TeV GAMMA RAYS FROM PLERIONS AND RESULTS OF CANGAROO PROJECT

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ABSTRACT

Ground-based detection of very high energy gamma rays at Tev energies is discussed by using as example the emission from pulsar nebulae and supernova remnants. Copious production of electrons and positrons characterizes the point sources of gamma rays, and the radiation of electrons links TeV region tightly to the other bands, giving us the means of the 'multi-wavelengths analysis' to investigate production, acceleration and interaction of energetic particles. The point-like source of gamma rays by proton progenitor still remains to be uncovered.

1 INTRODUCTION

The unique feature 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 widely opened 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 the X-ray band in 1970's. The satellite detection in HE region has discovered about 200 sources which consist of pulsars, AGN (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 at 'the CGRO Era' is summarized and discussed in Weekes et al. 1997 and references therein. In this paper, we present 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) to discuss about the VHE results mainly on plerions.

2 CANGAROO and VHE gamma ray sources

The first object firmly confirmed as 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',

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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 EGRET pulsars, PSR B1706-44 (Kifune et al. 1995; Chadwick et al. 1997) 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 pulsar nebula. Koyama et al. (1995) detected non-thermal X-rays from the shell of the supernova (SN) remnant SN 1006 and the result motivated CANGAROO to attempt observation on SN 1006 and to find evidence of VHE gamma ray emission from the same direction of the non-thermal X-ray emission (Tanimori et al. 1998b). The detection provides direct evidence of ~100TeV electrons accelerated by SN shock, and suggests that protons are also likely shock-acceletated at the shell of the SN. The VHE gamma rays from the point-like sources so far discovered are explained by the inverse Compton radiation of electrons, which should have the counter part of synchrotron radiation in the lower energy bands.

Three AGN (active galactic nuclei) at redshift $\sim$ 0.03 are found as VHE emitter by Whipple group. Efforts of CANGAROO for detecting VHE signals from AGNs in the southern sky are so far with negative results (Roberts et al. 1998). CANGAROO has attempted observations also on Centaurus A, binary pulsar such as PSR B1259-63, a few X-ray binaries, EGRET unidentified sources and supernova remnants, and 'after glow' of several gamma ray bursts which BeppoSAX satellite detected with about one arcminute accuracy.

3 VHE Gamma Ray Emission and Multi-Wavelengths Spectrum

3.1 Crab and other nebulae: Any prototype ?

The 'entire' spectrum over 'multi wavelengths' is availalbe only in the case of the Crab nebula, which is consistent with the 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 one pulsar nebula that has been so far seen in the EGRET GeV band, and no unpulsed GeV gamma rays from the others are consistent with weaker magnetic field in the pulsar nebulae. The CANGAROO observation has shown that the Crab spectrum extends up to several tens TeV gamma rays (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 proton component (*e.g.* Aharonian 1997). Observations on the other nebulae are not robust to provide us with 'entire profile' of the energy spectrum like the Crab case. The ratio between the two luminosities L_{sync} and L_{ic} of synchrotron and inverse Compton radiation from common progenitor electrons is equal to the ratio of the energy density of magnetic field (W_B) to the seed photons of the Compton scattering (W_{photon}), $L_{sync}/L_{ic} = W_B/W_{photon}$. By using the luminosity of VHE gamma ray and X-ray as L_{sync} and L_{ic}, respectively, and by putting W_{photon} to be the energy density of 2.7K 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

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

where ε is the energy of target photons of Compton scattering. The relation (1) shows tnat VHE gamma rays and X-rays can be considered to be from electrons of the same energy, under the condition that the magnetic field is not much stronger than 1μG and 2.7K microwave background is the main contributor to the Compton scattering. Thus 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 Vela and

