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RELATIVISTIC JETS AND GAMMA-RAY BURSTS FROM NEUTRON STAR MERGERS

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Abstract

A defining characteristic of gamma-ray bursts (GRBs) is the presence of jetted outflows. These jets are shaped by their launching mechanism and interactions with the environment (both close and further distant) of the GRB, as revealed to us when the jets decelerate from the ultra-relativistic to the non-relativistic. Due to its close proximity and off-axis orientation, multi-messenger event GRB 170817A has been particularly informative in this regard. In this talk I will review the characteristics of GRB jets, paying special attention to recent developments in the field prompted by observation and numerical study of the afterglow of short GRBs from neutron star mergers.

1 Introduction

Gamma-ray bursts (GRBs) have long been associated with neutron stars. A well-established dichotomy exists between long GRBS from collapsing massive stars ("collapsars"), lasting more than about two seconds in the observer frame, and short GRBs that last less than two seconds [21]. It is the latter category that has been linked to the merging of two neutron stars [33, 10]. For both categories the brief or permanent creation of a highly magnetic neutron star ("magnetar") has been a persistent alternative in the literature to the direct formation of a black hole. The connection between short GRBs and the merging of neutron stars has been confirmed directly by the recent detection of gravitational waves from a merger pair along with a short GRB in GW170817 / GRB 170817A [1], but the evidence for possible neutron star remnants remains indirect.

GRBs are produced by non-thermal emission from relativistic flows. Over the years, evidence has accumulated that these flows are collimated in the form of jets, even if this has to be inferred indirectly in close to all events. Due to strong relativistic beaming, the emission from a GRB jet is dominated by a small area of surface where the balance happens to be optimal between beaming angle and intrinsic strength of emission at the time of the departure of the radiation. At first, the geometry of the outflow is therefore not apparent to the observer, but the large luminosity of the source renders it unlikely that its emission was released in all directions (relativistic beaming that emphasises the observer direction notwithstanding). Following the prompt GRB emission in gamma rays, bursts normally produce a fading afterglow peaking at progressively longer wavelengths from X-rays to radio. A second indication of jetted emission therefore can be found in the light curves of the afterglows, which at some point (the "jet break") fade faster than they would have for spherical outflows (this is both because there is no more material available at larger angle to enter into the line of sight and because jetted outflow will at some point begin to spread sideways and dissipate faster than purely radial flow would). Finally, and again involving GRB 170817A, very large baseline interferometry (VLBI) observations have been able to reveal motion of the centroid of emission consistent with outflow with at least some degree of collimation [29, 13].

In these proceedings I briefly review some developments in GRB jets from neutron star-neutron star (NS-NS) mergers associated with short GRBs.

2 How solid is the short-long divide?

Given the clearly different formation channels between short and long bursts referred to above, one would expect that long GRBs are unrelated to neutron stars at least as far as their progenitor systems are concerned. Nevertheless, in the past years a surprisingly large number of events have been reported that appear to blur the divide.

Normally, the bulk characteristics of the populations are as follows. The short bursts are spectrally harder in their prompt emission, have less temporal lag between soft and hard gamma ray arrival times (hard gamma rays are often delayed relative to soft gamma rays for both burst types) and have shorter timescales in their variability. Long bursts are spectrally softer, have larger temporal lag and variability timescales (the latter two are indicative of a larger emission radius). Long bursts release significantly more isotropic equivalent energy $E_{\gamma,iso}$ (which relates to the jetted energy E_γ according to $E_\gamma = (2\Omega/4\pi)\, E_{\gamma,iso}$ for a bi-polar jet of solid opening angle Ω per jet; the isotropic equivalent energy does not require knowledge of Ω to determine). Both long and short bursts obey a relation between their prompt emission peak energy and total prompt energy release (the "Amati" relation and variations thereof [5]) where a higher frequency peak corresponds to a larger total energy release, but both relationships are calibrated differently. The long bursts population peaks around redshift $z \sim 2$, comparable to the peak of star formation, as expected for a phenomenon associated with short-lived massive stars. Being intrinsically fainter, short bursts are detected at smaller redshifts and often at an offset from their host galaxy (not unexpected for an event produced by a binary pair of neutron stars that previously experienced two supernova explosions that will have imparted a net momentum to the pair). The most utterly unambiguous determinant of the origin of a given long burst remains the observation of a supernova (of broad-lined type Ic, in practice) spatially coincident with the burst. For short bursts, a detection of gravitational waves and/or a kilonova would be similarly unambiguous.

