MODEL-DEPENDENT ESTIMATE ON THE CONNECTION BETWEEN FAST RADIO BURSTS AND ULTRA HIGH ENERGY COSMIC RAYS

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ABSTRACT

The existence of fast radio bursts (FRBs), a new type of extragalactic transient, has recently been established, and quite a few models have been proposed. In this work, we discuss the possible connection between the FRB sources and ultra high energy (>10^{18} eV) cosmic rays. We show that in the blitzar model and the model of merging binary neutron stars, which includes the huge energy release of each FRB central engine together with the rather high rate of FRBs, the accelerated EeV cosmic rays may contribute significantly to the observed ones. In other FRB models, including, for example, the merger of double white dwarfs and the energetic magnetar radio flares, no significant EeV cosmic ray is expected. We also suggest that the mergers of double neutron stars, even if they are irrelevant to FRBs, may play a nonignorable role in producing EeV cosmic ray protons if supramassive neutron stars are formed in a sufficient fraction of mergers and the merger rate is >10^{3} yr^{-1} Gpc^{-3}. Such a possibility will be unambiguously tested in the era of gravitational wave astronomy.

Key words: acceleration of particles – cosmic rays – radio continuum: general

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1. INTRODUCTION

In a recent survey for pulsars and fast transients, Thornton et al. (2013) confirmed Lorimer et al. (2007) and Keane et al.’s (2012) discovery by uncovering four millisecond-duration radio bursts (hereafter fast radio bursts (FRBs)) that are all more than 40° from the Galactic plane. Current data favor a celestial rather than terrestrial origin, and the host galaxy and intergalactic medium models suggest that they have cosmological redshifts (z) of 0.5–1 and distances of up to ~3 Gpc. The millisecond duration suggests that the central engine is likely either a neutron star (NS) or a stellar-mass black hole. Currently, quite a few models have been proposed to interpret FRBs, including the mergers of binary NSs (Hansen & Lyutikov 2001; Totani et al. 2013; Lipunov & Pruzhinskaya 2014), energetic magnetar radio flares (Popov et al. 2007), delayed collapses of supramassive neutron stars (SMNSs) to black holes (i.e., the so-called blitzar model, Falcke & Rezzolla 2014), a highly relevant hypothesis is the possible connection between gamma-ray bursts (GRBs) and FRBs Bannister et al. 2012; Zhang 2014; Ravi & Lasky 2014), mergers of binary white dwarfs (Kashiyama et al. 2013), and flaring stars if FRBs are instead in the Galaxy (Loeb et al. 2014). A discussion of the advantages and disadvantages of these models can be found in Kulkarni et al. (2014) and is beyond the scope of this work. The rate of FRBs is high up to ~10^4 sky^{-1} day^{-1} (Thornton et al. 2013). If a huge amount of energy was released into the circuminterstellar medium by the central engine of FRBs, ultra high energy cosmic rays may be accelerated. The main purpose of this work is to estimate the possible contribution of FRB central engines in producing ultra high (>10^{18} eV) energy cosmic rays.

2. POSSIBLE HIGH-ENERGY COSMIC RAY ACCELERATION: THE MODEL-DEPENDENT ESTIMATE

In this section, we focus on the cosmological models and, in particular, the blitzar model, the merging double NS model, and the model of mergers of binary white dwarfs. This is because the total energy released in the models of magnetar giant radio flares (Popov et al. 2007) and Galactic flaring stars (Loeb et al. 2014) is too small to be sufficient to accelerate and then account for a nonignorable fraction of ultra high energy cosmic rays.

