Hyperforna model for ultra-high energy cosmic rays

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Abstract: There is growing evidence that some hypernovae produce semi-relativistic ejecta that carries a substantial amount of the energy. We show that the semi-relativistic shock front driven by such ejecta can accelerate particles to ultra-high energies. The event rate of hypernovae in the universe is sufficient to provide the observed flux of extragalactic UHECRs. We also discuss the composition of UHECRs in the hypernova model.

Keywords: cosmic rays; supernova

1 Introduction

There is a general consensus that galactic supernova remnants (SNRs) are responsible for the CRs at energies below the “knee” at $\sim 3 \times 10^{15}$ eV [1], most probably through the diffusive shock acceleration mechanism [2]. Galactic SNRs expanding into their former stellar wind have been suggested to be responsible for CRs above the knee [3]. The data from the KASCADE experiment suggest that heavy elements of nuclear charge $Z_e$ are accelerated by the galactic SNRs to the magnetic rigidity limit $\sim 3 \times 10^{15} Z_e$ eV [4]. Thus galactic SNRs may be able to produce CRs to at least $\sim 10^{17}$ eV, an energy slightly below the “second knee” in the CR spectrum at $\sim 6 \times 10^{17}$ eV (see e.g. [5]).

The transition energy from galactic to extragalactic origin in high-energy cosmic ray spectrum remains inconclusive. The GRB model assume that extragalactic component starts from $10^{19}$ eV, while some AGN models favor an extra-galactic origin of all CRs above $10^{16}$ eV [6]. In the paper [7] we have shown that the energetics and spectrum of CRs above the second knee may be due to extragalactic hypernovae, similar to the hyper-energetic supernova SN1998bw. There is growing evidence that some hypernovae produce semi-relativistic ejecta that carries a substantial amount of the energy. UHECRs can be accelerated at the forward shock formed when the semi-relativistic ejecta is expanding in the stellar wind. The situation is very similar to the acceleration of Galactic cosmic ray by supernova remnants expanding into their former stellar wind, but with a much higher, mildly-relativistic relativistic velocity ejecta.

2 What are hypernovae

SN1998bw, the first hypernova detected, was striking not only in its unusually large explosion energy, $E \sim 3 - 5 \times 10^{52}$ erg (so called “hypernovae” [8]), but also in that it was associated with a very sub-energetic GRB, GRB980425, with an isotropic equivalent gamma-ray energy $E_{\gamma} \sim 10^{48}$ erg [9]. The observations of the radio afterglow of this event showed that about $10^{50}$ erg of kinetic energy were released in the form of a mildly relativistic ejecta [11]. Due to the large supernova explosion energy and the much lower than typical GRB energy, attempts have been made to ascribe the GRB event to the shock from the mildly relativistic ejecta as it breaks out through the hypernova progenitor’s outer envelope [12, 13]. A recently detected strong thermal X-ray emission component in another sub-energetic burst (GRB060218), associated with SN2006aj, may also be associated with a semi-relativistic supernova shock breakout, in which the mildly relativistic supernova ejecta has an energy $> 10^{49}$ erg [15]. The radio observations of this burst, as well as those of another hypernova burst, GRB031203/SN2003lw, also indicate that there is a significant energy in the mildly relativistic ejecta [16]. We will use the term semi-relativistic hypernovae to denote such supernovae exhibiting a mildly relativistic ejecta component, seen in association with GRBs. Radio observations of the the recently discovered SN2006bb, for which no associated GRB is found, also suggest that more than $10^{50}$ erg is coupled into the mildly-relativistic jet[17]. The recent proposed engine-driven supernova are identical to the hypernovae in nature, since both have much more energy in semi-relativistic ejecta than normal supernova although there is no GRB or x-ray flash detected associated
Figure 1: The expected spectrum of CRs as a function of energy $\varepsilon$ produced by hypernova remnants with a distribution of the ejecta kinetic energy with velocity $E_k \propto (\Gamma \beta)^{-\alpha}$. Dashed lines indicate the flat, injection spectrum ($\varepsilon^2 dn/d\varepsilon \propto \varepsilon^0$) from single velocity ejecta for three different velocities. The convoluted contribution from different velocity ejecta, denoted by the solid line, leads to a spectrum $\varepsilon^2 dn/d\varepsilon \propto \varepsilon^{-\alpha/2}$. The inset shows the kinetic energy distribution of three nearby hypernovae associated with sub-energetic GRBs. The data points are from Ref.[18]. The solid and blank circles denote the energy of the slowest ejecta and the mildly relativistic ejecta, respectively. A kinetic energy distribution $E_k \propto (\Gamma \beta)^{1-\alpha}$ gives a rough fit to the data of SN1998bw/GRB9802425 and SN2006aj/GRB031203 with $\alpha \sim 2.4$, while for SN2006aj/GRB060218, the slope is $\alpha \sim -1.7$.

