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Recent developments in gamma-ray afterglow theory

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Abstract

Gamma-ray burst (GRB) afterglows have long played a key role in our understanding of the physics of GRBs. The recent detection of the electro-magnetic counterparts including an afterglow jet to a neutron star merger indicate that this will remain so in the future. With the detection of GRB 170817A, afterglow observations have fully caught up again with theory and we have been provided with an opportunity to discard old jet models, refine alternative jet geometry models already in the literature and to think hard about future predictions. The GRB community has admirably stepped up to the plate and observational, theoretical and computational progress has been very rapid over the past years. Additionally, large-scale electro-magnetic surveys, observations at extremely high frequencies and an increasing number of gravitational-wave detections of merging neutron stars offer tantalizing prospects of further upheavals in afterglow and GRB theory. In these proceedings, I will take stock of some theoretical progress on afterglow theory made in the past few years.

Key words: workshop: proceedings — LaTeX2e: style file — instructions

1. Introduction: the basic picture

Afterglows have for years been detected across a broad band of frequencies from radio to X-rays. The basic theoretical picture of GRB afterglows has been firmly established ever since the phenomenon was proposed prior to discovery (Meszaros & Rees 1993). A substantial amount of energy E is deposited within a small region of space, giving rise to a blast wave moving radially outward at a Lorentz factor Γ that can reach up to thousands and approximately obeys $E = \Gamma^2 M c^2$, where M the total mass swept up by the blast wave. Emission is produced by shock-acceleration of electrons, which lose their energy through emitting synchrotron radiation under the influence of small-scale magnetic fields that are also generated at the shock front of the blast wave. The synchrotron spectrum consists of a series of connected power-law regimes in frequency. High frequencies (i.e. X-rays) that only probe the hottest electrons are affected the strongest by the post-shock cooling of the electrons. Low frequencies (i.e. radio at sufficiently long wavelengths) probe a regime at which the plasma has become opaque to its own emission and synchrotron self-absorption begins to play a role. In the observer frame, this spectrum evolves over fairly short time scales, and a single light curve will typically probe different dynamical regimes of the blast wave, as it evolves from relativistic flow along radial lines to a sideways spreading jet and ultimately a quasi-spherical Newtonian blast-wave remnant. Which parts of this evolutionary path are captured by a given observatory depend on how rapidly it can be on-target, and on the overall shift to lower frequency of the emission peak. For example, the X-ray Telescope on the Neil Gehrels Swift Observatory routinely captures the tail-end of the prompt emission occurring on the order of seconds to minutes after the initial burst of gamma-rays, whereas instruments like the Very Large Array have been used to observe afterglows for years after the GRB.

The spreading dynamics of the jet can be modeled at various level of sophistication, from semi-analytical toy model to multi-dimensional high-resolution relativistic hydrodynamics simulation. The emission from a relativistic jet is highly beamed, and since GRB jets are typically not spatially resolved by observations, the jet nature of the blast wave becomes apparent observationally only once the visible patch (limited in size due to the beaming) on the curved jet surface has grown to encompass the edges of the jet. At this point the light curve will steepen relative to its prior baseline, revealing a jet break. These breaks have been detected across a range of times. This range persists even if the impacts of explosion energy, circumburst density and redshift are accounted for by rescaling. This would indicate an intrinsic range of jet opening angles, or alternatively a jet with some universal lateral structure in energy seen at random orientations (Lamb, Donaghy & Graziani 2005). Although the universal jet has been disproved by observations (Nakar, Granot & Guetta 2004), actual jets realized in nature for long *and* short GRBs will inevitably have *some* measure of nonuniformity in the angular energy profile imprinted during launch or at a later stage (Aloy, Janka & Müller 2005; Morsony, Lazzati & Begelman 2007; Mizuta & Aloy 2009). Below we will see how in particular the observations of GRB 170817A have demonstrated that this feature cannot be ignored for the modeling of jets not seen on-axis.

There are various further ways in which this basic picture can and has been extended. Adding a baryon loading to the initial energy release will give rise to a massive ejecta that first accelerates to a maximum velocity by converting internal energy to kinetic energy, then coasts along at constant velocity and starts to decelerate once the balance of energy content tips from the ejecta to the swept-up medium. A reverse shock runs through the ejecta, and can in theory act as an acceleration site for charged particles as well. The basic synchrotron emission model can be complicated either by adding details to the evolution of the charges and magnetic fields responsible for the emission or by expanding the details of the emission processes. The launching and propagation of the jet can be simulated in detail to study these processes as well as their implications for the afterglow stage. The environment can be described in further detail to assess its implications on the afterglow appearance, and the tools for modeling afterglows can be sharpened based on advances in theory and numerics.

