Beaming Effects in GRBs and Orphan Afterglows

Y. F. Huang  
*Department of Astronomy, Nanjing University, Nanjing 210093, China*

T. Lu  
*Purple Mountain Observatory, CAS, Nanjing 210008, China*

K. S. Cheng  
*Department of Physics, The University of Hong Kong, Hong Kong, China*

June 1, 2004

**Abstract.** The overall dynamical evolution and radiation mechanism of γ-ray burst jets are briefly introduced. Various interesting topics concerning beaming in γ-ray bursts are discussed, including jet structures, orphan afterglows and cylindrical jets. The possible connection between γ-ray bursts and neutron stars is also addressed.

**Keywords:** γ-ray bursts

1. Introduction

The discovery of γ-ray burst (GRB) afterglows in 1997, triggered by the famous Italian-Dutch BeppoSAX satellite, definitely shows that most, if not all, long GRBs are of cosmological origin. The so-called “fireball model” is strongly favored theoretically. In this standard model, the GRB fireball is assumed to be isotropic. However, as early as in 1997, Rhoads (1997) has already suggested that GRB outflows may be highly collimated. In the beaming case, as the ultra-relativistic jet decelerates, it will expand laterally at approximately co-moving sound speed. Naturally, photons are emitted into larger and larger solid angle. As the result, an obvious break should be observed in the multi-band afterglow light curves. The break time is determined by $\gamma \sim 1/\theta$, where $\gamma$ is the bulk Lorentz factor of the jet and $\theta$ is its half opening angle.

Observationally, the jet hypothesis gains some support soon in 1997. The γ-ray energy release of GRB 971214, if isotropic, is as large as $\sim 0.17M_\odot c^2$, well beyond the energy scope of a stellar object. Similar difficulty also exists in many other examples, such as GRBs 980703 ($\sim 0.06M_\odot c^2$), 990123 ($\sim 1.9M_\odot c^2$), 990510 ($\sim 0.16M_\odot c^2$), 991208 ($\sim 0.07M_\odot c^2$), 991216 ($\sim 0.38M_\odot c^2$), 000131 ($\sim 0.6M_\odot c^2$), 000926 ($\sim 0.15M_\odot c^2$), 010222 ($\sim 0.3M_\odot c^2$), and 020813 ($\sim 0.55M_\odot c^2$). In all these cases, emission should be highly collimated, so that the true energy release can be reduced to $\sim 10^{50} - 10^{51}$ ergs, within the energy output of a stellar object.
Also it is very interesting that light curve breaks do have been observed in a few afterglows, for example, in GRBs 990123, 990510, 991216, 000301C, 000926, 010222, 011121, 020124, 020813, 030226, and 030329. Such breaks have been widely regarded as being due to jet effect. In a few other cases (GRBs 980326, 980519, 990705, 991208, 000911, 01007, 020405), although no breaks were observed, the light curves are still abnormal since the afterglows decay quite steeply ($\sim t^{-2}$). Such rapid fading of optical afterglows has also been argued as evidence for collimation (Huang, Dai & Lu 2000b).

Beaming is an interesting topic in the field of GRBs. There are many researches concerning it, and many interesting results have been revealed. For example, Frail et al. (2001) suggested that the intrinsic energy releases of GRBs, after correction for the beaming angle, are strikingly clustered around $5 \times 10^{50}$ ergs. Recently, it is also discovered that a GRB jet should be highly structured, but not homogeneous.

In this article, we mainly discuss beaming effects in GRB afterglows. The dynamics and radiation mechanism will be described in Section 2. Structures of jets are then introduced in Section 3. The possible existence of cylindrical jets is addressed in Section 4. Section 5 is about orphan afterglows, and Section 6 investigates the possibility that the launch of a GRB jet may be associated with the kick of a high speed neutron star. The final section is a brief discussion.

