REVISITING THE DISPERSION MEASURE OF FAST RADIO BURSTS ASSOCIATED WITH GAMMA-RAY BURST AFTERTOWNS

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ABSTRACT

Some fast radio bursts (FRBs) are expected to be associated with the afterglow emission of gamma-ray bursts (GRBs), while a short-lived, supermassive neutron star (NS) forms during the GRBs. I investigate the possible contributions to the dispersion measure (DM) of the FRBs from the GRB ejecta and the wind blown from the precollapsing NS. On the one hand, sometimes an internal X-ray plateau afterglow could be produced by the NS wind, which indicates that a great number of electron–positron pairs are carried by the wind. If the pair-generation radius satisfies a somewhat rigorous condition, the relativistic and dense wind would contribute a high DM to the associated FRB, which can be comparable to and even exceed the DM contributed by the intergalactic medium. On the other hand, if the wind only carries a Goldreich–Julian particle flux, its DM contribution would become negligible; meanwhile, the internal plateau afterglow would not appear. Alternatively, the FRB should be associated with a GRB afterglow produced by the GRB external shock, i.e., an energy-injection-caused shallow-decay afterglow or a normal single-power-law afterglow if the impulsive energy release of the GRB is high enough. In the latter case, the DM contributed by the high-mass GRB ejecta could be substantially important, in particular, for an environment of main-sequence stellar wind. In summary, a careful assessment on the various DM contributors could be required for the cosmological application of the expected FRB–GRB association. The future DM measurements of GRB-associated FRBs could provide a constraint on the physics of NS winds.

Key words: gamma-ray burst: general – radio continuum: general – stars: neutron

1. INTRODUCTION

Fast radio bursts (FRBs) are newly discovered radio transient sources; they have a typical duration of a few milliseconds and a flux of a few to a few tens of Jansky at ~1 GHz (Lorimer et al. 2007; Thornton et al. 2013). Due to the low angular resolutions of the radio surveys for FRBs, no counterpart in other bands has been reported to be associated with them. In view of their anomalously high dispersion measures (DMs; ~500–1000 cm−3 pc) coupled with their high Galactic latitudes, FRBs are increasingly suggested to have cosmological distances (Thornton et al. 2013). The corresponding redshifts are inferred to be z ∼ 0.5–1 by ascribing the DMs to the host galaxies and the intergalactic medium (IGM; Thornton et al. 2013). Consequently, the peak radio luminosity is estimated to be ~10^{42–43} erg s−1 and the total energy release is ~10^{39–40} erg. Based on such an energy scale and the millisecond duration, some cosmological FRB models have been proposed, such as hyperflares of soft gamma-ray repeaters (Popov & Postnov 2007), collapses of supra-massive neutron stars (NSs) to black holes at several thousand to million years old (Falcke & Rezzolla 2014), mergers of double NSs (Totani 2013) or binary white dwarfs (Kashiyama et al. 2013), and synchrotron maser emission from relativistic, magnetized shocks due to magnetar flares (Lyubarsky 2014).

It is believed that a supermassive NS could form during some gamma-ray bursts (GRBs; in particular, the short-duration ones) and subsequently collapse into a black hole after hundreds to thousands of seconds from its birth. Therefore, following Falcke & Rezzolla (2014), Zhang (2014) proposed a possible connection between a small fraction1 of FRBs and GRBs, although no such association (even a positional coincidence) has yet been reported. It was further suggested that the combination of the DM measurements of FRBs and the redshift measurements of GRBs could open a new window to study cosmology (i.e., to probe the history of the free electron column density and thus the cosmic reionization; Deng & Zhang 2014; Gao et al. 2014; Zhou et al. 2014). This attempt could be feasible and effective if the DM of FRBs is indeed overwhelmingly determined by the combination of the IGM and the Galaxy. However, conservatively speaking, some uncertainties could still arise because some substantial DM contributions could be provided from somewhere else.

