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RADIO TRANSIENTS FROM GAMMA-RAY BURSTERS

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ABSTRACT

The rapid time variability of gamma-ray bursts implies the sources are very compact, and the peak luminosities are so high that some matter must be ejected at ultrarelativistic speeds. The very large Lorentz factors of the bulk flow are also indicated by the very broad and hard spectra. It is natural to expect that when the relativistic ejecta interact with the interstellar matter, a strong synchrotron radio emission is generated, as is the case with supernova remnants and radio galaxies. We estimate that the strongest gamma-ray bursts may be followed by radio transients with peak fluxes as high as 20 mJy. The time of peak radio emission depends on the distance scale; it is less than a minute if the bursts are in the galactic halo, and about a week if the bursts are at cosmological distances.

Subject headings: cosmology: theory — gamma rays: bursts — radio continuum: general — relativity

1. INTRODUCTION

The isotropic distribution of gamma-ray bursts over the sky and nonuniform distribution in distance (Meegan et al. 1992) indicates that we are located at or near the center of a spherical and bound distribution of sources. This is easiest to understand if the sources are at cosmological distances (Paczyński 1991; Dermer 1992; Mao & Paczyński 1992; Piran 1992). The inferred peak luminosity is $\sim 10^{51}$ ergs $s^{-1} > 10^{17} L_{\odot}$, which is in excess of Eddington luminosity for any object with $M < 10^{13} M_{\odot}$, and is highly super-Eddington for any object that might generate a variability on a submillisecond time scale. This implies that the radiation pressure must drive an ultrarelativistic wind (Paczyński 1990, and references therein). This conclusion remains valid even if the radiation is beamed into a small solid angle. The observed spectra are very broad and nonthermal, extending to at least 10 MeV and in some cases beyond 100 MeV and showing no evidence for a pair creation cutoff at ~ 511 keV (Schaefer et al. 1992, and references therein). This is independent evidence for ultrarelativistic outflow (Goodman 1986; Paczyński 1986; Fenimore, Epstein, & Ho 1992, 1993).

There are two other types of gamma-ray sources with spectra as broad as burst spectra: some radio pulars (Ruderman & Cheng 1988) and some AGNs (Hartman et al. 1992; Dermer & Schlickeiser 1992). Both classes of object are also strong radio emitters. There may be a very general reason for this, as both radio and gamma-ray emission require the presence of relativistic particles. Therefore, it is natural to expect that gamma-ray bursts may give rise to radio emission as well (Paczyński 1992).

There is plenty of evidence that all explosive events in astrophysics give rise to synchrotron radio emission when the ejecta interact with the ambient medium. Radio jets generated by active galactic nuclei create "hot spots" when they are stopped by extragalactic matter, and the products of the collision create giant radio lobes, which outshine the core sources at low frequencies. Supernova remnants are also powerful radio sources.

The most spectacular radio supernova known to date is SN 1986J in NGC 891, at a distance of ~ 12 Mpc. The peak intensity was ~ 100 mJy over the frequency range 1–10 GHz (Rupen et al. 1987), and the emission lasted for a few years. The total radio energy generated by the supernova was $E_{\rm radio} \approx 10^{46}$ ergs, and a surface brightness of $T_b \approx 5 \times 10^{11}$ K was reached, close to the Compton limit of 10^{12} K (Kellerman & Pauliny-Toth 1969). The kinetic energy of supernova ejecta is typically $E_{\rm kin} \approx 10^{51}$ ergs; hence, the radio efficiency of SN 1986J was $\sim 10^{-5}$. We note that a 10 minute observation with the Very Large Array (VLA) reaches sensitivity limits $\sim$(0.08, 0.1, 0.06, 0.2, 0.3) mJy at frequencies (1.4, 5.0, 8.4, 15, 23) GHz, respectively (Very Large Array Observational Status Summary, 1993 May 26). Therefore, a supernova like SN 1986J is detectable out to a distance $d \approx 0.4$ Gpc.