And yet, as said, the odd cases appear to pile up (they are of course of interest from the perspective of aiming for a high-profile publication, so there is some selection bias at play here). Among them are the following, to name a few with publication titles that speak for themselves. *No supernovae associated with two long-duration γ-ray bursts* (GRB 060505, GRB 060614) [12], *The* *second-closest gamma-ray burst: sub-luminous GRB 111005A with no supernova in a super-solar metallicity environment* [27], *Discovery and confirmation of the shortest gamma-ray burst from a collapsar* [2] and *A peculiarly short-duration gamma-ray burst from massive star core collapse* [52] (GRB 200826A). A particularly promising recent case is *A nearby long gamma-ray burst from a merger of compact objects* [45], *A long-duration gamma-ray burst with a peculiar origin* [49], *A kilonova following a long-duration gamma-ray burst at 350 Mpc* [37] and *The case for a minute-long merger-driven gamma-ray burst from fast-cooling synchrotron emission* [15] (all GRB 211211A). This burst is unambiguously of long duration (lasting over 50 seconds), most likely associated with a host galaxy at 350 Mpc but lacking a supernova that at this distance really should have been detected. Instead, a kilonova of similar properties as the well-studied kilonova AT 2017gfo associated with GRB 170817A appears to stand out among the afterglow emission. Its temporal lag, minimum variability timescale and placement on the Amati relation calibration are also consistent with the neutron star merger population rather than the collapsar population. What makes this event so promising is that it therefore potentially signals a population of bursts directly detectable in gravitational waves in forthcoming runs [36] that was previously not recognized as such. Given that we currently still have only one solid multi-messenger detection in GW170817 / GRB 170817A, this additional neutron star connection is a quite appealing prospect.

3 Basic jet features since 170817

Certainly at the toy model level, the jet model of GRB outflows scales straightforwardly between bursts from neutron star mergers and from collapsars. On the one hand, collapsar jets are presumed to be more energetic (at least in the isotropic equivalent sense, the general distribution of opening angles of short GRBs is not well enough constrained to make too strong statements on how their jet energies relate). On the other hand, happening on the outskirts of galaxies, short bursts are presumed to occur in a more dilute environment than their long counterparts. Because jet (isotropic equivalent) energy and circumburst density ρ always occur in the form of a ratio E_{iso}/ρ in expressions for characteristic times and radii of the jet model, such as jet break times and the transition point to non-relativistic flow, in these aspects the differences between short and long burst jet are maybe less then one would expect from considering the different density and energy scales separately. The reason for this ratio, by the way, is to eliminate the mass dimension of both variables in expressions that only carry dimensions of time and/or distance.

A big reveal of GRB 170817A has been the observability of the lateral energy distribution of the jetted outflow, which is of interest in that it carries the fingerprints of jet launching and propagation. Being cosmologically distant sources, a strong observational bias exists for GRBs to be seen on-axis. Relativistic beaming strongly depends on angle, so jets not directed towards observers are significantly less likely to trigger a gamma-ray detector. When seen on-axis, afterglow emission from near the centre of the jet will dominate the received flux, while emission from higher latitudes gradually comes into view. As a consequence, subtleties in the lateral distribution of energy that set apart a "top-hat" jet (constant energy up to a truncation angle) from structured jets (e.g. a Gaussian, power law or other more gradual decrease in energy with angle), have little noticeable impact on the light curve temporal slope other than a slight modification of the temporal curvature around the jet break [23].

