (W_B) and seed photons of the Compton scattering (W_{photon}) multiplied by the energy of progenitor electrons given as

$$L_{sync} = \frac{4}{3}\sigma_T c\gamma^2 W_B \quad \text{and} \quad L_{ic} = \frac{4}{3}\sigma_T c\gamma^2 W_{photon}, \tag{1}$$

where σ_T is the Thomson cross section and γ the Lorentz factor of electrons. Thus, we can infer the strength of magnetic field from the ratio of the two luminosities we observe.

The target photons which contribute to W_{photon} in the expression (1), are the photons of 2.7K microwave cosmic background in most cases of the Galactic TeV sources except for intense objects such as the Crab where the synchrotron photons by the same progenitor electrons dominate the others (SSC; Self Synchrotron Compton process). The detection of VHE gamma rays from pulsar nebulae PSR B1706-44 and Vela as well as from SN 1006 suggests a few to 10 μG. The detection of VHE gamma rays provides direct evidence of $\sim$100TeV electrons accelerated by supernova shock, and makes it likely that the same shock mechanism accelerates also protons at the shell of the supernova. However, if the VHE gamma rays from SN 1006 were of proton origin, the gamma rays from π_0 decay would follow the monotonously decreasing spectrum of power law, which would predict the flux of GeV gamma rays above the EGRET upper limit.

It is widely believed that the gamma rays of EGRET AGN are from a relativistic jet which is orientated towards us. The bulk motion of the jet enhances the gamma ray luminosity, explaining why these AGN can become an observable emitter of gamma rays, by a factor of δ^4, where the beaming factor $\delta = 1/(, (1-\beta cos\theta))$ and , is the Lorentz factor of the bulk motion of the jet and θ the angle between the jet and our line of sight. There are several possibilities about the target photons of the inverse Compton process; the external photons coming from outside the jet; the SSC photons; or mixed of those. The W_{photon} in the expression (1) is affected by the beaming factor in the case of "the external photons" differently from the "SSC" case, providing the means to distinguish these cases by observation of covering multi-wavelengths as well as on time-varying features during outbursts. The detection of VHE gamma ray outburst from Markarian 501 has lead simultaneous observation over multi-wavelengths from radio, optical, X-ray to gamma rays. It was the first of such campaign that was initiated by VHE gamma ray observation, providing us with useful information such as the ratio between the photon energies at the two spectral peaks of synchrotron and inverse Compton radiations. Based on muti-wavelength data on various AGN, Kubo et al. (1998) argue that $\delta \sim 10$ and magnetic field B = 0.1-1 G.

The analysis over uti-wavelengths is useful commonly to all the sources of VHE gamma rays. The X-ray data has motivated the VHE observation on SN 1006 by CANGAROO. Also in order to argue about VHE gamma ray emission from the the other supernova remnants, we need to study the energy spectrum in a broad range from radio to gamma rays.

3. Copious production of electrons and VHE gamma ray observation

The most dominant emission in HE gamma ray band is from the Galactic disk and is due to cosmic ray protons colliding with the interstellar matter. However, electrons and positrons are the likely progenitor for (except for enhancement of flux from the regions of dense molecular cloud) all of the gamma ray emission from the point-like sources so far identified; AGN and pulsars of 100 MeV to 10 GeV by EGRET detector of CGRO; VHE gamma rays sources of AGN, pulsar nebula and supernova remnant. The origin of cosmic ray protons which reside abundantly in the Galactic disk still remain to uncover the site of their production and acceleration.

Alternatively, HE and VHE gamma ray astronomy has discovered unexpectedly rich, energetic phenomena of abundant production of electron and positrons in the various objects. The more copious production of electrons may imply gamma ray source of the brighter luminosity. However, such objects are also likely to have the higher number density of radiation field, where VHE gamma rays could more frequently collide with soft ambient phtons and be more likely absorbed through the creation of electron-positron pair, resulting in unlikely escape of VHE gamma rays out of the emission region. In the case of AGN, however, the beaming effect of the jet could produce luminous VHE gamma rays towards the observer, also by the relavistic bulk motion similarly in the case of gamma ray bursts (Rees and Meszaros 1992).

Extensive efforts have been made to detect pulsed VHE gamma rays from young, EGRET pulsars with the results of, however, unpulsed signal *i.e.* from the pulsar nebulae outside the pulsar magnetosphere. The fact can be considered reasonably natural, since the pulsar magnetosphere of much more compact size than the nebula has higher density of radiation field as the model caclulations usually take the effect of the pair creation by TeV gamma rays into consideration.