2.1. The Blitzar Model

In the blitzar model, the FRBs were triggered by the collapse of the SMNSs to black holes. As a result of the collapse of an SMNS, the magnetic-field lines will snap violently. Accelerated electrons from the traveling magnetic shock cause a significant fraction of the magnetosphere to dissipate and produce a massive radio burst that is observable out to cosmological distances (Falcke & Rezzolla 2014). The difference between an SMNS and a normal NS is that the former has to rotate very quickly in order to prevent itself from collapsing since the gravitational mass of an SMNS is larger than that allowed for a nonrotating NS (Friedman et al. 1986). The rapid uniform rotation can enhance the maximum gravitational mass by a factor of ~0.05 (P_{0}/1 ms)^{-2} and can thus help make the SMNS stable (Friedman et al. 1986). In addition to the core-collapse supernovae (ccSNe) proposed in Falcke & Rezzolla (2014), the merger of some binary NSs can also produce an SMNS or even a normal NS if the equation of state of the NS material is stiff enough (e.g., Davis et al. 1994; Dai & Lu 1998a; Dai et al. 2006; Shibata et al. 2000; Baumgarte et al. 2000; Gao & Fan 2006; Metzger et al. 2008; Zhang 2013). Usually the nascent NSs formed in both ccSNe and the merger of double NSs are differentially rotating and the differential rotation is suggested to be more efficient at keeping the supernova (SN) stable. However, the differential rotation is expected to be terminated very quickly by the magnetorotational instability as well as magnetic braking (Cook et al. 1992, 1994; Hotokezaka et al. 2013). That is why we only consider the effect of uniform rotation in stabilizing the SMNS. Here we concentrate on the ccSN-formed SMNS.
and will discuss the merger-formed SMNS in some detail in Section 2.2.

Before discussing the high-energy cosmic ray acceleration, we examine whether or not the blitzer model can account for the observed dispersion measures. The SN outflow likely has a total mass of \( M_{\text{sh}} \sim n_{\text{few}} M_{\odot} \), and the observed dispersion measures DM \( \sim 10^{23} \text{ cm}^{-2} \) (Thronton et al. 2013; Lorimer et al. 2007) require that the SN outflow should reach a radius of \( R_{\text{sh}} > (M_{\text{sh}}/4\pi n_{\text{few}}(1+z)\text{DM})^{1/2} \sim 10^{18} \text{ cm} (M_{\odot}/10 M_{\odot})^{1/2} (1+z)^{-1/2} \), where the term \((1+z)^{-1}\) is introduced to address the effects of both the cosmological time dilation and the frequency shift on the measured DM. Clearly, at such a huge radius, the SN shell is also transparent (\( 1+z \)) is introduced to address the effects of both the cosmological time dilation and the frequency shift on the measured DM.

