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Probing GRB Jet Structure from Prompt Emission

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Abstract Gamma-Ray Burst (GRB) prompt emission contains information that can be used to infer structure of the relativistic outflow. Spectral lags, the Internal Luminosity Function (ILF), and Color-Color Diagrams are attributes that provide diagnositcs with which jet structure can be studied. These attributes help delineate properties of internal shocks originating in the large Lorentz factor, tightly-beamed central core of the jet and external shocks resulting when the jet slows down by decelerating into the external medium. The external shock signature has a smaller Lorentz factor and a larger beaming angle than the central jet core, yet both components are present in the prompt emission of some GRBs.

Key words: techniques: gamma rays: bursts — supernovae: general — stars: winds, outflows — ISM: jets and outflows

1 INTRODUCTION

Based on microquasar kinematics, Mirabel (2004) has proposed that microquasars might represent the evolution of some Long GRBs (e.g. those with BATSE T90 durations ≥ 1.6 seconds (Hakkila et al. 2000)). The link between the two types of objects might be closer than an evolutionary one; there are behavioral similarities between GRBs and microquasars indicating that similar physics might take place in both phenomena. Specifically, GRB prompt emission appears to signify jet structure; these jets are relativistic, beamed outflows which have characteristics in common with microblazars (e.g. Romero et al. 2002). The main difference seems to be that GRBs are much shorter-lived, and have higher energies and have significantly larger Lorentz factors than microblazars.

The favored GRB model involves the collapsing core of an evolved massive He star (e.g. Zhang et al. 2003, and references therein). As the core collapses, a torus develops, and jets form and punch their way through the stellar envelope. The jets are highly relativistic, and they accelerate as they break out of the envelope. Bursts of gamma-ray emission are presumably produced by collisions of shocks found within the jets. The GRB emission time is short because

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the shocks quickly lose energy as they interact with the surrounding interstellar medium and slow. Astronomers have historically debated whether GRB pulses are associated with *internal* or *external* shocks.

Internal shocks represent collisions between shells or turbulence withing a relativistic wind or jet. Much of GRB pulse structure is consistent with simplified internal shock models (Sari & Piran 1997, Kobayashi, Piran, & Sari 1997, Daigne & Mochkovitch 1998, Ramirez-Ruiz & Fenimore 2000, Nakar & Piran 2002). For example, GRB pulses are typically short with short pulse separations; they are sometimes spectrally hard.

External shocks represent collisions between relativistic shells and an external medium. They are characterized by broad pulses and long pulse separations, and broadening and spectral softening of pulses is expected as bursts progress (Fenimore, Madras, & Nayakshin 1996, Sari & Piran 1997, Fenimore et al. 1999, Fenimore & Ramirez-Ruiz 1999b). Evidence for external shocks coupled to the initiation of the afterglow is present in some GRBs that have soft emission occuring preferentially towards the end of the burst (Giblin et al. 1999, Burenin et al.. 1999, Giblin et al. 2002). Extended soft emission suggestive of the onset of afterglow has also been detected statistically in a large sample of BATSE GRBs (Connaughton 2002).

Given that *the vast majority of GRB pulses exhibit characteristics consistent with internal shocks,* it is difficult to demonstrate that the expected external shock pulse signatures exist. Yet, the number of GRBs with afterglows implies that such signatures exist and should be present in many GRBs. How can external shock signatures be identified in GRB pulse structure?

2 EXTERNAL SHOCK SIGNATURES IN QUIESCENT GRBS

A quiescent GRB is one in which the emission drops to the background for an extended period of time greater than or equal to the duration of the initial emission episode (Ramirez-Ruiz & Merloni 2001; Ramirez-Ruiz, Merloni, & Rees 2001; Hakkila & Giblin 2004). Since the emission of quiescent GRBs is separated into distinct episodes, it is possible that internal and external shocks might be separated in some quiescent bursts.

