A Model for Non High Energy Gamma Ray Bursts and Sources of Ultra High Energy Cosmic Rays
-super strongly magnetized milli-second pulsar formed from a (C+O) star and a neutron star (black hole) close binary system-

Takashi NAKAMURA
Yukawa Institute for Theoretical Physics, Kyoto University, 606, Japan

ABSTRACT

As a progenitor of NHE (Non High Energy) GRBs (Gamma Ray Bursts), we propose a (C+O) star and a neutron star (black hole) close binary system with separation $\sim 0.2 R_\odot$. Since the (C+O) star is tidally locked, the collapsing core should have a spin angular momentum $\sim 6 \times 10^{48}$ cgs so that a newborn pulsar should be a milli-second pulsar (MSP) ($P \sim 1$ ms). $\alpha - \Omega$ dynamo in the first 10s after the bounce of the core will generate a superstrong magnetic field ($B \sim 10^{16}$ G). The beam of the energy from the super strongly magnetized milli-second pulsar (SSM-MSP) can punch a hole in the supernova ejecta. Then the beam of gamma rays flows out of the ejecta for $\sim 10$ s with the total energy up to $\sim 2 \times 10^{51}$ erg. If we observe this beam from the lateral direction, the energy of gamma rays should be smaller than 500 keV due to the electron scattering and the total energy of gamma rays should be much smaller than $\sim 2 \times 10^{51}$ erg, which is the very characteristics of NHE-GRBs. In SSM-MSP model of NHE-GRB, GRB event should be associated with Type Ib/Ic supernova like GRB980425/SN1998bw. If SSM-MSP is produced in a fraction ($\sim$ a few %) of Type Ib/Ic supernovae, the event rate as well as the isotropic and homogeneous distribution of NHE-GRBs are also explained. In this model the pulsar with the spin period $P \sim 1.4 s (B/10^{16}) (t/4\text{ month})^{1/2}$ should exist in SN1998bw so that the searches for this pulsar in all the wave length are urgent. SSM-MSPs can accelerate protons up to $\sim 3 \times 10^{22} (P/1\text{ ms})^{-2} (B/10^{16}\text{ G}) \text{ eV}$. If a few % ($\sim 10^{50} \text{ erg}$) of the beam energy of SSM-MSP in NHE-GRB event ($> 5 \times 10^{51} \text{ erg}$) is in the form of high energy protons of energy $\sim 10^{20}$ eV, the flux of the observed UHECRs (Ultra High Energy Cosmic Rays) can be explained. Then along the direction of each UHECR, a supernova remnant should be found. As a natural consequence of our model, it is suggested that NHE-GRB is the progenitor of the soft gamma ray repeater which has also the superstrong magnetic field ($B \sim 10^{15}$ G) and is in the supernova remnant.
1 Introduction

Galama et al.\cite{1} reported the discovery of very luminous Type Ic supernova SN1998bw in the BeppoSAX Wide Field Camera error box of GRB 980425\cite{2}, which occurred within about a day of the gamma ray burst. The duration of GRB 980425 is \( \sim 30\text{sec} \) and the burst fluence is \((4.4 \pm 0.4) \times 10^{-6}\text{erg/cm}^2\). Since no burst of emission is detected above 300keV, GRB 980425 belongs to a so called NHE(Non High Energy) burst\cite{3} which is characterized by the lack of fluence above 300keV, lower peak flux and the apparent isotropic and homogeneous distribution. A quarter (\( \sim 250 \) events/\( y \)) of GRBs is NHE bursts.\cite{3}

The host galaxy of SN1998bw is a spiral galaxy at a distance of \( \sim 40\text{Mpc} \). The chance probability of the coincidence is \( \sim 10^{-4} \).\cite{1} Motivated by the coincidence of Type Ic SN with GRB, Wang and Wheeler\cite{4} examined six recent SN Ib/c for which an outburst epoch can be estimated with some reliability and found that all are correlated in time and space with BATSE gamma ray bursts. Since the joint probability of all six correlations is \( 1.5 \times 10^{-5} \) and no such correlation exists for SN Ia and SN II, Wang and Wheeler\cite{3} proposed that all gamma ray bursts are associated with Type Ib/c supernovae. In this paper I follow the proposal by Wang and Wheeler. I assume that all NHE-GRBs are associated with Type Ib/c supernovae, which should be confirmed in future observationally. I propose a model that a (C+O) star and a neutron star(black hole) close binary is a progenitor of NHE gamma ray burst and argue the details of the model.