In view of the sensitive dependence of stabilization on \( P_{\text{rot}} \), the SMNS is unlikely to exist for \( P_{\text{rot}} > 2 \text{ ms} \) unless there is some fine tuning by which the mass of the SMNS is just a little bit above that allowed by the nonrotating NS. The rotational kinetic energy of the SMNS is quite large, i.e., \( E_{\text{rot}} \approx 3 \times 10^{52} \text{ erg} (I/1.5 \times 10^{45} \text{ g cm}^2)/(P_{\text{rot}}/1 \text{ ms})^{-2} \), where \( I \) is the moment of inertia. Before collapsing into a black hole, the SMNS should have lost its rotational energy mainly via magnetic dipole radiation and possibly also gravitational wave radiation (Usom 1992; Duncan \& Thompson 1992; Fan et al. 2013b). The amount of energy injected into the surrounding medium is \( E_{\text{inj}} \sim E_{\text{SN},r}/2 \times 1.5 \times 10^{52} \text{ erg} (I/1.5 \times 10^{45} \text{ g cm}^2)/(P_{\text{rot}}/1 \text{ ms})^{-2} \), if the gravitational wave radiation is not dominant. The frequency of the electromagnetic wave is \( \sim 10^4 \text{ Hz} \), which is much lower than the surrounding plasma’s frequency \( \omega_{\text{p}} \approx 5.6 \times 10^8 \text{ Hz} n_{e}^{-1/2} \), where \( n_{e} \) is the number density of the free electrons in the plasma (i.e., the SN outflow) and can be estimated as \( 1.5 \times 10^{45} \text{ g cm}^{-3} (R_{\text{sh}}/10^{18} \text{ cm})^{-3} (P_{\text{rot}}/1 \text{ ms})^{3/2} (M_{\odot}/10 M_{\odot})^{-1/2} \), where \( B_{\text{NS}} = \alpha B_{\odot} \) is the surface magnetic field strength at the pole, \( R_{\text{NS}} \) is the radius of the NS, and \( \alpha \) is the angle between the rotational and dipole axes. Hence the SMNS should not be significantly magnetized, otherwise the FRB source cannot be accounted for (see also Falcke \& Rezzolla 2014). We denote such a request as Request-I. Another highly related request is that the gravitational wave radiation should be weak enough that it does not dominate over the dipole radiation of the pulsar (i.e., Request-II). In terms of the ellipticity \( (\varepsilon) \) of the pulsar, we need \( \varepsilon < 5 \times 10^{-6} (I/1.5 \times 10^{45} \text{ g cm}^2)^{-1/2} (P_{\text{rot}}/1 \text{ ms})^{3/2} (R_{\text{sh}}/10^{18} \text{ cm})^{-2} (\text{Shapiro \& Teukolsky 1983}) \). Alternatively, for a rapidly rotating pulsar, some instabilities, for example the Chandrasekhar–Friedman–Schutz instability (Chandrasekhar 1970; Friedman \& Schutz 1978), may occur when the ratio \( \mathcal{R} = T/|W| \) of the rotational kinetic energy to the gravitational binding energy \( |W| \) is sufficiently large. In the Newtonian limit, the \( \mathcal{R} \approx 2 - f \text{-mode} \), which has the shortest growth time of all polar fluid modes (i.e., \( \tau_{\text{GW}} \approx 5 \times 10^{-6} (R_{\odot}/10^{14} \text{ cm})^{4} (\mathcal{R} - \mathcal{R}_{\text{sec}})^{-5} \), see Lai \& Shapiro 1995), becomes unstable when \( \mathcal{R} > \mathcal{R}_{\text{sec}} \approx 0.15 \). Hence \( \mathcal{R} - \mathcal{R}_{\text{sec}} \lesssim 10^{-3} \) is needed to satisfy \( \tau_{\text{GW}} > t_{\text{life}} \approx 10^{5} \), otherwise the SMNSs collapsed too early to get a sufficiently small DM. Finally, the contribution to the DM by the circumburst medium is less clear. In the estimate of winding field structure at the end of the Wolf–Rayet stage of the massive star, Chevalier et al. (2004) assumed that the surrounding medium has a density typical of the hot, low-density phase of a starburst galaxy (i.e., \( n \gtrsim 0.2 \text{ cm}^{-3} \)). If this is the case, the contribution to the DM by the surrounding medium can be ignored. However, the ccSN may be born in a molecular cloud with a typical number density \( n_{\text{cloud}} \sim 10^{2} \text{ cm}^{-3} \) and a size of \( R_{\text{cloud}} \sim (3M_{\text{cloud}}/4\pi n_{\text{cloud}}P_{\text{rot}}^{2})^{1/3} \sim 10^{16} \text{ pc} (M_{\odot}/10 M_{\odot})^{1/3} (n_{\text{cloud}}/10^{2} \text{ cm}^{-3})^{-1/3} \), which can give rise to an observed DM \( \sim 10^{19} (M_{\odot}/10 M_{\odot})^{1/3} (n_{\text{cloud}}/10^{2} \text{ cm}^{-3})^{2/3} \text{ pc cm}^{-3} \). Therefore, the surrounding molecular cloud should not be very massive/dense (i.e., \( M_{\text{cloud}} < 10^{2} M_{\odot} \) for \( n_{\text{cloud}} < 10^{2} \text{ cm}^{-3} \)) otherwise the central ccSN could not be viable progenitors of the observed FRBs. Such a request is denoted as Request-III. Each of these three requests imposes some challenges on the ccSN scenario in the blitzer model. Nevertheless, the blitzer model can explain some aspects of FRBs (e.g., Falcke \& Rezzolla 2014) and is still widely adopted in the literature. Below we discuss the possible high-energy cosmic-ray acceleration in such a scenario.

4 The above estimate is for the assumption that at a radius of \( R_{\text{sh}} > 10^{18} \text{ cm} \) the SMNS wind is still Poynting-flux dominated. If instead the SN outflow at such a large distance is electron/positron pair dominated and the Poynting flux is a tiny amount (for example \( < 0.1 \text{ of the total} \) (e.g., Kennel \& Coroniti 1984), most of the wind energy will be converted into radiation and the acceleration of the high-energy cosmic rays by the supernova outflow is less significant.

