GAMMA-RAYS of TeV ENERGY FROM PLERIONS AND RESULTS OF CANGAROO PROJECT

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ABSTRACT

Copious production of electrons and positrons results in very high energy gamma-rays from the sources such as pulsar nebulae and supernova remnants. The emission at TeV energies is characterized and controlled by the interaction of high energy photons and electrons. The radiation of electrons links the TeV region tightly to the other bands, giving us the means of 'multiwavelengths analysis' to investigate production, acceleration and interaction of energetic particles. The absoption of TeV gamma-rays due to creation of electron and positron pairs puts constraints on the emission size of detectable sources. The point-like source of gamma-rays by proton progenitor still remains to be uncovered.

1 INTRODUCTION

The way of seeing the Universe with High Energy (HE; at 100 MeV - 10GeV energies) and Very High Energy (VHE; in the region of 100 GeV to TeV energies) gamma-rays is characterized by the interactions of energetic particles. The observation window at the shortest wavelengths of electromagnetic radiation was made widely open thanks to Compton Gamma-Ray Observatory (CGRO) launched in 1991 as well as due to the success of ground-based technique for TeV gamma-rays. The current status of gamma ray astronomy can be said, when taking the number of point sources for comparison, to be similar to that of X-ray band in 1970's. The EGRET instrument of CGRO has discovered about 200 HE sources which consist of pulsars, AGNs (active galactic nuclei) and unidentified sources. The number of VHE sources is approaching 10; several EGRET pulsars, a few AGN and a supernova remnant. The VHE gamma-ray astronomy in 'the CGRO Era' is summarized and discussed in Weekes et al. 1997 and references therein.

In Section 2 is presented a summary of CANGAROO (Collaboration between Australia and Nippon for a GAmma Ray Observatory in the Outback) observations in South Australia (*e.g.* Kifune et al. 1997) and the implication of our results is argued about in Section 3 paying attention to the 'multiwavelength data'. The unique feature of VHE photons is their conversion into/from electrons (and positrons) via soft ambient photons. The process depends on, for example, the spatial size of VHE emission, possibly affecting the type of the sources so far discovered (Section 4).

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2 CANGAROO and VHE GAMMA RAY SOURCES

The first object firmly confirmed as a VHE source is the Crab nebula. The detection by the Whipple group, or the break-through achieved by IACT (Imaging Air Čerenkov Telescope) after a long 'dark age', was almost simultaneous with the launch of CGRO, and has stimulated searches for VHE signal in the gamma-ray pulsars of EGRET detection. The 3.8m telescope of CANGAROO commenced observation in 1992, as the second IACT following the Whipple telescope. Two gamma-ray pulsars, PSR B1706-44 (Kifune et al. 1995) and Vela pulsar (Yoshikoshi et al. 1997), have been found to be VHE gamma-ray sources. The VHE signals are unpulsed; not modulated by the pulsar spin period as detected in HE band. The pulsed emission of GeV gamma-rays originates in the pulsar magnetosphere which corotates with the neutron star. The signal is replaced at higher energies by unpulsed one from the pulsar nebula. As for the shell-type SN (supernova) remnant presumably without plerion, Koyama et al. (1995) detected non-thermal X-rays from the shell of SN 1006. This result motivated our VHE observation to search TeV gamma-rays from the direction of the non-thermal X-ray emission (Tanimori et al. 1998b). The VHE signal provides direct evidence of ~100TeV electrons accelerated by the SN shock, and suggests that protons are also likely to be shock-acceletated at the shell of the SN.

Three AGNs classified as blazars at redshift ~ 0.03 are found as VHE emitters by the Whipple group. Efforts of CANGAROO to detect TeV gamma-rays from the AGNs in the southern sky have so far been negative results (Roberts et al. 1998). CANGAROO has also attempted observations of Centaurus A, binary pulsar such as PSR B1259-63 (Sako et al. 1997), X-ray binaries, EGRET unidentified sources and supernova remnants, and 'after glow' of GRB (gamma ray bursts) which BeppoSAX satellite detected with one arcminute accuracy.