The most probable intrinsic DM contributor for GRB-associated FRBs could be the GRB ejecta, whose contribution was estimated (but somewhat underestimated) by Deng & Zhang (2014) by using the usual DM definition for stationary medium. In fact, for the relativistically moving ejecta, relativistic transformation should be taken into account in the DM calculations. More importantly, the DM of an FRB could also be contributed by the wind blown from the precollapsing NS. The existence of the NS wind was evidenced by its significant influence on the GRB afterglow emission either by injecting energy into the GRB external shock (Dai & Lu 1998a, 1998b; Zhang & Mészáros 2001) or by producing internal emission through energy dissipation of the wind (Troja et al. 2007; Mao et al. 2010; Yu et al. 2010). The efficiency of the wind emission depends on the specific dissipation mechanisms and, more directly, the amount of electrons carried by the wind. As an intuitive consideration, more electrons are probably required by brighter wind emission, which then could determine a higher DM for the corresponding FRB.

Therefore, the primary purpose of this paper is (1) to clarify the possible DM contributions to FRBs from GRB ejecta and NS winds and (2) to reveal the consequent implications for the cosmological application of the expected FRB–GRB association.

1 The event rate of FRBs is considered to be much higher than the GRB rate (Thornton et al. 2013).
where the Lorentz factor $\Gamma$ and the mass of the GRB ejecta (the shocked medium), respectively. Moreover, we have $\Gamma_{ej} = \Gamma_{sm}$ and $M_{sm} = 4\pi r^3nm_p/(3 - k)$, where $r$ is the radius of the GRB external shock from the central engine. As usual, the density of the circumburst medium can be written as $n = Ar^{-4}\text{cm}^{-3}$ with the index $k = 0$ and 2 corresponding to the interstellar medium and main-sequence stellar wind environments, respectively (Dai & Lu 1998c; Chevalier & Li 2000).

By considering of the possible energy injection from an NS wind to the GRB ejecta and shocked medium, the temporal dependence of the isotropically equivalent total energy can be written as

$$E(t) = E_0 + \dot{E}_w t/(1 + z), \quad (4)$$

where $E_0$ is the initial energy of the ejecta impulsively released during the GRB, $\dot{E}_w$ is the energy flux of the NS wind, and the time $t$ is measured in the observer’s frame. GRB afterglow observations implied that GRB NSs are millisecond magnetars, i.e., with a polar magnetic field of $B_p \sim 10^{14}$ G and a spin period of $P \sim 1$ ms (Zhang et al. 2006; Fan & Xu 2006; Yu & Dai 2007; Yu et al. 2010; Rowlinson et al. 2013; Gompertz et al. 2013). Then, the wind energy flux determined by the spin-down luminosity of the NS can be estimated as $2^{\dot{E}_w} = L_{sd}/\dot{f}_b \approx B_p^2 R^6 \Omega^2/(6\pi c f_b) = 10^{48}B_{p,14}^2 R_{14}^6 \Omega_{14}^2 f_{b,-1}^{-1} \text{erg s}^{-1}$, where $R$ and $\Omega$ are the radius and angular frequency of the NS, respectively, and the factor $f_b$ is introduced due to the possible beaming of the NS wind. Hereafter the conventional notation $Q_4 = Q/10^4$ is adopted in cgs units.

Combining Equations (3) and (4), the Lorentz factor of the ejecta can be approximately expressed as

$$\Gamma_{ej}(t) \approx \begin{cases} \left(\frac{E_0}{M_{sm}c^2}\right)^{1/2}, & \text{for } t < t_{dec}, \\
\left[\frac{\dot{E}_w t}{(1 + z)M_{sm}c^2}\right]^{1/2}, & \text{for } t > t_{ei}, \end{cases} \quad (5)$$

where $\eta = E_0/M_{ej}c^2$ represents the initial value of $\Gamma_{ej}$. $t_{dec}$ is the deceleration timescale determined by the condition $M_{sm} = M_{ej}/\eta$, and $t_{ei} = (1 + z)E_0/\dot{E}_w$ is the time at which the injected energy starts to influence the dynamics by exceeding the initial energy of the ejecta. Obviously, the relative importance of the energy injection effect depends on the competition between the initial energy $E_0$ and the total injected energy $\dot{E}_w t_{col}/(1 + z)$, where $t_{col}$ is the NS collapsing time. More strictly, it is probable that, actually, only a fraction (sometimes a small fraction) of the wind energy can be injected into the external shock, because the other fraction is emitted directly by the wind itself to produce the internal afterglow emission (see Section 4.2). In any case, for a typical value of $t_{col} \sim 10^5$ s indicated by the observed internal plateaus, the total injected energy can be estimated to be at most $\sim 10^{51}$ erg.