A "typical" gamma-ray burst radiates $\sim 10^{52}$ ergs in the 20–2,000 keV range, assuming spherical symmetry. Adopting $\sim 10\%$ gamma-ray efficiency, the total energy in the burst may be as large as $E_0 \approx 10^{53}$ ergs. If the ejecta of some bursts are as efficient radio emitters as SN 1986J, then they may be detectable with the VLA out to 1 Gpc and beyond.

In the following section we make the case for radio emission from gamma-ray bursters somewhat more quantitative, and in the last section we discuss the observable consequences of our scenario.

2. RADIO FIREBALL

There are ~ 40 gamma-ray bursts per year per 4π sr out to a redshift $z \approx 0.2$ (Mao & Paczyński 1992). Every year the positions for a handful of the strongest bursts are determined with $\sim 1'$ accuracy using the interplanetary network (IPN) (Cline et al. 1992, 1993, and references therein). A typical distance to these bursts is likely to be 0.5 Gpc or so.

The following sequence of physical conditions seems to be fairly general and does not depend on the mechanism responsible for the primary energy source or on the nature of the bursting object. The energy density at the source is so enormous that the optical depth to all elementary processes is very high and the conditions are close to local thermodynamic equilibrium, which implies that the gamma-ray spectrum in the region is close to blackbody form (Goodman 1986; Paczyński 1986). However, the observed spectra are very broad and very different from any blackbody (Schaefer et al. 1992), and therefore the observed emission cannot be due to the original fireball. Fortunately, even a small "baryon loading" is sufficient to convert almost all the original energy into kinetic energy of the relativistic wind (Paczyński 1990; Shemi & Piran 1990). In the observer's frame the fireball looks like a thin spherical shell expanding ultrarelativistically (Blandford & McKee 1976; Shemi & Piran 1990). The shell cools rapidly because of adiabatic expansion.

The absence of the pair creation cutoff in the observed spectra implies that the bulk Lorentz factor at the time of gamma-ray emission is very large, $\Gamma_\gamma \geq 10^2$ (Fenimore et al. 1992, 1993). The initial bulk Lorentz factor of the fireball Γ_0 can only be larger. The collision between the ejecta and circumsource matter, and later interstellar and/or intergalactic matter, will gradually lower the bulk Lorentz factor, while converting the bulk kinetic energy into random energy of relativistic particles as described by Rees & Mészáros (1992) and Mészáros & Rees (1993) in their model of gamma-ray bursts. This "randomized" energy is partly radiated away and partly used up for further expansion; it is reconverted into kinetic energy of the bulk flow. Ultimately, after a long enough time interval, all the initial energy is either radiated away or "wasted" in the Hubble expansion of the universe.

Assuming that the emission is incoherent, one can estimate the synchrotron and inverse Compton radiation from the fireball (van der Laan 1966; Rees 1967; Gould 1979). There is an upper limit $T_B \lesssim 10^{12}$ K to the brightness temperature of an incoherent synchrotron source (Kellerman & Pauliny-Toth 1969; Kellerman 1974). In the observer's frame this limit is increased by the Lorentz factor of the bulk flow. Beyond this limit the energy density in radiation ($u_{\rm rad}$) exceeds that in magnetic fields (u_B), resulting in the so-called Compton catastrophe, where the emitting electrons lose energy very rapidly through inverse Compton scattering. Such conditions are likely to occur early in the evolution of the blast wave, while all energy densities are still very high. If they do occur, the resulting inverse Compton emission may produce the observed gamma-ray bursts—a scenario similar to the model of Rees & Mészáros. When the expansion continues and the energy density falls below some critical level, synchrotron emission dominates over inverse Compton losses. This is the regime we are interested in.

