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HOW TO TELL A JET FROM A BALLOON: A PROPOSED TEST FOR BEAMING IN GAMMA-RAY BURSTS

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ABSTRACT

If gamma-ray bursts are highly collimated, radiating into only a small fraction of the sky, the energy requirements of each event may be reduced by several ($\sim$4–6) orders of magnitude, and the event rate is increased correspondingly. Extreme conditions in gamma-ray bursters lead to highly relativistic motions (bulk Lorentz factors of $\Gamma \gtrsim 100$). This results in strong forward beaming of the emitted radiation in the observer's rest frame. Thus, all information on gamma-ray bursts comes from those ejecta emitted in a narrow cone (opening angle of $\sim 1/\Gamma$) pointing toward the observer. We are at present ignorant of whether there are ejecta outside that cone or not.

The recent detection of longer wavelength transients following gamma-ray bursts allows an empirical test of whether gamma-ray bursts are well-collimated jets or spherical fireballs. The bulk Lorentz factor of the burst ejecta will decrease with time after the event, as the ejecta sweep up the surrounding medium. Thus, radiation from the ejecta is beamed into an ever-increasing solid angle as the burst remnant evolves. It follows that if gamma-ray bursts are highly collimated, many more optical and radio transients should be observed without associated gamma rays than with them. Published supernova searches may contain enough data to test the most extreme models of gamma-ray beaming. We close with a brief discussion of other possible consequences of beaming, including its effect on the evolution of burst remnants.

Subject headings: gamma rays: bursts — ISM: jets and outflows — radio continuum: general — ultraviolet: general — X-rays: general

1. INTRODUCTION

Relativistic expansion is a generic feature of fireball models for gamma-ray bursts. This can be seen in several ways. First, the bursts are luminous (peak of $\sim 10^{17}\,L_\odot$ in gamma rays for cosmological distances) and vary on timescales of milliseconds. The variability requires them to be small [$\lesssim$ a few $\times\,10^{13}\,(\Gamma/100)^2$ cm; Woods & Loeb 1995]. This in turn guarantees that they exceed the Eddington limit on luminosity of an object in equilibrium, because the Eddington mass for $L \sim 10^{17}\,L_\odot$ comfortably exceeds the mass required to form a black hole in a region $\lesssim 10^{13}$ cm across.

The observed gamma-ray fluences imply total burst energies of order 10^{52} ergs in the gamma-ray range (20–2000 keV; see, e.g., Paczyński & Rhoads 1993), assuming spherical symmetry. Together with the size limit, this implies energy densities of $\gtrsim 10^{12}$ ergs cm^{-3}. This limit is sufficient to imply a large optical depth to electron-positron pair creation ($\gamma\gamma \rightarrow e^+e^-$). Thus, the energy will not escape directly as electromagnetic radiation but will be converted into a relativistic wind of pairs and baryons. The observed radiation is presumably generated later by interactions in such a wind (see, e.g., Paczyński & Xu 1994; Rees & Mészáros 1994) or with an ambient medium (Rees & Mészáros 1992; Mészáros & Rees 1993). The nonthermal gamma-ray spectra provide additional support for this scenario (Goodman 1986; Paczyński 1986; Fenimore, Epstein, & Ho 1993; Woods & Loeb 1995).

If we are to understand the physical origin of the gamma-ray bursts, we need to know about their distance, their luminosity, their frequency, and their environments. The recent detection of a variable optical counterpart to gamma-ray burst 970508 (Bond 1997) and the detection of interstellar absorption lines at redshift $z = 0.835$ in its spectrum (Metzger et al. 1997) clearly shows that at least some bursts are at cosmological distances, while the observed isotropy of the burst distribution on the sky (Briggs et al. 1996) supports a cosmological origin for the overwhelming majority of the population. With the distance scale established, the largest remaining uncertainty in the burst energy is the solid angle into which the bursts radiate. This is also the dominant uncertainty in the burst event rate. If bursters beam their gamma rays into solid angle Ω_γ, the burst energy scales as $\Omega_\gamma/(4\pi)$ and the event rate scales as $4\pi/\Omega_\gamma$ relative to the case of isotropic emission.