If an FRB is produced by an NS collapse at the observational time $t$, the radius of the GRB ejecta, where the FRB crosses it, can be approximately calculated by

$$r_{ej,c} = \frac{cv_{ej}t}{c - v_{ej}} \approx \frac{2\Gamma_{ej}^2 ct}{(1 + z)}. \quad (6)$$

2. DISPERSION IN RELATIVISTIC MOVING MATERIAL

It is widely accepted that both GRB ejecta and NS winds move at ultra-relativistic speeds (e.g., Lithwick & Sari 2001; Zhang et al. 2003; Zou & Piran 2010; Coroniti 1990; Lyubarsky & Kirk 2001; Drenkhahn 2002; Metzger et al. 2008). Thus, the usual definition of DM for stationary medium as the column density of electrons could become inappropriate for GRB ejecta and NS winds. Alternatively, the Lorentz transformation between the observer’s frame and the comoving frame needs to be taken into account. Throughout this paper, the comoving quantities are labeled by a superscripted prime.

When an electromagnetic wave propagates through an ionized medium of electron number density $n'$, the group velocity of the wave would become frequency-dependent, which reads $v'_e = c[1 + v'_p/(v'_e - v'_p)]^{-1/2}$, where $v'_p = (n'e^2/\pi nm_z)^{1/2} = 9 \times 10^9 n^{-1/2}$ Hz is the plasma frequency (Rybicki & Lightman 1979). Therefore, after propagating through the medium, the arrival of the electromagnetic wave of frequency $v'_e > v'_p$ should be delayed by a time $\Delta t' = (1/c) \int (v'^2/2v'^2) dl'$ with respect to the arrival time in vacuum. Then, in the observer’s frame, the arrival time delay of a radio pulse between two frequencies $\nu_1$ and $\nu_2$ can be calculated using

$$\Delta t = \frac{(1 + z)\Delta t'}{D},$$

$$\approx \frac{\nu^2}{2\pi mc^2} \left(\frac{1}{\nu_1^2} - \frac{1}{\nu_2^2}\right) \int \frac{D}{1 + z} n' dl', \quad (1)$$

where $z$ is the cosmological redshift of the medium and $D$ is the Doppler factor due to the relativistic speed $v$ of the medium. As usual I denote $\beta = v/c$, the Lorentz factor $\Gamma = (1 - \beta^2)^{-1/2}$, and $D = [\Gamma(1 - \beta \cos \theta)]^{-1}$ with $\theta$ being the angle between the line of sight and the direction of medium motion. In Equation (1), the DM of the radio pulse measured by the observer is defined as

$$\text{DM} \equiv \int \frac{D}{1 + z} n dl, \quad (2)$$

where the Lorentz invariance of the column density (i.e., $n' dl' = n dl$) is considered. In comparison with the usual DM definition, two extra quantities appear in Equation (2), i.e., the Doppler factor $D$ and redshift $z$.

3. DM CONTRIBUTED BY GRB EJECTA

Following Huang et al. (1999, 2000), the dynamical evolution of a GRB ejecta, which propagates into the surrounding medium and shocks it, can be determined from the energy conservation law as follows:

