GAMMA-RAY BURSTS FROM
BLAST WAVES AROUND GALACTIC NEUTRON STARS

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Submitted to M.N.R.A.S. Pink Pages, Aug. 4, 1993; in press.

ABSTRACT

1. INTRODUCTION

The remarkable isotropy of classical gamma-ray bursts (GRBs) sampled by the BATSE instrument on GRO (Meegan et al. 1992; Fishman et al. 1993) requires their sources to be located at cosmological distances, in an extended halo of the Galaxy, or in a more local distribution ($\lesssim 1 - 2$ Kpc) which contrives to be almost isotropic about us. Many authors have attributed "galactic" bursts to violent disturbances in the magnetospheres of neutron stars (e.g., Blaes et al. 1990; Ramaty et al. 1981); however, the details of the emission mechanisms have generally been left unspecified. While the tenuous plasma filling the magnetosphere may be responsible for much of the high-energy radiation, any disturbance of the kind proposed is also likely to expel magnetic flux and plasma into the interstellar medium (ISM) surrounding the neutron star, possibly at relativistic speed. In this Note, we point out that the blast wave driven into the ISM by a magnetospheric disturbance could also produce a flash of gamma-rays with the characteristics observed to be typical of GRBs. We tentatively associate these two modes of emission with the short/variable and long/smooth subgroups of bursts, respectively, which have recently been identified through analyses of BATSE data (Kouveliotou et al. 1993; Lamb, Graziani, & Smith 1993). Moreover, bursts associated with emission from blast waves would become more conspicuous in the gamma-ray band when they occur in a denser environment, thus providing a possible explanation for modulation associated with spiral arm structure, as has been claimed by Quashnock & Lamb (1993).

2. INTERSTELLAR ENVIRONMENT OF AN ISOLATED NEUTRON STAR

Although neutron stars are believed to begin their lives in the rarefied stellar wind bubbles and supernova remnants created by their progenitor stars, within about $10^5$ yr they will be interacting with the general ISM (Shull, Fesen, & Saken 1989). Even for modest values of the surface dipole field $10^{11} B_{11}$ G and spin period $P$ s, electromagnetic forces will prevent the ambient interstellar gas (of density $n_\infty$) from reaching the surface of the neutron star. When gravitational focusing is unimportant, the dipole spindown energy loss will create a standoff bow shock in the ISM with a radius

$$r_W \sim 8 \times 10^{13} \frac{B_{11}}{P^2 v_{100} n_\infty^{1/2}} \text{ cm},$$

where $v_{100}$ is the propagation speed of the blast wave in units of $10^3$ cm/s. The standoff distance is also given by (1).
where $100v_{100}$ km s$^{-1}$ is the (supersonic) speed of the neutron star through the ISM and we have assumed a neutron star radius of 10 km. Such bow shocks have recently been observed in optical (Cordes, Romani, & Lundgren 1993) and X-ray (Wang, Li, & Begelman 1993) emission. If $R_W$ shrinks inside the Bondi radius

$$r_B = 1.3 \times 10^{12} m v_{100}^{-2} \text{ cm},$$

(2)

(where $m$ is the mass in solar units), then gravitational focusing will cause the standoff distance to collapse to the so-called Alfvén radius,

$$r_A \sim 2 \times 10^{10} B_{11}^{4/7} n_\infty^{-2/7} v_{100}^{6/7} \text{ cm},$$

(3)

where we have assumed that the density varies as $n_\infty (r/r_B)^{-3/2}$ inside $r_B$. Accretion onto the surface of the neutron star will then occur only if the corotation speed at $r_A$ is smaller than the local Keplerian speed, corresponding to

$$P > 10^3 B_{11}^{6/7} n_\infty^{-3/7} v_{100}^{9/7} \text{ s};$$

(4)

otherwise, the gas will be prevented from accreting by the “propeller mechanism” (Illar-ionov & Sunyaev 1975). Thus, only a very old (slowly rotating and weakly magnetized) neutron star is capable of accreting from the ISM. Otherwise, $r_W$ or $r_A$ demarcates the boundary between the relatively dense circumstellar ISM and the near-vacuum “magneto-spheric region”.