If a GRB jet is observed at an angle, the imprint of lateral jet structure is more stark [38, 39]. Jets observed at a slight angle (i.e. within the opening angle θ_0 of a top-hat flow, or the characteristic width θ_c of a Gaussian energy distribution, reflect their orientation angle θ_{obs} in their temporal slope and delayed jet break [47, 38, 51] (the far angle is now $\theta_0 + \theta_{obs}$, rather than θ_0). If the jet is observed further off-axis, like GRB 170817A was, then an earlier rising stage of the light curve exists whose slope directly constrains [39] θ_{obs}/θ_c. The fact that the afterglow light curves in radio and X-rays for this event rose gradually for the length of time that they did, immediately rules out top-hat jets that would have appeared into view far more abruptly. At the gradually rising light curve stage, a quasi-spherical outflow fits the data equally well, perhaps produced by a "choked jet" or outflow dominated by a cocoon of energy dissipated during the early propagation stages of the jet through the NS merger debris [22, 30, 24]. However, such a scenario would not be able to produce the later decay stage slope of GRB 170817A [42, 43, 44] in the manner a Gaussian structured jet model can.

The jet structure need not be exactly Gaussian, though, and such a structure is mostly introduced as a convenient means to capture a potentially more complicated profile inferred from more detailed physical models (mostly detailed relativistic magnetohydrodynamics simulations). In fact, observations can be used to constrain the jet profile more generally and the local rising light curve slope of a GRB 170817-like event can be inverted to infer a local energy distribution slope [41].

4 Simulating jets from neutron star mergers

The conditions of formation and propagation of afterglow jets of GRBs have been simulated numerically for decades by now, including seminal papers on long and short GRBs [25, 3, 50, 4]. Jetted flow from a neutron star remnant has been studied in depth [7, 8], but many works in the literature concentrate on black holes as the central jet engine. There are various research questions of interest accessible through high-resolution jet simulations. The launching mechanism of relativistic jets remains an open question. There is no clear consensus on the degree of collimation of afterglow jets, neither from observations nor from simulations and it is not known whether there is naturally a broad or narrow range of collimation angles to be expected. The discovery of GRB 170817A and its implication for jet structure have provided new impetus for the simulation of jets from short GRBs. For example, broad wings of low energy relative to the jet tip can indicate the presence surrounding the jet of a lot of material produced by the neutron star merger.

Power-law and Gaussian lateral energy distributions can be seen to map well onto a diversity in simulation results (see e.g. [39], comparing to simulations from [4, 28, 9, 24, 26]). A few things should be kept in mind however when doing so. Obviously, actual jets will have a radial fluid profile as well as an angular fluid profile, but the assumption of a homogeneous shell can be quite effective when predicting broadband afterglow emission. GRB jets differ from jets from, for example, active galactic nuclei in that the engine powering the jet is only active briefly relative to the lifetime of the jet. After the engine switches off, at a timescale comparable to the duration of the prompt burst, the jet will evolve towards a blast wave shell.

It is only when the energy powering the flow along a given radial line has on balance been conferred to swept-up circumburst medium that the energy profile alone fully capture the large-scale flow dynamics. At earlier time, the velocity of the original ejecta still shapes the outflow Lorentz profile. The

Lorentz factor might well differ in its angular distribution from the energy distribution, and thus provide more freedom to model to prompt emission if it is extracted from the same jetted flow. All afterglow observations of GRB 170817 are following the deceleration of the ejecta and thus of a shock-wave in the external medium.

Another thing to keep in mind is that the simulation inspiring a simplified energy profile might not represent the end stage of "sculpting" of the jet. There might be more strong interactions with the burster environment that are not accounted for in the modelling, or beyond the range of the computational grid during a simulation run. This aspect has received a lot of attention in recent years. Focusing on neutron star merger simulations, the major players are the accretion disc [11], the dynamical ejecta from the mergers [18] and the neutrino-driven wind from the disc [35]. General relativistic magnetohydrodynamics simulations of the jet-accretion disc interaction [20] already produce a jet with lateral energy structure. This is not unexpected, given that, really, a top-hat jet is as unrealistic as it is simplistic; top-hat models ignore the presence of structure under the assumption that it is of minor importance for jet dynamics and emission predictions, which is not the same as asserting the structure does not exist.