3 VHE GAMMA RAY EMISSION and MULTI-WAVELENGTHS SPECTRUM

3.1 Crab and other nebulae: Any prototype ?

The 'entire' spectrum over 'multiwavelength' is reasonably well known only for the Crab nebula. The profile is consistently explained by a magnetic field $B \sim 200\mu$G and 'synchrotron self Compton' (SSC) mechanism, *i.e.* synchrotron photons served as the target of the Compton scattering. The strong magnetic field allows the nebula to have synchrotron emission into the energy region as high as $\sim$ 100MeV. Thus, the Crab is the only pulsar nebula in the EGRET GeV band, while no unpulsed GeV gamma-rays from the others are consistent with weaker magnetic field in those pulsar nebulae. The CANGAROO observation has shown that the Crab spectrum extends up to several tens of TeV (Tanimori et al. 1998a), and may suggest deviation from the SSC spectrum; possibly due to gamma-rays from either another population of the inverse Compton process or a proton component (*e.g.* Aharonian 1997). The ratio between the two luminosities L_{sync} and L_{ic} of synchrotron and inverse Compton radiation from the common progenitor electrons is equal to the ratio of the energy density of magnetic field (W_B) to the seed photons undergoing the Compton scattering (W_{photon}). By using the luminosity of the VHE gamma rays and X-rays as L_{sync} and L_{ic}, respectively, and by putting W_{photon} to be the energy density $W_{2.7K}$ of 2.7K MWB (micro wave background) radiation, we obtain $B \sim$ a few μG for the pulsar nebulae of PSR B1706-44 and Vela. Electrons of energy E emit approximately monochromatic radiation at the photon energy of

$$k_{sync} \approx 0.2(\frac{B}{10^{-6}\mathrm{G}})(\frac{E}{100\mathrm{TeV}})^2\,\mathrm{keV} \quad \text{and} \quad k_{ic} \approx 5(\frac{\varepsilon}{10^{-4}\mathrm{eV}})(\frac{E}{100\mathrm{TeV}})^2\,\mathrm{TeV}, \tag{1}$$

where ε is the energy of target photons involved in Compton scattering. As the relation (1) shows, the same $\sim$ 100 TeV electrons radiate X-rays and VHE gamma-rays under the condition that the magnetic field is not much stronger than 1μG and 2.7K MWB is the main contributor to the Compton scattering.

The approximation of putting $L_{sync}/L_{ic} = L_X/L_\gamma$ can be justified *a posteriori and self-consistently* by the consequent result, *i.e.* magnetic field $\sim$ a few μG in the Vela and PSR B1706-44 nebulae. However, stronger justification must await more detailed energy spectra in the X-ray and TeV gamma-ray bands as well as for the 'entire' spectral profile through X-rays to gamma-rays.

3.2 Relic and escaping electrons: Multiple populations ?

The emission region of the VHE gamma rays is displaced from the position of the Vela pulsar by about $0.1°$, apparently in accordance with the birth place of the pulsar. The radiation can be from the electrons which have survived since the pulsar was born (Harding et al. 1997). A comparison with the upper limit on VHE gamma-rays from the compact nebula at the pulsar position would put constraints on the evolution of the Vela pulsar nebula during its life time. de Jager and Baring 1997 studied multiwavelength spectrum of the Vela compact nebula by including the radio and CGRO OSSE data, which suggest $B = 6 - 20\mu$G. Although de Jager and Baring (1997) presumed that the OSSE flux at MeV energies is from the compact nebula, we may argue that it contains contribution from the birth place of the Vela pulsar or the direction of the VHE emission. If so, the synchrotron counterpart of the TeV gamma-rays is in the MeV gamma-ray band instead of the X-ray band, and the TeV luminosity should be compared with the MeV one to give a higher value of W_B/W_{photon}, which then implies; lower energy of the progenitor electrons, stronger B and/or a contribution of infrared photons to W_{photon}. In addition, the site of the synchrotron and the inverse Compton radiations can differ from each other, because W_B and W_{photon} as well as distribution of progenitor electrons generally have spatially varying structure. As discussed in Aharonian et al. 1997 for the case of PSR B1706-44, a magnetic field as strong as 20μG can be compatible with the X- and VHE gamma-ray data when we assume electrons at $\sim$ 20TeV have an escape time of $\sim$ 10 yrs from the central $\sim$ 1 pc to the outer region of B $\sim 1\mu$G. We have uncertainty about the size of the emission region which are not yet spatially resolved from the X-ray and VHE observations.

