EVIDENCE FOR AND AGAINST COLLIMATION OF GAMMA RAY BURSTS

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The degree to which gamma ray bursts are collimated is now the dominant uncertainty in their energy requirements and event rates. In this review I begin with the reasons for studying GRB collimation, then discuss existing tests for collimation and their applications to date, and finally outline some possible future tests. The most important conclusions are that (1) mean collimation angles much tighter than 1° appear ruled out; (2) the collimation angle appears to vary from burst to burst (like most other GRB properties). Some alternative explanations of apparent collimation signatures remain, but it should be possible to distinguish them from true collimation with future data sets and may be possible already. New satellites, improved followup observations, and new tests for collimation all promise continued rapid progress in coming years.

1 Introduction

There are two main reasons to look for evidence of collimation in gamma ray bursts (GRBs). First, collimation is an extremely common phenomenon in astrophysical outflows. Jets have been observed on scales ranging from parsecs (protostellar objects) up to tens of kiloparsecs (radio galaxies) and with speeds ranging from \( v \approx 100 \text{ km/s} \) (protostellar objects) up to \( \Gamma \approx 10 \) (active galactic nucleus jets). It is thus natural to suspect that GRBs may also be collimated.

Second, the energy requirements of gamma ray bursts have long been cause for discussion, and in some quarters concern. Present data show these requirements to exceed \( 10^{54} \text{ ergs} \) in gamma ray production for the most energetic bursts if the bursts are isotropic. Such energies are regarded as an “energy crisis” for some classes of burst progenitor models. Collimation allows these energy requirements to be relaxed by a factor of \( \Omega_\gamma/(4\pi) \), where \( \Omega_\gamma \) is the solid angle into which the gamma rays are emitted. At the same time, the required event rate of GRBs scales as \( 4\pi/\Omega_\gamma \). Constraining \( \Omega_\gamma \) is thus a necessary prerequisite for knowing what classes of object can produce the observed gamma rays and how common or rare burst progenitors must be.

By considering the relativistic nature of GRBs, we can see both the reasons collimation angles were unconstrained in past and the means for current progress in the field. Until 1997, all of our information on GRBs came from gamma ray observations. These observations showed that (a) GRBs are highly energetic, with fluences \( \sim 10^{-5} \text{ erg cm}^{-2} \) “representative” for bright bursts; (b) burst light curves are highly structured with variability on time scales down to \( \sim 10^{-3} \text{ s} \); and (c) bursts have nonthermal spectra reasonably described by broken power laws. These three characteristics imply that (a) burst energies are \( 10^{52} \text{ erg} \) and above for cosmological distances and isotropic radiation; (b) the bursters are small, with a characteristic size naïvely estimated at \( 10^{-3} \text{ s} \times c \approx 3 \times 10^{7} \text{ cm} \); and (c) the gamma rays must come from an optically thin region to avoid being thermalized. However,
the energy density implied by (a) and (b) would require a very high density of gamma rays in a static source model, with a consequent optical depth $\tau_{\gamma\gamma} \gg 1$ for $\gamma + \gamma \rightarrow e^- + e^+$ and an expectation of a thermal emergent spectrum. To resolve this apparent conflict, it is sufficient and probably necessary for the source to be in bulk relativistic expansion, which relaxes both the constraint on source size (since observed variations appear more rapid when the emitting matter is approaching at nearly lightspeed) and the pair creation optical depth (since the photons in question can have energies much below 511keV in a relativistically moving frame). (See Paczyński 1986; Goodman 1986; Krolik & Pier 1991). The implied minimum Lorentz factors are in the range $100 \lesssim \Gamma \lesssim 1000$ (Woods & Loeb 1994), making GRBs the best known astrophysical laboratory for the study of ultrarelativistic shocks.

These high Lorentz factors immediately imply the possibility of substantial collimation. Burst ejecta that emit isotropically in their rest and move with Lorentz factor $\Gamma$ relative to the lab frame will appear to beam their emission forward into a cone of characteristic opening half angle $1/\Gamma$. This implies that whether or not the bursts are isotropic, the gamma rays that we observe come from material moving within angle $1/\Gamma \lesssim 1/100$ radian of the line of sight, and we cannot determine the presence or absence of ejecta outside that narrow cone from these gamma rays alone. The reduction in energy requirements from collimation could therefore be as extreme as $10^{-5} \gtrsim \Omega_{\gamma}/(4\pi) \gtrsim 10^{-7}$ for $100 \lesssim \Gamma \lesssim 1000$.