It is difficult to find examples of external shock signatures in quiescent GRBs. However, two GRBs have been found that have post-quiescent emission consistent with external shocks (Hakkila & Giblin 2004). These are GRBs 960530 (BATSE trigger 5478) and 980125 (BATSE trigger 6581). The BATSE 4-channel data are shown for these bursts in Fig. 1 and Fig. 2.

How can it be determined that the post-quiescent pulses of these GRBs are indeed indicative of external shocks? Hakkila & Giblin (2004) have applied three data analysis tools to these pre- and post-quiescent emission episodes to answer this question. They have studied energy-dependent spectral lags as obtained from the cross-correlation function, the best-fit power-law and curvature indices of the Internal Luminosity Function, and spectral evolution as obtained from Color-Color Diagrams.

An energy dependent lag is the temporal shift between two energy channels. An effective way of obtaining lags is from the cross-correlation function (e.g. Band 1997). It has been assumed that the spectral lag observed between any two energy channels is the same for all emission episodes occuring within a GRB (Norris, Marani, & Bonnell 2000). However, the post-quiescent emission episodes of GRBs 960530 and 980125 exhibit lags that are significantly longer (roughly an order of magnitude so) than those found in the pre-quiescent episodes (Hakkila & Giblin 2004).

The Internal Luminosity Funciton (ILF) has been found to act as a GRB morphology indicator. The ILF is the distribution of luminosity within a GRB; it is obtained from the burst's flux distribution (Horack & Hakkila 1997, Hakkila et al. 2003). The ILF can be modeled accurately with a power-law index and a power-law curvature index. The two attributes strongly correlate: if a burst has a flat power-law index, then the ILF shows essentially no curvature (a constant decrease with log(luminosity)), while a steep ILF is accompanied by a large curvature

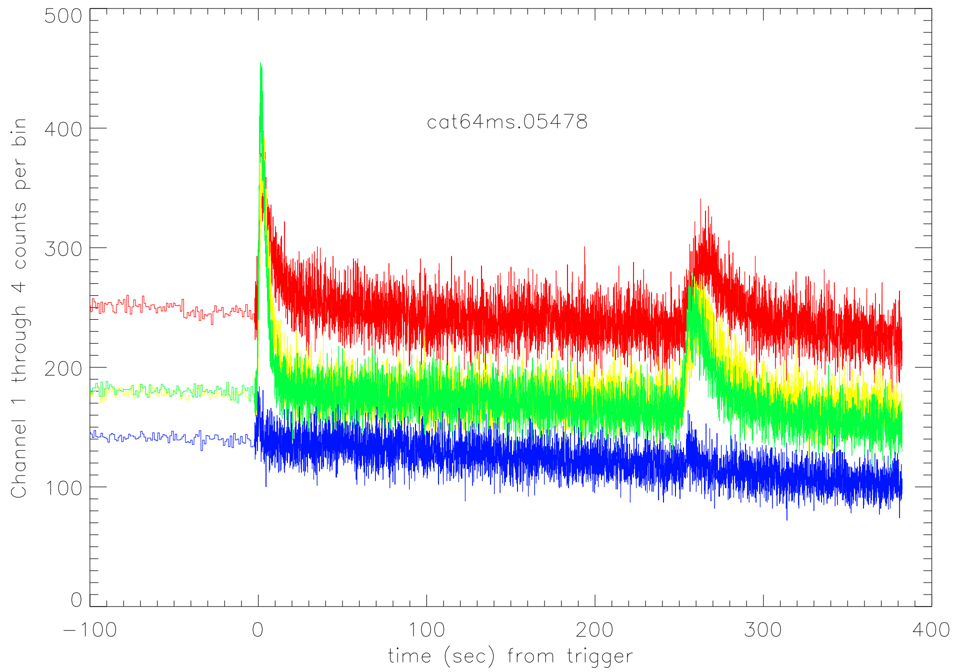

Fig. 1 GRB 960530 (BATSE trigger 5478).