The arguments given above apply only in the fluid limit. Since $n_\infty \lesssim 10$ cm$^{-3}$ typically (except during relatively rare passages through molecular cloud complexes), the column density of ISM spanning $r_B$ is usually less than $10^{14}$ cm$^{-2}$. The typical cross section for inelastic collisions between neutrals is $\sim 10^{-16}$ cm$^2$ and that between neutrals and ions, due to charge exchange, can be an order of magnitude larger. Thus, if the ISM is predominantly neutral at $r_B$ it will behave like a collisionless gas rather than a fluid (Begelman 1977), unless the timescale for photoionization is shorter than the dynamical time. Collisional ionization will be unimportant at the densities and particle energies likely to be present. The density inside $r_B$ will then scale as $r^{-1/2}$, giving an inward matter flux $\propto r$. If there are no other UV sources, the photoionization time scale will be very sensitive to the surface temperature of the neutron star; temperatures exceeding $\sim 10^5$ K should be sufficient to ensure fluid-like behavior. If ionization is weak, the neutral component of the ISM will be able to penetrate the pulsar wind and outer magnetosphere, and may couple to the magnetic field much closer to the neutron star, with implications for the spindown rate and wind properties of isolated pulsars. However, hard photons emitted either in the reverse shock within the pulsar wind, or in the ISM bow shock, may also preionize the neutrals, leading to a self-consistent fluid-like structure. There could also be circumstances where the burst itself might photoionize the ISM before (or immediately after) the blast wave hits it. The importance of this effect depends on how much UV comes out of the
burst. To take a numerical example (from which one can do simple scaling) suppose that the burst emits a few times $10^{35}$ ergs of energy in the XUV. This corresponds to about $10^{46}$ photons which, at a radius of order $10^{13}$ cm, corresponds to a flux of about $10^{19}$ cm$^{-2}$. Since the photoionization cross section is about $10^{-17}$ cm$^2$, most neutral atoms would be ionized by this passing shell of photons, and would be swept up by the relativistic flow.

3. RADIATIVE PROPERTIES OF BLAST WAVES

Suppose an amount of energy $E_0 \sim 10^{39} E_{39}$ ergs is released in a medium of number density $n(r)$ cm$^{-3}$, where $r$ is the distance from the source of the energy. This release may be assumed to be impulsive if it occurs over a time shorter than typical dynamical time scales in the subsequent flow. The initial energy produces a highly relativistic fluid, with Lorentz factor $\eta$, if the mass $M_0$ initially released along with the energy satisfies $E_0/M_0 c^2 \equiv \eta \gg 1$. After an amount $\eta^{-1} M_0$ of external mass has been swept up a blast wave forms ahead of the ejecta, which starts to decelerate. In this decelerating regime, if radiation were inefficient the bulk Lorentz factor of the blast wave, after having reached the value $\Gamma \simeq \eta$, would vary with radius according to

$$\Gamma \sim \left( \frac{3E_0}{4\pi m_pc^2nr^3} \right)^{1/2}. \quad (5)$$

The blast wave, however, may radiate away enough of its energy in a sufficiently short time scale to be of interest for explaining GRBs. The most promising radiation mechanism is nonthermal synchrotron radiation by relativistic electrons accelerated at the shock front which propagates into the ISM, or present in the reverse shock which slows the ejecta (Mészáros, Laguna, & Rees 1993). The former can occur if the magnetic energy density is amplified behind the shock front (due to turbulent shear, etc.) to a significant fraction ($\lambda$) of equipartition with respect to the shocked ambient gas. In the latter case, magnetic domination is virtually guaranteed by the nature of the flow. If the synchrotron radiative efficiency approaches one, the synchrotron-self-Compton losses also become important. However, for Galactic bursts, synchrotron is probably responsible for most of the photons below 100 MeV, and detectable fluences can be obtained even with efficiencies as small as $10^{-3}$.

In the comoving frame, the magnetic field is given by

$$B' \sim 0.3\lambda^{1/2} n^{1/2} \Gamma \text{ G.} \quad (6)$$

To produce synchrotron photons of observed (Doppler-boosted) energy $\varepsilon_{MeV}$ MeV requires that electrons be accelerated to random Lorentz factors (in the fluid frame) $\gamma$ such that

$$\gamma \Gamma \sim 2.6 \times 10^7 (\lambda n)^{-1/4} \varepsilon_{MeV}^{1/2}. \quad (7)$$

This is several orders of magnitude higher than the mean Lorentz factor per electron, $\sim (m_p/m_e) \Gamma$, which would apply if energy were shared equally among all particles behind
the shock. However, such an unequal distribution of energies is expected from models of Fermi acceleration behind strong shocks, which predict that a significant fraction of the shock energy can be pumped into the upper end of the relativistic electron energy distribution (Ellison & Reynolds 1991). The synchrotron radiative efficiency of electrons accelerated in the blast wave, as a function of $\gamma$ and $r$, is given by $\epsilon_{\text{rad}} \sim \min[1, t'_\text{exp}/t'_\text{syn}]$, where $t'_\text{exp} \sim r/c\Gamma$ is the expansion timescale of the blast wave and $t'_\text{syn} \sim 4\pi m_e c/\sigma_T (B')^2\gamma$ is the synchrotron cooling time, both measured in the comoving frame. Substituting from equations (6) and (7), we have

$$t'_\text{exp}/t'_\text{syn} \sim 1.5 \times 10^{-13}(\lambda n)^{3/4} r^{1/2}_M \epsilon_{\text{MeV}}^{1/2}. \quad (8)$$

Thus, for blast wave radii $\gtrsim 10^{13}$ cm and typical interstellar conditions $n \sim 1$ cm$^{-3}$, the emission of synchrotron radiation at energies above 1 MeV can be highly efficient.