$$E(t) = (\Gamma_{ej} - 1)M_{ej}c^2 + (\Gamma_{sm}^2 - 1)M_{sm}c^2, \quad (3)$$

association. In the next section, I give a relativistic definition of the DM. The DM contribution from the GRB ejecta is estimated in Section 3, where the dynamical influence on the GRB external shock by the energy injection effect is taken into account. In Section 4, I pay attention to the DM contribution from the NS wind by considering two different lepton-loading cases. The conclusion and discussion are given in Section 5.
Therefore, the DM of the FRB contributed by the GRB ejecta can be calculated as
\[
DM_{ej} = \frac{2\Gamma_{ej}}{(1+z)4\pi r_{ej}^2 c} \frac{M_{ej}}{m_p},
\]
where \(D_{ej} \approx 2\Gamma_{ej}\) is taken for \(\theta \approx 0^\circ\). On one hand, for a mild GRB explosion with \(E_0 \ll 10^{51}\) erg, the dynamical evolution of the ejecta should be taken as \(\Gamma_{ej} = [\dot{E}_w/(1+z)M_{SN}c^2]^{1/2}\) and \(\Gamma_{ej} \propto t^{-(2-k)/(8-2k)}\). This yields
\[
DM_{ej}^{k=0} = 0.1(1+z)^{3/4} \dot{E}_{w,48}^{3/8} E_{50,52}^{-1} A_{35.5,53}^{-2} 13^{-5/4} \text{ cm}^{-3} \text{ pc}^{-1}.
\]
As shown, the DM contribution from the GRB ejecta here is insignificant in contrast to the IGW’s contribution, although the energy of the ejecta is finally increased. This is because the low-energy ejecta has too few electrons. On the other hand, if the GRB explosion is very powerful with \(E_0 \gg 10^{51}\) erg, which meanwhile indicates a high-mass ejecta, the “standard” dynamics \(\Gamma_{ej} = (E_0/M_{SN}c^2)^{1/2}\) and \(\Gamma_{ej} \propto t^{-(3-k)/(8-2k)}\) should be taken for the ejecta. Then we can get
\[
DM_{ej}^{k=2} = 8(1+z)\dot{E}_{w,48}^{3/4} E_{50,52}^{-1} A_{35.5,53}^{-2} \text{ cm}^{-3} \text{ pc}^{-1}.
\]
In comparison with Deng & Zhang (2014), the above values have obviously increased due to the relativistic correction. In particular, in the case of the main-sequence stellar wind environment, the GRB ejecta could provide a substantial contribution to the DM of the corresponding FRB. Finally, in all cases, the plasma frequency of the GRB ejecta can be found to be safely lower than the radio frequency (∼10^9 Hz).

In addition, the DM contribution from a shocked medium with much fewer electrons than the ejecta can definitely be neglected.

4. DM CONTRIBUTED BY NEUTRON STAR WIND

The corotating magnetosphere of an NS is filled with electron and positron pairs (Goldreich & Julian 1969). Beyond the light cylindrical radius \(r_L = c/\Omega\), the corotation can no longer hold and the magnetocentrifugal force exerted on the pairs would throw them with relativistic speed. Therefore, it is widely considered that an NS wind probably carries a certain amount of leptons, while the energy of the wind is initially dominated by Poynting flux. In this section, the DM contribution of such a lepton-loaded NS wind is assessed, including cases where (1) the leptons are only provided by the NS magnetosphere and (2) a great amount of leptons are provided from somewhere else other than the magnetosphere. In the sight of afterglow emission, these two types of NS winds correspond to a shallow-decay (or a normal) afterglow and an internal plateau afterglow, respectively. The former one is emitted from the GRB external shock that is energized by the NS wind, while the latter one is produced by the NS wind itself.

