TeV gamma-rays from Galactic objects: pulsars, pulsar nebulae and supernova remnants

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Abstract. Pulsar nebula, supernova remnant and nucleus of active galaxy are found as TeV gamma ray emitter, and the number of such sources is now approaching 10. All of them so far evidenced are explained by electron progenitor. The emission process in the TeV energy region is characterized and controlled by the particle interaction of high energy photons and electrons. The radiation by electrons implies a tight link of emission in the TeV region to the other bands, raising importance of the 'multi-wavelengths analysis' in order to investigate production, acceleration and interaction of energetic particles. The absoption of TeV gamma rays due to pair creation of electron and positron becomes more serious for smaller size of emission region. The constraint on the emission size is discussed and found consistent with the VHE sources so far discovered. 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 the X-ray band in 1970's. The EGRET instrument of CGRO has discovered about 200 HE sources which consist of pulsars, AGN (active galactic nuclei) and unidentified sources. The detection technique for VHE gamma rays experienced a "break-through" by IACT (imaging air Čerenkov telescope) since the success of establishing the Crab signal by Weekes et al. (1989). The number of VHE sources is now 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 for examples in Weekes et al. 1997 and Ong 1998 with references therein.

Table 1. List of Galactic TeV objects

Type	Object	group
pulsar nebula	Crab	many groups
	PSR 1706-44	Cangaroo, Durham
	Vela pulsar	Cangaroo
	PSR 1509-58	Cangaroo (preliminary)
supernva remnant	SN 1006	Cangaroo
X-ray binary	Cen X-3	Durham
Micro-quasar	GRS 1915+105	HEGRA ?

The list of galactic sources of TeV gamma-rays is given in Table 1. Among them, TeV signals from the Crab nebula are now detected by a number of groups establishing the object as a standard candle of very high energy gamma rays. Other pulsar nebulae are detected by CANGAROO group. One of these, PSR 1706-44, was recently confirmed by Durham group who reported $\sim$ 300GeV emission from the object. CANGAROO group has detected signal from the direction of the Vela pulsar repeatedly every year from 1993 to 1997, but efforts have not been done by other groups for confirmation. The search for pulsed VHE signal from the rotating neutron star deep inside the nebulae still remains to be continued by using IACTs of the next generation with reduced threshold energy lower than 100 GeV. The SN 1006 is so far the only case that VHE gamma-ray emission are found from supernova remnants. The fact stimulates discussions of argueing about why from this particular object and not from the other supernova remnants. It is noted that SN 1006 seems to be a pecular one of having a clear nonthermal emission of synchrotron X-rays, while the emission nature in other bands like GeV gamma rays of EGRET detection are rather obscure in the case of other supernova remnants. Extensive study over various types of supernova remants remain to be done.

Emission of VHE gamma rays from X-ray close binaries was a central topic in 1980's. Recent report by Durham group of detecting Cen X-3 is in this context very interesting and requests futher study or confirmation by other groups.

We summarize the status of VHE study on pulsars to include early efforts in 1980's. Then in Section 3 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 4 paying attention to 'multi wavelengths 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 5).

2. VHE gamma-ray emission from pulsars

As shown in the VHE summary on EGRET pulsars of Table 2, efforts have so far failed to detect pulsed signal though there are several hints reported on Crab, Vela and Geminga, which have not been confirmed by the other groups.

Among more than 500 pulsars so far known about 10% of those are with period shorter than 100 ms, including further a half of them as binary pulsars. Only Geminga and six radio pulsars have been found by EGRET to emit high energy gamma rays, with upper limits set for 40 other short period pulsars. The VHE survey with decent observation time is still limited to a small number of pulsars, and has failed to detect pulsed signal from the EGRET pulsars. However, there are several claims reported from 1980's observations on non-EGRET pulsars. The observational status can be seen in Fig. 1.