In §2 a formation scenario of a (C+O) star and a neutron star (black hole) close binary system is discussed. In §3 I discuss a supernova explosion of the (C+O) star which yields a super strongly magnetized milli-second pulsar(SSM-MSP) . In §4 I explain how SSM-MSP emits NHE-GRB. §5 will be devoted to discussions and astrophysical implications of our SSM-MSP GRB model.

2 Formation of a (C+O) star and a neutron star(black hole) close binary system

Similar to the scenario of formation of double neutron star systems\cite{5, 4} we assume that our (C+O) star-neutron star(black hole) binary is formed as follows:\cite{4}:

1) Consider a binary system composed of two main-sequence stars 1 and 2 of mass \( \sim 25 \text{M}_{\odot} \) which has a helium core mass \( \sim 8\text{M}_{\odot} \),

2) Roche lobe overflow of star 1, which becomes a helium star 1,

3) the first supernova explosion of helium star 1 to form a neutron star 1,

4) Roche lobe overflow of star 2 which leads to a spiral-in of neutron star 1 into star 2. The system shrinks and finally it consists of a neutron star 1 and a helium star 2. Here
we note that if the super Eddington accretion is possible, a neutron star becomes a black hole of mass $\sim 2.4M_\odot$ in this spiral-in phase.

5) During the presupernova evolution of helium star 2, the helium envelope expands as its core contracts. The radii of star 2 with mass $3 \sim 8M_\odot$ are $4 \sim 1R_\odot$. So if the Roche radius of star 2 is smaller than $4 \sim 1R_\odot$, a spiral-in of neutron star (black hole) 1 occurs again. Now the system consists of (C+O) star 2 and neutron star (black hole) 1. The mass of the (C+O) cores are 6.0 and 3.8 $M_\odot$ for mass of helium stars 8 and 6 $M_\odot$, respectively, while the radius of the (C+O) star is $\sim 0.1R_\odot$. Since the radii of helium stars of mass 8 and 6 $M_\odot$ are 1.3 and 1.9 $R_\odot$, respectively, at the onset of Roche lobe overflow, the separation after the spiral-in of neutron star (black hole) 1 will be significantly smaller than $1R_\odot$, say, $0.2R_\odot$. Such a (C+O) star in a close binary may be a progenitor of Type Ic supernova such as SN1994I.

3 Super Strongly Magnetized Milli-Second Pulsar

Now I discuss an evolution of our close binary system with separation $a \sim 0.2 R_\odot$ which consists of a (C+O) star of mass $M_2 \sim 6 M_\odot$ and a neutron star (black hole) of mass $M_1 = 1.4(2.4)M_\odot$. There are three important time scales in this system:

1) $t_{\text{ev}}$ : the evolution time of the (C+O) star. They are 100 yr and 450 yr for $M_2 = 6$ and 3.8 $M_\odot$, respectively.

2) $t_{\text{gw}}$: coalescing time of the binary due to the emission of gravitational waves which is given by

$$t_{\text{gw}} = 4 \times 10^3 yr \left(\frac{M_1}{1.4M_\odot}\right)^{-1} \left(\frac{M_2}{6M_\odot}\right)^{-1} \left(\frac{M_1 + M_2}{7.4M_\odot}\right)^{-1} \left(\frac{a}{1.4 \times 10^{10} cm}\right)^4.$$  \hspace{1cm} (1)

3) $t_{\text{synch}}$: the tidal synchronization time which is given by

$$t_{\text{synch}} \sim \frac{I\Omega_{\text{orb}}}{N},$$  \hspace{1cm} (2)

$$\Omega_{\text{orb}} = 1.9 \times 10^{-2} s^{-1} \left(\frac{M_1 + M_2}{7.4M_\odot}\right)^{0.5} \left(\frac{a}{1.4 \times 10^{10} cm}\right)^{-1.5},$$  \hspace{1cm} (3)

where $I$, $\Omega_{\text{orb}}$ and $N$ are the moment of the inertia of the (C+O) star 2, the orbital angular velocity and the tidal torque, respectively. $N$ is estimated as