With SN2009bb. The estimated event rate of SN2009bb-like supernovae is also comparable to the hypnov rate. In Figure 1 (inset) we show the kinetic energy distribution of the supernova ejecta associated with these three nearby sub-energetic GRBs, ranging from the bulk of the ejecta at $\Gamma \beta \simeq 0.1$ to the mildly relativistic ejecta ($\Gamma \beta \simeq 1$), where $\beta = v/c$ and $\Gamma$ are the ejecta normalized velocity and bulk Lorentz factor, respectively. Surprisingly, even though the energy estimates of the high velocity ejecta from the radio observations are crude, all three hypernovae give a roughly consistent extrapolation of the slope of the kinetic energy distribution from the low to the high velocity end. Notice that if the explosion is aspherical, the kinetic energy released in SN1998bw may be lower, $\sim 2 \times 10^{52}$ erg, which will lead to a slightly shallower slope. It has been shown in [18] that the relatively shallow decay of the radio afterglow of GRB060218/SN2006aj can be modelled with a shock expansion $r \propto t^{0.35}$, appropriate for a core-collapse supernova explosion with a continuous distribution of ejecta velocities [19], propogating into a stellar wind environment of density $\rho \propto r^{-2}$. This provides a plausible scenario for a continuous distribution of the ejecta kinetic energy over velocities, ranging from the low velocity (0.1$c$) supernova bulk ejecta to the mildly relativistic ejecta within the same explosion, of the form

$$E_k \propto (\Gamma \beta)^{-\alpha}. \quad (1)$$

Standard hydrodynamic collapse calculations involving non-relativistic shocks result in a kinetic energy profile $E_k \propto (\Gamma \beta)^{-5}$ [13], with a negligible fraction of the kinetic energy at mildly relativistic velocities, consistent with the radio observations of, e.g., local type Ib/c supernovae 1994I and 2002ap. This very steep velocity profile implies negligible contribution to the highest energy CRs by high velocity ejecta [14]. On the other hand, ultra-relativistic shocks result in a much flatter profile, $E_k \propto (\Gamma \beta)^{-\alpha}$ with $\alpha \approx 1$ [13]. For shocks in the trans-relativistic velocity regime, the energy distribution has not been calculated, but the above assumed slope of $\alpha \sim 2$ seems to be intermediate between the two extreme regimes. Different hypernova could have different slope $\alpha$. An important implication of such a continuous energy distribution in the semi-relativistic regime is that there is a significant amount of energy in the high-velocity ejecta of a hypernova. At this higher velocity, the hypernova blast wave could accelerate CRs to energies as high as $10^{19}$ eV, as we show below.