The maximum plausible degree of collimation for electromagnetic radiation from a burster is opening angle $\zeta_\gamma \sim 1/\Gamma$, where Γ is the bulk Lorentz factor of the radiating matter. This is the opening angle into which photons emitted isotropically in the rest frame of the radiating matter travel in the observer's frame (see Rybicki & Lightman 1979; Pacholczyk 1970). It is of course possible for the burst to be less collimated, if the ejecta move into a cone of opening angle $\zeta_m > \zeta_\gamma$, but we still see only those photons emitted by matter in the smaller cone of opening angle ζ_γ.

Collimated jets are remarkably common in astrophysical sources. We observe them at small scales (protostars) and large scales (radio galaxies). The most widely accepted taxonomy of active galactic nuclei relies on orientation effects in accretion disk plus jet models to explain a variety of spectral features. Some sources have been observed with relativistic bipolar outflows (e.g., Galactic microquasars; Mirabel & Rodriguez 1994), and these can show a marked asymmetry in apparent brightness between the approaching and receding

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jets that is well modeled as an effect of relativistic beaming (Mirabel & Rodriguez 1994; Bodo & Ghisellini 1995). Some possible mechanisms for gamma-ray bursts allow naturally for beaming, through very strong magnetic fields, accretion disks, or a combination of the two (e.g., the Blandford & Znajek 1977 mechanism).

Lower energy transient sources are expected to follow gamma-ray bursts as the fireball ejecta plow into the surrounding medium (Paczyński & Rhoads 1993; Katz 1994; Mészáros & Rees 1997a; Waxman 1997; Wijers, Rees, & Mészáros 1997). The spectrum at a fixed time is generally modeled as a broken power law, resulting from synchrotron emission from a power-law distribution of electron energies in a magnetic field at or reasonably near the equipartition value. The break in the spectrum shifts to lower frequencies as the burst remnant ages, primarily because the bulk Lorentz factor of the ejecta decreases, reducing the relativistic blueshift of the emitted spectrum. In general, the break frequency is expected to decrease as a power law in time since the burst. While our imperfect understanding of relativistic, magnetized shocks leaves large uncertainties in these models, they are now observationally justified by the observed X-ray, optical, and radio counterparts to bursts 970508 (IAU Circs. 6654–6663) and 970228 (Wijers et al. 1997, and references therein).

Because the shift to lower frequencies accompanies the shift to lower bulk Lorentz factors, the minimum solid angle into which the transient can radiate increases with time. This leads directly to our proposed test for isotropy of gamma-ray burst emission. If bursts are highly collimated, the gamma rays will radiate into a small solid angle, the optical transient into a larger one, and the radio transient into a larger one still. Thus, we expect to see more optical transients than gamma-ray bursts, and still more radio transients. On the other hand, if gamma-ray bursts emit isotropically, we do not expect there to be optical transients unaccompanied by gamma-ray bursts. The ratio of event rates for burst transients at two frequencies thus gives the ratio of the mean solid angle into which the burst transients radiate at those frequencies. We know the gamma-ray burst rate well already, and within a few months we should have a reasonable statistical sample of optical counterparts to observed gamma-ray bursts. Establishing the total event rate for all optical transients with the characteristics of observed burst counterparts (whether gamma rays are seen or not) is a large but quite feasible task with present instruments.

2. MODEL-INDEPENDENT LIMITS ON BEAMING

The simplest model-independent form of our test states simply that the ratio of event rates at two observed frequencies, $\nu_{\oplus,1}$ and $\nu_{\oplus,2}$, should be $\hat{N}_1/\hat{N}_2 = \Omega_1/\Omega_2$, where Ω_i is the solid angle into which the flux is beamed at frequency $\nu_{\oplus,i}$ and $\hat{N}_i$ is the event rate at $\nu_{\oplus,i}$ integrated over all fluxes.

Unfortunately, we do not have the luxury of infinitely sensitive instruments. We therefore need to replace $\hat{N}_i$ with $\hat{N}_i$, the rate of events at $\nu_{\oplus,i}$ exceeding a flux detection threshold $f_{\mathrm{min},i}$. Observed differences in N_1, N_2 can then be explained either by different degrees of collimation at different frequencies or by insufficient sensitivity to detect some transients at one or another frequency. (The situation becomes more complicated if we are unable to select a sample of transients caused by a common physical mechanism.)

