OVERVIEW AND PERSPECTIVES OF TeV OBSERVATION OF CANGAROO

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Abstract

The gamma ray sky is bright with more than 150 point-like sources at GeV energies and several sources at even higher energies of TeV. The current status of TeV gamma ray astronomy is described by using as example results of CANGAROO. The gamma rays provide direct evidence on energetic non-thermal processes of the Universe. The likely process to explain the emission of the currently known sources is the inverse Compton effect by electrons. We are allowed to infer, by also using the data of synchrotron radiation at longer wavelengths, the strength of magnetic field in the emission region of gamma rays, as well as to argue about the features of the progenitor electrons of non-thermal origin.

1. Introduction

A rapid progress is being made in VHE (Very High Energy) gamma ray astronomy (Weekes et al. 1997) by using the imaging Čerenkov technique (Cawley and Weekes 1995), since the detection of the signal from the Crab by the WHIPPLE group (Weekes et al. 1989). Discovery of the second plerion of VHE emission soon followed by PSR B1706−44 detected with the 3.8 m imaging Čerenkov telescope of the CANGAROO. The telescope, in operation since 1992 and located in the southern hemisphere, has attempted observation of a number of pulsars.

The CANGAROO results are presented in separate papers in the Proceedings of this Symposium (references of CANGAROO works are therein); Kawachi et al. for a summay; Yoshikoshi et al. for Vela; Sako et al. for PSR B 1509-58; Tanimori et al. for the supernova remnant SN 1006; Daseley et al. for PSR B 1259-63. Based on the results in these, attempted in this paper is to outline the current status of VHE gamma ray observations and a 'bulk motion' we seek to go along for VHE contribution to the understandings of pulsar and plerion.

The next generation IACTs (imaging air Čerenkov telescope) aim at covering the energy region of 50 - 300 GeV, which remains as unexploited between the satellite and the ground-based observation and where the gamma ray pulsars of EGRET detection apparently cease to emit pulsed signal, *i.e.* radiation from the pulsar magnetosphere, with senstivities as good as $\sim 10^{-12}$ erg cm^{-2} s^{-1}.

2. Tne current status of VHE observations

Table 1. List of Claimed VHE Sources

objects	confirmation by repeated observations	EGRET source in association	type of object
Crab	√	√	plerion
PSR B1706−44	√	√	plerion
Vela	√	√	plerion
SN 1006	√		shell type SNR
PSR B1509−58			plerion
J1105−6107		possibly	plerion?
GRS1915+105			micro quasar
Cen X−3	claimed in the past	time-variable	X-ray binary
Mrk 421	√	√	AGN
Mrk 501	√		AGN
1ES2304+514			AGN
PKS 2005−61		√	AGN

In Table 1 is listed the objects reported as VHE gamma ray sources by using IACT. A view of paying a special attention to the reconfirmation by independent observation would give six "established sources", and the number has rapidly increased from only one at the time of the CGRO (Compton Gamma Ray Observatory) launching, raising a hope of more sources in the years to come. Multiple groups have reported detection of the Crab nebula. The earlier detection of PSR B1706-44 by CANGAROO was confirmed by Durham group at 300 GeV threshold (Chadwick et al. 1997). The majority of the claimed Galactic sources are single pulsar or plerion left after supernova explosion.

The GeV gamma rays detected by CGRO EGRET instrument, from the young pulsars, has encouraged VHE attempts to observe these pulsars. Some of the 'EGRET pulsars', the Crab, Vela and PSR B 1706-44, are, indeed, found to be a TeV source, but the TeV emission is unpulsed, not modulated with the spin period of the pulsars. There exist earlier reports on pulsed emission from Crab, Geminga and Vela, but they are not commonly accepted yet (*e.g.* see review

Kifune 1996). The recent results by IACT are consistent with a view that the emission site changes from the pulsar magnetosphere to outer region at plerion activity as gamma ray energy goes up from GeV to TeV band. The plerion activity is not necessarily limited to the EGRET pulsars and efforts are extended to investigate other young, 'rotation powered' pulsars of high spin-down luminosities. Preliminary evidence was reported on PSR B1509-58, and on PSR J1105-6107 (Chadwick et al. 1997) of 63 ms period which is located within the error circle of EGRET unidentified source 2EG J1105-6107 (Kaspi et al. 1997).

