

# Low frequency radio pulses from gamma-ray bursts?

V.V. Usov<sup>1</sup> and J.I. Katz<sup>2</sup>

<sup>1</sup> Weizmann Institute of Science, Department of Condensed-Matter Physics, Rehovot 76100, Israel

<sup>2</sup> Washington University, Department of Physics and McDonnell Center for the Space Sciences, St. Louis, Mo. 63130, USA

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**Abstract.** Gamma-ray bursts, if they are generated by relativistic strongly magnetized winds, 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 tens of MHz and be detected, especially if the strength of the magnetic field of the wind is extremely high.

**Key words:** magnetic fields – radiation mechanisms: non-thermal – shock waves – gamma rays: bursts – radio continuum: stars

## 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 et al. 1993; Baring & 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; Wheeler et al. 2000). 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 Smolksy & Usov (1996, 2000) and Usov & Smolksy (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 non-stationarity 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 GRBs 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, 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 et al. 1996; Katz 1997; Kluźniak & Ruderman 1998; Spruit 1999; Wheeler 1999; Woosley 1999; Ruderman, Tao, & Kluźniak 2000).

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,  $\Gamma_0 \simeq 10^2 - 10^3$  (e.g., Usov 1994). The wind structure at a time  $t \gg \tau_\Omega$  is similar to a shell with radius  $r \simeq ct$  and thickness of  $\sim c\tau_\Omega$ , where  $\tau_\Omega$  is the characteristic deceleration time of the compact object's rotation, or the dissipation time of a transient accretion disc.

Send offprint requests to: V.V. Usov

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

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

where  $R \simeq 10^6$  cm is the radius of the compact object,  $\Omega \simeq 10^4 \text{ s}^{-1}$  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. Eq. (1) gives the real value of  $B$  at the wind front if both the magnetic field of the compact object is strictly dipolar and the thickness of the wind shell does not increase essentially in the process of the shell outflow.

The distance at which deceleration of the wind due to its interaction with an ambient gas becomes important is (Mészáros & Rees 1992; Piran 1999)

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

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 Eq. (1), we have the following estimate for the magnetic field at the wind front at  $r \sim r_{\text{dec}}$ :

$$B_{\text{dec}} \simeq 10^4 \epsilon_B^{1/2} \left( \frac{B_s}{10^{16} \text{ G}} \right) \left( \frac{\Omega}{10^4 \text{ s}^{-1}} \right)^2 \times \left( \frac{Q_{\text{kin}}}{10^{53} \text{ ergs}} \right)^{-1/3} \left( \frac{n}{1 \text{ cm}^{-3}} \right)^{1/3} \left( \frac{\Gamma_0}{10^2} \right)^{2/3} \text{ G}, \quad (3)$$

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,  $B_s \simeq 10^{16}$  G,  $\Omega \simeq 10^4 \text{ s}^{-1}$ ,  $Q_{\text{kin}} \simeq 10^{53}$  ergs,  $\Gamma_0 \simeq 10^2 - 10^3$  and  $n \sim 1 \text{ cm}^{-3}$ , from Eq. (3) we have  $B_{\text{dec}} \simeq (1 - 5) \times 10^4 \epsilon_B^{1/2}$  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 Eq. (3), for typical parameters of cosmological  $\gamma$ -ray bursters we have  $B_0 \simeq (0.5 - 1) \times 10^2 \epsilon_B^{1/2}$  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

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

$\alpha$	$\langle \Gamma_e^{\text{out}} \rangle$	$\langle B_w^2 \rangle$	$\delta$
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

The accuracy of the derived parameters is  $\sim 20\%$  at  $0.4 < \alpha < 2$  and decreases out of this range of  $\alpha$ .