To account for flux thresholds, consider the joint probability distribution $p(\hat{f}_1, \hat{f}_2)$ for a burst to have angle-averaged fluxes $\hat{f}_1$, $\hat{f}_2$ at our two frequencies. ["Angle-averaged" means that $\hat{f} = f\Omega/(4\pi) = L/(4\pi d^2)$, where f is observed flux, L is the source luminosity, and d is the luminosity distance to the source.] Then our observations at frequency $\nu_{\oplus,1}$ will detect a fraction F_1 of all transients, where

$$F_1 = \left(\frac{\Omega_1}{4\pi}\right) \int_{f_{\mathrm{min},1}\Omega_1/4\pi}^{\infty} \int_0^{\infty} p(\hat{f}_1, \hat{f}_2)\, d\hat{f}_2\, d\hat{f}_1 . \tag{1}$$

A similar equation gives F_2, while the fraction of events seen at both frequencies is

$$F_{12} = \frac{\min(\Omega_1, \Omega_2)}{4\pi} \int_{f_{\mathrm{min},1}\Omega_1/4\pi}^{\infty} \int_{f_{\mathrm{min},2}\Omega_2/4\pi}^{\infty} p(\hat{f}_1, \hat{f}_2)\, d\hat{f}_2\, d\hat{f}_1 . \tag{2}$$

We then examine the ratio F_{12}/F_1:

$$\frac{F_{12}}{F_1} = \left[\int_{f_{\mathrm{min},1}\Omega_1/4\pi}^{\infty} \int_{f_{\mathrm{min},2}\Omega_2/4\pi}^{\infty} p(\hat{f}_1, \hat{f}_2)\, d\hat{f}_2\, d\hat{f}_1 \Big/ \int_{f_{\mathrm{min},1}\Omega_1/4\pi}^{\infty} \int_0^{\infty} p(\hat{f}_1, \hat{f}_2)\, d\hat{f}_2\, d\hat{f}_1 \right] \times \frac{\min(\Omega_1, \Omega_2)}{\Omega_1} . \tag{3}$$

The term in brackets is ≤ 1 because p is strictly nonnegative. Also, $\min(\Omega_1, \Omega_2)/\Omega_1 \leq \Omega_2/\Omega_1$. Thus, $\Omega_2/\Omega_1 \geq F_{12}/F_1$, regardless of the details of the joint flux distribution, p. Likewise, $\Omega_1/\Omega_2 \geq F_{12}/F_2$. Although the F_i are defined as fractions of the (unknown) total transient population, the ratios we care about can be expressed in terms of measurable event rates: $F_i/F_j = N_i/N_j$. Combining these results, we find that

$$\frac{N_{12}}{N_2} \leq \frac{\Omega_1}{\Omega_2} \leq \frac{N_1}{N_{12}} . \tag{4}$$

It is of course necessary that the flux thresholds $f_{\mathrm{min},1}, f_{\mathrm{min},2}$ used to measure N_{12} be the same ones used to measure N_1 and N_2.

If we can constrain p well, we may go beyond this analysis and actually estimate Ω_1/Ω_2. The resulting estimate will be sensitive to errors in p, however, and such errors will remain substantial until the lower frequency counterparts of gamma-ray bursts are better studied. For now, we prefer to emphasize the inequalities in equation (4), which are model independent.

3. EXPECTATIONS IN AN ILLUSTRATIVE MODEL

We now turn our attention to modeling the expected transient event rate as a function of frequency. We are most interested in $\Gamma_p(\nu_\oplus)$, the bulk Lorentz factor of the ejecta when the flux density peaks at observed frequency $\nu_\oplus$. As with most predictions of relativistic fireball models, $\Gamma_p(\nu_\oplus)$ turns out to be a power law $\Gamma_p \propto \nu^{\mu}_{\oplus}$ over a large range of $\nu_\oplus$ and Γ_p. Published values of μ cover a substantial range, from $\mu = \frac{1}{4}$ (for the "impulsive fireball" model in Mészáros & Rees 1997a) to $\mu = \frac{9}{16}$ (from Paczyński & Rhoads 1993). More secure quantitative predictions may be expected later, when uncertainties in the input physics of the models (particularly the electron energy spectrum) have been removed by confrontation with newly available counterpart observations (cf. Waxman 1997).