PSR B1706-44 nebulae. However, a stronger justification must wait for more detailed energy spectra in the two energy bands of X-ray and TeV gamma ray 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 VHE gamma rays appears displaced from the position of the Vela pulsar by about 0.1°, apparently in accordance with the birth place of the pulsar. The emission can be from electrons which have survived since the pulsar was created (Harding et al. 1997). The comparison with the upper limit of VHE gamma rays from the compact nebula at the pulsar would put constraints on the evolution of the Vela pulsar nebula during its life time. De Jager and Baring 1997 studied a multi-wavelengths spectrum of the Vela compact nebula to include the radio and CGRO OSSE data, which may suggest $B = 6 - 20\mu G$. Although De Jager and Baring (1977) presumed the OSSE flux at MeV energies is from the compact nebula at the pulsar position, 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 TeV gamma rays is in the MeV gamma ray band instead of the X-ray band, and the TeV luminosity should be compared with MeV one to give a higher value of W_B/W_{photon}, which then implies; lower energy of progenitor electrons, stronger B and/or a contribution of infrared photons to W_{photon}. The site of synchrotron and 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 has an escape time of $\sim$10 yrs from the central $\sim$1 pc to the outer region of B $\sim$ 1μG. We have uncertainty about the size of emission region which the X-ray and VHE observations do not spatially resolve yet.

3.3 Supernova remnants: Proton progenitor ?

The Galactic disk emission is the most intense HE gamma ray source and widely believed as 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 VHE gamma rays from these objects. Interestingly, SN 1006 is a 'reversed case' in which TeV gamma rays are enhanced against GeV gamma rays. If the VHE gamma rays from 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 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 2.7K microwave background, the magnetic field is estimated to be about 10μG. Similarly, the emission of the unidentified EGRET sources with a SN remnant could be explained by electrons radiating dominantly into GeV gamma ray region. We need to carefully investigate the cases; the association with SN remnant is accidental; the GeV gamma rays are by the electrons intense in the supernova shell; effects of environmental conditions in individual objects such as injection of electrons from associated plerion and the density of matter sorrounding 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 certainly necessary from SN remnants. The sources of non-thermal X-rays similar to SN 1006 exists such as RXJ1713.7-3946, which is now being observed by CANGAROO.

4 Conclusion

X-ray observation by ROSAT and ASCA satellites has revealed that most of luminous pulsars are accompanied with synchrotron X-ray nebula, which suggests also ‘inverse Compton nebula’ at young pulsars. It has been found that a much larger fraction of rotational energy loss of EGRET pulsars is spent into HE gamma rays than radio and X-rays. The VHE gamma rays also appear to have high luminosity, and will provide a systematic study over a more number of VHE sources to infer the general tendency how the emission or particle acceleration process depends 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 on more pulsars to reveal more examples of the processes of copious production of electrons and positrons. More advanced comparison between synchrotron and inverse Compton emission is necessarily and to be based on the ‘entire’ energy spectrum.

Generally, as the emission region becomes smaller or draws nearer to the central compact source like pulsar, the energy density W_{source} of the radiation from the object itself increases as $W_{source}/W_{2.7K} \approx (L/10^{33} erg\, s^{-1})(r/0.1pc)^{-2}$, where L is the source luminosity (used as a measure of the radiation field emitted by the concerned object contributing to the seed photons of inverse Compton scattering) and r the distance to the central source. However, the increase of W_{source} leads to stronger absorption of TeV gamma rays through creation of a pair of electron and positron. Close binary system such as PSR B1259-63, X-ray pulsars and bursters or ‘micro quasar’ GRS1915+105 which HEGRA group reported a possible detection of VHE burst can be characterized by much smaller spatial size than ~1pc of pulsar nebula and SN remnant, and thus signals from those if detected provide a new example and insight on the production and interaction mechamism of VHE gamma rays. The radiation of electrons are likely to exhibit rapidly variable, violent time feature. New population of gamma ray sources may have been already indicated in the unidentified EGRET sources that seem to exhibit violent time variation (Tavani et al. 1998). The time variablity may suggest emission from smaller size of denser radiation field than ~1 pc of the pulsar nebulae or SNR, as in the case of AGN outbursts.

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