The radiative efficiency of the blast wave at a given photon energy is controlled by the particle acceleration process, many details of which are uncertain. The maximum energy reached by electrons is probably dictated by a balance between the acceleration and cooling time scales. If we assume that shock acceleration to a Lorentz factor $\gamma$ requires $100\zeta$ gyro-orbital times, then the maximum synchrotron photon energy coming from the blast wave is given by

$$\epsilon_{\text{max}} \sim 0.4\zeta^{-1} \Gamma \text{MeV}. \quad (9)$$

Note that $\epsilon_{\text{max}}$ is independent of assumptions about the magnetic field strength, but does depend on the highly uncertain shock acceleration rate through $\zeta$. The overall radiative losses from the blast wave are also affected by the fraction of shock energy that goes into relativistic electrons, as a function of radius. If this is a fixed fraction of the energy dissipated in the shock, say, $dE/dr \sim -\mu E/r$, then the total energy in the blast wave will decrease as $E(r) \sim E_0(r/r_0)^{-\mu}$, where $r_0$ is the radius at which the shock starts decelerating. The bulk Lorentz factor is then given by eq. (5) with $E(r)$ replacing $E_0$. Photons of energy $\epsilon$ will come predominantly from inside the radius at which $\epsilon \sim \epsilon_{\text{max}}$, i.e., where the blast wave has slowed to $\Gamma \sim 2.5\zeta \epsilon_{\text{MeV}}$. In the limit $\mu \ll 1$, this radius is given by $r_{\text{max}} \sim 3 \times 10^{13}(E_{39}/n\zeta^2)^{1/3} \text{cm}$, corresponding to a maximum burst duration of $\Delta t_{\text{max}} \sim r/c\Gamma^2 \sim 160(E_{39}/n)^{1/3} \zeta^2 \epsilon_{\text{MeV}}^{-8/3} \text{s}$. This estimate suggests that the maximum burst duration might be anticorrelated with energy of the observing band. Note, however, that the extreme sensitivity to $\zeta$ makes it difficult to extract useful numerical estimates from this formula.

If the blast wave begins to decelerate at radii much smaller than $r_{\text{max}}$, a significant flux at energies $\sim \epsilon$ could emerge on shorter timescales. A rough estimate for a minimum timescale would correspond to the radius at which the synchrotron radiative efficiency (eq. [8]) first approaches unity, $r_{\text{rad}} \sim 6.7 \times 10^{12}(\lambda n)^{-3/4} \epsilon_{\text{MeV}}^{-1/2} \text{cm}$. The Lorentz factor of the blast wave at this radius (for $\mu \ll 1$) is $\Gamma_{\text{rad}} \sim 23(E_{39}/n)^{1/2}(\lambda n)^{9/8} \epsilon_{\text{MeV}}^{3/4}$ and the characteristic timescale is $\Delta t_{\text{rad}} \sim 0.4E_{39}^{-1} \lambda^{-3} n^{-2} \epsilon_{\text{MeV}}^{-2} \text{s}$. A necessary condition for the
blast wave to radiate efficiently at energy $\varepsilon$ is that $r_{\text{rad}} < r_{\text{max}}$, which is equivalent to the condition

$$n > 0.03 E_{39}^{-4/5} \lambda^{-9/5} \xi^{8/5} \varepsilon_{\text{MeV}}^{2/5} \text{cm}^{-3}. \quad (10)$$

While the numerical values of the parameters in eq. (10) are very uncertain, the condition suggests a correlation between burst efficiency (and therefore detectability) and the density of the ambient ISM.

### 4. INFERENCES FROM BURST STATISTICS

If bursts repeat on a timescale of order $t_r$ years, then the local population of bursters comprises of order $10^4 t_r$ neutron stars. Given a Galactic pulsar birthrate of $\sim 10^{-11} \text{ pc}^{-2} \text{ yr}^{-1}$ (Narayan and Ostriker 1990), the mean age of a bursting neutron star is $t_{\text{burst}} \sim 10^7 R_{\text{kpc}}^3 (t_r/f) \text{ yr} \equiv 10^{10} t_{10} \text{ yr}$, where $R_{\text{kpc}}$ is the mean distance to bursts in kpc and $f$ is the fraction of the time during which the deposition of burst energy in the ISM would lead to a detectable burst. Since the dipole spindown time of a pulsar is $\sim 10^9 P^2 B_{11}^{-2} \text{ yr}$, the typical spin period of neutron stars responsible for the local bursts would be $\sim 3 B_{11} t_{10}$ s. If $t_{10} < 3 (v_{100}/B_{11})^{1/2} n_{10}^{-1/2}$, these pulsars would still be producing wind-driven bow shocks in the ISM, and would not be accreting interstellar gas.