The fast ejecta from GRBs must eventually encounter a sufficient column density of ambient medium to slow down. A natural consequence is that the bulk kinetic energy of the ejecta is converted into other forms, and some can be radiated in an afterglow (Paczyński & Rhoads 1993; Katz 1994; Mészáros & Rees 1997). Because the afterglow allows us to probe the evolution of the GRB remnant while the Lorentz factor decreases from $\Gamma_0$ to $\sim 1$, afterglow studies open the way for comparatively straightforward tests of GRB collimation.

2 Orphan Afterglows

As the GRB blast wave sweeps up the ambient medium and decelerates, the peak emission frequency of the afterglow becomes lower (scaling as $\Gamma^4$ in the simplest models) while the degree of relativistic beaming lessens ($\Omega_{\gamma} \propto \Gamma^{-2}$). Thus, observers situated too far from the axis of the ejecta to see the GRB itself may begin to see the afterglow at some point in its evolution, and the observed event rate increases with wavelength. The statistics of such “orphan afterglows” can be used to constrain the mean collimation angle of the GRB population (Rhoads 1997; Perna & Loeb 1998). Finite detection thresholds introduce some subtlety in applying this method: Limits can be placed on the ratio of opening angles at two observed wavelengths in a model-independent way, but actual measurements of the opening angle ratio require some knowledge of the flux ratio distribution at these wavelengths.

This method has now been applied in at least a preliminary way to X-ray, optical, and radio wavelengths. The present state of the art in X-ray orphan afterglows is work of Greiner (1999), who searched the ROSAT All-Sky Survey data for transient events, finding a sample of 23 sources. However, their optical followup of the
X-ray events showed that red stars were present in essentially all cases, and that the subset of these stars observed spectroscopically all had dMe star spectra. The observed transients were therefore mostly or entirely stellar flares. After accounting for this foreground, Greiner et al conclude that no difference in collimation between the $\gamma$-ray and X-ray events is required by the data. Similar conclusions were reached by Grindlay (1999) based on Ariel 5 data.

At optical wavelengths, many existing data sets may be suitable for orphan afterglow tests (e.g., high redshift supernova searches, microlensing studies, or any other large variability survey with time sampling of a few days). One particularly suitable data set where I know that an orphan afterglow analysis is well underway is work of Schaefer et al (2001), who have surveyed an area of $\sim 200$ square degrees repeatedly to depths $R \sim 21$ over the course of $\sim 2$ weeks. Present analysis shows no viable orphan afterglow candidates in their data (Schaefer 2000, private communication). This data set would be expected to contain $\sim 0.2$ afterglows if bursts are isotropic, so the absence of orphan afterglows suggests $\Omega_{\text{opt}}/\Omega_\gamma \ll 100$, which is enough to rule out the most extreme collimation scenarios.

Finally, at radio wavelengths, Perna & Loeb (1998) have used published source counts and variability studies to place a limit on the collimation angle, $\theta_\gamma \gtrsim 5^\circ$. (Because radio afterglows last into the nonrelativistic phase of the GRB remnant evolution, the radio afterglows are expected to radiate essentially isotropically, and the orphan afterglow limits on $\Omega_{\text{radio}}/\Omega_\gamma$ immediately imply a limit on $\Omega_\gamma$ itself.) The uncertainty in this calculation is difficult to assess, because Perna & Loeb combined three different radio surveys at two different wavelengths.

The main worry in applying orphan afterglow tests is that other classes of transient source may provide a false positive signal. Greiner et al have already demonstrated the importance of identifying such foreground sources at X-ray wavelengths. In general, both the light curve and spectral energy distribution of a transient source should match expectations for collimated afterglows if the source is to be a viable orphan afterglow candidate. A good screening tool for possible candidates is that the spectral energy distribution should usually be consistent with a power law, implying a specific color-space locus for afterglows (Rhoads 2001). Another tool is the spatial distribution of orphan afterglows, which should presumably be isotropic like that of GRBs and unlike many classes of foreground variable source. The most subtle class of confusing source may turn out to be “dirty fireballs”: Events like GRBs where the initial ejecta suffer from more baryon pollution and hence have initial Lorentz factors $1 \ll \Gamma_0 \ll 100$. Such events will not produce GRBs (for which $\Gamma_0 \gtrsim 100$) but can certainly produce afterglows. Fortunately, the light curve method (below) should serve to distinguish isotropic dirty fireballs from orphan afterglows of collimated GRBs.