4.1. Goldreich–Julian Wind

The leptons carried by an NS wind can at least be provided by the NS magnetosphere, where the particle density can be expressed as \(n_{GJ}(r) \approx (\Omega B_p/2\pi ce)(r/R)^{-3}\) (Goldreich & Julian 1969; Shapiro & Teukolsky 1983). Here the angle dependence of the density is ignored for simplicity. Moreover, the NS wind is considered to be approximately isotropic initially and gradually becomes collimated far away from the star (denoted by a beaming factor \(f_b\)). Then the particle number flux of the NS wind can be calculated by
\[
\dot{N}_{GJ} \approx 4\pi r_L^2 n_{GJ}(r) c/f_b = 5.5 \times 10^{39} B_{p,14}^{-2} R_p^{-1} \text{ cm}^{-2} \text{ s}^{-1}.
\]
After the collapse of the NS, the energy supply to the NS wind is turned off and the remnant wind material expands outside quickly. Therefore, the FRB can cross the Goldreich-Julian (GJ) particles only when it catches up with the wind at the radius \(r_{w,c} \approx 2\Gamma_{w}^2 r_L\), where \(\Gamma_{w}\) is the Lorentz factor corresponding to the bulk motion of the wind. The wind velocity is considered to have a radial direction due to large-scale acceleration and collimation, although it is initially dominated by the tangential component at \(r_L\).

The process of wind acceleration at large radii is uncertain, but it is widely considered that magnetic reconstructions could play an important role in it. Following Lyubarsky & Kirk (2001) and Drenkhahn (2002), magnetic reconnection acceleration could determine the dynamical evolution to be \(\Gamma_{w}(r) \sim \Gamma_{w}(r/r_c)^{\alpha}\), where the index \(\alpha\) could be within the range of 1/3–1/2.

The initial speed of the wind at the light cylinder is set to the Alfvén speed, and the corresponding Lorentz factor reads \(\Gamma_{w} \sim \sqrt{\Omega}\), where \(\sigma_{t}\) is the initial ratio between the Poynting flux and the matter energy flux (Drenkhahn 2002). Therefore, from the expression \(\dot{E}_w = (\sigma_{t} + 1)\Gamma_{w} n_{GJ} m_e c^2\), we can derive \(\Gamma_{w} \sim (\dot{E}_w/\dot{N}_{GJ} m_e c^2)^{1/3} = 6 \times 10^4 B_{p,14}^{1/3} r_p^{-2/3} R_p\).

Due to such a high initial Lorentz factor and subsequent acceleration, the crossing radius \(r_{w,c}\) can easily be larger than the radius of the GRB ejecta. This means that the wind material would merge into the GRB ejecta before it is caught up by the FRB. After the merger of the wind and ejecta, their DM contributions can simply be compared through their lepton numbers as \(M_{ej}/m_p = \dot{E}_0/n_{GJ} m_e c^2 \sim 2.2 \times 10^{41} E_{50,52}^{-1} \dot{E}_{50,51}^{-1} \dot{E}_{50,51}^{-1}\) and \(n_{GJ}(1+z) \sim 5.5 \times 10^{39} (1+z)^{-1} B_{p,14}^{-2} R_p^{-1} f_b^{-1}\). Obviously, the DM contribution of the GJ particles is negligible.

4.2. Internally Emitting Wind

The most substantial evidence for a remnant GRB NS is the observed internal X-ray afterglows, which exhibit a plateau followed by an extremely steep decay (Troja et al. 2007; Liang et al. 2007; Rowlinson et al. 2010, 2013), typically with a luminosity of \(L_X \sim 10^{46–47}\) erg s^{-1} in the X-ray band. As far as I can see, no similar temporal behavior has been found in the optical and high-energy afterglows. The extremely steep decay probably indicates the collapse of the NS. Therefore, Zhang (2014) suggested that the steep decay following an internal plateau could be associated with an FRB signal that is produced by the NS collapse.

Although our knowledge of the internal dissipation mechanism of NS winds is very limited, an intuitive idea could arise that strongly emitting NS winds could carry much more leptons than the GJ flux. Thus, here I take the particle number flux \(\dot{N}_{IE}\) as a free parameter. Then the emission luminosity of a wind, most of which is assumed to enter into the X-ray band according to the present observations, can be written as
\[
L_X \sim \dot{N}_{IE}(\Gamma_{w}) \gamma' m_e c^2,
\]
where \(\Gamma_{w}\) and \(\gamma'\) are the bulk Lorentz factor of the wind and the comoving random Lorentz factor of electrons, respectively.
Furthermore, the wind emission is assumed to be dominated by synchrotron radiation, i.e., (Sari et al. 1998)

\[
(1 + z)\nu_{\infty} \sim \frac{eB' y'^2}{2\pi m_e c}, \tag{14}
\]

where \(\nu_{\infty} \sim 3 \times 10^{17}\) Hz is taken as a reference frequency and \(B'\) is the comoving strength of the magnetic field in the NS wind. By introducing an equipartition factor \(\epsilon\), we can write

\[
\frac{B'^2}{8\pi} \sim \frac{\dot{N}_{\text{IE}} \epsilon m_e c^2}{4\pi r_c^2 \Gamma_{\omega c}}, \tag{15}
\]

where the emission is considered to mainly happen at the radius \(r_c\).

