LOW FREQUENCY RADIO PULSES FROM GAMMA-RAY BURSTS?

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ABSTRACT

Gamma-ray bursts, if they are generated in the process of interaction between relativistic strongly magnetized winds and an ambient medium, may be accompanied by very short pulses of low-frequency radio emission. The bulk of this emission is expected to be at the frequencies of \( \sim 0.1 - 1 \) MHz and cannot be observed. However, the high-frequency tail of the low-frequency radio emission may reach a few ten MHz and be detected, especially if the strength of the magnetic field of the wind is extremely high.

Subject headings: gamma-rays: bursts - radio emission: pulses
1. Introduction

The prompt localization of gamma-ray bursts (GRBs) by BeppoSAX led to the discovery of X-ray/optical/radio afterglows and associated host galaxies. Subsequent detections of absorption and emission features at high redshifts ($0.43 \leq z \leq 3.42$) in optical afterglows of GRB and their host galaxies clearly demonstrate that at least some of the GRB sources lie at cosmological distances (for reviews, see Piran 1999; Vietri 1999).

A common feature of all acceptable models of cosmological $\gamma$-ray bursters is that a relativistic wind is a source of GRB radiation. The Lorentz factor, $\Gamma_0$, of such a wind is about $10^2 - 10^3$ or even more (e.g., Fenimore, Epstein, & Ho 1993; Baring and Harding 1997). A very strong magnetic field may be in the plasma outflowing from cosmological $\gamma$-ray bursters (Usov 1994; Blackman, Yi, & Field 1996; Vietri 1996; Katz 1997; Mészáros & Rees 1997). A relativistic, strongly magnetized wind interacts with an ambient medium (e.g., an ordinary interstellar gas) and decelerates. It was pointed out (Mészáros & Rees 1992) that such an interaction, assumed to be shock-like, may be responsible for generation of cosmological GRBs.

The interaction between a relativistic, strongly magnetized wind and an ambient plasma was studied numerically by Smolsky & Usov (1996, 2000) and Usov & Smolsky (1998). These studies showed that about 70% of the wind energy is transferred to the ambient plasma protons that are reflected from the wind front. The other $\sim 30\%$ of the wind energy losses is distributed between high-energy electrons and low-frequency electromagnetic waves that are generated at the wind front because of nonstationarity of the wind—ambient plasma interaction (see below). High-energy electrons, accelerated at the wind front and injected into the region ahead of the front, generate synchro-Compton radiation in the fields of the low-frequency waves. This radiation closely resembles synchrotron radiation and can reproduce the non-thermal radiation of GRBs observed in the Ginga and BATSE ranges (from a few KeV to a few MeV).

Ginzburg (1973) and Palmer (1993) suggested that GRB might be sources of radio emission, and that it might be used to determine their distances and, through the dispersion measure, the density of the intergalactic plasma. Here we consider some properties of the low-frequency waves generated at the wind front. We argue that coherent emission by the high-frequency tail of these waves may be detected, in addition to the high-frequency (X-ray and $\gamma$-ray) emission of GRBs, as a short pulse of low-frequency radio emission (Katz 1994, Katz 1999).
2. Low-frequency electromagnetic waves generated at the wind front

Our mechanism for production of short pulses of low-frequency radio emission from relativistic, strongly magnetized wind-generated cosmological GRBs applies very generally. For the sake of concreteness, we consider wind parameters that are natural in a GRB model that involves a fast rotating compact object like a millisecond pulsar or dense transient accretion disc with a surface magnetic field $B_s \sim 10^{15} - 10^{16}$ G (Usov 1992, Blackman, Yi & Field 1996; Katz 1997; Kluzniak & Ruderman 1998; Spruit 1999).

In this model the rotational energy of compact objects is the energy source of cosmological GRBs. The electromagnetic torque transfers this energy on a time scale of seconds to the energy of a Poynting flux-dominated wind that flows away from the object at relativistic speeds, $\Gamma_0 \sim 10^2 - 10^3$ (e.g., Usov 1994). The wind structure at a time $t \gg \tau_\Omega$ is similar to a shell with radius $r \sim ct$ and thickness of $\sim c\tau_\alpha$, where $\tau_\alpha$ is the characteristic deceleration time of the compact object’s rotation, or the dissipation time of a transient accretion disc.