ratio of the energy densities of the ambient gas and the magnetic field,  $B_0$ , of the wind

$$\alpha = 8\pi n_0 m_p c^2 (\Gamma_0 - 1) / B_0^2, \quad (4)$$

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,  $r \ll r_{\text{dec}}$ ,  $\alpha$  is  $\ll 1$ , but it increases in the process of the wind expansion as  $B_0$  decreases. At  $r \sim r_{\text{dec}}$ , when  $\alpha$  is more than  $\alpha_{\text{cr}} \simeq 0.4$ , the interaction between the wind and the ambient gas is strongly non-stationary, and effective acceleration of electrons and generation of low-frequency waves at the wind front both begin (Smolsky & Usov 1996, 2000; Usov & Smolsky 1998). For  $\alpha_{\text{cr}} < \alpha < 1$ , the mean Lorentz factor of outflowing high-energy electrons  $\Gamma_e^{\text{out}}$  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

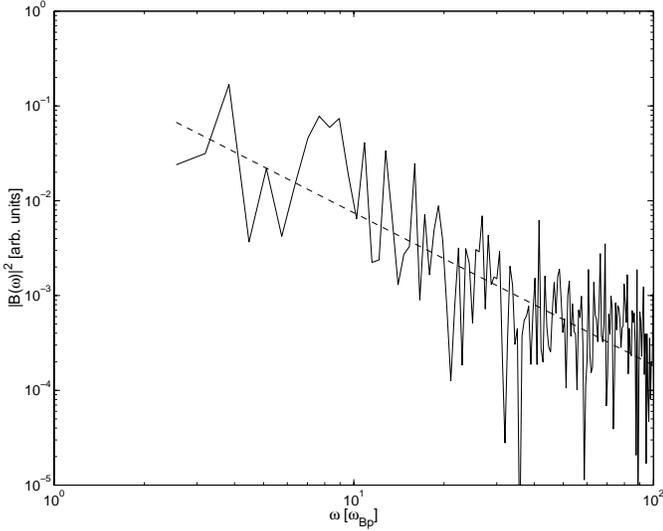
$$\langle \Gamma_e^{\text{out}} \rangle \simeq 0.2 (m_p/m_e) \Gamma_0, \quad (5)$$

$$\langle B_w \rangle = (\langle B_z \rangle^2 + \langle E_y \rangle^2)^{1/2} \simeq 0.1 B_0 \quad (6)$$

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.

Fig. 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  $\omega'_{\text{max}}$  which is about three times higher than the proton gyrofrequency  $\omega_{Bp}$  in the wind field  $B_0$ :

$$\omega'_{\text{max}} \simeq 3\omega_{Bp} = 3 \frac{eB_0}{m_p c \Gamma_0}. \quad (7)$$



**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).

### 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  $l_\gamma \simeq m_e c^3 n \langle \Gamma_e^{\text{out}} \rangle$  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

$$\delta = \frac{l_w}{l_\gamma} = \frac{2 m_p \langle B_w \rangle^2}{\alpha m_e B_0^2} \frac{\Gamma_0}{\langle \Gamma_e^{\text{out}} \rangle}. \quad (8)$$

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  $\tau_r$  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).

From Eq. (7), 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

$$\begin{aligned} \nu_{\text{max}} &\simeq \frac{2\Gamma_0}{1+z} \frac{\omega'_{\text{max}}}{2\pi} \simeq \frac{eB_0}{(1+z)m_p c} \\ &\simeq \frac{1}{1+z} \left( \frac{B_0}{10^2 \text{ G}} \right) \text{ MHz}, \end{aligned} \quad (9)$$

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  $\nu_{\text{max}} \simeq (0.2 - 0.5) \epsilon_B^{1/2}$  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 (Smolksy & Usov 2000):

$$|B(\nu)|^2 \propto \nu^{-\beta}, \quad (10)$$

where  $\beta \simeq 1.6$  (see Fig. 1). In the simulations of the wind—ambient gas interaction (Smolksy & Usov 1996, 2000; Usov & Smolksy 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 (10) is measured reliably only at  $\nu < 10\nu_{\text{max}}$ . The amplitudes of the computed oscillations with  $\nu > 10\nu_{\text{max}}$  are so small ( $< (0.2 - 0.3) \langle B_w \rangle$ ) that they cannot be distinguished from computational noise (Smolksy & 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,  $\nu_{\text{max}} \simeq (0.2 - 0.5) \epsilon_B^{1/2}$  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