Here I highlight a few recent developments, and since both the discovery of GW170817 / GRB 170817A and the first detection of TeV emission from a GRB loom so large over the recent picture, I will discuss these first. At four pages, it is impossible to do all recent work published on afterglows justice, so all citations should be read with an '*...and references therein*' in mind.

2. GRB 170817A and the era of gravitational wave / electro-magnetic multi-messenger astrophysics

The first-ever discovery of an electro-magnetic (EM) counterpart (Abbott et al. 2017) to directly detected gravitational waves (GW) remains a staggering breakthrough in high-energy astrophysics. The first X-ray and radio EM observations and upper limits not associated with the kilonova, taken up to about two weeks following the GW trigger, could still plausibly be modeled as a top-hat jet (i.e. a collimated flow without lateral energy profile) seen off-axis (Hallinan et al. 2017; Troja et al. 2017), albeit under the condition that it was nearing its peak of emission (for an alternative take, see Gill et al. (2019)). The subsequent steady rise of the light curve for the next 150 days however, required a mechanism to both lower the rise slope and extend the rise stage. This is naturally achieved by allowing the energy to taper off towards the jet edge rather than drop abruptly, and also makes sense for interpreting the initial GRB accompanying GW170817 (Goldstein et al. 2017). Although this GRB was extraordinary weak, it was recognized immediately that accounting for this weakness purely from a relativistic beaming argument (with observer outside of the beaming cone) would have led to an even weaker signal and that lower velocity outflow at larger angles of a structured jet would be able to account for the difference (Troja et al. 2017). There is however a limit to how much the Lorentz factor of the flow along a given radial line can be reduced before opacity becomes an issue. By now the arguments about the implications of the GRB for the outflow geometry have been refined further, and the most likely explanations split the difference between beaming and jet structure by placing the prompt emission at an angle between observer and jet tip and/or allowing for a different angular drop profile for jet energy and Lorentz factor (Ioka & Nakamura 2019; Matsumoto, Nakar & Piran 2019; Beniamini & Nakar 2019).

In recent years, studies had begun the explore the possibility of a dense environment surrounding the merger of two neutron stars (Nagakura et al. 2014; Murguia-Berthier et al. 2014). A viable alternative to jetted emission capable of explaining the extended rising phase would be a choked jet scenario (Lamb & Kobayashi 2016), where the jet fails to emerge and transfers all its energy into a cocoon of shocked circum-merger material. Basic cocoon models place the peak counterpart emission at a timescale of hours to days rather than weeks or months (Nakar & Piran 2017; Lazzati et al. 2017; Gottlieb, Nakar & Piran 2018), but this peak time can be delayed by adding a stratification of velocities to the radial profile (Mooley et al. 2018b). It was only once the light curve turned over around 160 days that we could test the prediction from Troja et al. (2018) that the decay slope would unambiguously distinguish between the scenarios: at $t^{-\alpha}$ and $\alpha = 2^{+0.8}_{-0.5}$, the slope was observed to be too steep to be consistent with decelerating quasi-spherical flow (Alexander et al. 2018; Troja et al. 2019). An independent spectacular confirmation of the jet nature came soon after, in the form of very large baseline interferometry (Mooley et al. 2018a; Ghirlanda et al. 2019).

Even though GRB 170817A turned out not to be a choked jet, this is no reason to believe this scenario is never realized in nature for short GRBs and over the past years various groups have kept exploring in depth the interaction between the jet and its environment (e.g. Duffell, Quataert & MacFadyen (2015); Lazzati & Perna (2019); Irwin, Nakar & Piran (2019)). In the long GRB case, the (partially) choked jet scenario naturally overlaps with that of an engine-driven supernova (Margutti et al. 2014; Chakraborti et al. 2015; Corsi et al. 2017). Choked jets in long GRBs have been argued to exist for a long time (e.g. Huang, Dai & Lu (2002)), as one would naturally expect a large amount of matter in the path of the jet from the collapsing stellar envelope. Long GRB models for jet-cocoon interaction (with a jet, a shocked cocoon, and a slower moving head of compressed material in front, Matzner (2003); Bromberg et al. (2011)) translate naturally to short GRBs, and can be tweaked by including further details such as e.g. a significant outwards velocity of the ejecta within which the jet propagates (Hamidani et al., in prep).