The strength of the magnetic field at the front of the wind may be as high as

$$B \simeq B_s \frac{R^3}{r_{lc}^2 r} \simeq 10^{15} \frac{R}{r} \left( \frac{B_s}{10^{16} \text{G}} \right) \left( \frac{\Omega}{10^4 \text{s}^{-1}} \right)^2 \text{G},$$

(1)

where $R \sim 10^6$ cm is the radius of the compact object, $\Omega \sim 10^4$ is the angular velocity at the moment of its formation and $r_{lc} = c/\Omega = 3 \times 10^6(\Omega/10^4 \text{s}^{-1})$ cm is the radius of the light cylinder.

The distance at which deceleration of the wind due to its interaction with an ambient gas becomes important is

$$r_{\text{dec}} \simeq 10^{17} \left( \frac{Q_{\text{kin}}}{10^{53} \text{ergs}} \right)^{1/3} \left( \frac{n}{1 \text{ cm}^{-3}} \right)^{-1/3} \left( \frac{\Gamma_0}{10^2} \right)^{-2/3} \text{cm},$$

(2)

where $n$ is the density of the ambient gas and $Q_{\text{kin}}$ is the initial kinetic energy of the outflowing wind. Eq. (2) assumes spherical symmetry; for beamed flows $Q_{\text{kin}}$ is $4\pi$ times the wind energy per steradian. At $r \sim r_{\text{dec}}$, the main part of $Q_{\text{kin}}$ is lost by the wind in the process of its inelastic interaction with the ambient medium, and the GRB radiation is generated.

Substituting $r_{\text{dec}}$ for $r$ into equation (1), we have the following estimate for the magnetic field at the wind front at $r \sim r_{\text{dec}}$:
\[ B_{\text{dec}} \simeq 10^4 \epsilon_B^{1/2} \left( \frac{B_s}{10^{16} \text{ G}} \right) \left( \frac{\Omega}{10^4 \text{ s}^{-1}} \right)^2 \left( \frac{Q_{\text{kin}}}{10^{53} \text{ ergs}} \right)^{-1/3} \left( \frac{n}{1 \text{ cm}^{-3}} \right)^{1/3} \left( \frac{\Gamma_0}{10^2} \right)^{2/3} \text{ G}, \]  

(3)

where we have introduced a parameter \( \epsilon_B < 1 \) which gives the fraction of the wind power remaining in the magnetic field at the deceleration radius. For plausible parameters of cosmological \( \gamma \)-ray bursters, \( B_s \simeq 10^{16} \text{ G}, \Omega \simeq 10^4 \text{ s}^{-1}, Q_{\text{kin}} \simeq 10^{53} \text{ ergs}, \Gamma_0 \simeq 10^2 - 10^3 \) and \( n \sim 1 \text{ cm}^{-3} \), from equation (3) we have \( B_{\text{dec}} \simeq (1 - 5) \times 10^4 \epsilon_B^{1/2} \text{ G}. \)

For consideration of the interaction between a relativistic magnetized wind and an ambient gas, it is convenient to switch to the co-moving frame of the outflowing plasma (the wind frame). While changing the frame, the magnetic and electric fields in the wind are reduced from \( B \) and \( E = B[1 - (1/\Gamma_0^2)]^{1/2} \simeq B \) in the frame of the \( \gamma \)-ray burster to \( B_0 \simeq B/\Gamma_0 \) and \( E_0 = 0 \) in the wind frame. This is analogous to the well-known transformation of the Coulomb field of a point charge: purely electrostatic in the frame of the charge, but with \( E \approx B \) in a frame in which the charge moves relativistically.

Using this and equation (3), for typical parameters of cosmological \( \gamma \)-ray bursters we have \( B_0 \simeq (0.5 - 1) \times 10^2 \epsilon_B^{1/2} \text{ G} \) at \( r \simeq r_{\text{dec}} \).