2. Dynamics and Radiation

After producing the main burst via internal shocks at a radius about $10^{13}$ cm, the GRB ejecta continues to expand ultra-relativistically in the circum-burst medium. The external shock occurs when the swept-up medium mass, $m$, exceeds $M_{ej}/\eta$, where $M_{ej}$ is the the initial mass of the ejecta and $\eta$ is the initial value of the Lorentz factor $\gamma$. Afterglows are produced by the shock-accelerated electrons. Denoting the radius of the external shock as $R$, the observer’s time as $t$, the medium number density as $n$, then the overall evolution of a GRB jet can be conveniently described as (Huang et al. 1999, 2000a, b, c),

$$\frac{dR}{dt} = \beta c \gamma (\gamma + \sqrt{\gamma^2 - 1}),$$

(1)

$$\frac{dn}{dR} = 2 \pi R^2 (1 - \cos \theta) n m_p,$$

(2)

$$\frac{d\theta}{dt} = \frac{c_s (\gamma + \sqrt{\gamma^2 - 1})}{R},$$

(3)
Beaming in GRB afterglows

\[
\frac{d\gamma}{dm} = -\frac{\gamma^2 - 1}{M_{ej} + \epsilon m + 2(1 - \epsilon)\gamma m},
\]

(4)

where \( \beta = \sqrt{\gamma^2 - 1}/\gamma \), and \( \epsilon \) is the radiative efficiency. \( c_s \) is the comoving sound speed, which can be further expressed as,

\[
c_s^2 = \hat{\gamma}(\hat{\gamma} - 1)(\gamma - 1)\frac{1}{1 + \hat{\gamma}(\gamma - 1)c^2},
\]

(5)

where \( \hat{\gamma} \approx (4\gamma + 1)/(3\gamma) \) is the adiabatic index.

This dynamical model has the advantage that it applies in both the ultra-relativistic and the non-relativistic phases, and that it describes the lateral expansion in an accurate way.

Synchrotron radiation is the main emission mechanism. To make our calculation appropriate even in the deep Newtonian phase (Huang & Cheng 2003), we assume that the shock-accelerated electrons distribute according to their kinetic energy as (Huang & Cheng 2003),

\[
\frac{dN_e'}{d\gamma_e} \propto (\gamma_e - 1)^{-p}, \quad (\gamma_{e,\text{min}} \leq \gamma_e \leq \gamma_{e,\text{max}}),
\]

(6)

where \( \gamma_e \) is the thermal Lorentz factor of electrons. Assuming that there is an equi-partition between the proton energy density, the magnetic energy density, and the electron energy density as well, it will then be relatively easy to calculate the afterglows by considering synchrotron radiation. Note that the equal-time-surface effect should be taken into account in calculations. Examples of such calculations have been given in Huang & Cheng (2003).

3. Jet Structure

The simplest jet model involves a homogeneous conical outflow. Recently it was realized by more and more authors that GRB jets may have complicate structures. Basically there are three kinds of structured jets: two-component jets (Berger et al. 2003), Gaussian jets (where the energy per unit solid angle depends as a Gaussian function on the angular distance from the axis), and power-law jets (where the energy density profile is a power-law function) (Mészáros, Rees & Wijers 1998; Dai & Gou 2001; Zhang & Mészáros 2002). Generally, the structured jet models have the potential of explaining normal GRBs, X-ray rich GRBs, and X-ray flashes in a uniform picture (Huang et al. 2004; Zhang et al. 2004).
Although the profile functions of Gaussian jets and power-law jets seem quite simple, their afterglows are in fact not easy to calculate, especially when the lateral expansion and the equal-time-surface effect are considered. The two-component jet model is relatively simple in these aspects. A two-component jet has two components: a narrow but ultra-relativistic outflow (with Lorentz factor typical of normal GRB fireballs, i.e. $\gamma \geq 100 - 1000$), and a wide but mildly relativistic ejecta (with $1 \ll \gamma \ll 100$). These two components are usually assumed to be coaxial. At first glance, the two-component jet model seems to be quite coarse, but interestingly enough, it gains some support from numerical simulations of the collapse of massive stars (Zhang et al. 2003). Additionally, Berger et al. (2003) found that the model can give a perfect explanation to the multiband observations of the famous GRB 030329. In their explanation, the gamma-ray and early afterglow emission of GRB 030329 come from the narrow component, while the radio and optical afterglows beyond 1.5 days are produced by the wide component.