However, recent simulations show examples of how a subsequent encounter of the jet with a neutrino-drive wind effectively resets and replaces the launch structure by the imprint of this later interaction [32]. For these particular simulations, which inject the jet into a detailed simulation including neutrino leakage scheme of neutrino-driven winds [34], the emerging profile reveals a slight energy spike at the tip on a central plateau, flanked by a drop in energy that holds an intermediate between a sharp top-hat distribution and a gradual Gaussian jet profile.

The question of whether jets end up choked or not by the presence of merger debris is likewise of interest for jet simulations. Recent work [16] explores whether a jet, sculpted by neutrino-driven wind interaction, manages to get past the ejecta. According to this study, the ejecta interaction is not as key to shaping the lateral energy profile as the wind, but might indeed end up choking the jet, leading to a mildly relativistic cocoon emerging rather than a highly relativistic and tightly collimated jet.

Finally, these simulation outputs can be used to predict the afterglow light curve. However, in most cases it is not possible to simply continue the simulation up to the relevant radii and times, since the jet evolves over many orders of magnitude (from $< 10^7$ cm to the parsec scale and well beyond), unless specialized moving mesh techniques are deployed [48, 6]. When not starting from a simplified shell model or analytical description of the jet lateral profile, the afterglow stage dynamics therefore need to be modelled by extrapolating simulations. This extrapolation needs to properly account for jet spreading dynamics though, because when not included this would result in an artificially shallow late-time lightcurve slope [31]. When spreading dynamics are included when extrapolating from a simulation (e.g. as in [32]), the late time slope steepens on account of the faster dissipation relative to non-spreading flow.

5 Jet models and neutron star merger afterglow emission modelling

The issue raised about jet simulations and afterglow modelling in the previous section is of interest in view of the long-term observations of GRB 170817A, the one nearby off-axis multi-messenger event that we have data for. Data from last year potentially suggested the emergence of an additional component in the X-ray emission, still visible at 3.3 years following the merger. This component could have been emission from another blast wave, this time associated with the kilonova, and thus constrain the kilonova physics. The evidence for this extra component, however, is not statistically strong [17, 46], and where based on a tension with jet model predictions, subject to caveats such as the uncertainty in long-term jet spreading behaviour mentioned above. Other aspects also impact the late time slope of the afterglow light curve and can help alleviate a tension between model and data (assuming one would actually emerge). These include the details of the emission modelling, which, like long-term jet evolution across many scales, is underresolved if no special mesh techniques are deployed [6] and which might need a reparametrization in the non-relativistic regime [40, 17, 6].

Which data and which *priors* and weights are attached to these data also matters in modelling. As always when comparing models to a diverse data set, it remains a challenge to find the most appropriate approach to weighing data points from separate sources (e.g. gravitational waves versus broadband afterglow versus centroid position) and to deciding how strongly to penalize or reward features from a model that ultimately remains an idealized approximation of an actual jet (no matter how elaborate the simulation underpinning the model). There are by now multiple efforts to combine multi-messenger data, VLBI, gravitational waves and broadband afterglow altogether, within a single framework (e.g. [19]). Future analysis is likely to include a full joint-fit of these data, for GRB 170817A or upcoming NS-mergers, rather than a "pipeline" approach (as was done first by [42]) where the posterior from the one analysis enters the other in the form of a prior. This ensures that all information is used even when constraining parameters that are not shared by models of different facets of the merger [14]. A joint fit of gravitational wave data and afterglow, for example, means fitting a merger model of gravitational wave emission (i.e. templates for the latter) that shares system orientation with an afterglow jet model, but does not share e.g. neutron star spin on the gravitational wave side or synchrotron emission efficiency on the afterglow side.

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