In the wind frame, the ambient gas moves to the wind front with the Lorentz factor \( \Gamma_0 \) and interacts with it. The main parameter which describes the wind—ambient gas interaction is the ratio of the energy densities of the ambient gas and the magnetic field, \( B_0 \), of the wind

\[ \alpha = 8\pi n_0 m_p c^2 (\Gamma_0 - 1)/B_0^2, \]  

(4)

where \( n_0 = n \Gamma_0 \) is the density of the ambient gas in the wind frame and \( m_p \) is the proton mass.

At the initial stage of the wind outflow, \( r \ll r_{\text{dec}}, \alpha \ll 1 \), but it increases in the process of the wind expansion as \( B_0 \) decreases. When \( \alpha \geq \alpha_{\text{cr}} \simeq 0.4 \) (at \( r \sim r_{\text{dec}} \)), the interaction between the wind and the ambient gas is strongly nonstationary, and effective acceleration of electrons and generation of low-frequency waves at the wind front both begin (Smolsky & Usov 1999, 2000; Usov & Smolsky 1998). For \( 0.4 \lesssim \alpha \lesssim 1 \), the mean Lorentz factor of outflowing high-energy electrons \( \Gamma_0^{\text{out}} \) accelerated at the wind front and the mean field of low-frequency waves \( \langle B_w \rangle \) weakly depend on \( \alpha \) (see Table 1) and are approximately given by

\[ \langle \Gamma_0^{\text{out}} \rangle \simeq 0.2 (m_p/m_e) \Gamma_0 \quad \text{and} \quad \langle B_w \rangle = (\langle B_z \rangle^2 + \langle E_y \rangle^2)^{1/2} \simeq 0.1 B_0 \]  

(5)
to within a factor of 2, where $B_z$ and $E_y$ are the magnetic and electric field components of the waves. The mechanism of generation of these waves is coherent and consists of the following: At the wind front there is a surface current that separates the wind matter with a very strong magnetic field and the ambient gas where the magnetic field strength is negligible. This current varies in time because of nonstationarity of the wind - ambient gas interaction and generates low-frequency waves.

3. Possible detection

At $\alpha \sim 1$, for the bulk of high-energy electrons in the region ahead of the wind front the characteristic time of their synchrotron energy losses is much less than the GRB duration. In this case, the luminosity per unit area of the wind front in $\gamma$-rays is $l_\gamma \simeq m_e c^4 n \langle \Gamma_{\text{out}} \rangle$ while the same luminosity in low-frequency waves is $l_w \simeq c \langle B_w \rangle^2 / 4\pi$. Using these, the ratio of the luminosity in low-frequency waves and the $\gamma$-ray luminosity is

$$
\delta = \frac{l_w}{l_\gamma} = 2 \frac{m_p}{\alpha m_e} \frac{\langle B_w \rangle^2}{\langle \Gamma_{\text{out}} \rangle} \frac{\Gamma_0}{B_0^2} \left( \frac{\langle \Gamma_{\text{out}} \rangle}{\Gamma_0} \right).
$$

(6)

From Table 1, we can see that the GRB light curves in both $\gamma$-rays and low-frequency waves have maximum when $\alpha$ is about 0.4, and the maximum flux in low-frequency waves is about two times smaller than the maximum flux in $\gamma$-rays ($\delta \simeq 0.5$). At $\alpha > 0.4$ the value of $\delta$ decreases with increasing $\alpha$. Therefore, we expect that the undispersed duration $\Delta t_r$ of the low-frequency pulse to be somewhat smaller than the GRB duration, and the energy fluence in low-frequency waves to be roughly an order of magnitude smaller than the energy fluence in $\gamma$-rays. The rise time of the radio pulse is very short because that the value of $\langle B_w \rangle^2$ increases very fast when $\alpha$ changes from 0.3 to 0.4 (see Table 1).