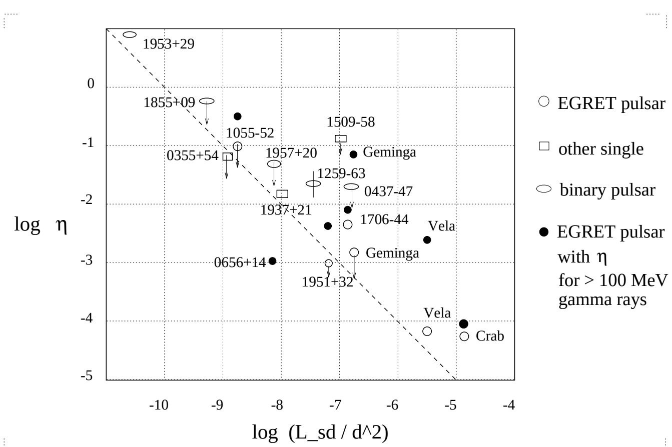

Fig. 1. Scatter plot of brightness in VHE gamma rays and rotational energy loss of pulsars.

Table 2. Observations of the Crab, PSR B 1706−44, Vela and Geminga

Group (reference)	Flux (cm^{-2} s^{-1})	$E_{th}^{(*)}$
============ Crab ============		
— unpulsed —		
Whipple (1993)	8.8×10^{-12} $(E/TeV)^{-1.69}$	0.4
Crimea (1995)	1.3×10^{-11}	1
ASGAT (1993)	2.7×10^{-11}	0.6
HEGRA (1995)	8×10^{-12} $\times (E/TeV)^{-1.7}$	1
Themistocle (1995)	2.3×10^{-12} $(E/3TeV)^{-1.4}$	2.3
CANGAROO (1994)	7.6×10^{-13}	7
— pulsed —		
Whipple (1995)	$< 2.0 \times 10^{-13}$	0.25
Gulmarg (1996)	$< 2.5 \times 10^{-12}$	4
Tata (1994)	$(9.7 \pm 4.3) \times 10^{-12}$	1
Durham (1984)	$(7.9 \pm 1.8) \times 10^{-12}$	1
============ PSR B 1706−44 ============		
— unpulsed —		
CANGAROO (1995)	8×10^{-12}	1
Durham (1997)	$\sim 1 \times 10^{-10}$	0.3
— pulsed —		
Potchefstroom (1993)	$< 5.8 \times 10^{-12}$	2.6
============ Vela pulsar ============		
— unpulsed —		
CANGAROO (1998)	$\sim 3 \times 10^{-12}$	~ 1
— pulsed —		
SAO/Sydney (1975)	$< 8.5 \times 10^{-11}$	0.3
Tata(1987)	$\sim 1 \times 10^{-12}$	5
Durham(1993)	$< 5 \times 10^{-11}$	0.3
Potchefstroom(1993)	$< 6 \times 10^{-12}$	2.3
Adelaide(1994)	$< 7 \times 10^{-11}$	0.8
============ Geminga ============		
— unpulsed —		
Whipple(Akerlof et al. 1993)	$< 8.9 \times 10^{-12}$	0.5
— pulsed —		
Durham(1993)	3×10^{-11}	1
Tata(1993)	$(2.1 \pm 0.8) \times 10^{-11}$	0.8
	$(4.4 \pm 3.5) \times 10^{-12}$	1.7
Whipple(1993)	$< 5 \times 10^{-12}$	0.5

(*) : Threshold energy of detected gamma ray in TeV.

In calculating the luminosity L_{VHE} in the VHE gamma ray band from the reported flux, there are many factors which cause systematic errors; the threshold energy of the observations, the shape of energy spectrum to be integrated, contamination of the background (above which the gamma ray signal is detected), as well as the distance to pulsar. Some of these conditions depend on the individual observations, the details of which are not clearly known. The results plotted in Fig. 1 assume, for all observations, the same photon index of −2.5 and the same energy range of 500 GeV to 10 TeV despite the varying threshold energies from observation to observation. The solid angle of emission is taken to be 4π and 1 steradian, respectively for unpulsed and pulsed emission. Some of the luminosities calculated here are considerably different from those given in the papers that reported the observation, which is not surprising in view of the existing uncertainties. In Fig. 1, the horizontal axis is log $(\mathrm{L_{sd}}/\mathrm{d}^2)$ in units of erg s^{-1} cm^{-2}, where d is the distance to the earth, and the vertical axis is log η, where η is the ratio of gamma ray luminosity to spin down luminosity $\mathrm{L_{sd}}$. The VHE luminosity is used for unfilled symbols ($\eta = \mathrm{L_{VHE}}/\mathrm{L_{sd}}$), and the luminosity in 100 MeV to 30 GeV is used (instead of $\mathrm{L_{VHE}}$) for EGRET pulsars, which are shown with a black circle. Data of a same flux at the earth will appear in parallel with the dotted line which represents $\mathrm{L_{VHE}}/\mathrm{d}^2$ = constant. Thus, we see that the observation is biased by the detection sensitivity.