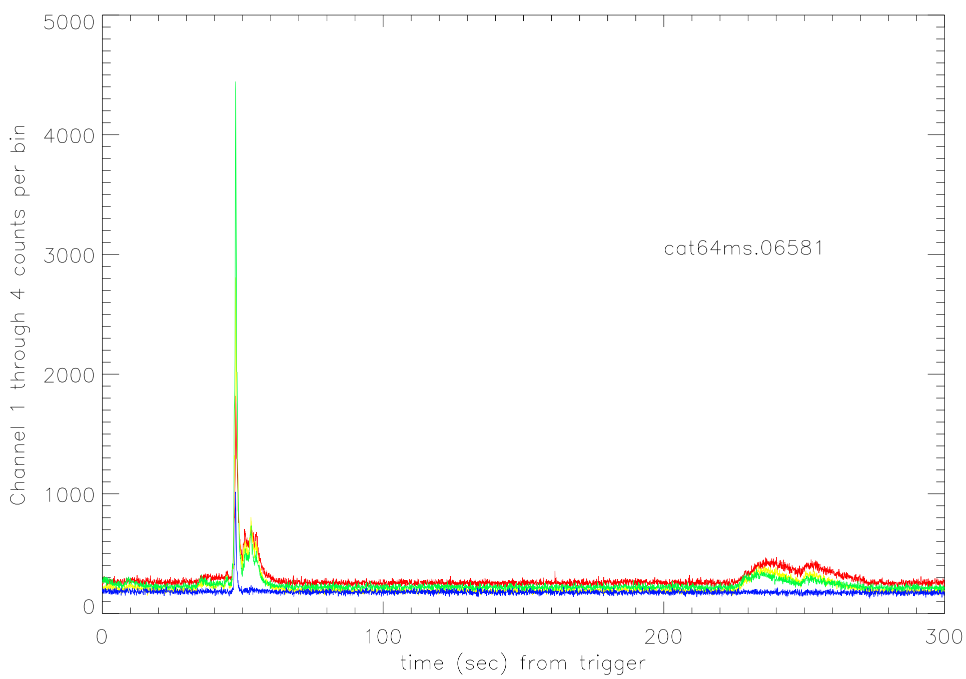

Fig. 2 GRB 980125 (BATSE trigger 6581).

(indicating a rapid increase with luminosity above the detection threshold followed by a rapid decrease at luminosities approaching the peak luminosity). Flat ILF power-law indices (with little curvature) tend to be found in GRBs containing few pulses (such as FREDs – Fast Rise Exponential Decay bursts). Steep ILF power-law indices (with large ILF curvatures) are found in two very different morphological types: long GRBs containing many pulses, and GRBs containing a single, broad, smooth pulse. The post-quiescent emission episodes in GRBs 960530 and 980125 have steep ILFs consistent with their broad, smooth pulse structures, and these ILFs differ from those associated with their pre-quiescent emission.

Time-dependent Color-Color Diagrams (CCDs) can be used to track GRB spectral evolution (Giblin et al. 2002). Although GRB spectra typically evolve from hard to soft, it is uncommon for their colors to be consistent with those predicted by theoretical synchrotron cooling models indicative of external shocks. However, the post-quiescent episodes of GRBs 960530 and 980125 are both consistent with these models.

The post-quiescent emission episodes of GRBs 960530 and 980125 also do not obey an established GRB behavior indicative of internal shocks. Ramirez-Ruiz & Merloni (2001) and Ramirez-Ruiz, Merloni, & Rees (2001) found that most quiescent GRBs have a post-quiescent emission duration that is similar to the duration of the quiescent time period. They interpreted this as a meta-stable outflow configuration allowing significant energy to be made available through subsequent internal shocks. The post-quiescent emission durations of GRBs 960530 and 980125 are three to four times larger than the quiescent duration, and are thus inconsistent with both other GRB observations and the model.