$$N = \frac{GM_1^2}{R} \left(\frac{R}{a}\right)^6 \alpha,$$  \hspace{1cm} (4)

where $R$ and $\alpha$ are the radius of star 2 and the angle between the orbital separation vector and the tidal bulge, respectively. $\alpha$ is expressed by the viscous damping time $t_{\text{vis}}$ as

$$\alpha = \frac{\Omega_{\text{orb}} R^3}{GM_2 t_{\text{vis}}}. $$  \hspace{1cm} (5)
Therefore $t_{\text{synch}}$ becomes

$$t_{\text{synch}} = \left(\frac{M_2}{M_1}\right)^2 \left(\frac{a}{R}\right)^6 t_{\text{vis}} \sim 1800 t_{\text{vis}}. \quad (6)$$

Since the convective core exists in the (C+O) star\[10\], $t_{\text{vis}}$ is estimated as

$$t_{\text{vis}} = \left(\frac{R}{v_{\text{conv}}}(\frac{R}{l_m}) \right) \quad (7)$$

where $v_{\text{conv}}$ and $l_m$ are velocity of convection and the mixing length, respectively. Putting $v_{\text{conv}} \sim 10^5 \text{cm s}^{-1}$ and $l_m \sim 0.2 R$, we have

$$t_{\text{synch}} \sim 20 \text{yr} \left(\frac{v_{\text{conv}}}{10^5 \text{cm s}^{-1}}\right)^{-1} \left(\frac{l_m}{0.2 R}\right)^{-1} \frac{R}{7 \times 10^9 \text{cm}} \quad (8)$$

Since we have the inequality as

$$t_{gw} \geq t_{ev} \geq t_{\text{synch}}, \quad (9)$$

the (C+O) star 2 is tidally locked in the carbon burning phase and the supernova explosion of star 2 occurs with essentially the same separation $a$. In tidally locked binary the spin angular velocity is the same as the orbital one so that the collapsing central $1.4M_\odot$ core of star 2 will have the spin angular momentum $J$ estimated as

$$J = I_{\text{core}} \Omega_{\text{orb}}, \quad (10)$$

where $I_{\text{core}}$ is the moment of inertia of the central $1.4M_\odot$ core. Inserting $I_{\text{core}}$ of $10^{50} \sim 10^{51} \text{gcm}^2$ in the carbon burning phase\[10\], we have

$$J = 2 \times 10^{48\sim49} \text{gcm}^2 \text{s}^{-1} \left(\frac{M_1 + M_2}{7.4M_\odot}\right)^{0.5} \left(\frac{a}{1.4 \times 10^{10} \text{cm}}\right)^{-1.5}. \quad (11)$$

This angular momentum is comparable to that of a 1 ms pulsar ($\sim 6 \times 10^{48} \text{g cm}^2 \text{s}^{-1}$), which means that the new born pulsar after the supernova explosion of star 2 is necessarily a milli-second pulsar.

Duncan and Thompson\[13, 14\] argued $\alpha-\Omega$ dynamo theory for such a rapidly rotating new born pulsar and concluded that such a milli second pulsar may have a superstrong magnetic field of $\sim 10^{16} \text{G}$ within 10s after the formation. Although Duncan and Thompson considered the accretion induced collapse, the same argument can apply to our (C+O) star. Recently such a superstrong magnetic field ($\sim 10^{15} \text{G}$) has been identified in a soft gamma ray repeater SGR1806-20\[15\] with the age $\sim 10^4 \text{y}$. This observation supports a model of soft gamma ray repeaters based on super strongly magnetized neutron stars\[16, 17\]. Therefore even relying only on the observational results, it may be possible to consider a superstrong magnetic field as strong as $\sim 10^{16} \text{G}$ in a new born milli-second
pulsar. Considering both theoretical suggestions and observations of such a superstrong magnetic field, we assume here that after the explosion of our (C+O) star a milli-second pulsar with the superstrong magnetic field \( B \sim 10^{16} \text{G} \) is formed in \( \sim 10 \) s. Here note that in vacuum there exists the maximum electric field \( E_c = 2\pi m_e^2 c^3/\hbar e = 4.4 \times 10^{15} \text{e.s.u} \) while the maximum magnetic field does not exist since the vacuum with such a strong field is shown to be unstable only for \( (E^2 - B^2) > 0 \). \(^{[18]}\) (See page 677 of reference 18.)