$$\tau(\nu) = \frac{D}{v} - \frac{D}{c} = \frac{e^2 \int n_e dl}{2\pi m_e c \nu^2} \simeq 1.3 \times 10^{-3} \frac{\int n_e dl}{\nu^2} \text{ s}, \quad (11)$$

where  $\int n_e dl$  is the intergalactic dispersion measure in electrons/cm<sup>2</sup>,  $v = cn$  is the group velocity of radio emission,  $n = 1 - (e^2 n_e / 2\pi m_e \nu^2)$  is the refractive index and  $\nu$  in Hz. From Eq. (11), for the plausible parameters of  $n_e \simeq 10^{-6}$  cm<sup>-3</sup> and a distance of  $10^{28}$  cm, at  $\nu = 30$  MHz we have  $\tau(\nu) \simeq 10^4$  s. This is time enough to steer a radio telescope for the radio pulse detection. In Eq. (11), 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

$$\tau_{\text{obs}}(\nu, \Delta\nu) = \max[\tau_r, 2(\Delta\nu/\nu)\tau(\nu)]. \quad (12)$$

For plausible parameters,  $\nu \sim 30$  MHz,  $\Delta\nu \sim 1$  MHz,  $\tau(\nu) \sim 10^4$  s and  $\tau_r \sim 1 - 10^2$  s, we have  $\tau_{\text{obs}}(\nu, \Delta\nu) \sim 7 \times 10^2$  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  $\Phi_r = \langle \delta \rangle \Phi_\gamma$  and a radio fluence spectral density

$$\Phi_\nu = \begin{cases} 0 & \text{for } \nu < \nu_{\max}, \\ \frac{\beta-1}{\nu_{\max}} \Phi_r \left( \frac{\nu}{\nu_{\max}} \right)^{-\beta} & \text{for } \nu \geq \nu_{\max}, \end{cases} \quad (13)$$

the radio spectral flux density is

$$F_\nu = \begin{cases} \frac{\langle \delta \rangle (\beta-1)}{\tau_r \nu_{\max}} \left( \frac{\nu}{\nu_{\max}} \right)^{-\beta} \Phi_\gamma & \text{for } \frac{2\Delta\nu}{\nu} \tau(\nu) < \tau_r, \\ \frac{\langle \delta \rangle (\beta-1)}{2\Delta\nu \tau(\nu)} \left( \frac{\nu}{\nu_{\max}} \right)^{1-\beta} \Phi_\gamma & \text{for } \frac{2\Delta\nu}{\nu} \tau(\nu) \geq \tau_r, \end{cases} \quad (14)$$

where  $\Phi_\gamma$  is the GRB fluence in  $\gamma$ -rays and  $\langle \delta \rangle \simeq 0.1\epsilon_B$  is the mean value of  $\delta$ . For the latter (dispersion-limited) case with the parameters  $\Phi_\gamma = 10^{-4}$  erg cm $^{-2}$ ,  $\beta = 1.6$ ,  $\nu_{\max} = 0.3$  MHz,  $\nu = 30$  MHz,  $\Delta\nu = 1$  MHz,  $\tau(\nu) = 10^4$  s we find  $F_\nu \approx 2 \times 10^6 \epsilon_B^{(\beta+1)/2}$  Jy.

The appropriate value of  $\epsilon_B$  is very uncertain. In some models it may be  $O(1)$ , but in internal shock models 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  $F_\nu < 10^2$  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 (13) is valid up to a frequency  $\nu \simeq 30$  MHz that may be hundreds of times higher than  $\nu_{\max}$ . As discussed above, the spectrum of low-frequency waves is calculated directly only at  $\nu < 10\nu_{\max}$ . At  $\nu > 10\nu_{\max}$ , the spectrum must be extrapolated, with unknown confidence, from the calculations. The radio spectral flux density at  $\nu \simeq 30$  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 GRBs.