4. Origin of cosmic rays of new types or beyond our Galaxy

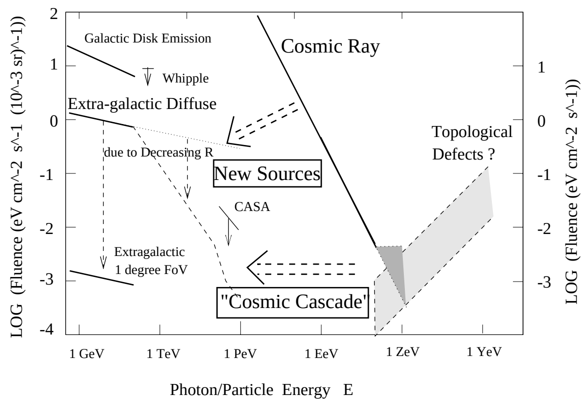

Fig. 2. Energy fluence of cosmic rays to suggest "hidden source" of VHE gamma rays and to detect "cosmic cascade". The energy fluence of cosmic rays is compared with extragalactic diffuse emission of gamma rays. The unit shown in the left of the vertical axis corresponds to the flux of extended emission within the field of view of 1° radius. The detection sensitivity is $\sim 10^{-12}$erg cm^{-2} s^{-1} for point source (in the right vertical axis).

The cosmic rays beyond 10^{15} eV can not be accelerated in the spatial size ∼1pc of supernova remnants. However, the energy they carry is much larger (as shown in Fig. 2) than the fluence $\sim 10^{2}$eV cm^{-2} s^{-1}, for example from Crab nebula at 1 TeV. The origin of cosmic rays above 10^{15}eV might suggest a new population of VHE gamma ray sources. VHE gamma rays from X-ray binaries were argued in 1980's but with no confirmation by the advanced current technique. Such sources at VHE emission could be of very violent time-variability and the efforts are still not satisfying.

The pair creation of electron and positron affects the propagation of gamma rays. Infrared photons in the extra-galactic space are capable, when they collide with TeV gamma rays, of producing a pair of electron and positron, thus giving the limited reach of VHE gamma rays which is at ∼1 TeV within ∼100 Mpc from our Galaxy. The AGN so far detected in VHE gamma rays are Markarian 501 and 421 of redshift as small as 0.03. The pair creation process, however, leaves secondary electrons which emit secondary gamma rays through collisions with background radiation such as 2.7K photons, initiating "cosmic cascade". The casdade process would produce TeV gamma rays from ultra high energy radiation up to 10^{20}eV or more if they exist, as suggested in Fig. 2. The energy flow of the extragalactic diffuse emission carried by the gamma ray photons up to several tens GeV as observed with EGRET detector is hardly extrapolated to higher energies without a change of slope. The dotted line shows an example of such an expected spectral change due to the absorption of VHE gamma rays converting into electron-positron pairs. If the spectrum turns out to have no such a break, it would suggest near-by sources such as an interesting case of the contribution from the halo of our Galaxy which the EGRET data may suggest.

The extragalactic space become less opaque with decreasing energy of VHE gamma rays. The VHE telescope of the next generation will improve the detection sensitivity by an order of magnitude as well as having lower threshold energy to probe deeper into the Universe. Several objects are likely emitters of gamma rays but with less intensity than HE and VHE emitting AGN. The predicted flux and the current upper limit are listed in Table 1 for several near-by galaxies and clusters of galaxies. Cosmic rays of higher production rate may be confined

Table 1. GeV/TeV Gamma Rays from (Normal/Cluster of) Galaxies

object	note	distance (Mpc)	100 MeV flux	100 MeV predicted	1 TeV expected
Coma	cluster of	97	<4	0.3 – 75 (*)	
Perseus	galaxies	77		0.23	0.47
M82	star burst galaxy	3.2	<5	0.13	0.26
M87	elliptic galaxy	2.1	<4	1.5	
M31	Andromeda	0.7	<8	2	
		(Mpc)	flux	predicted	assumptions
SMC	Small Magellanic	0.07	<4	24	metagalactic CR
	Cloud			12	quasi-equiribrium
				2 - 3	disrupted state
LMC	Large Magellanic	0.05	15±3	20±4	dynamic balance
	Cloud			12	

The energy flux (in the unit of eV cm^{-2} s^{-1} is given in the Table. (*) Expected gamma rays are those from electron progenitor, and thus the flux varies with the assumed value of magnetic field.

within a cluster of galaxy for a much longer time than in our Galaxy (Völk et al. 1996). If the confinement time is close to or larger than the Hubble time, we could see the cosmic rays created at the time when the star formation rate is much higher than the present time.

5. Conclusion

Copious production of electron and positron is noted in the point sources of VE and VHE gamma rays, in contrast to relatively silent protons. VHE gamma rays from supernova remnants do not indicate straightforwardly the site of proton acceleration. Advancing senstitivity of gamma ray detection, however, encourages us to expand VHE observations beyond our Galaxy shedding a new light on clarifying the origin of cosmic rays. The high density of energy and radiation field generally prevents VHE gamma rays escaping from such region in the object. Apparent high luminosity of HE and VHE gamma rays from AGN are due to the beaming effect of relativistic jet. Violent time-varying phenomena would become more important to observe, when we attempt to go nearer to the central area of gamma ray sources.

The gamma ray astronomy requires large instruments of heavy weight to be launched in satellites, which has made it rather slow to open the observation window at the shortest band of electromagnetic radiation. The ground-based detection of VHE gamma rays has an advantage of much less expense than the satellite detectors. The technique, however, needs dry, good weather of very clear sky hard to find a suitable observation site in Japan. The author and the project CANGAROO owes much to Prof. H. Sato who has continuously encouraged Japanese VHE observation in New Zealand on supernova 1987A and then the following project in collaboration with Australia.

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