The following analysis will be done assuming spherical symmetry of the fireball. We begin with the injection of energy E_0 into a small volume ($r_0 \lesssim 300$ km) with the initial rest mass M_0. The initial fireball quickly evolves into a thin shell expanding with bulk Lorentz factor $\Gamma_0 = E_0/M_0 c^2$. By the time it has expanded to $\sim\Gamma_0 r_0$, it becomes cold in the comoving frame, i.e., the internal Lorentz factor $\gamma_i \approx 1$. We assume that the ambient medium is at rest and has a uniform mass density ρ. As the blast wave expands, this material is swept up and mixes with the shell, which is reheated and decelerated in the process. Parameterizing the swept up rest mass by $M = M_0(1+f)$, we can write energy and momentum conservation as

$$\Gamma_0 + f = (1+f)\gamma_i \Gamma \,, \tag{1}$$

$$\Gamma_0 \beta_0 = (1+f)\gamma_i \Gamma \beta \,, \tag{2}$$

where $\Gamma = (1-\beta^2)^{-1/2}$ is the bulk Lorentz factor, $\beta = v/c$ as usual, and γ_i is the internal Lorentz factor of the particles moving randomly within the expanding shell. Solving these gives Γ and γ_i as functions of f:

$$\beta = \frac{\Gamma_0 \beta_0}{\Gamma_0 + f} \,, \quad \Gamma = (1-\beta^2)^{-1/2} = \frac{\Gamma_0 + f}{\sqrt{1 + 2\Gamma_0 f + f^2}} \,, \tag{3}$$

$$\gamma_i = \frac{\Gamma_0 + f}{(1+f)\Gamma} = \frac{\sqrt{1 + 2\Gamma_0 f + f^2}}{1+f} \,, \quad \beta_i = (1 - \gamma_i^{-2})^{1/2} \,. \tag{4}$$

Notice, that even though the fireball expanding with the initial bulk Lorentz factor $\Gamma_0 \gg 1$ is assumed to be cold, it is reheated to a relativistic condition $[\gamma_{i,\rm max} \approx (\Gamma_0/2)^{1/2} \gg 1]$ by the time the swept-up mass is comparable to the initial mass, i.e., $f \approx 1$.

There are three different measures of time which are relevant. The first, t, is measured in the rest frame of the burster, so that

$$r \approx ct \,, \quad M = M_0(1+f) = M_0 + \frac{4\pi}{3}(ct)^3 \rho \,, \tag{5}$$

where r is the radius of the shell. The second, $t_{\rm co}$, is measured in the frame comoving with the shell, so that

$$t_{\rm co} = \int_0^t \frac{dt}{\Gamma} \,. \tag{6}$$

The third, $t_\oplus$, is measured in the terrestrial observer's frame and must account for apparent superluminal motion, so that

$$t_\oplus = t - \frac{r}{c}\cos\theta \,. \tag{7}$$

We may write these in terms of f as

$$t = \frac{1}{c}\left(\frac{3M_0}{4\pi\rho}\right)^{1/3} f^{1/3} \,, \tag{8}$$

$$t_{\rm co} \approx \frac{t}{\Gamma_0}(1 + 0.32\Gamma_0 f)^{1/2} \,, \quad 0 \leq f \lesssim \Gamma_0 \tag{9}$$

$$t_\oplus \approx \frac{t}{2\Gamma_0^2}(1 + 0.5\Gamma_0 f) \,, \quad 0 \leq f \lesssim \Gamma_0 \,. \tag{10}$$

Here the approximate form for $t_{\rm co}$ interpolates between results accurate for $f \ll \Gamma_0^{-1}$ and for $\Gamma_0^{-1} \ll f \ll \Gamma_0$, while $t_\oplus$ is calculated for $\theta = 0$, i.e., along the line of sight. It is convenient to develop our model first in terms of f and later transform to $t_\oplus$.

The expanding shell as seen in its comoving frame will expand at a rate comparable to the sound speed $c/3^{1/2}$, so that the thickness is $\Delta r \approx ct_{\rm co}$. The shell's surface is perpendicular to the direction of expansion, so it is the same in the comoving and stationary frames, $A = 4\pi(ct)^2$. Thus, in the frame comoving with the shell, its volume is given as

$$V \approx 4\pi(ct)^2(ct_{\rm co}) \approx \frac{3M_0}{\rho\Gamma_0} f(1 + 0.32\Gamma_0 f)^{1/2} \,, \tag{11}$$

and its total energy as

$$E_i = u_i V = M_0(1+f)\gamma_i c^2 = M_0 c^2(1 + 2\Gamma_0 f + f^2)^{1/2} \,, \tag{12}$$

where u_i is the total energy density.