3.3 Supernova remnants: Proton progenitor ?

The Galactic disk is the most intense HE gamma-ray source and widely believed to be due to cosmic ray protons. There are several unidentified EGRET sources associated with SN remnant. If the GeV gamma-rays are from the protons accelerated in the SN shock, the GeV gamma-rays will have an energy spectrum of power index ≈ -2, which suggests detectable flux of VHE gamma-rays. However, efforts have so far failed to detect the VHE gamma-rays from these objects. Interestingly, SN 1006 is a 'reversed case' in which TeV gamma-rays are enhanced compared to the GeV gamma-rays. If the VHE gamma-rays from the SN 1006 are due to protons, GeV gamma-rays are expected with intensity above the EGRET upper limits. Thus, the VHE gamma-rays are likely to be from the non-thermal electrons. By using the radio to X-ray data to infer the spectrum of progenitor electrons and by assuming that the seed photons for Compton scattering is dominated by the 2.7K MWB, the magnetic field is estimated to be about 10μG. Similarly, the emission of the unidentified EGRET sources with SN remnants could be explained by electrons radiating dominantly into the GeV gamma-ray region. We need to carefully investigate the following possibilities; the association with the SN remnant may be accidental; the GeV gamma rays are from the electrons concentrated in the supernova shell; effects of environmental conditions in the individual objects such as possible injection of electrons from associated plerion and various matter density sorrounding the SN remnant; the shock acceleration mechanism is to be developed to reconcile with the observations (*e.g.* Völk 1997; de Jager and Baring 1997). More examples of VHE emission are necessary, and CANGAROO recently made observation of RXJ 1713.7-3946 (G347.5-0.5), a SN remnant quite similar to SN 1006, showing non-thermal X-ray emission.

4 SIZE AND ENERGY DENSITY OF EMISSION REGION

In the EGRET pulsars, the emission region apparently changes from the pulsar magnetosphere to the outer nebula when we increase gamma-ray energy from GeV to TeV band. Generally, as the emission region becomes smaller or nearer to the central compact source, the radiation field becomes more intense, the magnetic field in the pulsar magnetosphere becomes stronger, and gamma-rays tend more likely to suffer from the cascade process of electromagnetic interactions. The TeV gamma-rays can be annihilated into electron-positron pairs when they collide with the infrared photons, and are prevented from escaping outwards. Let us consider a simplified case in which the number density n_{ir} of infrared photons is