The detection of radio emission from gamma-ray burst 970508 (Frail et al. 1997) at $z > 0.835$ suggests that Γ_p (8.46 GHz) $\gtrsim$ a few. Extrapolating boldly to optical and gamma-ray wavelengths, and using the relatively conservative scaling exponent $\mu = \frac{1}{4}$, we infer that $\Gamma_p(R \text{ band}) \gtrsim 30$ and that $\Gamma_p(\gamma) = \Gamma_0 \gtrsim 500$. This Γ_0 is consistent with the observational constraints of Woods & Loeb (1995). The maximum beaming for the gamma-ray regime (taking $\Gamma = 500$) is then into $10^{-6} \times 4\pi$ sr. The optical regime ($\Gamma = 30$) gives $2.8 \times 10^{-4} \times 4\pi$ sr, while the radio ($\Gamma = 2$) gives $0.06 \times 4\pi$ sr (though the $\zeta \propto 1/\Gamma$ scaling is not very accurate at such low Γ). The precise values of Γ are less important than their ratios.

The observed gamma-ray burst rate from BATSE (the Burst and Transient Source Experiment aboard the *Compton Gamma Ray Observatory* satellite) is about 1 burst per day (Meegan et al. 1996). The four bursts well localized by the *BeppoSAX* satellite (970111, 970228, 970402, and 970508) have resulted in two probable optical counterpart detections. Thus, the rate of optical counterparts to observable classical gamma-ray bursts is of order 200 per year, or 1 per square degree per 200 years. We infer that if gamma-ray bursts are maximally beamed, there should instead be of order 1 optical transient per square degree per year and of order 1 radio transient per square degree per day.

Whether the radio transients predicted under this extreme beaming scenario would be visible is doubtful: the ratio of their peak radio flux to gamma-ray fluence will be reduced by a factor $[\Gamma_p(\text{radio})/\Gamma_p(\gamma)]^2 \sim 10^{-5}$ relative to the isotropic burst case, assuming that all burst ejecta have about the same initial Lorentz factor. The reduction of flux would be less dramatic under scenarios in which ejecta have a wide range of Lorentz factors, like the layered jet model (Mészáros & Rees 1997b; Wijers et al. 1997) and the hypernova model (Paczyński 1997). In these cases, material ejected from the burster at comparatively low Γ might contribute substantially to afterglow flux at low energies and negligibly at high energies.

4. OBSERVATIONAL PROSPECTS

The rate of gamma-ray bursts is already fairly well known. We consider here the requirements for determining the rates of transient optical and radio events like that observed following gamma-ray burst 970508.

The peak optical emission of the 970508 transient was about $R = 19.78 \pm 0.05$ mag (37 ± 2 μJy) (Mignoli et al. 1997). The counterpart to burst 970228 was a little fainter ($\approx 17 \mu$Jy at V and I bands; Groot et al. 1997). The events lasted a few days each. We will assume that transients of this nature would be detected by daily observations to limiting 5 σ sensitivity $R \approx 22$. Such observations take a few minutes per field with a 1 m class telescope. The best field of view presently available at Kitt Peak National Observatory (1°, using the Mosaic CCD camera on the 0.9 m telescope) would allow one to survey roughly 3 fields per hour, or of order 20 deg^2 per night, allowing for overheads. Thus, event rates of the order discussed in the extreme beaming scenario could be tested in ~10–20 nights on the telescope.