It should be again noted that the results shown in Fig. 1 are compiled from early observations withou using the imaging technique, and are mostly about short period radio pulsars unless they are not EGRET pulsars. However, there are increasing number of pulsars of short periods which are found to emit X-rays by ROSAT and ASCA satellites, and a systematic study for these are left undone in VHE energy region.

3. 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 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. The result motivated our VHE observation to find evidence from the same direction of the non-thermal X-ray emission (Tanimori et al. 1998b). The VHE signal provides direct evidence of $\sim$100TeV electrons accelerated by SN shock, and suggests that protons are also likely shock-acceletated at the shell of the SN.

Three AGNs classified as blazars at redshift ~ 0.03 are found as VHE emitters by Whipple group. Efforts of CANGAROO for the 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 (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.

Preliminary upper limits from the analysis of the CANGAROO data on X-ray binaries, Vela X-1 and Cen X-3, seem to exclude the case of intense emission $> 10^{-11}$ cm^{-2} s^{-1} ($>\sim$ 1 TeV) of a flat energy spectrum as suggested from early observations in 1980's. However, the data so far accumulated for less than 20 hours duration can be consistent with the recent Durham result on Cen X-3. VHE gamma rays from X-ray binaries can be due to emission mechamism which is quite different from the one in pulsar nebulae or supernova remnant, possibly proton acceleration in the accretion disk of the binary. In particular, the suggested sporadic nature of the signal is common with the recent report of detecting a burst from micro quasar GRS 1915+105 by HEGRA group. These possible detections would open a new area of VHE gamma ray astronomy, but the current observational situation is too premature to argue about the implication.

4. VHE gamma-ray emission and multi-wavelengths spectrum

4.1. Crab and other nebulae: Any prototype ?

The 'entire' spectrum over 'multi wavelengths' is reasonably well known only for the Crab nebula. The profile is consistently explained by 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 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 proton component (*e.g.* Aharonian 1997). 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}). 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 $W_{2.7K}$ 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

$$k_{sync} \approx 0.2(\frac{B}{10^{-6}\mathrm{G}})(\frac{E}{100\mathrm{TeV}})^2\,\mathrm{keV} \quad (1)$$

$$k_{ic} \approx 5(\frac{\varepsilon}{10^{-4}\mathrm{eV}})(\frac{E}{100\mathrm{TeV}})^2\,\mathrm{TeV}, \quad (2)$$

where ε is the energy of target photons of Compton scattering. As the relation (1) shows, the same electrons of $\sim$ 100 TeV 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 Vela and PSR B1706-44 nebulae. However, 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.

4.2. Relic and escaping electrons: Multiple populations ?

The emission region of 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). The 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 a multi-wavelengths spectrum of the Vela compact nebula by including the radio and CGRO OSSE data, which may suggest $B = 6 - 20\mu$G. Although de Jager and Baring (1997) presumed 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 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}. In addition, 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 $\sim 1\mu$G. We have uncertainty about the size of emission region which the X-ray and VHE observations do not spatially resolve yet.

4.3. 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 MWB, 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 then 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 possible injection of electrons from associated plerion and various matter density 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 are necessary to observe VHE emission from a variety of different types of supernova remnants. The CANGAROO group recently made observation of RXJ 1713.7-3946 (G347.5-0.5), a quite similar to SN 1006, when the non-thermal X-ray emission is concerned.