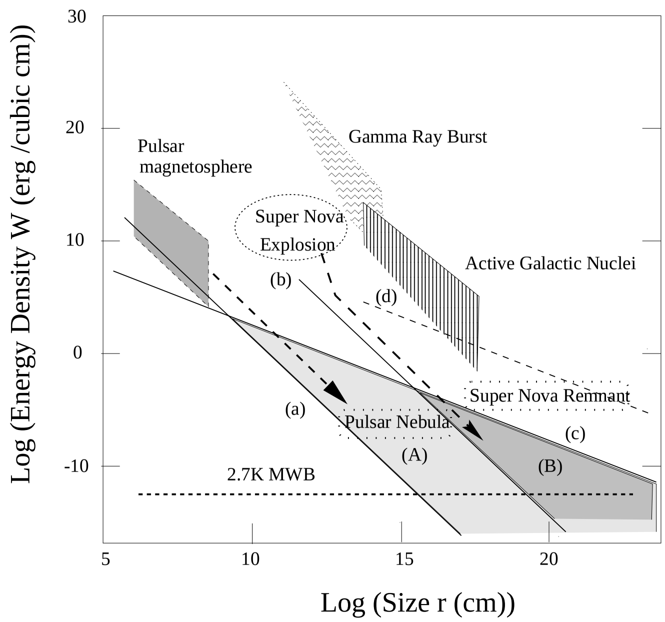

Figure 1: The energy density of radiation is plotted against spatial size. The energy density W of photons from interesting objects is calculated from $L/(4\pi r^2 c)$ and plotted in the vertical axis against the distance r from the central compact object. The line (a) and (b) corresponds to the least luminosity located at 3 kpc and 100 Mpc, respectively, that is detectable with the VHE sensitivity of $\sim 10^{-12}\,\mathrm{erg\,cm^{-2}\,s^{-1}}$. A point source of a given luminosity is to follow the relation r^2W =constant, a line in pararell with the ones (a) and (b). The line (c) indicates the condition that the size r is equal to the mean free path of electron-positron pair creation by VHE photons in collision with the ambient radiation of the source itself. The dashed line (d) corresponds to the compactness parameter (see text) $l = 1$, and is plotted for comparison. The density of 2.7K MWB is also shown by the dotted line.

proportional to the luminosity L averaged over wavelength and thus also to the energy density of radiation field W_{source},

$$n_{ir} = \frac{W_{source}}{\varepsilon} \approx \frac{L}{4\pi r^2 c\,\varepsilon}. \tag{2}$$

where c is the light velocity, and ε the energy of the target photons (in the infrared band, *i.e.* $\approx 10^{-14}$ erg). The mean free path $\lambda = 1/(n_{ir}\sigma_{pair})$ of pair creation with the cross section σ_{pair} varies with the distance r from the emission center. In order that the VHE gamma-rays can escape, λ must be greater than $r = r_{min}$, as an order of estimate, $\approx 10^{14}\mathrm{cm} \cdot (L/(10^{33}\mathrm{erg\,s^{-1}})(10^{-2}\mathrm{eV}/\varepsilon)$. The condition is schematically illustrated in Fig. 1 as a function of the energy density W and the spatial size r. The VHE gamma-rays are free from absorption if the source is below the line (c). The luminosity must be above the detection threshold indicated by the line (a) and (b) which are for the cases of 3kpc and 100Mpc distance, respectively, for the source to be observable. Thus, the VHE objects are to be in the shaded region (A) or (B) in Fig. 1. The known Galactic sources, pulsar nebulae and SN remnants, are located in the region (A), demonstrating that such 'fairly extended' sources (angular size is smaller than the field of view of the VHE telescope) are appropriately detectable with the current technique. The parameter $l = L\sigma_T/(4\pi r m_e c^2) = r/\lambda_{MeV}$ is commonly used for estimating the compactness of the AGNs, where σ_T and m_e are the Thomson cross section and electron mass, respectively, and λ_{MeV} is the mean free path of Thomson scattering against 'MeV photon density', *i.e.* $W_{source}/(m_e c^2)$. The compactness parameter $l = r/\lambda_{MeV} = 1$ along the dashed line (d), and most of the AGNs are outside the allowed region of the boundary line (c) of $r/\lambda = 1$. The detection of the VHE signals from blazars is due to the beaming factor $\delta \sim 10$ enhancing the luminosity when observed from the jet direction. GRB and the sizes less than $\sim 10^{10}$ cm are also outside the region, implying that we can not expect easy, 'straightforward' detection of VHE gamma-rays from compact sources. The result in Fig. 1 is, however, based on the static conditions and simplified assumptions about the radiation field, and for example, time-variable phenomena as well as asymmetrical geometries can make the constraint less tight. Observations of the VHE gamma-rays have been mainly made on stable, 'DC' sources (at least for the Galactic objects). Studies of violently time variable sources, as well as objects with the phenomena similar to the relativistic jets as we see in blazars, will be of increasing importance, possibly providing us with information on the central compact objects.

Simultaneously with the absorption of the VHE gamma-rays by pair creation, we need to investigate the opposite effect of the higher energy density enhancing the VHE emission. The relative strength of the radiation field of the object itself against the abundant 2.7K MWB increases with decreasing r as $W_{source}/W_{2.7K} \approx (L/10^{33}\mathrm{erg\,s^{-1}})(r/0.1\mathrm{pc})^{-2}$. More number of the ambient soft photons, the 'seed photons', at smaller r can be Compton-scattered into VHE gamma rays (by assuming that VHE electrons are accelerated at small r). Such example is 'SSC' of synchrotron radiated photons, known to take place in the Crab nebula and blazars. The soft photons by other processes will contribute as well to VHE gamma rays, called as the 'external seed photons' when assumed in blazars.