5 As already mentioned in the above paragraph, to be a valid source of the observed FRBs, the SMNS formed in the normal ccSNe should have a typical dipole magnetic field strength \( B_{\text{dip}} \lesssim 10^{12} \text{ gauss} \) while the SMNS candidates found in both long and short GRBs usually have \( B_{\text{dip}} > 10^{14} \text{ gauss} \). The energy available for generating FRBs of the GRB SMNSs is about four orders of magnitude larger than that of normal ccSN. Some differences between the FRBs from these two different groups of central engines may be expected. On the other hand, the dipole radiation timescales of such FRB pulsars are so long that at early times the associated supernovae are still “normal” with a typical energy of \( \ll E_{\text{inj}} \gtrsim 10^{52} \text{ erg} \), and do not belong to the so-called hypernovae.
Now we discuss the cosmic-ray particle generation by the SMNS wind-accelerated outflow of the ccSNe. The progenitor star of a ccSN would experience a significant mass-loss stage and then the surrounding medium would usually not be a simple free-wind structure or a constant density structure. For simplicity, here we adopt the structure shown in Figure 1 of Chevalier et al. (2004) to estimate the maximum energy of the protons accelerated at the shock front of the SMNS wind-driven outflow. In such a scenario, significant particle acceleration takes place at \( R \approx 5 \times 10^{18} \) cm, where the supergiant shell with a number density \( n \approx 10^{-2} - 10^{3} \) cm\(^{-3}\) is located. Following Bell & Lucek (2001), the maximum energy of the protons accelerated by the forward shock can be estimated as

\[
\epsilon_{p,M}^{\text{ccSN}} \approx 10^{18} \text{eV} \left( \frac{V}{10^{12} \text{cm} \text{s}^{-1}} \right)^{2} \left( \frac{n}{10^{2} \text{cm}^{-3}} \right)^{1/2} \left( \frac{\epsilon_{B}}{10^{-2}} \right)^{1/2},
\]

where \( \epsilon_{B} \) is the fraction of shock energy given to the magnetic field and the velocity of the shell has been estimated to be \( V_{\text{sh}} \approx (E_{\text{inj}}/M_{\text{tot}})^{1/2} - 10^{15} \) cm s\(^{-1}\) (\( M_{\text{tot}}/10^{2} M_{\odot} \))\(^{-1/2}\) (\( E_{\text{inj}}/10^{52} \) erg)\(^{1/2}\). The charged particles reach energies larger by a factor of \( Z \), the charge number. The magnetic field generated by the shock is \( B \approx 10^{-3} \) gauss (\( \epsilon_{B}/10^{-2} \))\(^{1/2}\) (\( n/10^{2} \) cm\(^{-3}\))\(^{1/2}\) (\( V_{\text{sh}}/10^{15} \) cm s\(^{-1}\)), which is too low to effectively cool the accelerating EeV cosmic rays.

The rate of FRBs is \( R_{\text{FRB}} \approx 10^{-3} \) yr\(^{-1}\) per galaxy (Thornton et al. 2013), which is about one order of magnitude lower than the ccSN rate \( R_{\text{ccSN}} \approx 10^{-2} \) yr\(^{-1}\) per galaxy. If FRBs are indeed the cry of the dying SMNSs, the energy released into the surrounding medium of each SMNS is \( E_{\text{inj}} \approx 10^{52} \) erg, implying that the total energy input by FRB sources is comparable to the total cosmic-ray energy at each energy decade. Then the corresponding cosmic-ray acceleration efficiency \( \epsilon_{\mathrm{CR}} \) can be estimated as

\[
\epsilon_{\mathrm{CR}} \gtrsim 10^{17} \eta \left( \frac{E_{\text{inj}}}{10^{52} \text{erg}} \right) \left( \frac{R_{\text{FRB}}}{10^{4} \text{yr}^{-1} \text{Gpc}^{-3}} \right) \text{erg yr}^{-1} \text{Mpc}^{-3}.
\]

2.2. The Model of Merging Double Neutron Stars

In the model of merging double NSs for FRBs, the radiation mechanism may be coherent radio emission, like radio pulsars, by magnetic braking when magnetic fields of NSs are synchronized to binary rotation at the time of coalescence (Totani et al. 2013). In addition to FRBs, the mergers of binary NSs may give rise to short GRBs or other kinds of violent explosions with possible central engines of magnetized millisecond NSs (e.g., Duncan & Thompson 1992; Davis et al. 1994; Dai & Lu 1998a; Baumgarte et al. 2000; Shibata et al. 2000; Duez et al. 2006; Price & Rosswog 2006; Rosswog 2007; Giacomazzo & Perna 2013). The latest numerical simulations suggest that the SMNS can be formed in the merger of an NS binary with \( M_{\text{tot}} \approx 2.6 M_{\odot} \) (note that among the ten NS binaries identified thus far, five systems have such a total gravitational mass Lattimer (2012) for reasonably stiff equations of state that are favored by current rest-mass measurements of pulsars (see Hotokezaka et al. 2013 and Fan et al. 2013a and the references therein). There are growing, though inconclusive, observational evidences for forming an NS–NS merger is usually not expected to be more than \(-\approx 0.01 M_{\odot} \) and could be accelerated to a mildly relativistic velocity by the wind of SMNS and then produce X-ray/optical/ radio afterglow emission (see Gao et al. (2013a) for a detailed numerical calculation of the lightcurves), which can account for the cosmological relativistic fading source PTF11agg, a remarkable event not associated with a high-energy counterpart (Wang & Dai 2013; Wu et al. 2014). It thus seems reasonable to assume that SMNSs, which likely collapsed at \( t_{c} \approx 10^{12} - 10^{14} \) s (Rowlinson et al. 2013), were formed in a good fraction of NS–NS mergers.