4 Supernova explosion of a (C+O) star and NHE gamma ray bursts

Now star 2 explodes as a Type Ic supernova with the ejecta of mass \( M_e = 2 \sim 5 M_\odot \). The column density \( (\Sigma) \) of the ejecta at time \( t \) from the explosion is given by

\[
\Sigma \sim 10^5 \text{g/cm}^2 \left( \frac{M_e}{M_\odot} \right)^2 E_{51}^{-1} \left( \frac{t}{1 \text{day}} \right)^{-2}
\]

where \( E_{51} \) is the explosion energy in the unit of \( 10^{51} \text{erg} \). Recently Woosley, Eastman and Schmidt\(^{[19]}\) made light curve models for SN1998bw and found that a 6\( M_\odot \) (C+O) star model with the unusually large explosion energy of \( \sim 2 \times 10^{52} \text{erg} \) can fit the light curve quite well. They also found that both shock break-out and relativistic shock deceleration in circumstellar material fail to produce a GRB of even the low luminosity\( (\sim 10^{48} \text{erg}) \) inferred for GRB980425. This means that the source of gamma rays should be inside the ejecta. Since the time difference between the supernova explosion and GRB 980425 is one day or so, from Eq. (12) the column density at \( t \sim 1 \text{day} \) is so high that any gamma rays emitted from the central new pulsar, neutron star or black hole can not reach the surface of the ejecta unless there is a hole in the ejecta. This reminds us the mysterious spot in SN1987A\(^{[20, 21]}\) which appeared 5-7 weeks after the explosion of Type II SN1987A at \( \sim 0.06 \text{arc-sec} \) away from SN1987A.

To explain mysterious spot in SN1987A, at least four mechanisms were examined to punch a hole in the ejecta\(^{[22, 23]}\). These mechanisms can apply to SN1998bw/GRB980425. They are;

1. Due to the existence of the secondary (a neutron star or black hole in this case) the density in the direction shadowed by the companion will be low\(^{[22]}\).

2. Rayleigh-Taylor instability in the ejecta may make a hole\(^{[22]}\).

3. The relativistic jets formed at the core collapse punch holes in the ejecta\(^{[23]}\).

4. Beams of energy from the super strongly magnetized millisecond pulsar may punch holes in the ejecta\(^{[23]}\).
In the first mechanism the relativistic plasma from the pulsar gradually inflates a bubble within the remnant. Since the remnant is punctured, the relativistic plasma from the over-pressured bubble would squirt into the surrounding. However the time needed for this mechanism to operate would be much longer than \( \sim 30 \text{s} \) unless the direction of the hole coincides with the direction of the beam from the pulsar or from the black hole with the accretion disk. In the second mechanism, the chance probability of such a hole would be very low for \( t \sim 30 \text{s} \). A chance coincidence of the hole and the direction of the beam is also needed.

In the third mechanism the direction of the hole should agree with the direction of the spin of the pulsar or the rotating axis of the black hole. General relativistic numerical simulations\[24\] have demonstrated that a rapidly rotating core collapses first along its rotation axis. Collapse continues along the equatorial directions, then bounces along the rotation axis to form jets. In one example, a 1.4\( M_\odot \) stellar core modeled as a \( \gamma = 3/4 \) polytrope produced jets with mass \( 0.007 M_\odot \), kinetic energy \( 5 \times 10^{51} \text{erg} \) and average velocity \( 0.6c \). Since the opening angle of this jet is a few degree, it is possible to punch a hole at the first 10 seconds or so. The total angular momentum in this model \( 2.4 \times 10^{49} \text{gcm}^2\text{s}^{-1} \) is four times larger than 1ms pulsar. Although this kind of jets may also be formed in MHD rotating core collapses \[25\], in general, with the increase of the angular momentum the kinetic energy of the explosion decreases since the bounces occur at the lower density and weaker gravitational potential, while SN1998bw has the unusually large kinetic energy. We therefore consider the fourth mechanism mainly in this paper.