Figure 1 shows a typical spectrum of low-frequency waves generated at the wind front in the wind frame. This spectrum has a maximum at the frequency $\omega'_{\max}$ which is about three times higher than the proton gyrofrequency $\omega_{Bp} = e B_0 / m_p c \Gamma_0$ in the wind field $B_0$. Taking into account the Doppler effect, in the observer’s frame the spectral maximum for low-frequency waves is expected to be at the frequency

$$
\nu_{\max} \simeq \frac{2\Gamma_0}{1+z} \frac{\omega'_{\max}}{2\pi} \simeq \frac{e B_0}{(1+z)m_p c} \simeq \frac{1}{1+z} \left( \frac{B_0}{10^2 \text{ G}} \right) \text{ MHz},
$$

(7)

where $z$ is the cosmological redshift. For typical parameters of cosmological GRBs, $B_0 \simeq (0.5 - 1) \times 10^2 \epsilon_B^{1/2}$ G and $z \simeq 1$, we have $\nu_{\max} \simeq (0.2 - 0.5) \epsilon_B^{1/2}$ MHz. Unfortunately,
the bulk of the low-frequency waves is at low frequencies, and cannot be observed. However, their high-frequency tail may be detected.

At high frequencies, $\nu > \nu_{\text{max}}$, the spectrum of low-frequency waves may be fitted by a power law (Smolsky & Usov 2000):

$$|B(\nu)|^2 \propto \nu^{-\beta},$$

where $\beta \approx 1.6$. In the simulations of the wind—ambient gas interaction (Smolsky & Usov 1996, 2000; Usov & Smolsky 1998) both the total numbers of particles of the ambient gas and the sizes of spatial grid cells are restricted by computational reasons, so that the spectrum (8) is measured reliably only at $\nu \lesssim 10\nu_{\text{max}}$. The amplitudes of the computed oscillations with $\nu > 10\nu_{\text{max}}$ are so small ($\lesssim (0.2 - 0.3)\langle B_w \rangle$) that they cannot be distinguished from computational noise (Smolsky & Usov 1996). Future calculations with greater computational resources may alleviate this problem.

The value of $\nu_{\text{max}}$ depends on many parameters of both the GRB bursters and the ambient gas around them, and its estimate, $\nu_{\text{max}} \approx (0.2 - 0.5)\epsilon_B^{1/2}$ MHz, is uncertain within a factor of 2–3 or so. In the most extreme case in which $\nu_{\text{max}}$ is as high as a few MHz, the high-frequency tail of low-frequency waves may be continued up to $\sim 30$ MHz where ground-based radio observations may be performed. In this case, the energy fluence in a pulse of radio emission at $\nu \sim 30$ MHz may be as high as a few percent of the GRB energy fluence in $\gamma$-rays.

A pulse of low-frequency radio emission is strongly affected by intergalactic plasma dispersion in the process of its propagation. At the frequency $\nu$, the radio pulse retardation time with respect to a GRB is

$$\tau(\nu) = \frac{D}{v} - \frac{D}{c} = \frac{e^2}{2\pi n_e c \nu^2} \int n_e \, dl \simeq 1.34 \times 10^{-3} \frac{\int n_e \, dl}{\nu^2} \, \text{s},$$

where $\int n_e \, dl$ is the intergalactic dispersion measure in electrons/cm$^2$, $v = cn$ is the group velocity of radio emission, $n = 1 - (e^2 n_e / 2\pi m_e c^2 \nu^2)$ is the refractive index and $\nu$ in Hz. From equation (9), for the plausible parameters of $n_e \simeq 10^{-6}$ cm$^{-3}$ and a distance of $10^{28}$ cm, at $\nu = 30$ MHz we have $\tau(\nu) \approx 10^4$ s. This is time enough to steer a radio telescope for the radio pulse detection. In equation (9), we neglected the radio pulse retardation time in our Galaxy, which is typically one or two orders of magnitude less than that in the intergalactic gas.

The observed duration of the low-frequency pulse at the frequency $\nu$ in the bandwidth
\( \Delta \nu \) is

\[
\Delta t_{\text{obs}}(\nu, \Delta \nu) = \max [\Delta t_r, 2(\Delta \nu/\nu)\tau(\nu)].
\]

(10)

For plausible parameters, \( \nu \sim 30 \text{ MHz} \), \( \Delta \nu \sim 1 \text{ MHz} \), \( \tau(\nu) \sim 10^4 \text{ s} \) and \( \Delta t_r \sim 1 - 10^2 \text{ s} \), we have \( \Delta t_{\text{obs}}(\nu, \Delta \nu) \sim 7 \times 10^2 \text{ s} \); the observed duration of low-frequency radio pulses is determined by intergalactic plasma dispersion, except for extremely long GRBs.