The contact discontinuity between the shocked pulsar wind and the ISM would be located at $r_W \sim 10^{13} B_{11}^{-1} t_{10}^{-1} v_{100}^2 n_{10}^{-1/2} \text{ cm}$. This number is smaller than $r_{\text{max}}$ for 1 MeV photons provided that $B_{11} t_{10} n^{1/2} > 0.3$, suggesting that detectable bursts from blast waves would come primarily from a relatively old population of pulsars, $t_{\text{burst}} \gtrsim 10^9 \text{ yr}$, and/or from neutron stars passing through the denser regions of the ISM. In either case, we estimate $t_r/f \gtrsim 100$. Note that, in the simplest interpretation, $f$ would be the volume filling factor of ISM with high enough density to make the blast wave readily detectable.

### 5. DISCUSSION

Given recent renewed speculation about the distances of GRBs, we have extended previous ideas about plausible radiation mechanisms for Galactic GRBs, pointing out that relativistic blast waves driven into the ISM by magnetospheric disturbances around neutron stars can yield bursts of gamma-rays with roughly the observed range of timescales and fluences. Our extremely simple conjectures about the radiative properties of synchrotron-emitting blast waves do not reveal the expected spectral properties of such bursts, but they do suggest a plausible correlation between the radiative efficiency at MeV energies and the density of the ambient medium.

The question of what might trigger gamma-ray bursts in this picture is unresolved. A model invoking neutron starquakes or other impulsive events that violently disturb the magnetosphere seems attractive on energetic grounds (Blaes et al. 1989). The energy in the dipole magnetic field is $\sim 10^{39} B_{11}^2 \text{ erg}$, which is enough for individual bursts but would require replenishment to explain frequent bursts. One possibility is the existence of a stronger non-dipole field close to the neutron star surface (Ruderman 1993) which could
transfer energy to the more distant magnetosphere. Rotational and, of course, gravitational energies would be adequate to power numerous bursts per neutron star. Since we argue that the neutron stars responsible for GRBs are probably not accreting, triggers due to gas falling on the neutron star surface do not seem as likely, although starquakes triggered by asteroid or comet impacts are possible (Harwit & Salpeter 1973).

Whatever trigger mechanism leads to violently shaking of a neutron star magnetosphere, we argue that a strong gamma-ray burst can be generated by interaction of the expanding energy flow (whatever its form) with the ISM. This does not exclude a burst of gamma-ray emission also coming from the magnetosphere itself, but the latter is liable to be highly variable, shorter and probably less efficient. In the light of the evidence for two classes of classical GRBs (Kouveliotou et al. 1993; Lamb et al. 1993), it would seem plausible to attribute the short bursts to the latter mechanism and the long ones ($\Delta t \gtrsim 2$ s) to the blast wave. The radiative efficiency of the blast wave depends on the density of the ISM (the structure of which may introduce longer timescale variability), so the variable component may be present in all bursts but the smooth component would be dominant (and overwhelm the former) for bursts occurring in regions where the ISM has reasonably large density (e.g., clouds, not necessarily molecular).

Old pulsars are expected to have a smooth distribution in the Galaxy, constituting a halo population or a disc population with a large scale height. If the bursts came from distances $\gtrsim 10$ kpc, one would expect a strong systematic concentration towards the Galactic Centre; on the other hand, if the burst distances were $\sim 1$ kpc or less (as has been favoured by most previous theoretical treatments involving Galactic models) and their distribution directly traced that of the old neutron stars, the non-uniformities revealed by $V/V_m$ would be perplexing. A log $N$ – log $S$ slope flatter than $3/2$ at low fluences can be easily understood in terms of a dropoff in the number of sources beyond a local density excess associated with our immediate neighbourhood. However, it seems a bit of a coincidence that the anisotropy is rather small relative to the deficit from Euclidean counts — this implies that we are relatively near the centre of a kpc-scale region where the mean ISM density is higher than on the outside.

This model, based on a local burst population made more conspicuous by a denser gaseous environment, would predict that the spatial distribution of smooth-burst sources should be modulated by the highly irregular and structured distribution of the ISM. The spiral-arm effects discussed by Quashnock & Lamb (1993) are a natural consequence of our proposal. Our explanation for these effects is more plausible than an alternative explanation attributing all bursts to neutron stars just a few million years old which still remember the spiral arm they came from, since the latter would require a much higher repetition rate.

We acknowledge partial support from NSF grant AST91-20599 and NASA grant NAG5-2026 (MCB), from NASA NAGW-1522 (PM), and from the Royal Society (MJR).

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