### 3 Light Curve Breaks

The most widely applied tests for GRB collimation so far derive from light curve breaks expected in the afterglows of collimated bursts (Rhoads 1997b, 1999; Sari, Piran, & Halpern 1999). Conceptually, there are two such breaks: The first occurs when the angle for relativistic beaming $1/\Gamma$ exceeds the collimation angle $\zeta_m$
of matter in the jet, and the second occurs when sideways expansion of the jet material increases the working surface of the expanding remnant enough to affect its dynamics. While the distinction between these breaks has been emphasized by some (e.g., Panaitescu & Mészáros 1999), they may be difficult to distinguish observationally because the time between them is less than the characteristic time for either break to occur. These breaks should be achromatic, i.e., should occur at the same time at all wavelengths.

The existence of such breaks implies two tests for collimation. First, good light curves (at any wavelength) can be used to detect the break directly. Second, the expected relation between spectral slope and light curve slope differs before and after the break, so that by measuring both it may be possible to identify collimated bursts even when the break preceded the first followup observations. Light curve breaks have now been directly observed in GRBs 990123 (Castro-Tirado et al 1999; Fruchter et al 1999; Galama et al 1999; Kulkarni et al 1999), 990510 (Stanek et al 1999; Harrison et al 1999; Kumar & Panaitescu 2000a), 000301C (e.g. Berger et al 2000; Masetti et al 2000; Sagar et al 2000b; Rhoads & Fruchter 2001), 000926 (Sagar et al 2000c), and (weakly) 991216 (Halpern et al 2000), while the absence of such breaks has been shown for GRB 970508 (Rhoads 1999b). The inferred opening angles range from \( \sim 2.5^\circ \) (GRB 970508, Rhoads & Fruchter 2001, if the break is indeed due to collimation) to lower limits \( > 30^\circ \) (GRB 970508, Rhoads 1999b). Comparisons of spectral and light curve slopes have lead to inferences of collimation for several more bursts, including GRBs 980519 (Halpern et al 1999; Sari, Piran, & Halpern 1999), and 000301C (Sagar et al 2000a).

These data remain open to alternative interpretations, however. Spectral and light curve slopes for isotropic bursts expanding into a stellar wind ambient medium (with density \( \rho \propto r^{-2} \)) can closely resemble the slopes expected from the post-break regime of a collimated afterglow (Chevalier & Li 1999; Halpern et al 1999). Also, the transition to the nonrelativistic regime can introduce a break into the afterglow light curve that may account for some of the observed breaks (Dai & Lu 1999). A third class of break can occur when the ambient medium has a sharp drop in density beyond some radius. Kumar & Panaitescu (2000b) explored this model in detail and find that a light curve slope as steep as \( t^{-3} \) can result, potentially explaining the behavior of GRB 000301C. Still, these other classes of break should produce a different relation between spectral and light curve slope that would be measurable given an adequate multiwavelength monitoring campaign.

Another unresolved issue is the sharpness of the observed breaks. The transition between the two asymptotic light curve slopes is expected to be rather slow in the models (Rhoads 1999a; Moderski, Sikora, & Bulik 2000; Panaitescu & Meszaros 1999). The most detailed analysis of this problem so far is by Kumar & Panaitescu (2000b) who found that the GRB 990510 break can be reproduced by combining a collimation break with the light curve break that occurs when the peak of \( f_\nu \) or \( \nu f_\nu \) shifts through the observed bandpass. This requires a coincidence that is acceptable once or a few times, but if such fortuitous circumstances appear in a large sample of afterglows it will indicate a problem with the model.
4 Polarization

GRB afterglows are thought to arise from synchrotron radiation in the expanding burst remnant. It is thus natural to expect some degree of polarization. However, if the burst is spherically symmetric, it is likely that the net polarization of the afterglow will be small, since there is no preferred position angle. Jetlike bursts allow the symmetry to be broken: If we are not precisely on the jet axis, then the projection of the jet axis on the sky defines a preferred direction and the polarization ought to be either parallel or perpendicular to that direction. Ghisellini & Lazatti (1999) and Sari (1999) have modeled the polarization of collimated burst afterglows and find that multiple polarization peaks are expected (at least two peaks, and three if sideways expansion of the ejecta is substantial). The position angle changes by $90^\circ$ between peaks. Observationally, this test has yet to be applied in a meaningful way, though the technology exists to do so. Several groups have reported attempting polarization measurements, resulting in one published measurement and a few upper limits. However, to really see multiple peaks would require $\gtrsim 10$ epochs of polarization measurement, far beyond anything yet achieved.