3. TeV emission from a GRB

GRB 190114C is a highly influentual GRB. A relatively nearby long GRB detected at $z = 0.425$, it is the first GRB for which we have a solid detection of TeV emission (MAGIC Collaboration 2019b). Because the electrons can only be accelerated up to the point where the cooling loss time scale becomes shorter than the acceleration time scale, the case that the TeV gamma rays are produced by inverse Compton emission is strong (MAGIC Collaboration 2019a). The resulting double-peaked spectrum is instantly recognizable to the blazar community, albeit with a significant shift of the peak positions relative to typical blazar values. In particular, the Fermi LAT GeV emission detected for 190114C is positioned in the valley between the peaks rather than near the top of the high energy peak (apropos, a joint contribution to the LAT emission from synchrotron and inverse Compton helps to alleviate the tension between observations and synchrotron-only models, Ackermann et al. (2014)). The prospects for further TeV emission detections from GRBs are promising (e.g. with the upcoming Cherenkov Telescope Array), and it is interesting to note that GRB 160821B (another candidate for TeV detection) is actually not a long GRB but a short one. A future joint detection of GW and TeV emission is certainly within the realm of possibility.

As far as afterglow physics is concerned, it is striking that the TeV emission is best modeled as produced by a decelerating forward shock (as opposed to internal shocks or any other mechanism used to interpret prompt emission). This continues the experience from Fermi LAT (Ghirlanda, Ghisellini & Nava 2010; Kumar & Barniol Duran 2010; Nava et al. 2014). One thing in particular to keep an eye on for future GeV / TeV detections is how they fit in with X-ray plateaus. If non X-Ray emission indicates a decelerating blast wave while in the presence of an X-ray plateau, the case for explaining plateaus from pre-decelerating jet dynamics, energy injection and/or an active reverse shock becomes significantly weaker.

4. Magnetars and magnetization

Magnetars remain an attractive alternative to black hole engines of GRBs (e.g. Usov (1992); Thompson (1994); Komissarov & Barkov (2007); Bucciantini et al. (2008); Giacomazzo & Perna (2013); Gao, Zhang & Lü (2016); Lü et al. (2018)), and various groups have interpreted observations of afterglow flares and plateaus as suggestive of a magnetar origin (e.g. Troja et al. (2007); Piro et al. (2019))— or at least explored the possibility of this scenario (e.g. Gompertz et al. (2015); Rowlinson, Patruno & O'Brien (2017); Knust et al. (2017); Gibson et al. (2018)). It is debatable whether GRB 170817A was driven by a magnetar (Pooley et al. 2018; Ciolfi et al. 2019; Gill, Nathanail & Rezzolla 2019), although certain magnetic field configurations may still allow for this option (Ai et al. 2018; Piro et al. 2019).

One expects magnetic fields to play a role in the launching of GRB (afterglow) jets (Bromberg & Tchekhovskoy 2016) although their impact on jet dynamics probably diminishes quickly (Granot et al. 2015). Detections of ejecta polarization are helpful for constraining the ejecta magnetization, but one needs to establish that the polarized emission is indeed produced by a reverse shock. The recent ALMA result for GRB 190414C (Laskar et al. 2019) appears at least to rule out large-scale ordered magnetic fields in the ejecta, but it is probably best to keep in mind that previous polarization measurements (e.g. Mundell et al. (2013); Wiersema et al. (2014) have so far not revealed a consistent picture for prompt and afterglow stages.

5. From theoretical model to observation and back

Bayesian statistics has become increasingly popular as a conceptual approach to the modeling of GRB afterglows. Additionally, whereas traditional GRB modeling has relied largely on a post-hoc interpretation of light curve and spectral slopes, it has become increasingly feasible to map complicated models (e.g. from multi-dimensional numerical jet simulations) directly to data. The latter can be done either by running a series of bespoke simulations, or by exploiting scale-invariance of the initial conditions of a simulation (van Eerten, van der Horst & MacFadyen 2012; van Eerten & MacFadyen 2012; Xie, Zrake & MacFadyen 2018)

Lateral structure can be modeled semi-analytically, and constrained from observations (e.g. Troja et al. (2018); Troja et al. (2019); Lamb et al. (2019); Ryan et al. (2019); Takahashi & Ioka (2019)), or bursts can be compared directly to the results of individual simulations with complex jet structure (e.g. Gottlieb et al. (2018); Kathirgamaraju et al. (2019)).

Studies of individual GRBs such as 170817A and 190114C and of larger samples continue to shape our understanding of afterglow theory. I close with a mention of two final recent developments. One, that by careful application of theoretical flux predictions for the radio, Beniamini & van der Horst (2017) have been able to establish that the energy in the accelerated electron population is clustered closely at a fraction $\epsilon_e \sim 0.1$ of available energy. Two, that a trend showing that on average, more luminous X-ray afterglows decay faster than less luminous ones has been found (Racusin et al. 2016), which provides a useful test for models for jet geometry.

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