### 3 Acceleration of cosmic rays by hypernovae

According to the simulation of hypernova explosion such as SN1998bw, the isotropic-equivalent kinetic energy of ejecta is roughly constant at angles larger than $20^\circ$, so we assume a spherical hypernova ejecta expanding into the circumbular wind medium. Particles are accelerated in the region where the ejecta is freely expanding before being decelerated by the swept-up circumbular medium. The size of this free-expansion phase region for ejecta of a particular velocity $\beta_{sh}c$ and kinetic energy $E_k$ is

$$R_{\text{HN}} \simeq 4 \times 10^{17} E_{k,51} (\Gamma \beta_{sh})^{-2} M_{\odot,5}^{-1/2} R_{w,3}^{-1/2} \text{ cm}, \quad (2)$$

where $\dot{M} = 10^{-5} M_{\odot} \text{ yr}^{-1}$ is the wind mass loss rate, whose average value is $3 \times 10^{-7} M_{\odot} \text{ yr}^{-1}$ for WR stars, and $v_{w,3} = 10^3 v_{w,3}$ km/s is the wind velocity. During the free expansion phase, the magnetic field energy density is $B^2/8\pi = 2e_B\rho_{\text{w}}(R_{\text{HB}}) c^2 \beta_{sh}^2$, where $e_B = 0.1 e_{B,-1}$ is the fraction of the equipartition value of the magnetic field energy and $\rho_{\text{w}}$ is the mass density of the stellar wind at radius $R_{\text{HN}}$. The magnetic field at the free-expansion radius $R_{\text{HN}}$ is

$$B = 0.5 e_{B,-1} R_{\text{HN},17} \beta_{sh} \dot{M}_{-5}^{1/2} v_{w,3}^{-1/2} \text{ G}. \quad (3)$$

From $t_{\text{acc}} = t_{\text{dyn}}$, the maximum energy is

$$E_{\Delta,\text{max}} \simeq Z e BR_{\text{HE}} \beta_{sh}/\eta \ \text{eV}, \quad (4)$$

Note that the synchrotron loss of UHE nuclei in the semi-relativistic hypernova scenario is much lower than the adiabatic loss, so it is not considered here.

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4 The energy generate rate by hypernovae

We estimate how many SN1998bw-like hypernovae per unit volume per unit time are needed to produce the CR flux from $\sim 10^{18}$ to $10^{19}$ eV. Assuming that the kinetic energy output from one SN1998bw-like hypernova is $E_{k,HN} = 5 \times 10^{52}$ erg, the local kinetic energy release rate by hypernovae is

$$\dot{E}_k(z=0) = R_{\text{HN}} E_{k,HN} = 2.5 \times 10^{46} \left( \frac{R_{\text{HN}}}{500 \text{Gpc}^{-3} \text{yr}^{-1}} \right) \text{erg Mpc}^{-3} \text{yr}^{-1}$$

(5)

Adopting an efficiency factor $1/6$ for the conversion of ejecta kinetic energy into CR energy [25], and 1/ln($\varepsilon_{\text{max}}/\varepsilon_{\text{min}}$) $\approx 0.1$ as the fraction of the total CR energy that is contributed by each decade of energy, the local CR energy generation rate per energy decade at $10^{17.5}$ Z eV, corresponding to $v = 0.1c$, is $\varepsilon_{CR,0} = 0.016 \dot{E}_k(z=0)$. The corresponding expected CR flux is

$$\varepsilon^2 J = \left( \frac{\epsilon}{4\pi H_0} \right) \varepsilon_{CR,0} f_z \int dz$$