5 CONCLUSION

The X-ray observation by ROSAT and ASCA satellites have revealed that most of the luminous pulsars are associated with synchrotron X-ray nebula, which also suggests 'inverse Compton nebula' with young pulsars. In the EGRET pulsars, a larger fraction of rotational energy loss is spent into the HE gamma-rays than radio and X-rays. In Fig. 2 is plotted the fraction of energy output into the pulsed signals in the X-ray and GeV gamma-ray band relative to the spin-down luminosity, as well as for unpulsed signals from the TeV measurements. The dependence on the spin-down luminosity is remarkably different between X-ray and GeV gamma-ray bands. It is premature to argue about such feature in the VHE gamma-rays. A fraction of the spin-down energy loss from the pulsars manifests in the form of VHE gamma-rays from the pulsar nebulae. A systematic study of a large number of VHE sources will provide an understanding of the dependence of the VHE emission on the rotational energy loss. The results from Crab, Vela and PSR B1706-44 have shown phenomena which differ from each other, thus encouraging VHE observation of more pulsars. The broad band energy spectrum from X-ray to VHE gamma-ray region is necessary for having better comparison between the synchrotron and the inverse Compton emission. No less important are the bands of longer wavelengths by the radio, infrared and optical light, which serve as 'seed' photons for the production of Compton-scattered VHE gamma-rays and also as 'partner' photons for annihilation into electron-positron pair. The 'entire' spectrum of photons is coupled to the VHE gamma-rays.

X-ray pulsars and bursters or 'micro quasars' such as GRS 1915+105 (from which a possible detection of a VHE burst has been reported by HEGRA group) as well as close binary systems like PSR B1259-63 can be characterized by spatial size much smaller than $\sim$ 1pc of pulsar nebula and SN remnant. Thus if the signal from those are detected, it will provide a new example and insight into the production and interaction mechamism of VHE gamma-rays. New population of gamma-ray sources may have already manifested itself by the unidentified EGRET sources that seem to exhibit violent time variation (Tavani et al. 1998). The time variablity may suggest emission from denser radiation field of size smaller than

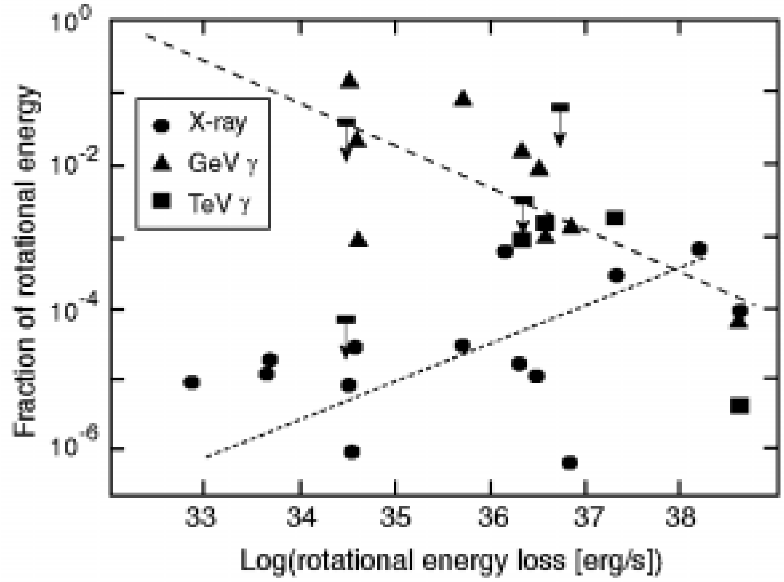

Figure 2: Brightness in X-ray, HE and VHE gamma-ray bands of young pulsars. The luminosity relative to spin-down luminosity (vertical axis) is plotted for individual pulsars versus spin-down luminosity. The data for X-ray (circle) and HE gamma-rays (triangle) is from the pulsed signal, and VHE ones (square) are unpulsed luminosities.

~ 1 pc of the pulsar nebulae or SN remnants, as in the case of the AGN outbursts and GRBs.

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