Reverse Shocks in Short Gamma-Ray Bursts
– The case of GRB 160821B and prospects as gravitational-wave counterparts –

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ABSTRACT

The shock system that produces the afterglow to GRBs consists of a forward- and a reverse-shock. For short GRBs, observational evidence for a reverse-shock has been sparse – however, the afterglow to GRB 160821B requires a reverse-shock at early times to explain the radio observations. GRB 160821B is additionally accompanied by the best sampled macronova without a gravitational-wave detection, and an interesting late time X-ray afterglow behaviour indicative of a refreshed-shock. The presence of an observed reverse-shock in an on-axis short GRB means that the reverse-shock should be considered as a potential counterpart to gravitational-wave detected mergers. As a gravitational-wave counterpart, the afterglow to an off-axis GRB jet can reveal the jet structure – a reverse-shock will exist in these structured jet systems and the signature of these reverse-shocks, if observed, can indicate the degree of magnetisation in the outflow. Here we show the case of GRB 160821B, and how a reverse-shock will appear for an off-axis observer to a structured jet.

Key words: Yamada conference LXXI: proceedings — gamma-ray bursts: GRB 160821B, general — gravitational wave: electromagnetic counterparts

1. Introduction

For a relativistic shell expanding into a medium, two shocks will form: a forward shock that propagates into the external medium, and a reverse shock that propagates into the shell [Sari & Piran(1995)]. In describing the reverse shock, two regimes are usually discussed, these are the thin shell, or Newtonian shock case, and the thick shell, or relativistic shock case [Kobayashi(2000), etc]. The relativistic shell will decelerate at the reverse shock crossing time in both regimes [Kobayashi et al.(1999)]. The duration and energetics of short gamma-ray bursts (GRBs) imply that any reverse shock in these systems will typically be described by the thin shell case [Lamb & Kobayashi(2018) 2019].

Emission from a reverse shock is an important probe of the conditions in a GRB outflow towards the central engine. Modelling the observed afterglow emission enables constraints to be placed on the magnetisation and the bulk Lorentz factor $\Gamma_0$, where $F_{\text{max},r} = \Gamma_0 F_{\text{max},f} C_F R_B$, and here $F_{\text{max}}$ is the maximum synchrotron flux from the reverse and forward shock, $r$ and $f$ respectively, $C_F$ is a correction factor, see [Harrison & Kobayashi(2013)], and $R_B \equiv \varepsilon_{B,r}/\varepsilon_{B,f}$ is the magnetisation parameter, see [Zhang et al.(2003)].

The reverse shock in short GRBs has been notoriously difficult to observe [Lloyd-Ronning(2018)], however, the short GRB 051221A has evidence of a reverse shock with a radio frequency detection and upper-limits [Soderberg et al.(2006)], and recently reverse shock emission has been shown to be consistent with the optical afterglow to the candidate short GRB 180418A [Becerra et al.(2019)], and radio observations of the afterglow to the short GRB 160821B require a reverse shock component [Lamb et al.(2019a) Troja et al.(2019a)]. These successes in observing the reverse shock in short GRBs, although rare, raise the prospect of identifying the reverse shock emission in gravitational-wave detected neutron star mergers, where the systems jet-axis is likely misaligned for an observer and so the afterglow and GRB will be observed off-axis [Lamb & Kobayashi(2017) 2018, 2019].

2. GRB 160821B

The short GRB 160821B, at a redshift of $z = 0.162$, had an isotropic gamma-ray energy of $E_{\gamma,\text{iso}} = (2.1 \pm 0.2) \times 10^{50}$ erg, based on the 8–10,000 keV band fluence of $(2.52 \pm 0.19) \times 10^{-6}$ erg cm$^{-2}$ [Liu et al.(2017)].
Fig. 1. The broadband afterglow to GRB 160821B. Dashed or dotted lines are the model light-curves, filled circles are data, and triangles are upper-limits, see [Lamb et al.(2019a)] for details. Left: the afterglow from radio to X-ray frequencies (top to bottom), a reverse shock contribution is required at early times to explain the radio observation, while at late times energy injection is needed to explain the X-ray, optical and radio data. From ~1–5 days an excess at optical and infrared indicates a macronova. Right top: expands the macronova and afterglow model with the data. Right bottom: shows the model fits versus data residual.