For the typical angular momentum in the core of our (C+O) star corresponding to a milli-second pulsar, \( \sim 6 \times 10^{48} \text{gcm}^2\text{s}^{-1} \), the collapse is essentially spherically symmetric because the ratio of the centrifugal force to the gravity is \( \sim 0.2 \) even for the neutron star radius. A milli-second pulsar has the rotational energy \( (E_{rot}) \) given by

\[
E_{rot} = 2 \times 10^{52} \text{erg} I_{45} P_{ms}^{-2},
\]

where \( I_{45} \) and \( P_{ms} \) are the moment of inertia in the unit of \( 10^{45} \text{gcm}^2 \) and the spin period in milli-second, respectively. The spin period and the luminosity \( (L) \) of the pulsar are given by

\[
P_{ms} = \sqrt{\left(\frac{P_i}{1\text{ms}}\right)^2 + \frac{t}{\tau}},
\]

\[
\tau = 5s B_{16}^{-2} I_{45} R_6^{-6},
\]

\[
L = 3.8 \times 10^{51} \text{erg/s} B_{16}^{2} R_6^{6} \left(\frac{P_i}{1\text{ms}}\right)^2 + \frac{t}{\tau} \right)^{-2},
\]

where \( P_i \), \( B_{16} \), \( R_6 \) and \( t \) are the initial spin period, the magnetic field in unit of \( 10^{16} \text{G} \), the radius of the neutron star in unit of \( 10^6 \text{ cm} \) and the time after the bounce of the core, respectively.
The expansion velocity \( V_{\text{exp}} \) of the ejecta is given by
\[
V_{\text{exp}} \sim 10^9 \text{cm/s} \left( \frac{M_e}{M_{\odot}} \right)^{-1/2} E_{51}^{1/2}.
\] (17)

For SN1998bw the observed expansion velocity is \( \sim 2 \times 10^9 \text{cm/s} \). This means that \( E_{51} \sim 20 \) for \( M_e \sim 5 M_{\odot} \). This unusually large explosion energy is consistent with a model of light curves \[19\]. The shock will reach the surface of the (C+O) star (\( \sim 10^{10} \text{cm} \)) in \( \sim 5 \text{s} \). Since the magnetic field will be amplified to \( \sim 10^{16} \text{G} \) within 10s \[13\], the superstrong magnetic field pulsar begins to operate after or just when the shock breaks out. The solid angle extended by the beam from the pulsar is given by \[27\]
\[
\Delta \Omega = \frac{4 \pi R}{P_c} \sim 0.05 \times 4 \pi P_{\text{ms}}^{-1}
\] (18)

Then the energy of \( \sim 10^{52} \text{erg} \) would be injected into 5% of the ejecta in \( \sim 10 \text{s} \). If this energy is converted to the kinetic energy of the ejecta within the cone of the beam, the velocity \( V_{\text{cone}} \) would be
\[
V_{\text{cone}} = 1.4 \times 10^{10} \text{cm/s} \left( \frac{M_e}{M_{\odot}} \right)^{-1/2}
\] (19)

This is much larger than \( V_{\text{exp}} \) so that a hole is punched out in the ejecta.

If, however, \( E_{51} \sim 1 \) and \( M_e \sim 5 M_{\odot} \) as usual, \( V_{\text{exp}} \sim 5 \times 10^8 \text{cm/s} \) and the shock will reach the surface in \( \sim 20 \text{s} \) so that the pulsar activity would start before the shock breaks out. Then a part of the energy of the beam would be used to expand the ejecta as a whole so that an effective explosion energy would increase and we may have \( V_{\text{exp}} \sim 10^9 \text{cm/s} \) finally. In this case \( V_{\text{cone}} \) will decrease but as far as \( V_{\text{cone}} > V_{\text{exp}} \sim 2 \times 10^9 \text{cm/s} \), we may regard the hole is punched out. For this the minimum energy needed is \( \sim 2 \times 10^{51} \text{erg} \) so that almost all the rotational energy of the milli-second pulsar might be used to the expansion energy of the ejecta. Note here that the unusually large explosion energy of SN1998bw is the same as the rotational energy of the milli-second pulsar. This may not be a chance coincidence. In any case a hole would be punched out by the beam of the pulsar in the first 10 s or so.