The expanding shell is reheated to relativistic energies and the internal Lorentz factor may be as large as $\gamma_{i,\rm max} \approx (\Gamma_0/2)^{1/2}$ (cf. eq. [4]). These are ideal conditions for synchrotron emission (cf. Rees & Mészáros 1992; Mészáros & Rees 1993, and references therein). We take the electrons to have the energy distribution $N(\mathscr{E}) \propto \mathscr{E}^{-2}$ for $\mathscr{E}_{\min} < \mathscr{E} < \mathscr{E}_{\max}$, i.e., a power-law distribution with equal energy per decade. This is similar to electron energy spectra inferred from synchrotron emission observed in a variety of sources, and the choice of exponent 2 reduces the sensitivity of the results to $\mathscr{E}_{\min}$ and $\mathscr{E}_{\max}$. Working for the moment in the frame of the shell, we adopt the standard results for synchrotron emission from a power law distribution of electrons (cf. Pacholczyk 1970, § 3.4). The spectrum takes the form $I_\nu \propto \nu^{5/2}(1 - e^{-\tau})$, where τ is the optical depth to synchrotron self-absorption. For a power law exponent of 2 and frequencies in the range $\nu_c(\mathscr{E}_{\min}) \lesssim \nu \lesssim \nu_c(\mathscr{E}_{\max})$, we have in the frame comoving with the shell

$$\tau = 0.35 w^{-1} \left(\frac{\Delta r}{c}\right) u_e u_B \left(\frac{\nu}{5\ \mathrm{GHz}}\right)^{-3} \mathrm{cgs}\,, \tag{13}$$

where $w \equiv \log_{10}(\mathscr{E}_{\max}/\mathscr{E}_{\min})$, Δr is the thickness of the emitting slab, u_e and u_B are the electron and the magnetic energy densities, and ν_c is the characteristic frequency for synchrotron emission of a single electron, given by $\nu_c(\gamma_e) \approx 5 \times 10^5[\mathscr{E}/(m_e c^2)]^2(B/\mathrm{G})$. It follows that the spectrum peaks at the frequency $\nu_{m,\mathrm{co}}$ for which $\tau = 0.35$, rising as $\nu^{5/2}$ at lower frequencies and falling off as $\nu^{-0.5}$ at higher ones. The peak specific intensity is

$$I_{\nu,m,\mathrm{co}} = 4.3 \times 10^{-7} \left(\frac{B}{\mathrm{G}}\right)^{-1/2} \left(\frac{\nu_{m,\mathrm{co}}}{5\ \mathrm{GHz}}\right)^{5/2} \left(\frac{\mathrm{ergs}}{\mathrm{cm^2\ s\ Hz\ sr}}\right). \tag{14}$$

We do not know the magnetic energy density $u_N = B^2/8\pi$ or the electron energy density u_e, so we express them in terms of dimensionless parameters,

$$u_B = \xi_B u_i\,, \quad u_e = \xi_e u_i\,, \tag{15}$$

and conservatively guess that $\xi_e \sim 0.01$, well below the equipartition value—the maximum plausible range is $(m_e/m_p) \lesssim \xi_e \lesssim 0.5$; given enough time the magnetic field tends to approach equipartition, but it is not likely to be that strong from the beginning of the sweeping-up phase, so it seems reasonable to take $\xi_B \sim 0.01$ as a representative value. We can constrain the range over which the electron distribution obeys $N(\mathscr{E}) \propto \mathscr{E}^{-2}$ by assuming that inverse Compton losses enforce $u_{\mathrm{rad}} \lesssim u_B$. This gives an upper bound on w typically in the range 2–8, with lower ξ_e allowing higher w.