5. Size and energy density of emission region

In 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 gets intenser as well as the magnetic field in the pulsar magnetosphere stronger, and gamma rays tend more likely to suffer from the cascade process of electromagnetic interactions. TeV gamma rays can be annihilated into electron-positron pairs when they collide with infrared photons, and are prevented from escaping outwards. Let us consider a simplified case that the number density n_{ir} of infrared photons is proportional to the luminosity L averaged over wavelength and thus also to the energy density of radiation field W_{source},

$$n_{ir} = \frac{W_{source}}{\varepsilon} \approx \frac{L}{4\pi r^2 c\,\varepsilon}. \quad (3)$$

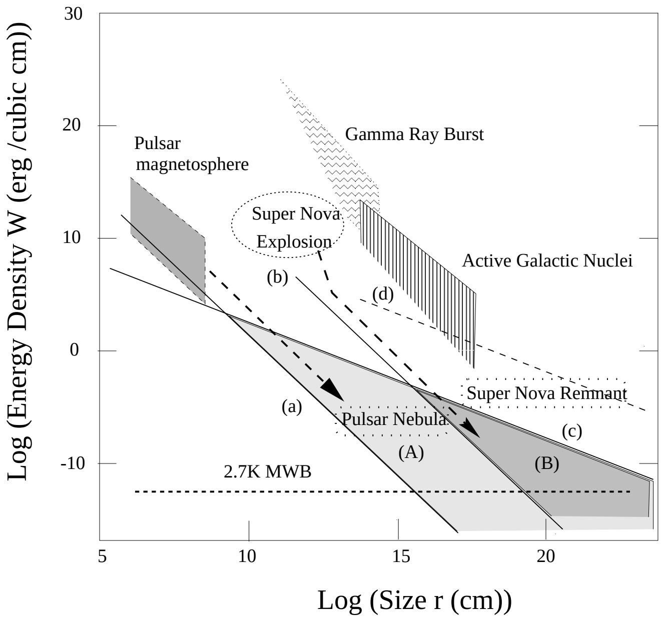

Fig. 2. The energy density of radiation is plotted against spatial size. The energy density W of photons from interesting objects is calculated from $L/(4\pi r^2 c)$ and plotted in the vertical axis against the distance r from the central compact object. The line (a) and (b) corresponds to the least 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 $r^2 W$ =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.

where c is the light velocity, and ε the energy of 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 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. VHE gamma rays are free from the 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 distance 3kpc and 100Mpc, 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 AGN, where σ_T and m_e are the Thomson cross section and electron mass, respectively, and λ_{MeV} 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 AGNs are outside the allowed region of the boundary line (c) of $r/\lambda = 1$. The detection of VHE signals from blazars owes 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 on the radiation field, and for example, time-variable phenomena as well as asymmetrical geometries can make the constraint looser. Observation of VHE gamma rays have been mainly made on stable, 'DC' source (at least about Galactic objects). Efforts for violently time variable sources, as well as 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 VHE gamma rays by pair creation, we need to investigate the opposite effect of the higher energy density enhancing 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.

It should be noted that the energy density of the vertical axis of Fig. 2 is commonly used for VHE radiation and for "target photons" of ambient background radiation, assuming that the luminosities emitted in various bands are approximately constant, *i.e.* valid for the case that is $\nu F_\nu \approx$ is constant over a wide energy band from infrafed to VHE region. The line (c) is determined by the energy density of infrared photons, while (a) and (b) are by VHE photons. Thus, if luminosity of the background radiation of the soft photons is smaller than VHE one, the line (c) is to be raised upward in the figure to allow us to detect VHE gamma rays from the region nearer to the central compact star. Next generation IACTs are expected to have better sensitivity and lower threshold energy of detectable gamma rays, which will move the line (a) downward or to the lefthand side, hopefully providing us with more VHE emitting objects. .

In order that VHE gamma rays come out from a smaller spatial size, the acceleration time must be reasonably short when compared with the confinement time and/or the the characteristic time of radiation loss of progenitor particles. Generally, acceleration to higher energies requires larger spatial sizes. Estimate of the accelation energy by the product of magnetic field and the spatial size and limitation by the energy loss to due to synchrotron radiation can be plotted similarly to the lines (a) and (c), respectively, when we use the energy density of magnetic field as the vertical axis of Fig. 2. It is interesting to note that the lines for such boundary conditions on acceleration of electrons are located at the positions not far from the ones of (a) and (c), The proton progenitor suffers from less radiation loss, and may give us opportunity to look deeper into smaller size.