It is now possible to estimate, given assumed values for the magnetic field, the amplitude of the signal produced. We also assume that the plasma field couples efficiently to the free space radiation field. For a radio fluence \( E_R = \delta E_{\text{GRB}} \) and a radio fluence spectral density

\[
E_\nu = \begin{cases} 
0 & \text{for } \nu < \nu_{\text{max}} , \\
\frac{\beta - 1}{\nu_{\text{max}}} (\frac{\nu}{\nu_{\text{max}}})^{-\beta} E_{\text{GRB}} & \text{for } \nu \geq \nu_{\text{max}} ,
\end{cases}
\]

(11)

the radio spectral flux density is

\[
F_\nu = \begin{cases} 
\frac{\delta(\beta - 1)}{\Delta t_r \nu_{\text{max}}} (\frac{\nu}{\nu_{\text{max}}})^{-\beta} E_{\text{GRB}} & \text{for } \frac{2\Delta \nu}{\nu} \tau(\nu) < \tau_r , \\
\frac{\delta(\beta - 1)}{2\Delta \nu \tau(\nu)} (\frac{\nu}{\nu_{\text{max}}})^{1-\beta} E_{\text{GRB}} & \text{for } \frac{2\Delta \nu}{\nu} \tau(\nu) \geq \tau_r .
\end{cases}
\]

(12)

For the latter (dispersion-limited) case with the parameters \( E_{\text{GRB}} = 10^{-4} \text{ erg cm}^{-2} \), \( \delta = 0.1\epsilon_B \), \( \beta = 1.6 \), \( \nu_{\text{max}} = 0.3 \text{ MHz} \), \( \nu = 30 \text{ MHz} \), \( \Delta \nu = 1 \text{ MHz} \), \( \tau(\nu) = 10^4 \text{ s} \) we find \( F_\nu \approx 2 \times 10^6 \epsilon_B(\beta+1)/2 \text{ Jy} \).

The appropriate value of \( \epsilon_B \) is very uncertain. In some models it may be \( O(1) \), but for GRB with sharp subpulses its value is limited by the requirement that the magnetic stresses not disrupt the thinness of the colliding shells (Katz 1997). For subpulses of width \( \zeta \) of the GRB width this suggests \( \epsilon_B < \zeta^2 \); typical estimates are \( \zeta \sim 0.03 \) and \( \epsilon_B < 10^{-3} \), leading to \( F_\nu \lesssim 10^2 \text{ Jy} \).

These large values of \( F_\nu \) may be readily detectable, although the assumed values of \( \epsilon_B \) are very uncertain. There are additional uncertainties. We have assumed that the radio pulse spectrum (11) is valid up to a frequency \( \nu \sim 30 \text{ MHz} \) that may be hundreds of times higher than \( \nu_{\text{max}} \). As discussed above, the spectrum (11) of low-frequency waves is calculated directly only at \( \nu \lesssim 10\nu_{\text{max}} \). At \( \nu > 10\nu_{\text{max}} \), the spectrum must be extrapolated, with unknown confidence, from the calculations. The radio spectral flux density at \( \nu \sim 30 \text{ MHz} \) may therefore be less than the preceding estimates. However, even in this case the very high sensitivity of measurements at radio frequencies may permit the detection of coherent low-frequency radio emission from GRB.
4. Discussion

In this Letter, we have shown that GRBs may be accompanied by very powerful short pulses of low-frequency radio emission. For detection of these radio pulses it may be necessary to perform observations at lower frequencies than are generally used in radio astronomy, which are limited by the problem of transmission through and refraction by the ionosphere. In particular, observations from space are free of ionospheric refraction and are shielded by the ionosphere from terrestrial interference. Although even harder to predict, detection from the ground at higher frequencies may also be possible.