Solving Equations (13)-(15), we can obtain the emission radius as follows:

\[
r_c \sim \frac{\epsilon \nu_{\infty}^2}{\pi m_e c^2 (1 + z)} \left( \frac{\epsilon L_X}{2e} \right)^{1/2} \left( \frac{1}{X^2} \right)^{1/2} \sim 2.3 \times 10^7 (1 + z)^{-1/2} y'^2 \epsilon^{1/2} L_{X,47}^{1/2} X_{17.5}^{1/2} \text{ cm}. \tag{16}
\]

Obviously, the emission radius of the wind should not be larger than the simultaneous radius of the GRB external shock (~10^{16-17} cm). Such a requirement gives \(y' \lesssim 3 \times 10^7 (1 + z)^{-1/2} X_{17.5}^{-1/2} L_{X,47}^{-1/2} \). On the other hand, the optical depth of the wind at the emission radius reads

\[
\tau = \sigma_T \frac{\dot{N}_{\text{IE}}/(1 + z)}{4\pi r_c^2} \sim 1.2 \times 10^6 (1 + z) \Gamma_{\omega}^{-1} y'^{-5} \epsilon^{-1/2} X_{17.5}^{-1/2} f_3, \tag{17}
\]

where \(\sigma_T\) is the Thomson cross section. In order to be consistent with the non-thermal assumption, the optical depth is required to be much smaller than unity, which yields \(y' \lesssim 480 (1 + z)^{1/6} a^{-1/6} \epsilon^{-1/6} X_{17.5}^{1/6} f_3\) with \(a \equiv \Gamma_{\omega} y' \). The value of the parameter \(a\) depends on the specific dissipation mechanisms of the wind.

With the derived range of \(y'\), the internal-emission-required electron flux

\[
\dot{N}_{\text{IE}} \sim \frac{L_X}{\Gamma_{\omega} \epsilon m_e c^2} = 1.2 \times 10^{30} \Gamma_{\omega}^{-1} y'^{-1} L_{X,47} S^{-1} \tag{18}
\]

can be roughly constrained to be within the range of

\[
1.4 \times 10^{34} a^{-1} S^{-1} \lesssim \dot{N}_{\text{IE}} < 5.3 \times 10^{37} a^{-2/3} S^{-1}, \tag{19}
\]

where the relatively certain parameters are omitted for clarity. The above result is drastically larger than the GJ flux presented in Equation (12), although an uncertainty still exists due to the uncertainty parameter \(a\). It is at least demonstrated that, in order to produce the bright internal plateau afterglows, a great number of electron–positron pairs must be generated and accelerated somewhere from the light cylinder to the emission radius (i.e., \(r_L < r_c < r_e\)).

The DM contributed by the spontaneously generated electron–positron pairs can be calculated from

\[
\text{DM}_{\omega} \approx \frac{2\Gamma_{\omega} \dot{N}_{\text{IE}} t/(1 + z)}{(1 + z)} \frac{\epsilon}{4\pi r_c^2}, \sim 1.6 \times 10^{36} L_{X,47} f_3 \epsilon c^{-1} \text{ cm}^{-3} \text{ pc}, \tag{20}
\]