The prospect of forming SMNS in the mergers can also be roughly estimated as the following. On the one hand, the gravitational mass \( (M) \) of the isolated NS is related to the baryonic mass \( (M_{b}) \) as \( M_{b} \approx M + \alpha M^{2} \), where \( \alpha \approx 0.08 M_{\odot} \) (Lattimer & Yahil 1989; Timmes et al. 1996). On the other hand, in the numerical simulations of mergers of binary NSs performed in full general relativity incorporating the finite-temperature effect and neutrino cooling, Sekiguchi et al. (2011) found that the effect of the thermal energy is significant and can increase the maximal gravitational mass \( M_{\text{max}} \) by a factor of 20%–30% for a high-temperature state with \( T \geq 20 \text{MeV} \). Since they are not supported by differential rotation, the supermassive remnants that were predicted to be stable until neutrino cooling, with a luminosity of \( \gtrsim 10^{43} \) erg s\(^{-1}\) removed the pressure support in a few seconds (Sekiguchi et al. 2011). After neutrino cooling, the supermassive remnant is still stable if

\[
\alpha M_{r,\text{max}}^{2} + M_{r,\text{max}} - (M_{1} + M_{2}) - \alpha (M_{1}^{2} + M_{2}^{2}) + m_{\text{loss}} > 0,
\]

where \( m_{\text{loss}} \) is the baryonic mass loss of the system during the merger, \( M_{r,\text{max}} \approx [1 + 0.05 (P_{0}/1 \text{ ms})^{-1/3}] M_{\text{max}} \), and \( M_{1} \) and \( M_{2} \) are the gravitational masses of the binary NSs, respectively, \( M_{r,\text{max}} \sim 10^{-3} \) to \( 10^{-2} M_{\odot} \) has been inferred in the numerical sim-
ual distribution, as a function of the gravitational masses of NSs as a diagnostic mass of 2 \(\times 10^{-2} M_\odot\) is needed (Tanvir et al. 2013; Berger et al. 2013; Fan et al. 2013b). As a conservative estimate, we take \(m_{\text{loss}} = 0.01 M_\odot\). In order to estimate the mass distribution of the NSs in the NS–NS binary systems, Özel et al. (2012) divided the sample into one of pulsars and one of the companions (For the double pulsar system J0737-3039A, they assigned the faster pulsar to the "pulsar" and the slower to the "companion" categories). Repeating the above inference for these two subgroups individually, Özel et al. (2012) found that the most likely parameters of the mass distribution for the pulsars are \(M_0 = 1.35 M_\odot\) and \(\sigma = 0.05 M_\odot\), whereas for the companions they are \(M_0 = 1.32 M_\odot\) and \(\sigma = 0.05 M_\odot\). Hence in our simulation, the distributions of gravitational masses of NSs as \(dN_{\text{NS}}/dM \propto \exp(-(M-M_0)^2/\sigma^2)\) with these parameters are adopted. The possibility distribution of the gravitational masses of supermassive remnants (i.e., \(M \ge (1 + \sqrt{1 + 4\alpha})M_1 + M_2 + \alpha(M_1^2 + M_2^2) - m_{\text{loss}}/1/2\)) formed in the simulated double NS mergers is presented in Figure 1. We find for \(M_{\text{max}} \ge 2.36 M_\odot\), about half of the mergers will produce SMNSs with \(P_0 = 1\) ms. Observationally, the pulsar PSR J0348+0432 has an accurately measured gravitational mass of 2.01 ± 0.04 \(M_\odot\) (Antoniadis et al. 2013) and J1748-2021B has a gravitational mass of \(2.74 \pm 0.21 M_\odot\) (Lattimer 2012). Hence \(M_{\text{max}} \ge 2.36 M_\odot\) is still possible, with which a sizeable fraction of NS–NS mergers may produce SMNSs.