Existing optical data may already be sufficient to apply a crude version of our test. Deep supernova searches by two groups (the High Redshift Supernova Search and the Supernova Cosmology Project) are ongoing and have now detected at least 37 (Schmidt et al. 1996) and 28 (Deustua et al. 1996; Kim et al. 1997) supernovae. Their search strategies often include observations separated by sufficiently short times (a few nights) that optical transients like the 970508 afterglow would be seen on multiple nights and confirmed as sources. We can estimate their total coverage as follows: the supernova rate is about 34 deg^2 yr^{-1} for $21.3 < R < 22.3$ (Pain et al. 1996). The 65 supernovae detected therefore translate to a coverage of about 2 deg^2 yr^{-1} for supernovae. The effective coverage for gamma-ray burst counterparts may be somewhat lower owing to the shorter timescale and hence reduced detection efficiency for these events. We will take the surveys to cover ~1 deg^2 yr^{-1}. The data are therefore sensitive to optical transient event rates $N_{\rm opt} \gtrsim 1$ deg^{-2} yr^{-1}.

Unfortunately, not every transient source detected by these searches is sufficiently well characterized to say whether or not it could be a gamma-ray burst afterglow. The High Redshift Supernova Search has detected some short-duration transient sources without obvious host galaxies that might be flare stars in the halo or thick disk of the Galaxy, but might potentially be gamma-ray burst afterglows (B. P. Schmidt 1997, private communication). Estimating the expected number of flare star events is possible (see Garibjanian et al. 1990) but beyond the scope of this work. Observations at a range of timescales would eliminate this possible source of confusion, since stellar flares have characteristic durations of minutes to hours (Krautter 1996), while the afterglows of GRB 970508 and 970228 had durations of days.

Comparing the previously estimated coverage of these surveys to the gamma-ray burst rate ($N_{\gamma\text{-ray}} \sim 0.01$ deg^{-2} yr^{-1}), we see that an absence of optical burst afterglows would imply that $\Omega_{\gamma\text{-ray}}/\Omega_{\rm optical} \gtrsim 0.01$. This is already slightly above the ratio $\Omega_{\gamma\text{-ray}}/\Omega_{\rm optical} \approx 0.004$ predicted in our illustrative maximal beaming model. On the other hand, detection of even one optical transient caused by a gamma-ray burster would imply that $\Omega_{\gamma\text{-ray}}/\Omega_{\rm optical} \approx 0.01$, i.e., that bursts are strongly beamed. In summary, present optical data cover enough sky for a preliminary application of our test, but firm conclusions would probably require reanalysis of the data with this test in mind. More definitive results would be possible with experiments designed at the outset to search for transients associated with gamma-ray bursters.

In the radio, the Faint Images of the Radio Sky at Twenty centimeters (FIRST) survey is using the Very Large Array to map the sky at 20 cm wavelengths. It is achieving limiting sensitivities of 1 mJy ($\gtrsim 5$ σ) in 3 minutes per observation over a field ~13′ in radius (Becker, White, & Helfand 1995). The observed radio flux of the 970508 transient has not yet peaked but seems likely to peak well above 1 mJy. Thus, the event rate in radio can be constrained to about the same level as the optical rate in a comparable amount of telescope time. Because the difference in event rates increases as the wavelength baseline increases in relativistic beaming models, a radio search could place the most stringent constraints on gamma-ray–burst beaming.

5. DISCUSSION

In addition to its effect on the transient rate at different wavelengths, beaming of gamma-ray bursts may have a few other observable consequences. One is that we will sometimes be near the center line of the jet and sometimes at its edge. Yi (1994) pointed out that this will broaden the apparent luminosity function of the bursts substantially and explored the implications of this effect for the statistical properties of the gamma-ray burst population.

Another consequence is for the light curve of any individual burst. The predicted strength of low-energy transients is greatly reduced in extreme beaming scenarios. If the burst is beamed into an angle $\zeta_m > 1/\Gamma_0$, we can expect a qualitative change in the behavior of the transient when the bulk Lorentz factor drops to $\Gamma < 1/\zeta_m$. Before this time, the burst will obey the predictions of an isotropic model, while afterward, a correction factor $\sim(\Gamma\zeta_m)^2$ must be applied to all the flux predictions for the isotropic case.