Space observations are possible at frequencies down to that at which the interstellar medium becomes optically thick to free-free absorption. This frequency is

$$\nu_{\text{abs}} = 1.0 \times 10^{6} \left( \frac{n_{e,0.03}}{T_{3}^{5/2}} \right)^{1/2} | \csc b^{II}|^{1/2} \text{ Hz}, \quad (13)$$

where \( n_{e,0.03} \equiv n_{e}/(0.03 \text{ cm}^{-3}) \) and \( T_{3} \equiv T / 10^{3} \text{K} \) \(^{[\text{Spitzer 1962}]\). \( n_{e} \) and \( T \) are the interstellar electron density and temperature, respectively, and \( b^{II} \) is the Galactic latitude. The expression \( \langle \rangle \) may be \( O(1) \), but could be substantially larger if the electrons are strongly clumped or cold. On the other hand, although much of the interstellar volume is filled with very hot \( (10^{6}\text{ K}) \) and radio-transparent gas, this probably contains very little of the electron column density. Intergalactic absorption poses a somewhat less restrictive condition if the medium is hot \( (10^{6}\text{ K}) \), as generally assumed.

At these low frequencies, and even at tens of MHz, interstellar scintillation \(^{[\text{Goodman 1997}]\)} will be very large. Observations of coherent radio emission from GRB would not only illuminate the physical conditions in their radiating regions, but would determine (through the dispersion measure) the mean intergalactic plasma density and (through the scintillation) its spatial structure.

The flux density implied by Eq. \( (12) \) appears impressively large, but it applies only to the brief period when the dispersed signal is sweeping through the bandwidth \( \Delta \nu \) of observation, so that it is unclear if it is, in fact, excluded by the very limited data \(^{[\text{Cortiglioni et al. 1981}]\)} available. Further, the extrapolation of the radiated spectrum to \( \nu \gg \nu_{\text{max}} \) is very uncertain. Finally, we have also not considered the (difficult to estimate) temporal broadening of this brief transient signal by intergalactic scintillation, which will both reduce its amplitude and broaden its time-dependence.

Searches for radio pulses started about 50 years ago, prior to the discovery of GRBs. During wide beam studies of ionospheric scintillations, simultaneous bursts at 45 MHz of 10 – 20 s duration were reported by Smith (1950) at sites 160 km apart. These events
were detected at night, approximately once a week. The origin of these bursts was never determined. The results of Smith (1950) were not confirmed by subsequent observations at frequencies of 150 MHz or higher.

Modern observations (Dessenne et al. 1996 at 151 MHz; Balsano et al. 1998 at 74 MHz; Benz & Paesold 1998 broadband; see Frail 1998 for a review) set upper bounds to the brightnesses of some GRB at comparatively high frequencies. These bounds are not stringent, and do not exclude extrapolations of the lower frequency fluxes suggested here. There are few data at lower frequencies.

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Table 1: Derived parameters of simulations for both high-energy electron Lorentz factor $\Gamma_{\text{out}}^e$ and low-frequency electromagnetic wave amplitudes $B_w$ and their power ratio $\delta$ in the region ahead of the wind front

| $\alpha$ | $\langle \Gamma_{\text{out}}^e \rangle / \Gamma_0$ | $\langle B^2 \rangle / B_0^2$ | $\delta$   |
|----------|---------------------------------------------|---------------------------|-----------|
| 0.2      | 9.5                                         | $10^{-5}$                 | 0.017     |
| 0.3      | 37                                          | $1.4 \times 10^{-4}$      | 0.048     |
| 0.4      | 396                                         | 0.021                     | 0.49      |
| 0.5      | 339                                         | 0.02                       | 0.42      |
| 0.57     | 296                                         | 0.011                     | 0.24      |
| 0.67     | 276                                         | 0.008                     | 0.16      |
| 1        | 214                                         | 0.005                     | 0.084     |
| 1.33     | 137                                         | $1.6 \times 10^{-3}$      | 0.032     |
| 2        | 75                                          | $4.4 \times 10^{-4}$      | 0.01      |
| 4        | 47                                          | $1.2 \times 10^{-4}$      | 0.0024    |

Note. — The accuracy of the derived parameters is $\sim 20\%$ at $0.4 \lesssim \alpha \lesssim 2$ and decreases out of this range of $\alpha$. 
FIGURE CAPTION

Fig. 1. Power spectrum of low-frequency electromagnetic waves generated at the front of the wind in the wind frame in a simulation with $B_0 = 300$ G, $\Gamma_0 = 300$, and $\alpha = 2/3$. The spectrum is fitted by a power law (dashed line).