In a recent study, Huang et al. (2004) further proposed that the optical afterglow light curve of X-ray Flash (XRF) 030723 can also be well fit by the simple two-component model. To re-produce the rebrightening of the afterglow of XRF 030723, Huang et al. (2004) assumed that the observer is off-axis, and that the intrinsic energy of the wide component is less than that of the narrow component. Figure 1 illustrates the result of their fitting. Anyway, it should be noted that the rebrightening in this event can also be explained by an underlying supernova (Fynbo et al. 2004; Tominaga et al., 2004).
Beaming in GRB afterglows

4. Cylindrical Jets

Usually GRB jets are assumed to be conical outflows. However, Cheng, Huang and Lu (2001) have suggested that the relativistic outflows in GRBs might also be cylindrical. They have studied afterglows of cylindrical jet detailedly. If a cylindrical jet does not expand laterally, it will remain in the ultra-relativistic phase for a very long period (typically longer than 10^9 s). The afterglow usually decays like \( S_\nu \propto t^{-p/2} \), where \( p \) is the power-law index of the electron distribution. On the other hand, if the cylindrical jet expands laterally, it will enter the Newtonian phase quickly. In this case, the afterglow light curve evolves from \( S_\nu \propto t^{-p} \) to \( S_\nu \propto t^{-(15p-21)/10} \). As the example, Figure 2 illustrates the optical afterglow light curves of some cylindrical jets.

Huang et al. (2002b) specially pointed out that for a cylindrical jet without lateral expansion, the afterglow light curve will become \( S_\nu \propto t^{-1} - t^{-1.3} \) if taking \( p = 2.0 - 2.6 \). Observationally, the decay of optical afterglows from many GRBs, such as GRBs 970508, 971214, 980329 and 980703, is in this range. In the most popular explanation, these GRBs are thought to be produced by isotropic fireballs. However, we should not omit the possibility that these events may in fact be due to cylindrical jets, as suggested by Huang et al. (2002b). Figure 3 shows that the cylindrical jet model can fit the afterglows of these events perfectly.

The concept of cylindrical jets has gained support observationally in fields other than GRBs. For example, it has long been found that jets in many radio galaxies are cylindrical, i.e. they maintain constant cross sections on large scales. Jets in many Herbig-Haro (HH) objects are also cylindrical (e.g., Ray et al. 1996). In fact, observations have

Figure 2. R-band afterglows from cylindrical jets without (left panel) and with (right panel) lateral expansion (Cheng, Huang & Lu 2001). The dashed, solid and dash-dotted lines in each panel correspond to \( p = 3, 2.5 \) and 2.2 respectively. The dotted lines correspond to conical jets with \( p = 2.5 \).
indicated clearly that HH jets are initially poorly focused, but are then asymptotically collimated into cylinders (Ray et al. 1996).

Theoretically, it is striking that cylindrical jets can be naturally produced in black hole-accretion disk systems (Shu et al. 1995; Krasnopolsky et al. 2003; Vlahakis & Königl 2003a, b; Fendt & Ouyed 2004). The collimation is mainly due to magnetic forces. It is well known that the poloidal component of a dipolar magnetic field decays as $B_P \propto r^{-3}$, where $r$ is the distance from the central object. It is also known that the motion of matter along poloidal magnetic field lines will unavoidably induce a strong toroidal field component, which decays as $B_T \propto r^{-1}$ (Fendt & Ouyed 2004). So, a magnetohydrodynamic (MHD) jet is asymptotically dominated by the toroidal magnetic field. This toroidal field exerts an inward force on the MHD jet through “hoop stress”, which provides the collimation. Numerous numerical results have shown that MHD jets are conical initially during the acceleration phase, but their half opening angles are turning smaller and smaller, until finally the outflows become cylindrical. Figure 4 shows examplar numerical results by Krasnopolsky et al. (2003). Of course, in the cases of GRBs, which are thought to occur in star forming regions, strong gradients in density might also play a role in collimating the jets.