(6)

where $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$ is the Hubble constant and

$$f_z = H_0 \int_0^{z_{\text{max}}} dz (dt/dz) S(z)(1+z)^{-1}$$

(7)

is the correction factor for the contribution from high-redshift sources. Here $(dt/dz) = H^{-1}(z)/(1+z)$, with $H(z)$ being the Hubble parameter at cosmological epoch $z$, and $z_{\text{max}}$ is the maximum redshift corresponding to the mean free path against photopion production in the CMB, whose value is $z_{\text{max}} > 4$ for protons with energies $< 10^{18}$ eV. The value of $f_z$ is $\sim 2 - 3$ for $z_{\text{max}} = 4$ and for the source evolution function $S(z)$ given by different star formation rates (SFR) in Ref. [23] or the broken power-law estimate in Ref. [24] for a standard ΛCDM cosmology. Here we assume $f_z \approx 3$. At $\varepsilon = 10^{17.5}$ Z eV, we get a CR flux of

$$J = 10^{-28} Z^{-2} \left( \frac{R_{\text{HN}}}{500 \text{Gpc}^{-3} \text{yr}^{-1}} \right) \left( \frac{f_z}{3} \right) \text{eV}^{-1} \text{sr}^{-1} \text{m}^{-2} \text{s}^{-1}$$

(8)

Comparing this to the observed CR flux of $1.5 \times 10^{-28} (\varepsilon/10^{17.5}) \text{ eV}^{-3.2}$, we infer a required hypernova rate of

$$R_{\text{HN}} = 750 Z^{-1.2} (f_z/3)^{-1} \text{Gpc}^{-3} \text{yr}^{-1}$$

(9)

Assuming $Z=1$ (or 2) and $f_z = 3$, one can derive a required hypernova rate of $330 - 750 \text{ Gpc}^{-3} \text{yr}^{-1}$. Comparing this with the local rate of “normal” type Ib/c SNe, $\sim 2 - 5 \times 10^4 \text{ Gpc}^{-3} \text{yr}^{-1}$ [21, 22], one can find that the ratio of the required hypernova rate to the normal Ib/c SNe rate is $\sim 1 - 4\%$, which is consistent with the value observed in the local universe $\sim 7\%$ [21]. The required semi-relativistic hypernova rate is also consistent with the observed rate of low-luminosity GRBs [18]. Since different SFR give different values of $f_z$, one can in principle use the required hypernova rate to constrain $f_z$ and therefore constrain the SFR.

5 The energy spectrum and composition of UHECRs produced by hypernovae

The composition of the observed ultra high energy cosmic rays remains disputed. Recent observations of the Pierre Auger Observatory (PAO) show a transition in the maximum shower elongations $< X_{\text{max}} >$ and in their fluctuations RMS$(X_{\text{max}})$ between $5EeV$ and $10EeV$ (26). These transitions are interpreted as reflecting a transition in the composition of UHECRs in this energy range from protons to intermediate mass or heavy nuclei. In the hypernova remnant scenario, cosmic ray particles originate from the material swept-up by the semi-relativistic hypernova shock front, or from material ejected at the time of hypernova explosion. The progenitors of hypernovae are thought to be Wolf-Rayet stars, as the spectral type of the discovered supernovae in these events is typically Ic. These stars are stripped of their hydrogen envelope and sometimes even the helium envelope, so the circum-stellar wind is rich of heavy elements, such as C and O, and this also guarantees of the heavy elements-rich ejecta. Thus, heavy or intermediate-mass UHE nuclei may naturally originate from the element-enriched stellar wind of Wolf-Rayet stars in the hypernova scenario.

In Fig. 2, we fit the cosmic ray spectrum with the hypernova model, assuming a source composition of type Ib/c Wolf-Rayet stars. The resulting composition at the earth is consistent with the heavy composition as implied by PAO observations.

![Figure 2: The predicted spectrum (including primary nuclei, secondary nuclei as well as secondary protons) of UHECRs from hypernovae, compared with the PAO data. $E_{Fe,max} = 10^{21}$eV, $E_{Fe,min} = 10^{19}$eV. We consider a mixture of different elements in the mass ratio of He:C:O:Fe=0.022:0.13:0.5:0.34, (see $Z = 0.008$, $M_{init} = 40M_\odot$ case in Table. 2 of [27], we assume all the heavy elements except CNO are Fe). The black solid line represents the total flux, while dots with different colors represent different component, as shown in the legend.](image-url)
References