5 GRB Remnant Statistics

Because collimation determines both GRB rates and energies, the numbers and sizes of GRB remnants are expected to scale with the collimation angle. Thus, if we can identify GRB remnants in a reasonably complete and unambiguous way, we can infer the event rate from their statistics. HI supershells were proposed as possible GRB remnants in 1998 (Efremov, Elmegreen, & Hodge 1998; Loeb & Perna 1998). However, there are more conventional explanations for supershells (OB association winds and/or multiple supernovae) that can produce energies comparable to an isotropic GRB and must be ruled out before any shell would be a compelling GRB remnant candidate. The best test so far suggested (Perna, Raymond, & Loeb 2000) is to look for recombination lines of the highly ionized species that will be produced by GRBs (with their hard UV and X-ray photons) but not by OB stars or supernovae. Like the polarization test, this method relies on reasonably proven technology but has yet to bear fruit.

It may also be possible to study collimation through GRB remnant shapes. A collimated burst will yield a long, narrow remnant for a time. However, this test does not seem immediately promising, both because of the high angular resolution required and because the remnant will likely become fairly round by the time the blast wave becomes nonrelativistic. A further difficulty is that for collimated bursts that we see, we will be nearly on-axis and will therefore see a fairly round projected image of the remnant.

6 Further Possibilities

The tests discussed above all rely (directly or indirectly) on the electromagnetic radiation from GRBs and their afterglows. In future, it may become possible exploit other types of astronomy for GRB collimation. In particular, coalescing neutron
star binaries are a promising class of GRB progenitor models, and are expected to be among the more readily detected gravitational wave sources in the universe. The angular distribution of these gravitational waves should be calculable. Moreover, the “radiative transfer” problem for these gravitational waves is simpler than that for the gamma rays and lower energy afterglow photons, for which many types of scattering and absorption potentially affect the observed properties of the burst. If neutron star inspiral events do indeed lead to GRBs, then, it should be possible to constrain the collimation of the gamma rays by comparing statistics of GRBs to statistics of gravitational wave bursts. Similar arguments may be applied to neutrino emission from GRBs, though the angular distribution of the neutrinos will probably depend more heavily on details of the model than would gravitational waves.

7 Conclusions

The study of gamma ray burst collimation is still a very young field, and though there is much yet to learn we have come a long way from what we knew at the beginning of 1997. This progress has been fueled in two ways by by the discovery of afterglows. First, by yielding GRB redshifts, afterglows finished the GRB distance scale debate. This left collimation as the dominant uncertainty in burst energy requirements and event rates, motivating research on collimation. Second, afterglows have provided most of the tools for constraining collimation angles discussed above, including both tools that have found substantial applications to date.

Two primary conclusions emerge from the data so far. First, the most extreme collimation scenarios (those with opening angles \( \sim 1/\Gamma_0 \lesssim 1/100 \) radian) appear to be ruled out by nondetections in orphan afterglow searches. The mean opening angle favored by these searches (which is only a lower bound) is a factor of 10 larger, \( \gtrsim 5^\circ \). Second, the collimation angle appears to vary substantially from burst to burst, based on the observed light curve breaks. While this statement might still be challenged (e.g. if some observed breaks are not due to collimation), it is consistent with the huge variations seen in other GRB properties (e.g., light curve shapes). Interestingly, the inferred collimation angle and the isotropic equivalent energy appear to anticorrelate, so that GRBs are more nearly standard candles after collimation corrections are applied (see Frail et al 2001 for further discussion of this possibility).

The current rapid progress in studying GRB collimation should continue in the coming decade. New high energy missions will provide better samples of bursts. Coordinated multiwavelength followup of these bursts will increase the sample of bursts with breaks (especially those with breaks at early times), and will yield data sets that can more easily distinguish between different classes of light curve break. The first good polarization curves for GRB afterglows are another likely result of increased rates of prompt, accurate burst locations. Finally, large variability surveys are becoming much easier thanks to new instruments, and will soon either find orphan afterglows or yield truly compelling limits on their frequency. And once we have measured the collimation of gamma ray bursts, we can begin to use their energy requirements and event rates as real constraints on progenitor models for
the first time.

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