5. Orphan Afterglows

If GRBs are really due to beamed ejecta, then the high-energy burst can be observed only when the observer is on-axis. However, in the off-axis case, since the afterglow emission is less beamed, it is still possible that the ejecta may be detected in optical and radio bands. These afterglows are called orphan afterglows, since they are not associated
Figure 4. Numerical results from the calculation of MHD jets launched by a stellar accretion disk (Krasnopolsky et al. 2003). Shown are streamlines (light solid lines) and isodensity contours (heavy solid lines and shades). The arrows are for poloidal velocity vectors, with length proportional to the speed. In the Left panel the jet is plot on 10 AU scale, and in the Right panel the jet is plot on 100 AU scale. It is clearly seen from the isodensity contours that the jet has a cylindrical shape.

with any known GRBs. Rhoads (1997) has pointed out that the ratio of orphan afterglows with respect to GRBs can potentially give a measure of the beaming angle of GRB jets.

However, Huang et al. (2002a) argued that the detection of orphan afterglows does not necessarily mean that GRBs are jetted. They argued that in the isotropic fireball model, there should exist many failed GRBs, i.e., fireballs with initial Lorentz factor $1 \ll \eta \ll 100 — 1000$. These fireballs cannot produce GRBs successfully. Huang et al. called them failed GRBs (FGRBs), although they sometimes are also called dirty fireballs (Dermer et al. 1999). It is obvious that FGRBs can also produce orphan afterglows. Huang et al. (2002a) thus suggest that when an orphan afterglow is observed, it should be monitored carefully for a relative long period so that its origin can be clarified. It can be used to estimate the beaming angle of GRBs only when we know for sure that it really comes from a jetted but off-axis GRB.

6. GRB Jets and Neutron Star Kicks

Since the discovery of afterglows in 1997, great progresses have been achieved in the field of GRBs. However, the energy mechanism of GRBs is still largely uncertain. Studies of beaming effects can potentially help to reveal this final enigma. A good example is the possibility that the launch of a GRB jet might be related to the kick of a neutron star. This
idea is proposed as early as in 1998 (Cen 1998), and has been discussed by a few authors (Dar & Plaga 1999; Huang et al. 2003).

In a recent study, Huang et al. (2003) further suggested that the neutron star should be a high speed one, with proper motion larger than $\sim 1000$ km/s. In this framework, when a new-born neutron star is kicked, a high-speed outflow should be launched into the opposite direction, whose energy can typically be $\sim 10^{52}$ ergs. The outflow may be composed of neutrinos and anti-neutrinos initially. However, annihilation of neutrinos and anti-neutrinos can deposit a small portion ($\sim 10^{-3} - 10^{-2}$) of its energy into an $e^\pm$ firecone. The isotropic equivalent energy of this firecone is $10^{50} - 10^{54}$ ergs, depending on the energy deposition efficiency and the half opening angle. It thus can give birth to a beamed GRB successfully.

This model, according to Huang et al.’s estimation, naturally meets many of the requirements of GRB engines. For example, the deposited energy is enough for normal GRBs; the collimation is naturally guaranteed; the ultra-relativistic motion is reasonably produced; the observed connection between GRBs and supernovae is well explained; the duration of GRBs is consistent with the timescale of a typical kick process; the event rate is satisfactory, i.e. consistent with the observed GRB rate of $\sim 1 - 3$ per day; the model naturally produces the rapid variability in GRB light curves. Finally, it also explains the standard energy reservoir hypothesis found by Frail et al. (2001).