We have briefly mentioned in Section 2.1 that in the blazar model a small fraction of FRBs may be relevant to the mergers of double NSs that produce SMNS remnants. In such a scenario, some FRBs are expected to be detected in the afterglow emission phase of short GRBs. In the model of merging double NSs, FRBs are generated at the time of coalescence of double NSs and are expected to precede short GRBs or other kinds of violent explosions (i.e., no FRB is expected to occur in the afterglow phase of short GRBs) and the three requests outlined in Section 2.1 do not apply. The follow-up observations of FRBs and short GRBs would be crucial to distinguish between the blazar model and the merging NS model. The origin of merging double NSs for FRBs, if confirmed in the future, has interesting implications on the sources of EeV cosmic-ray protons. This is because there is some tentative evidence for the formation of SMNSs in a sizeable fraction of NS–NS mergers and such a kind of long-lived central engine can accelerate the materials ejected during the merger to very high velocities (Fan & Xu 2006; Gao et al. 2013a; Wu et al. 2014). The physical reason for converting the SMNS wind energy into the kinetic energy of the forward shock is the same as that in the case of ccSNe. Within a radius of \(\mathcal{R}_{\text{sh}} \lesssim c t_{\gamma} \sim 3 \times 10^{14} \text{cm} (\gamma t/10^5 \text{s})\), the SMNS wind is likely Poynting-flux dominated rather than electron/positron pair dominated (Vlahakis 2004). The frequency of the electromagnetic wave of the SMNSs (\(\sim 10^{13} \text{Hz}\)) is much smaller than the surrounding plasma’s frequency \(\omega_p \sim 5.6 \times 10^6 \text{Hz} n_e^{1/2}\), where \(n_e \sim 3 \times 10^{13} \text{cm}^{-3} (M_\odot/0.01 M_\odot)(\mathcal{R}_{\text{sh}}/0.1)^{-1} (\mathcal{R}_{\text{sh}}/3 \times 10^{14} \text{cm})^{-3}\) is the number density of the free electrons in the merger outflow with a rest mass of \(M_0 \sim 0.01 M_\odot\). As a result, the electromagnetic wave is "trapped" by the plasma. The high magnetic pressure works on and hence accelerates the surrounding plasma (see Yu et al. 2013 and the references therein). The SMNS-driven outflow, almost isotropic, will generate energetic forward shocks and then accelerate ultra high energy cosmic rays.

The maximum energy of the cosmic rays accelerated by the wide outflow driven by the SMNSs can be estimated as

\[
E_{\text{p,m}}^{\text{NS–NS}} \sim \beta Z e B_d R_d \sim 1.5 \times 10^{18} \text{eV} \left(\frac{\beta}{0.5}\right) \left(\frac{E_{\text{inj}}}{10^{52} \text{erg}}\right)^{1/2} \left(\frac{n}{10^{-2} \text{cm}^{-3}}\right)^{1/2} \left(\frac{\epsilon_B/0.1}{2}\right)^{1/2} \left(\frac{\Gamma}{2}\right)^{2/3},
\]

where \(\beta\) is the velocity of the ejecta in units of the speed of light \(c\), \(e\) is the electron’s charge, \(R_d \sim 1.2 \times 10^{18} \text{cm} (E_{\text{inj}}/10^{52} \text{erg})^{1/2} (n/10^{-2} \text{cm}^{-3})^{-1/4} (\Gamma/5)^{-1/2}\) is the deceleration radius, and \(B_d = 0.02 \text{gauss}\beta (\Gamma/5) (n/0.01 \text{cm}^{-3})^{1/2} (\epsilon_B/0.1)^{1/2}\) is the magnetic field strength at \(R_d\). The \(\beta\) has been normalized to 0.5 since, in the presence of a highly magnetized SMNS, the material ejected during the NS–NS merger is expected to be accelerated to a trans-relativistic or even mildly relativistic velocity (Fan & Xu 2006). Different from the ccSN scenario, we normalize \(n\) to the value of \(10^{-2} \text{cm}^{-3}\) to address the fact that some mergers of NSs are expected to take place in the low-density medium. Again the cooling of the accelerating EeV cosmic rays do not suffer significant energy loss via synchrotron radiation due to the low \(B_d\).