The following is a rather tedious task. First we have to express τ, $\nu_{\mathrm{co},m}$ and $I_{\nu,m,\mathrm{co}}$ from equations (13) and (14) in terms of the fireball parameters given in equations (3)–(5). Next, we have to transform to the frame of the Earth-bound observer. The relativistic transformations of the frequency and the specific intensity are

$$\nu_\oplus = (1+\beta)\Gamma\nu_{\mathrm{co}} \approx 2\Gamma\nu_{\mathrm{co}}\,,$$
$$I_{\nu,\oplus} = (1+\beta)^3\Gamma^3 I_{\nu,\mathrm{co}} \approx 8\Gamma^3 I_{\nu,\mathrm{co}}\,. \tag{16}$$

To go from the specific intensity to a flux density we multiply by the apparent size of the source,

$$F_{\nu,\oplus,m} \approx \frac{\pi(ct)^2}{d^2\Gamma^2}\, 8\Gamma^3 I_{\nu,\mathrm{co},m}\,. \tag{17}$$

The relation between f and $t_\oplus$ is given in equation (10). We will restrict our attention to the regime $\Gamma_0^{-1} \lesssim f \lesssim \Gamma_0$, so that $t_\oplus \approx (ft)/(4\Gamma_0)$.

After some algebra we find that the time from the beginning of the fireball to the observed peak in the flux at frequency $\nu_\oplus$ is

$$t_{\oplus,m} \approx 12\ \mathrm{day}\ C_t \left(\frac{E_0}{10^{53}\ \mathrm{ergs}}\right)^{1/2} \left(\frac{\rho}{10^{-24}\ \mathrm{g\ cm^{-3}}}\right)^{1/2} \times \left(\frac{\nu_\oplus}{5\ \mathrm{GHz}}\right)^{-3/2} \tag{18a}$$

$$\approx 7\ \mathrm{day}\ C_t \left(\frac{\xi_\gamma}{0.1}\right)^{-1/2} \left(\frac{d}{0.5\ \mathrm{Gpc}}\right) \left(\frac{S}{10^{-4}\ \mathrm{ergs\ cm^{-2}}}\right)^{1/2} \times \left(\frac{\rho}{10^{-24}}\right)^{1/2} \left(\frac{\nu_\oplus}{5\ \mathrm{GHz}}\right)^{-3/2}, \tag{18b}$$

and that the corresponding peak flux is

$$F_{\nu,\oplus,m} \approx 56\ \mathrm{mJy}\ C_F \left(\frac{d}{0.5\ \mathrm{Gpc}}\right)^{-2} \left(\frac{E_0}{10^{53}}\right)^{7/8} \times \left(\frac{\rho}{10^{-24}}\right)^{1/8} \left(\frac{\nu_\oplus}{5\ \mathrm{GHz}}\right)^{5/8} \tag{19a}$$

$$\approx 20\ \mathrm{mJy}\ C_F \left(\frac{\xi_\gamma}{0.1}\right)^{-7/8} \left(\frac{d}{0.5\ \mathrm{Gpc}}\right)^{-1/4} \left(\frac{S}{10^{-4}}\right)^{7/8} \times \left(\frac{\rho}{10^{-24}}\right)^{1/8} \left(\frac{\nu_\oplus}{5\ \mathrm{GHz}}\right)^{5/8} \tag{19b}$$

where

$$C_t \equiv \left(\frac{\xi_e}{0.01}\frac{\xi_B}{0.01}\frac{5}{w}\right)^{1/2},$$
$$C_F \equiv \left(\frac{\xi_e}{0.01}\right)^{5/8} \left(\frac{\xi_B}{0.01}\right)^{9/24} \left(\frac{5}{w}\right)^{5/8}, \tag{20}$$

are dimensionless coefficients of order unity, S is the burst fluence as measured at Earth ($E_\gamma = 4\pi d_0^2 S$), and $\xi_\gamma = E_\gamma/E_0$ is the fraction of fireball's energy radiated in gamma rays in the range 20–2000 keV. The bulk Lorentz factor at the time of peak emission at $\nu_\oplus$ is

$$\Gamma_{\mathrm{radio}} \approx 3C_t^{-3/8} \left(\frac{E_0}{10^{53}}\right)^{1/16} \left(\frac{\rho}{10^{-24}}\right)^{-5/16} \left(\frac{\nu_\oplus}{5\ \mathrm{GHz}}\right)^{9/16}. \tag{21}$$