7. Discussion and Conclusions

In this article we introduce various beaming effects in GRBs. A convenient way to calculate afterglows of beamed GRBs is introduced. Structures of GRB jets are described, with the major attention being paid on the two-component model. We also discussed the possible existence of cylindrical jet in GRBs. The method of using orphan afterglow surveys to measure the beaming of GRB jets is discussed in some detail. It is shown that failed GRBs may play a role in the process, and thus make the problem much more difficult. We also addressed the possible connection between GRB jets and neutron star kicks. We believe it is an interesting idea that the launch of a GRB jet may be associated with the kick of a high speed neutron star.

Collimation is important in GRBs, since it provides important clues on the progenitors. Collimation can also be identified via effects other than those mentioned above. For example, optical afterglows from a jet can be significantly polarized, in principle up to tens of percents (Gruzinov 1999; Mitra 2000). In fact, polarization has already been
observed in a few afterglows on the level of a few percents (Bersier et al. 2003). These observations strongly indicate that GRBs are collimated. However, such observations still cannot be directly used to measure the beaming angle. Radio afterglows in the very late phase can be used to estimate the intrinsic kinetic energy of GRB remnant, and thus may provide information of beaming indirectly but independently.

Acknowledgements

We thank the referee for useful comments and suggestions. This research was supported by the Special Funds for Major State Basic Research Projects, the Foundation for the Author of National Excellent Doctoral Dissertation of P. R. China (Project No: 200125), Projects 10003001, 10233010 and 10221001 supported by NSFC, and an RGC grant of Hong Kong SAR.

References

Berger E., et al., 2003, Nature, 426, 154
Bersier D., et al., 2003, ApJ, 583, L63
Cen R., 1998, ApJ, 507, L131
Cheng K.S., Huang Y.F., Lu T., 2001, MNRAS, 325, 599
Dai Z.G., Gou L.J., 2001, ApJ, 552, 72
Dar A., Plaga R., 1999, A&A, 349, 259
Dermer C.D., Chiang J., Böttcher M., 1999, ApJ, 513, 656
Fendt C., Ouyed R., 2004, ApJ, 608, 378
Fraga D.A., et al., 2001, ApJ, 562, L55
Fynbo J.P.U., et al., 2004, ApJ, 609, 962
Gruzinov A., 1999, ApJ, 525, L29
Huang Y.F., Cheng K.S., 2003, MNRAS, 341, 263
Huang Y.F., Dai Z.G., Lu T., 1999, MNRAS, 309, 513
Huang Y.F., Gou L.J., Dai Z.G., Lu T., 2000a, ApJ, 543, 90
Huang Y.F., Dai Z.G., Lu T., 2000b, A&A, 355, L43
Huang Y.F., Dai Z.G., Lu T., 2000c, MNRAS, 316, 943
Huang Y.F., Dai Z.G., Lu T., 2002a, MNRAS, 332, 735
Huang Y.F., Tan C.Y., Dai Z.G., Lu T., 2002b, Chin. Astron. Astrophys., 26, 414
Huang Y.F., et al., 2003, ApJ, 594, 919
Huang Y.F., et al., 2004, ApJ, 605, 300
Krasnopolsky R., Li Z.Y., Blandford R.D., 2003, ApJ, 595, 631
Mészáros P., Rees M.J., Wijers R.A.M.J., 1998, ApJ, 499, 301
Mitra A., 2000, A&A, 359, 413
Ray T.P., et al., 1996, ApJ, 468, L103
Rhoads J., 1997, ApJ, 487, L1
Shi F.H., et al., 1995, ApJ, 455, L155
Tominaga N., et al., 2004, ApJ, submitted (astro-ph/0405151)
Vlahakis N., Königl A., 2003a. ApJ, 596, 1080
Vlahakis N., Königl A., 2003b. ApJ, 596, 1104
Zhang B., Mészáros P., 2002. ApJ, 571, 876
Zhang B., et al., 2004. ApJ, accepted, astro-ph/0311190
Zhang W., Woosley S.E., MacFadyen A.I., 2003. ApJ, 586, 356