#### 4. Discussion

In this paper, we have shown that GRBs may be accompanied by very powerful short pulses of low-frequency radio emission. In our consideration we based on recent simulations of interaction between a relativistic, strongly magnetized wind and an ambient gas (Smolsky & Usov 1996, 2000; Usov & Smolsky 1998). In these simulations it was shown that particles of the ambient gas are reflected from the wind front, and outflowing electrons may be accelerated up to the energy of protons. These electrons may be responsible for the non-thermal emission of GRBs. The current that separates the strongly magnetized matter of the outflowing wind and the ambient gas where the magnetic field strength is negligible varies in time because of nonstationarity of the wind-ambient gas interaction and generates low-frequency waves. The high-frequency tail of these waves may reach a few tens of MHz and be detected.

High-energy particles reflected from the wind front interact with the ambient gas. This interaction is a very poor studied process. There are two possibilities. The first possibility assumed

in the GRB model of Smolsky & Usov (1996, 2000) is that a collisionless shock does not form ahead of the wind front, and the wind front interacts with the ambient gas during all time of GRB generation. In this case, the undispersed duration of a low-frequency radio pulse is of the order of the GRB duration (see above). The second possibility is that a collisionless shock forms ahead of the wind front as it is assumed in the standard external shock model of GRBs (for a review, see Piran 1999). If the last is true, simulations of Smolsky & Usov (1996, 1998, 2000) relate only to the first stage of the wind-ambient gas interaction when the shock is only forming. In this case, the undispersed duration of a low-frequency radio pulse is about the characteristic time of the shock formation and may be much shorter than the GRB duration. Therefore, observations of such radio pulses may be used for diagnostics of interaction between a relativistic strongly magnetized wind and an ambient gas.

It is noted above that our mechanism for production of short pulses of low-frequency radio emission applies very generally. All GRBs generated by relativistic, strongly magnetized winds may be accompanied by short pulses of low-frequency radio emission irrespective of the mechanism of GRB generation. In the case, for example, if the GRB radiation (or its main part) is produced by internal shocks (e.g., Piran 1999 and references therein), not all energy of the outflowing wind is converted to  $\gamma$ -rays. At the distance  $r_{\text{dec}}$  the process of the wind deceleration becomes essential, and a short low-frequency radio pulse may be generated as we discuss.

For detection of short low-frequency 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.

The possibility of detecting of a coherent radio pulse generated in the initial explosion of a supernova has been discussed in (Colgate 1975; Meikle & Colgate 1978 and references therein). However, the mechanism for the production of such a pulse is entirely different from that of our paper.

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

$$\nu_{\text{abs}} = 1.0 \times 10^6 \left\langle \frac{n_{0.03}^2}{T_3^{3/2}} \right\rangle^{1/2} |\csc b^{II}|^{1/2} \text{ Hz}, \quad (15)$$

where  $n_{0.03} \equiv n_e / (0.03 \text{ cm}^{-3})$  and  $T_3 \equiv T / 10^3 \text{ K}$  (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. In fact, determination of  $\nu_{\text{abs}}$  by space measurements of interstellar absorption of bright extragalactic radio sources is a useful probe of the spatial and thermal structure of the interstellar electron gas, giving information which cannot be obtained from dispersion measure and

scintillation studies alone. The frequency dependences of interstellar inverse bremsstrahlung absorption and self-absorption at the source are quite different, so these two processes should be distinguishable in accurate data obtained at several well-chosen frequencies.

Much of the interstellar volume is filled with very hot ( $10^6$  °K) and radio-transparent gas. Pressure balance arguments suggest that this has a very low density ( $< 10^{-3}$  cm $^{-3}$ ) and probably contains very little of the electron column density. Most of the interstellar dispersion must be attributed to denser and more radio-opaque regions. Intergalactic absorption poses a somewhat less restrictive condition than interstellar absorption because of the likely high temperature ( $10^6$  °K), and low density of intergalactic gas.

At the low frequencies we suggest for observations of coherent radio emission from GRBs, and even at tens of MHz, interstellar scintillation (Goodman 1997) will be very large. Successful observations of this emission would not only illuminate the physical conditions in the 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. (14) 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 (Cortiglioni 1981) available. Further, the extrapolation of the radiated spectrum to  $\nu \gg \nu_{max}$  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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