By combining equations (18) and (19) with the spectrum we find that at a fixed frequency the flux rises as $t_\oplus^{5/4}$ prior to $t_{\oplus,m}$ and declines as $t_\oplus^{-3/4}$ thereafter, so that the total time above half maximum is about $2t_{\oplus,m}$. We can also use equations (18) and (19) to calculate the peak brightness temperature $T_{b,m} = c^2 I_{\nu,\mathrm{co},m}/(2\nu_{\mathrm{co},m}^2 k)$. The result is approximately 10^{11} K and is extremely insensitive to all parameters of the model.

3. DISCUSSION

Observational upper limits to the radio emission from GRBs are available in the literature for timescales $t_\oplus \lesssim 10$ hr (Baird et al. 1975; Cortiglioni et al. 1981) and for $t_\oplus \approx 5$ yr (Schaefer et al. 1989). Baird et al. (1975) used ~full sky coverage at frequencies $\nu_\oplus \lesssim 151$ MHz to watch for strong radio bursts ($F_\nu \gtrsim 100$ kJy, duration $\lesssim 100$ s) and later checked for events that had occurred within 10 hr of recorded GRBs. Cortiglioni et al. (1981) used a similar method at 151 and 408 MHz, attaining a somewhat higher sensitivity ($F_\nu \gtrsim 1$ kJy) and looking for closer time coincidence ($\lesssim 10$ minutes) with GRBs. Schaefer et al. (1989) used the VLA at 15, 5, and 1.4 GHz to conduct a deep search for quiescent emission in IPN GRB error boxes, with sensitivity from 0.1 to 0.8 mJy. Other potentially relevant searches have been done by Vaughan & Large (1987) and by Amy, Large, & Vaughan (1989). However, none of these studies found anything above a normal rate of background events. Other efforts are underway, but there have been no confirmed detections of radio emission from GRBs, nor are we aware of published limits on a timescale of a few days. Hanlon, Bennett, and Spoelstra reported a candidate detection (76 mJy at 0.6 GHz, and <1 mJy at 5 GHz) three days after GRB 930309 (IAU Circ. 5749; cf. also IAU Circs. 5750, 5755, 5763, and 5764 [1993]), but IPN data showed the radio source and GRB positions to be inconsistent.

None of these experiments provides serious restrictions on our scenario. If gamma-ray bursts are at cosmological distances, then we expect the peak of the radio emission to follow the burst within a week or so, and for the strongest bursts to be up to 0.1 Jy at frequencies of a few GHz. It is clear that a dedicated search with the VLA or other sensitive radio instruments should follow accurate position determinations from the Interplanetary Network as soon as possible. It would be best to observe the rise as well as the fall of the radio transient as this would provide very good diagnostics for the burst environment, and in particular for the distance scale. If the bursts are in the galactic halo, their energies are likely to be $\sim 10^{43}$ ergs rather than 10^{53} ergs, and so the time scale of the transient would be ~ 10 s, i.e., practically simultaneous with the gamma-ray bursts (cf. eq. [18]). The peak radio flux depends weakly on the distance scale (cf. eq. [19]); still the galactic halo radio transients might be as strong as ~ 1 Jy.