Moreover, the dynamical evolution of a beamed burst can change qualitatively once $\Gamma < 1/\zeta_m$. In a spherical model, or while $\Gamma > 1/\zeta_m$, the surface area of the expanding blast wave scales as r^2. However, the burst ejecta and swept-up matter expand at the sound speed $c_s \sim c/\sqrt{3}$ in the comoving frame. The transverse size of the ejecta will thus be the larger of $r\zeta_m$ and $c_s t_{\rm co}$, where $t_{\rm co}$ is the time since the burst in a frame comoving with the ejecta. The second term dominates for $\Gamma \ll 1/\zeta_m$, so that the surface area increases more rapidly with r and the ejecta decelerate more abruptly. Specifically, we find that the bulk Lorentz factor $\Gamma \propto \exp(-r/r_\Gamma)$ for $1/\zeta_m \gg \Gamma \gtrsim 2$, where $r_\Gamma = [M_0 \Gamma_0 c^2/(\pi\rho c_s^2)]^{1/3}$. (Here M_0 and Γ_0 are the initial mass and Lorentz factor of the ejecta, and ρ is the mass density of the ambient medium. Note the implicit scaling $M_0 \propto \zeta_m^2$ for fixed observable gamma-ray properties.) The observer frame time $t_\oplus$ also evolves exponentially with r in this regime, so that most directly observable properties follow power-law evolution, with a break when $\Gamma \sim 1/\zeta_m$. We explore the consequences in a generalization of the Paczyński & Rhoads (1993) afterglow model, whose sole spectral feature is a break where synchrotron self-absorption becomes important. We concentrate on the regime where the ratio f of swept-up mass to initial mass lies between $1/\Gamma_0$ and Γ_0. Under these conditions, the observed frequency of peak emission $\nu_{\oplus,m}$, flux density at that frequency $F_{\nu,\oplus,m}$, and apparent angular size of the afterglow θ scale as $\nu_{\oplus,m} \sim t_\oplus^{-2/3}$, $F_{\nu,\oplus,m} \sim t_\oplus^{-5/12}$, and $\theta \sim t_\oplus^{5/8}$ before the break and as $\nu_{\oplus,m} \sim t_\oplus^{-1}$, $F_{\nu,\oplus,m} \sim t_\oplus^{-3/2}$, and $\theta \sim t_\oplus^{1/2}$ afterward. Numerical integrations confirm these relations, though the transition between the two regimes is quite gradual for $\nu_{\oplus,m}$. Combining these scalings with the spectral shape ($F_{\nu,\oplus} \propto \nu_\oplus^{5/2}$ at $\nu_\oplus < \nu_{\oplus,m}$ and $F_{\nu,\oplus} \propto \nu_\oplus^{-1/2}$ at $\nu_\oplus > \nu_{\oplus,m}$) yields predictions for the light-curve at a fixed observed frequency. The most dramatic feature is in the light curve shape for $\nu_\oplus > \nu_{\oplus,m}$, which changes from $F_{\nu,\oplus} \sim t_\oplus^{-3/4}$ to $F_{\nu,\oplus} \sim t_\oplus^{-2}$. These exponents are generally sensitive to the assumed electron energy distribution in the blast wave and so should be taken as illustrative of the type of break expected in a beaming scenario. They could be refined by considering models in which the electron population is fitted to observed data.

Note finally that the scaling exponents are also sensitive to the burster's environment. As an example, the apparent size in the $\Gamma > 1/\zeta_m$ regime becomes $\theta \sim t_\oplus^{(5-k)/(8-2k)}$ if we take the medium around the burster to have radial density profile $\rho \propto r^{-k}$. This implies that high-resolution studies of these sources (e.g., with very long baseline interferometry) would have to follow the evolution of the source over a factor of $\gtrsim 4$ in angular size (and $\gtrsim 10$ in $t_\oplus$) if they are to distinguish between expansion into a uniform density medium ($k = 0$) and a wind environment ($k = 2$).

To summarize, we propose a new test for beaming of gamma-ray bursts. Observational constraints on beaming will help eliminate the dominant remaining uncertainty in the total event rate and gamma-ray luminosity of the bursts. This in turn will help us determine which classes of energetic events have the correct frequency to cause the gamma-ray bursts. The observations required are feasible with present instruments, and existing data may already be sufficient to test the most extreme beaming scenarios.

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