How large is \(E_{\text{inj}}\)? The answer is somewhat uncertain since the SMNSs that formed in double NS mergers might suffer significant energy loss in addition to the regular dipole magnetic radiation. For GRB 130603B displaying a SMNS signature, \(E_{\text{inj}} \gtrsim 2 \times 10^{51} \text{erg}\) is needed to account for the multiwavelength afterglow data. In a good fraction of short GRBs with distinguished X-ray afterglow plateaus, as reported in Rowlinson et al. (2013), the energy release by the central SMNS is found to be \(E_{\text{inj}} < 10^{52} \text{erg}\). The inferred \(E_{\text{inj}}\) is also favored by the weak radio afterglow emission of most short GRBs and has been suggested to be the signature of the significant gravitational wave radiation of the SMNSs (Fan et al. 2013a, 2013b), that may be possible if the interior toroidal magnetic field is high up to \(\sim 10^{17} \text{gauss}\) which can give rise to a sizeable deformation \(\epsilon \sim 0.01\) of the magnetar or the secure instability occurring with a \(\mathcal{R} \sim \mathcal{R}_{\text{sec}} + 0.03 \sim 0.165\). While in the modeling of GRB 051221A and PTF11agg, \(E_{\text{inj}} \sim 10^{52} \text{erg}\) is needed, on average, \(E_{\text{inj}}\) is likely \(\sim \text{quite a few} \times 10^{51} \text{erg}\). With Equation (3), it is straightforward to show that \(\eta \sim 0.1 (E_{\text{inj}}/3 \times 10^{51} \text{erg})^{-1}\) is needed, otherwise the accelerated ultra high energy cosmic rays cannot account for a sizeable fraction of
the observed EeV ones. We then suggest that in the model of merging double NSs (Totani et al. 2013), the FRBs may still have a significant connection with ultra high-energy cosmic-ray sources; though, the argument is less direct than in the blitazar model. Possible byproducts are high-energy neutrinos if there are dense/energetic seed photons. Even with very optimistic assumptions, the resulting PeV neutrinos are likely too weak to give rise to significant detections for IceCube-like detectors (see Gao et al. (2013b) for a relevant estimate).

2.3. The Model of Merger of Binary White Dwarfs

In the model of the merger of binary degenerate white dwarfs, the FRBs were produced by coherent emission from the polar region of a rapidly rotating, magnetized massive white dwarf, which formed after the merger (Kashiyama et al. 2013). The energy budget of the nascent massive white dwarf can be estimated as $E_{\text{bag}} \sim GM_{\text{wd}}^2 / R_{\text{wd}} \sim 3 \times 10^{50} \text{erg} (M_{\text{wd}} / 1 M_\odot)^2 (R_{\text{wd}} / 10^9 \text{cm})^{-1}$. Magnetic activity of the post-merger object has been demonstrated by recent numerical simulations (Ji et al. 2013), in which the magnetic energy of the remnant at its peak is found to exceed $10^{48}$ erg (the corresponding volume-averaged magnetic field strength is $B \sim 10^{15}$ gauss) and about $M_{\text{ej,wd}} \sim 10^{-3} M_\odot$ mass is ejected from the system over the run time of the simulations, i.e., $t \sim 2 \times 10^2$ s. With a spin-down luminosity of the magnetized massive white dwarf $L_{\text{sd},\text{wd}} \sim 2 \times 10^{38} (B_{\perp,\text{wd}} / 10^9 \text{G})^2$, the ejected material, as well as the swept circum medium with a density of $n \sim 0.01 \text{cm}^{-3}$, cannot be accelerated to a velocity larger than $\sim 10^5 \text{cm} \text{s}^{-1}$, where we have normalized $B_{\perp,\text{wd}}$ to a value of $10^9 \text{G}$, the surface magnetic field strength of the highly magnetized white dwarfs observed thus far. With Equation (4), we find that the cosmic-ray protons that are more energetic than $\sim 10^{16} \text{eV}$ cannot be accelerated, and are therefore not of interest to us. If some FRBs are associated with type Ia SNe, as suggested in Kashiyama et al. (2013), the SN outflow can also accelerate cosmic rays. However, it is widely known that the SNe Ia outflow cannot accelerate cosmic rays to the so-called “knee” of the cosmic-ray spectrum (i.e., $\sim 3 \text{PeV}$). Therefore, in the model of the merger of binary white dwarfs, EeV cosmic rays are not expected.