6. Conclusion

X-ray observation by ROSAT and ASCA satellites has revealed that most luminous pulsars are accompanied by a synchrotron X-ray nebula, which suggests also an 'inverse Compton nebula' at young pulsars. In the EGRET pulsars, a more fraction of rotational energy loss is spent into HE gamma rays than radio and X-rays. In Fig. 2 is plotted the fraction of energy output into the pulsed signals in X-ray and GeV gamma ray band relative to the spin-down luminosity, as well as for unpulsed signals from TeV measurements. The dependence on the spin-down luminosity is remarkably different between X-ray and GeV gamma ray bands, but premature, in VHE gamma rays, to argue about such feature. However, the VHE emission from pulsar nebulae also appear that a fraction of the spin-down energy loss is given, and will provide a systematic study over a more number of VHE sources to infer the tendency how the emission 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. The broad band energy spectrum from X-ray to VHE gamma ray region is necessary for having more advanced comparison between synchrotron and inverse Compton emission. No less important are the bands of longer wavelengths of radio, infrared and optical light, which serve as 'seed' photons for production of Compton-scattered VHE gamma rays and also as 'partner' photons for annihilation process into electron-positron pair. The 'entire' spectrum of photons is coupled to VHE gamma rays.

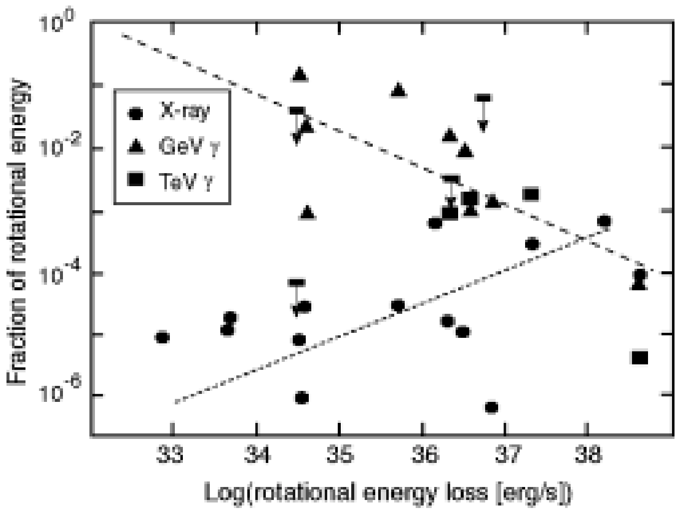

Fig. 3. Brightness in X-ray, HE and VHE gamma ray bands of young pulsars. The luminosity relative to spin-down luminosity (horizontal axis) is plotted for individual pulsars versus spin-down luminosity. The data for X-ray (circle) and HE gamma rays (triangle) is from the pulsed signal, and VHE ones (square) are unpulsed luminosities.

X-ray pulsars and bursters or 'micro quasars' such as GRS 1915+105 (from which HEGRA group reported the possible detection of a VHE burst) as well as close binary systems like PSR B1259-63, from which CANGAROO detected marginal hint of VHE emission at an orbital phase after the periastron (Sako et al. 1997), can be characterized by much smaller spatial size than $\sim$ 1pc of pulsar nebula and SN remnant, and thus the signal from those if detected provides a new example and insight on the production and interaction mechamism of VHE gamma rays. Close X-ray binaries are another example of the candidates for VHE emission from smaller region than nebulae and SN remnants. Revisit to these like Cen X-3 are worth attempting by using IACTs. 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 smaller size of denser radiation field than $\sim$ 1 pc of the pulsar nebulae or SN remnants, as in the case of AGN outbursts and GRB.

Compared with a numerous number of objects which have been observed in the other bands like X-rays, VHE study so far done is quite limited to a small class of pulsars like EGRET pulsars. Currently, systems of IACTs are planned by the Whipple group (VERITAS), the HEGRA group (HESS) and also by CANGAROO group. It is hoped that these next generation detectors for ground-based VHE gamma rays will soon provide with a systematic study of pulsars and other Galactic objects with sensitivity $\sim 10^{-13}$ erg cm^{-2} s^{-1} which is not very far from the one in X-ray band.

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