Ray, optical, and radio frequency observations of the afterglow to GRB 160821B were performed from 0.06–23.23 days after the burst; for a full list of the observations used here see [Lamb et al.(2019a)]. Early infrared observations put limits on the presence of a macronova [Kasliwal et al.(2017)], however, more complete broadband observations revealed emission at optical and infrared frequencies in excess of that expected from afterglow modelling of the X-ray and radio data [Lamb et al.(2019a), Troja et al.(2019a)]

In Fig. 1 we show the afterglow data and our preferred model. The complex behaviour of the afterglow is explained variously by: the contribution of a reverse shock travelling into a mildly magnetised ($R_B \sim 8$) shell at early times ($\sim 0.1$ days), we estimate a bulk Lorentz factor for the initial outflow $\Gamma_0 \sim 60$; a jet break at $\sim 0.3 - 0.4$ days followed by an injection of energy from a fallback powered second jet episode [Rosswog(2007), Kagawa et al.(2019)] that rebrightens the afterglow [Granot et al.(2003) etc]; and a macronova contribution at $\sim 1 - 5$ days. The best-fitting macronova model [Kawaguchi et al.(2018)] consists of two-components: a dynamical ejecta mass of $\sim 0.001 M_\odot$, and a post-merger or secular ejecta mass of $\sim 0.01 M_\odot$.

3. Reverse Shocks as Gravitational Wave Counterparts

The GRB 170817A and its macronova and afterglow in association with the gravitational-wave detected merger of a binary neutron star at $\sim 40$ Mpc [Abbott et al.(2017)] has shown that short GRBs are produced in binary neutron star mergers. The late-time afterglow to GRB 170817A indicated that the resultant jets from neutron star mergers, when viewed at a higher inclination than the central jet axis, will reveal the outflow structure [Lamb & Kobayashi(2017)]. The post-peak rapid decline of the late-time afterglow [Lamb et al.(2019b), Troja et al.(2019b)], along with VLBI observations [Ghirlanda et al.(2019), Mooley et al.(2018)], cleared any ambiguity in the jet-core dominated origin of the afterglow [Lamb et al.(2018)].

For neutron star mergers discovered via gravitational-waves, the reverse shock in the afterglow can potentially be observed for systems that are inclined < 20°, at a luminosity distance < 100 Mpc, and that have some lateral structure; see Fig 2 and [Lamb & Kobayashi(2019)].
Fig. 2. The afterglow light-curve for four jet structure models following those in [Lamb & Kobayashi(2017)] but including sideways expansion, synchrotron self-absorption, and a reverse shock for an ejecta shell characterised by a magnetic parameter $R_B = [1, 50, 500]$, bold lines in green (solid), yellow (dashed), and blue (dash-dotted) respectively, see [Lamb & Kobayashi(2019)]. The light-curves for an afterglow at 5 GHz and 100 Mpc are shown at $[0^\circ, 12^\circ, 18^\circ, 36^\circ, 54^\circ, 72^\circ, 90^\circ]$. The effects of scintillation are shown with the grey shaded regions at early times while the size emitting region is still small [Granot & van der Horst(2014)]. Insets on each panel show the spectra at the times indicated by ‘A’ and ‘B’.

Additionally, a magnetisation parameter $R_B \sim$ a few is required and observations should ideally commence at $\sim$ 0.1 days post merger and at radio frequencies < 100 GHz. For such cases, scintillation may complicate the observations, however, carefully measured scintillation can be used to constrain the size of the emitting region [Granot & van der Horst(2014)].

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