The post-quiescent emission in GRB 960530 is a single pulse. This pulse is a broad, smooth pulse having an extremely long lag, a soft spectrum, and a steep ILF. Since the very long lag emission can exist as a separate episode, it is possible that some bursts might exhibit only the smooth, long lag (external shock) component. There are over 300 faint, soft, very long lag GRBs in the BATSE catalog (Norris 2002) that might be external shock signatures for which the internal shock signature is unobserved.

However, the post-quiescent emission in GRB 980125 consists of two pulses. The first of these pulses is a broad, smooth pulse having an extremely long lag, a soft spectrum, and a steep ILF. A standard FRED pulse follows and is somewhat blended with the decaying emission from the broad pulse. This demonstrates that an external shock does not have to be the final event in a GRB; it can apparently precede other pulses that are indicative of internal shocks. There are many BATSE GRBs that appear to contain narrow pulses blended with fainter, broad, smooth pulses. Thus, external shock signatures may be common but unrecognized as such in GRBs.

3 INFERRING JET STRUCTURE FROM SHOCKS

Images of GRB jets do not exist, as they do for some microquasars. Neither do repeated spectroscopic measurements from which jet structure is implied (such as those available for SS433). Instead, the jet morphology must be indirectly inferred from internal and external shock signatures of individual bursts as well as from statistical GRB samples.

Both the internal and external shocks are thought to arise from the same collimated relativistic outflow. The internal shocks appear to result from colliding shells in the high-Γ, tightly-collimated jet center (e.g. Mészáros, Rees, & Wijers 1998, Kumar & Piran 2000), where Γ is the bulk Lorentz factor. The external shocks initiating the onset of afterglow are presumably produced by a low-Γ, slowly-expanding shock found at the interface between the jet and the external medium. The opening angle of the jet should increase as deceleration sets in (e.g. Ramirez-Ruiz & Fenimore 1999). Determination of the detailed jet structure performed using numerical hydrodynamic codes (e.g. Zhang, Woosley, & MacFadyen 2003, Aloy et al. 2003) indicate that the beaming angle of the high-Γ component is $\leq 5^\circ$, whereas the low-Γ component can have a beaming angle $\geq 15^\circ$ (Zhang, Woosley, & MacFadyen 2003). The angular expansion of the external shock can be aided by a "cocoon jet", which is a secondary jet structure that forms when energy is deposited in a stellar cavity prior to breakout (Ramirez-Ruiz, Celotti, & Rees 2002).

In the standard internal/external shock model, deceleration of the relativistic ejecta into the surrounding medium occurs at a deceleration distance inversely proportional to Γ and results in a temporal delay between the prompt internal shock γ-ray emission and the afterglow (Ramirez-Ruiz, Celotti, & Rees 2002). A temporal overlap between internal and external shock emission would be expected in these cases, producing complex γ-ray light curves.

The many long-lag GRBs found in the BATSE database are often initiated by and/or are blended with narrow, short-lag pulses. It is tempting to interpret these as GRBs produced by jets with small deceleration distances: few internal shocks are observed, and the onset of afterglow is thus the defining characteristic of their prompt emission. However, this hypothesis is complicated by suggestions that other related phenomena such as X-ray rich GRBs (XRRs), X-Ray Flashes (XRFs), orphan afterglows, and even the Short class of GRBs, also result from off-axis GRB viewing. Some of these authors (e.g. Mészáros, Rees, & Wijers 1998, Zhang et al. 2004) suggest that off-axis viewing results in spectral softening, while others (Yamazaki, Ioka, & Nakamura 2004) instead suggest that discrete subjets are seen off-axis which can be very hard and short.

4 CONCLUSIONS

GRBs are consistent with microquasar models, although they exhibit their behaviors for only a short period of time. Two emission components are present in some GRBs; the short lag component is consistent with internal shocks while the long lag appears to represent external shocks. The broad, long lag component might be present but unrecognizable in many bursts, yet may dominate others. Whether it is seen or not may depend on many GRB characteristics, including the initial jet outbreak velocity, the density of the surrounding medium, and the viewing angle from which the GRB is observed.