Earlier results (*e.g.* see review Chadwick et al. 1993) before 'the era of IACT' have suggested TeV gamma rays from X-ray binaries, *i.e.* from 'accretion powered' pulsars, and several msec pulsars. The recent hint of TeV signal from Cen X-3 is encouraging, but the TeV emission from pulsars other than the single, young rotation powered pulsars remains to be confirmed.

The sky seen with GeV and TeV gamma rays indicates copious production of energetic electrons and positrons in point(-like) sources, which is, in the Galactic case. as a result of the pulsar activity. The VHE gamma rays are from inverse Compton radiation by electrons and our interest is in comparinh the VHE gamma ray data with synchrotron radiation by common progenitor electrons.

3. Notes on VHE gamma ray efforts for pulsar/plerion study

Crab nebula is so far the unique case in which the energy spectrum has been revealed over almost twenty decades of photon energies. The relative intensity of synchrotron to inverse Compton radiation indicates the nebula magnetic field $\sim 300\mu$G, which is consistent with the equipartition of energy densities in the particles and the field. The strong magnetic field allows synchrotron radiation up to as high as 100 MeV, and the mechanism for the dominant emission changes to inverse Compton process in the region of 100 MeV $\sim$ 1 GeV energy. This explains, together with the fact that the Crab is the pulsar of the highest spin-down luminosity, the reason why Crab nebula is so far the only plerion that has detectable emission in unpulsed GeV gamma rays. The spectrum continues to have a constant power index up to at least 50 TeV and possibly to $\sim$100 TeV. The energy spectrum at higher energies is an important key to select adequate theoretical models (see *e.g.* the paper by F.A. Aharonian in this Proceedings).

The situation in the PSR B1706-44 and Vela cases is less mature for such arguements, but the intensity of VHE gamma rays relative to X-ray band already restricts the magnetic field, as well as for constraints, to some extent, on the confinement conditions of energetic electrons. The magnetic field is estimated to be as weak as $\sim 3\mu$G, If so, the energy density of energetic electrons is higher, by an order of magniutde, than that of magnetic field, $B^2/8\pi$, the two energy densities not in equi-partition. A clear and no less important consequence of the VHE gamma ray emission is the existence of electrons of energies beyond TeV. Emission of X-rays around the Vela pulsar show a geometrically complicated structure, which varies, to some extent, depending on the analysed energy region or the instruments of different satellite missions. The VHE gamma rays displaced by $\sim 0.1^\circ$ from the Vela pulsar position clearly demonstrate the non-thermal nature of the ROSAT X-rays in the bright spot positition, but not of the X-rays from the other regions of suspected synchrotron radiation.

The estimate of magnetic field from the ratio, $\eta = L_s/L_{ic}$, of synchrotron to inverse Compton luminosity is usually made with simplified assumptions on the related quantities. The consequence can be affected, for example, by a possible contribution of local infrared radiation added to 2.7K microwave background, and also by different energy spectra of progenitor electrons (see *e.g.* Aharonian et al. 1997). In addition, the magnetic field will be, generally, stronger near the central region of nebula than the peripheral. For instance, if we divide the nebula into two region 1 and 2, then the ratio η can be expressed as a weighted sum of the ratios η_1 and η_2 of the two regions, $\eta = (\eta_2 + A\cdot\eta_1)/(1+A)$, where $A = \tau_{esc}/\tau$ is the ratio of escape time τ_{esc} of progenitor electrons (from the central 1 to outer region 2) to the total life time τ of electrons in region 2. In the case of PSR B1706-44, magnetic field $B_1 \sim 20\mu$G can explain both of the VHE and X-ray data, if we assume the escape time τ_{esc} is as fast as $10 \cdot (E/20\mathrm{TeV})^{-\delta}$ yrs with $\delta = 0 \sim 0.5$ (Aharonian et al. 1997).

Based on currently available, detailed data of spatial and spectral structure of the Crab nebula, De Jager and Baring (1997) argue that the GeV gamma rays may be associated with a radio nebula by relic electrons of the plerion, which has a larger spatial extent and a weaker magnetic field of $\sim 100\mu$G than the optical/TeV nebula due to fresh, more energetic electrons. In the case of the Crab nebula, the power index of the energy spectrum at TeV is going to be settled around ~ -2.5. The differential energy spectrum of TeV photons is now reported by several groups to argue the spectral slope, instead of the '*used to be common*' one, the flux integrated above the threshold energy. It would be worth pointing out that the differential spectrum is a result of many progresses in the VHE technique in such as energy resolution and background rejection. Efforts are under way in the CANGAROO analyses to derive the differential energy spectrum also for Vela and other VHE sources. The importance of spectral information is again emphasized when we consider a likely contribution from the proton progenitor, particularly in the case of supernova remnants. Abundant protons are quite likely injected into the "accelerator" in the supernova shell and gamma rays will have a monotonously flat spectrum over a wide energy range compared with the electron progenitor case.