We assume here that at \( t \sim 10 \text{s} \) the hole is punched out. Then the period of the pulsar is \( \sim 2 \text{ms} \) and the rotational energy is \( \sim 5 \times 10^{51} \text{erg} \). The energy beam of the pulsar will flow out from the hole. This situation is similar to the millisecond pulsar models of GRBs based on the accretion induced collapse of magnetized white dwarfs \[28, 29\]. The beam of the energy would be finally converted to the beam of gamma rays \[28, 29\]. As a whole \( \sim 5 \times 10^{51} \text{erg} \) of gamma rays would be emitted in a cone of the solid angle \( \sim 0.025 \times 4 \pi \). The chance probability that the line of the sight is in the cone is \( \sim 0.025 \). We will observe the beam of the gamma rays, in general, from the lateral direction so that only gamma
rays scattered by the thin matter blown off from the ejecta in the first 10s will come along the line of sight.

In Compton scattering the energy of the scattered photon ($\omega$) is given by

$$\frac{1}{\omega} = \frac{1}{\omega_0} + \frac{1 - \cos \theta}{m_\text{e}c^2}$$

where $\theta$ is the scattered angle and $\omega_0$ is the incident energy. Even for $\omega_0 \gg m_\text{e}c^2$, unless $\theta$ is small such that $\omega_0(1 - \cos \theta) \ll m_\text{e}c^2$, $\omega < m_\text{e}c^2$. That is, the energy of the scattered gamma ray should be smaller than 500keV. This explains the lack of fluence above 300keV for NHE-GRBs. The scattered photon is more or less distributed isotropically, that is, it is observed from almost all the direction and the total energy would be much smaller than $\sim 10^{51}$ erg because only a small fraction of the beamed gamma rays would be scattered by the very low density plasma. This is also consistent with the total energy ($\sim 10^{48}$erg) of GRB980425.

About a fourth of gamma ray bursts ($\sim 250$ events/y) is NHE-GRBs[3]. The event like GRB980425 will not be observed if it occurred at 20 times farther $\sim 800$ Mpc. The number of galaxies within 800Mpc is $\sim 2 \times 10^7$ and the event rate of TypeIb/Ic supernova is $\sim 10^{-3}$/y/galaxy[31] so that the event rate of TypeIb/Ic supernova within 800Mpc is $\sim 2 \times 10^4$/y. This suggests that only a fraction ($\sim$ a few%) of TypeIb/Ic supernova becomes NHE gamma ray burst which is different from the suggestion by Wang and Wheeler[4]. This is, however, consistent with our model. Depending on the initial separation and initial mass of the binary, only a fraction of the binary yields the super strongly magnetized milli-second pulsar.

After an NHE-GRB event the luminosity of the pulsar is given by

$$L = 1.3 \times 10^{43}\text{erg/s}B_{16}^{-2}I_{45}^{-2}R_6^{-6}(\frac{t}{1\text{day}})^{-2}$$

For SN1998bw, the above luminosity is much smaller than the observed luminosity so that the existence of the pulsar will not affect the light curve of the supernova.

5 Discussion

It is not clear at present that our model can explain HE(High Energy) GRBs and its afterglow also. However if we observe NHE-GRB in our model along the beam direction and if we regard that the energy is emitted isotropically, then the total energy amounts to $\sim 2 \times 10^{53}$erg, which is comparable to the maximum observed energy of GRBs[31]. We here argue the event rate of NHE-GRBs up to $z \sim 3$. Adopting that $\Omega_M \sim 0.2$ and $\Omega_\Lambda \sim 0.8$ and $H_0 =$65km/s/Mpc, the total number of NHE-GRBs up to $z \sim 3$ is $\sim 10^5$/y. If NHE-GRBs observed along the cone of the pulsar beam look like HE GRBs, the event rate of HE GRBs would be $\sim 10^3$/y, which is comparable to the event rate of HE GRBs.
The maximum energy of a proton accelerated by the SSM-MSP is given by [27]

\[ E_{\text{max}} = 7.5 \times 10^{21} eV R_6^3 B_{16} \left( \frac{P}{2 \text{ms}} \right)^{-2}. \]  