There are many theoretical models that attempt to simultaneously explain Long and Short GRBs, XRRs, XRFs, and orphan afterglows. Most of these models have not yet attempted to account for the observations of internal and external shocks described in this manuscript. We believe that these observations provide valuable constraints that will eventually help us to link GRBs and related phenomenon with microquasars.

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References

Aloy M.-A., Martí J.-M., Gómez J.-L., Agudo I., Müller E., Ibanéz J.-M., 2003, ApJ, 585, L109
Band D. L., 1997, ApJ, 486, 928
Burenin R. A. et al., 1999, A&A, 344, L53
Connaughton V., 2002, ApJ, 567, 1028
Daigne F., Mochkovitch R., 1998, MNRAS, 296, 275
Fenimore E. E., Madras C. D., Nayakshin S., 1996, ApJ, 473, 998
Fenimore E. E., Ramirez-Ruiz E., 1999b, In: Gamma-Ray Bursts: The First Three Minutes, ASP Conf. Ser. 190, 67
Fenimore E. E., Cooper C., Ramirez-Ruiz E., Sumner M. C., Yoshida A., Namiki M., 1999, ApJ, 512, 683
Giblin T. W., van Paradijs J., Kouveliotou C., Connaughton V., Wijers R. A. M. J., Briggs M. S., Preece R. D., Fishman G. J., 1999, ApJ, 524, L47

Giblin T. W., Connaughton V., van Paradijs J., Preece R. D., Briggs M. S., Kouveliotou C., Wijers R. A. M. J., Fishman G. J., 2002, ApJ, 570, 573
Hakkila J., Haglin D. J., Pendleton G. N., Mallozzi R. S., Meegan C. A., Roiger R. J., 2000, ApJ, 538, 165
Hakkila J., Giblin T. W., Roiger R. J., Haglin D. J., Paciesas W. S., Meegan C. A., 2003, ApJ, 582, 320
Hakkila J., Giblin T. W., 2004, ApJ, 610, 361
Horack J. M. , Hakkila J., 1997, ApJ, 479, 371
Kobayashi S., Piran T., Sari R., 1997, ApJ, 490, 92
Kumar P., Piran T., 2000, ApJ, 535, 152
Mirabel I. F., In: F. Combes, D. Barret, T. Contini, F. Meynadier and L. Pagani, eds., SF2A-2004: Semaine de l'Astrophysique Francaise, Paris: P-Sciences, Conference Series, 85
Mészáros P., Rees M. J., Wijers R. A. M. J., 1998, ApJ, 499, 301
Nakar E., Piran T., 2002, ApJ, 572, L139
Norris J. P., Marani G. F., Bonnell J. T., 2000, ApJ, 534, 248
Norris J. P., 2002, ApJ, 579, 386
Ramirez-Ruiz E., Celotti A., Rees M. J., 2002, MNRAS, 337, 1349
Ramirez-Ruiz E., Fenimore E. E., 1999, A&AS, 138, 521
Ramirez-Ruiz E., Fenimore E. E., 2000, ApJ, 539, 712
Ramirez-Ruiz E., Merloni A., 2001, MNRAS, 320, L25
Ramirez-Ruiz E., Merloni A., Rees M. J., 2001, MNRAS, 324, 1147
Romero G. E., Kaufman Bernadó M. M., Mirabel I. F., 2002, A&A, 393, L61
Sari R., Piran T., 1997, MNRAS, 287, 110
Yamazaki R., Ioka K., Nakamura T., 2004, ApJ, 607, L103
Zhang W., Woosley S. E., MacFadyen A. I., 2003, ApJ, 586, 356
Zhang B., Dai X., Lloyd-Ronning N. M., Mészáros P., 2004, ApJ, 601, L119