A majority of the X-ray nebulae shows a spatial extent larger than 0.1°. The current technique of identifying VHE gamma rays tends to lose sensitivity with increasing emission size. There are two paths to improve the current 'semi-one-dimensional' angular resolution $\sim 0.1°$ of IACT; (1) 'stereoscopic' observation by using a system of multiple IACTs and (2) the advanced analysis of Čerenkov image into more details to infer the gamma ray direction two-dimensionally, which enables to plot a map of gamma ray intensity from the observation by single IACT (le Bohec and Degrange 1995; Lessart et al. 1997; Yoshikoshi et al, 1997). At the present time, however, a region of fainter emission tends to be masked by stronger emission which may exist in the neighborhood, with an example given, possibly in the case of SN 1006, by the south-western rim of the supernova shell under the shadow cast by the intense emission from the north-east one.

4. Prospect of VHE study

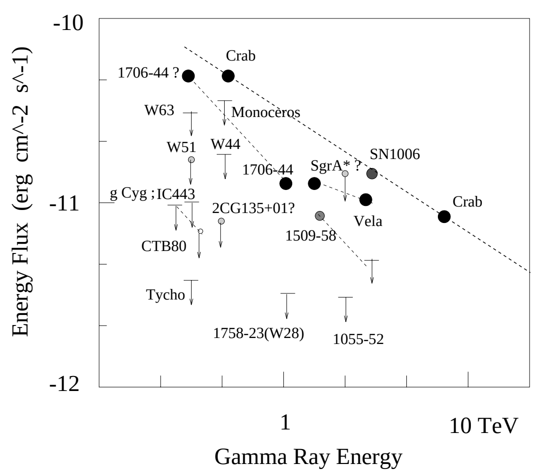

Fig. 1. Fluence from various Galactic objects. The fluence is approximated to be the product of the gamma ray energy of detection threshold and the integral flux above the threshold.

The fluxes and upper limits of TeV gamma rays are shown against gamma ray energy in Fig. 1. The results of WHIPPLE and HEGRA groups for supernova remnants and several other objects are also included. We see the detection sensitivity is now at $\sim 10^{-11}$ erg cm^{-2} s^{-1}. A telescope of 7 m diameter of CANGAROO will commence operation in 1998 with the threshold energy $\sim$ 100 GeV and the sensitivity of $\sim 10^{-12}$ erg cm^{-2} s^{-1}. We expect to increase the number of the pulsar nebulae of synchrotron X-rays that also emit VHE/inverse Compton gamma rays. A systematic study will be available over a number of nebulae of estimating magnetic field and confinement conditions of progenitor electrons to infer their dependence on the evolution of pulsar.

The VHE results so far obtained are biased toward closer distances, higher spin down luminosities and higher values of the fraction f of energy output into VHE gamma rays. The sensitivity 1×10^{-12} erg cm^{-2} s^{-1} allows us to detect VHE luminosity of 3×10^{33} erg s^{-1} from the pulsars at the distance $d = 5$kpc. In about 30 pulsars having the highest values of the maximum fluence measured at the Earth as given by the spin-down energy loss (i.e., $L_{sd}/(4\pi d^2)$), the majority has the spin-down luminosity $L_{sd} = 10^{35} \sim 10^{36}$ erg s^{-1} and $d \leq 5$ kpc, with more than ten pulsars among them appearing to accompany X-ray synchrotron nebula. Thus, the search becomes almost bias-free to $d = 5$ kpc for $f = 10^{-2} \sim 10^{-3}$ (the case of PSR B 1706-44 and Vela falls in this range) and, for smaller f ($\sim 10^{-4}$ for Crab), the study is limited within closer distances. However, a considerable number of pulsars can be still hidden at close distances in the dense matter region, because the detection by radio to soft X-ray bands suffers from absorption effect in the region. These hidden pulsars may be associated with the unidentified EGRET sources, and are likely to show bright, gamma ray activities.

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