where \(r_{\omega,c} = 2\Gamma_{\omega} y' r_c\). If the DM of FRBs is mainly attributed to the IGM, then we should require \(\text{DM}_{\omega} \ll 10^3 \text{ cm}^{-3} \text{ pc}\), which constrains the pair-generation radius to \(r_e \gg 1.3 \times 10^9 (1 + z)^{-1} a_0^{-2} y'^{-5/2} L_{X,47}^{1/2} \text{ cm}\). Such a condition does not seem unreachable, since after all the radius \(r_e\) is at least larger than the radius of the NS. In contrast, if the pair-generation radius is indeed small, it could become possible that the DMs of some FRBs are actually dominated by NS winds. Nevertheless, a high DM usually corresponds to a high plasma frequency, which should of course be lower than the radio frequency, i.e.,

\[
\nu_p = \frac{\Gamma_{\omega} (e^2 c^4 \dot{N}_{\text{IE}})^{1/2}}{1 + z} \sim \frac{2.6 \times 10^{24} L_{X,47}^{1/2}}{(1 + z) \Gamma_{\omega}^{1/2} y'^{-1/2} r_e c} \text{ Hz} \ll 10^9 \text{ Hz}. \tag{21}
\]

This requires \(r_e \gg 8.1 \times 10^7 (1 + z)^{-1} a_0^{-2} y'^{-5/2} L_{X,47}^{1/2} \text{ cm}\). Otherwise, the FRB signal would be absorbed by the wind plasma. Therefore, for \(10^9 a_0^{-2} y'^{-5/2} \lesssim r_e \lesssim 10^9 a_0^{-2} y'^{-5/2} \text{ cm}\), the wind material could contribute an extremely high DM to the corresponding FRB, which exceeds the IGM’s contribution.

5. CONCLUSION AND DISCUSSION

Since a supermassive NS could form during some GRBs and live for hundreds and thousands of seconds after the birth, the GRBs are expected to be associated with an FRB which is produced by the collapse of the NS. (1) GRB observations showed that the wind of some GRB NSs could produce bright internal afterglow emission, which indicates that a great number of electron–positron pairs are generated and accelerated beyond the light cylinder of the NS. If the pair-generation radius is small enough, these leptons could contribute a high DM to the FRB signal, which can be comparable to and even exceed the DM contribution from the IGM. (2) If the leptons carried by the NS wind are only supplied by the NS magnetosphere (i.e., for a GJ wind), the wind emission is probably very weak and most wind energy will be injected into the GRB external shock. In such a case, the FRB could be associated with a shallow-decay afterglow rather than an internal plateau. Meanwhile, the DM of the FRB could be overwhelmingly contributed by a combination of the IGM and the Galaxy. (3) Finally, in the GJ-wind case, the FRB could also be associated with a normal single-power-law afterglow, if the impulsive energy released during the GRB is larger than the total injected energy. The huge prompt energy indicates a high mass of the ejecta, so a DM of the order of \(\sim 100 \text{ cm}^{-3} \text{ pc}\) could be predicted for a circumburst environment of main-sequence stellar wind. Such a situation could appear in some long-duration GRBs.

In summary, on one hand, we must be very careful to assess the various possible contributions to the FRB’s DM when we use the FRB–GRB association as a cosmological probe. On the other hand, the DM measurements of GRB-associated FRBs could provide a constraint on the physics of NS winds.

In principle, by considering of various possible DM contributors, the Galactic origin of FRBs cannot be ruled out before their cosmological redshifts are measured. For example, Loeb et al. (2014) recently proposed that FRBs could be rare eruptions of flaring main-sequence stars within \(\sim 1 \text{ kpc}\), where the high DMs of the FRBs arise from a blanket of coronal plasma around the host stars. Following a similar consideration, in the...
NS scenarios, a high DM could also be contributed by the relativistic NS wind with some peculiar properties (e.g., with a millisecond period and a normal magnetic field of $10^{11-12}$ G). Of course, some difficulties could be argued against such intrinsic DM origin models, e.g., the density of the plasma could be too high to enable the penetration of radio emission (Luan & Goldreich 2014; Tuntsov 2014; Dennison 2014). In any case, it could be valuable to deeply investigate the dynamical evolution of a steady NS wind (rather than the remnant wind discussed in this paper) to judge whether the Galactic NSs could produce FRBs or not.

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