It should be noted that there is one major uncertainty in our estimate: the gamma-ray burst may be strongly beamed, perhaps to a solid angle as small as $\pi\Gamma_\gamma^2 \sim 10^{-5}$. In this case the energy required to power the burst may be reduced to a value as small as $E_0 \sim 10^{48}$ ergs without affecting the observable properties of the gamma-ray burst, but strongly reducing the radio power which peaks at $\Gamma_{\rm radio} \approx 3$ (cf. eq. [21]). The modest amount of the radio beaming may bring the equivalent fireball energy up to $E_0 \sim 10^{49}$ ergs, but our estimate of the peak radio power is reduced by a factor $\sim 10^4$ making the radio transient undetectable (cf. eq. [19]). To maximize the likelihood of detecting a radio transient, one should observe at the highest frequency possible, as the total radio power increases with frequency (cf. eq. [19]) and the radio beaming factor increases as $\Gamma_{\rm radio}^2$ (cf. eq. [21]). Of course, the higher the radio frequency, the more rapid the radio transient (cf. eq. [18]), and the more rapidly must the radio observation follow the gamma-ray burst.

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REFERENCES

Amy, S. W., Large, M. I., & Vaughan, A. E. 1989, Proc. Astron. Soc. Australia, 8, 172
Baird, G. A., et al. 1975, ApJ, 196, L11
Blandford, R. D., & McKee, C. F. 1976, Phys. Fluids, 19, 1130
Cline, T. L., et al. 1992, in The Compton Observatory Science Workshop, ed. C. R. Shrader, N. Gehrels, & B. Dennis (NASA Conference Publication 3137), 60
Cline, T. L., et al. 1993, in Compton Gamma-Ray Observatory, ed. M. Friedlander, N. Gehrels, & D. J. Macomb (AIP Conf. Proc. 280) (New York: AIP), 774
Cortiglioni, S., Mandolesi, N., Morigi, G., Ciapi, A., Inzani, P., & Sironi, G. 1981, Ap&SS, 75, 153
Dermer, C. D. 1992, Phys. Rev. Lett., 68, 1799
Dermer, C. D., & Schlickeiser, R. 1992, Science, 257, 1642
Fenimore, E. E., Epstein, R. I., & Ho, C. 1992, in Gamma-Ray Bursts, ed. W. S. Paciesas & G. J. Fishman (AIP Conf. Proc. 265) (New York: AIP), 158
———. 1993, A&AS, 97, 59
Goodman, J. 1986, ApJ, 308, L47
Gould, R. J. 1979, A&A, 76, 306
Hartman, R. C., et al. 1992, ApJ, 385, L1
IAU Circ., Nos. 5749, 5750, 5755, 5763, and 5764. 1993
Kellerman, K. I. 1974, in Galactic and Extragalactic Radio Astronomy, ed. G. L. Verschuur & K. I. Kellerman) (Berlin: Springer-Verlag), 320
Kellerman, K. I., & Pauliny-Toth, I. I. K. 1969, ApJ, 155, L71
Mao, S., & Paczyński, B. 1992, ApJ, 388, L45
Meegan, C. A., et al. 1992, Nature, 355, 143
Mészáros, P., & Rees, M. J. 1993, ApJ, 405, 278
Pacholczyk, A. G. 1970, Radio Astrophysics (San Francisco: W. H. Freeman & Co.)
Paczyński, B. 1986, ApJ, 308, L43
———. 1990, ApJ, 363, 218
———. 1991, A&A, 41, 257
———. 1992, Princeton Observatory Preprint 463
Piran, T. 1992, ApJ, 389, L45
Rees, M. J. 1967, MNRAS, 135, 345
Rees, M. J., & Mészáros, P. 1992, MNRAS, 258, 41P
Ruderman, M., & Cheng, K. S. 1988, ApJ, 335, 306
Rupen, M. P., et al. 1987, AJ, 94, 61
Schaefer, B. E., et al. 1989, ApJ, 340, 455
Schaefer, B. E., et al. 1992, ApJ, 393, L51
Shemi, A., & Piran, T. 1990, ApJ, 365, L55
van der Laan, H. 1966, Nature, 211, 1131
Vaughan, A. E., & Large, M. I. 1987, Astrophys. Lett. Comm., 25, 159
Very Large Array Observational Status Summary. 1993 May 26 (Socorro, NM: NRAO), 9