3. DISCUSSION

Since the origin of FRBs has yet to be pinned down, in this work, we have carried out a model-dependent estimate of the possible role that FRB sources play in accelerating EeV cosmic rays. In the models of magnetar giant radio flares, the merger of binary white dwarfs, and Galactic flaring stars, significant EeV cosmic-ray acceleration is not expected. While in the blitazar model the cosmological FRB sources are likely to be significant EeV cosmic-ray accelerators, thanks to huge energy, release into the surrounding medium by each SMNS (see Section 2.1). In the model of merging NSs, FRBs may still be promising ultra high-energy cosmic-ray sources if SMNSs are formed in a considerable fraction of binary NS mergers (see Section 2.2). We also suggest that, in the blitazar model, the GRB-related FRBs may show some difference from the normal ccSN-related FRBs.

The NS mergers, if irrelevant to FRBs, are expected to have rates lower than $R_{\text{GRB}}$. Even so, their role in producing EeV cosmic rays may be non-negligible. We are aware that the role of NS–NS–merger outflow in accelerating $\lesssim 10^{17}$ eV cosmic ray protons has been discussed in (Takami et al. 2014), where energy injection and then acceleration of the outflow caused by the SMNS central engine have not been taken into account. However, as summarized in Section 2.2, there is growing evidence for the formation of SMNS in a plausible non-negligible fraction of binary NS mergers, which help to accelerate cosmic rays. For example, inserting the physical parameters inferred from the modeling of GRB 130603B with an SMNS central engine (Fan et al. 2013b) into Equation (4), we have $E_{\text{NS–NS}} \sim 2 \times 10^{18} \text{eV}$. Based on extrapolations from observed binary pulsars in the Galaxy, a likely coalescence rate of binary NSs is $\sim 10^{-3} \text{yr}^{-1}$ per a Milky-Way Equivalent Galaxy (Abadie et al. 2010), which is about one order of magnitude lower than the observed rate of FRBs (the very optimistic estimate of the NS–NS merger rate could be comparable to the rate of FRBs). The beaming-corrected estimates of the short GRB rate can be as high as $\sim 10^{-3} \text{yr}^{-1} \text{Gpc}^{-3}$ (Coward et al. 2012), and the merger rate of binary NSs is expected to be higher. These two independent estimates are consistent with each other. If each merger injects energy of $\sim 10^{52}$ erg into the surrounding material (i.e., the rotational energy of SMNS is mainly lost via magnetic dipole radiation), and then drives trans-relativistic shocks ($\beta > 0.5$), the flux of cosmic rays with the energy of $\sim 10^{18}$ eV detectable on the Earth would be $\sim 10^{-29} (E_{\text{inj}} / 10^{52} \text{erg}) m^{-2} s^{-1} \text{sr}^{-1} \text{eV}^{-1}$, which can account for $\sim 1/3$ of the observed flux $\sim 3 \times 10^{-30} \text{m}^{-2} \text{s}^{-1} \text{sr}^{-1} \text{eV}^{-1}$, for a reasonable EeV cosmic-ray acceleration efficiency $\eta \sim 0.1 (E_{\text{inj}} / 10^{52} \text{erg})^{-1}$. As summarized in Section 2.2, if $E_{\text{inj}}$ is only a few Beths (i.e., $10^{51}$ erg), as found in GRB 130603B, the binary NS mergers may produce only $\sim 10$% of the observed EeV cosmic rays. Nevertheless, the importance of NS–NS mergers in producing $> 10^{18}$ eV cosmic rays can be reliably estimated in the foreseeable future, since (1) the gravitational wave observations by advanced LIGO/VIRGO will pin down or impose a tight constraint on the merger rate of binary NSs or (2) the dedicated electromagnetic counterpart searches of the merger events will help us to tightly constrain the total energy injected into the surrounding medium.

In view of the fact that all the active galactic nuclei (Ginzburg & Syrovatskii 1964; Hillas 1984), bright GRBs (Waxman 1995; Vietri 1995) and low-luminosity GRBs (Murase et al. 2006; Liu et al. 2011), Type Ic SNe, in particular, the so-called hypernovae associated with GRBs (Dermer 2001; Wang et al. 2007; Budnik et al. 2008; Fan 2008; Chakraborti et al. 2011; Liu & Wang 2012), and clusters of galaxies (Murase et al. 2008) can also accelerate cosmic rays to energies of $\gtrsim 10^{18}$ eV, we suggest that the $> 10^{18}$ eV cosmic rays consist of multiple components from different astrophysical sources, possibly including those producing FRBs.

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The Astrophysical Journal, 797:33 (6pp), 2014 December 10

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6