This is larger or comparable to the maximum energy of the cosmic rays so far observed. Such a high energy cosmic ray can propagate only up to the distance of \( \sim 100 \text{Mpc} \) due to the production of pion through the collision with the microwave background radiation. Then the number density of UHECRs (Ultra High Energy Cosmic Rays \( E > 10^{20} \text{eV} \)) is estimated as \( n_{\text{cr}} \sim 10^{-30} \text{cm}^{-3} \). [32] If UHECRs are supplied by NHE-GRBs, the total energy of UHECR per one NHE-GRB-event is estimated as \( \sim 10^{50} \text{erg} \). This energy is only 0.05% of the total energy of the milli-second pulsar and 2% of the energy emitted by the pulsar after the hole is punched out in our model. Very recently Agasa [33] team reported possible clustering in position of UHECRs, which may be in favor of GRB model of UHECRs [34]. Since the time broadening of the pulse of UHECRs due to the intergalactic magnetic field is more than 100 y [32], the arrival time of UHECR does not coincide with the GRB event. However in our model there should exist the supernova remnant in the direction of each UHECR if the time broadening is shorter than the maximum age of the observable supernova remnant.

The relation between soft gamma ray repeaters (SGRs) and NHE-GRBs in our model is quite interesting. NHE-GRBs in our model is a strongly magnetized pulsar in the supernova remnant with the event rate of \( 10^{-4} \sim 10^{-5} \text{events/yr/galaxy} \). This is exactly the same as the characteristics of soft gamma ray repeaters. This suggests that progenitors of SGRs are NHE-GRBs in our model.

**Acknowledgments**

The author would like to thank Prof. F. Takahara for useful discussions. This work was supported in part by Grant-in-Aid of Scientific Research of the Ministry of Education, Culture, Science and Sports, 09640351.
References

[1] T. J. Galama et al., astro-ph/9806175

[2] P. Soffita et al. IAU Circ. No. 6884(1998)

[3] G. N. Pendelton et al., Astropys. J. 489(1997), 175.

[4] L. Wang and J. C. Wheeler, astro-ph/9806212

[5] D. Bhattacharya and E. P. J. van den Heuvel, Phys. Rep. 203(1991), 1. and reference therein

[6] H. Yamaoka, T. Shigeyama and K. Nomoto, Astron. Astrophys. 267(1993), 433.

[7] H. Hanami, T. Nakamura and T. Murakami, Prog. Theor. Phys. 94(1995), 1001.

[8] R. A. Chevalier, Astropys. J. 411(1993), L33.

[9] H. A. Bethe and C. E. Brown, astro-ph/9802084

[10] K. Nomoto and M. Hashimoto, Phys. Rep. 136(1988), 13.

[11] K. Nomoto et al., Nature 371(1994), 227.

[12] L. Bildsten and C. Cutler, Astropys. J. 400(1992), 175.

[13] R. C. Duncan and C. Thompson, Astropys. J. 392(1992), L9.

[14] C. Thompson and R. C. Duncan, Astropys. J. 408(1993), 194.

[15] C. Kouveliotou et al., Nature 393(1998), 235.

[16] C. Thompson and R. C. Duncan, Mon. Not. R. Astro. Soc. 275(1995), 255.

[17] C. Thompson and R. C. Duncan, Astropys. J. 473(1996), 322.

[18] J. Shwinger, Phys. Rev. 82(1951), 664. See page 677 of this paper.

[19] S. E. Woosley, R. G. Eastman and B. P. Schmidt, astro-ph/9806299

[20] M. Karovska et al. IAU Circ. No. 4382(1987)

[21] S. J. Matcher et al. IAU Circ. No. 4369(1987)

[22] M. Rees, Nature 328(1987), 207.

[23] T. Piran and T. Nakamura, Nature 330(1987), 28.
[24] T. Nakamura and H. Sato, *Prog. Theor. Phys.* 66(1981), 2038.

[25] J. M. LeBlanc and J. R. Wilson, *Astropys. J.* 161(1970), 541.

[26] E. Patat *et al.* *IAU Circ.* No. 6917(1998)

[27] P. Goldreich and W. H. Julian, *Astropys. J.* 157(1969), 869.

[28] V. V. Usov, *Nature* 357(1992), 472.

[29] V. V. Usov, *Mon. Not. R. Astro. Soc.* 267(1994), 1035.

[30] S. Kulkarni *et al.*, *Nature* 393(1998), 35.

[31] F. Cappellaro *et al.*, astro-ph/9611191

[32] E. Waxman, *Astropys. J.* 452(1995), L1.

[33] Hayashida *et al.*, *Phys. Rev. Letters* 77(1996), 1000.

[34] E. Waxman, astro-ph/9612061