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GRB 170817A and the long-term aftermath of neutron star mergers

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Abstract. GW170817 / GRB 170817A has had a huge impact on our understanding of gamma-ray burst (GRB) afterglows, and has prompted a huge sustained effort at modeling the details of the geometry and emission from GRB jets. While no additional electro-magnetic counterparts have been detected to gravitational wave emission from neutron star mergers so far, it is certainly reasonable to expect further detections in the future. Whether these will be very similar in nature to GRB 170817A or instead will provide us with samplings of afterglow model parameters across a wide parameter space remains an open question. In this presentation I will survey some of the work done by the various active groups worldwide in theoretical modeling and understanding afterglows post 170817A.

Keywords. plasmas, shock waves, gamma rays: bursts, stars: neutron, radiation mechanisms: nonthermal, black hole physics

1. Introduction

It is now over four years since the first joint detection of gravitational waves (GW) and electromagnetic (EM) counterpart emission from neutron star (NS) merger GW170817 / GRB 170817A (Abbott *et al.* 2017). Yet, the long-term afterglow has remained observable for most of this time (and possibly still is). This is a surprising result which has implications for our understanding of gamma-ray burst jet dynamics, the nature of the remnant and observational follow-up strategies of multi-messenger events in general, among other things. Here we aim to give an overview of the some of the main developments since the first discovery of GW170817.

1.1. *Short gamma-ray bursts up to GRB 170817*

The GRB population can be divided into two categories, based on spectral hardness and burst duration, with long bursts lasting over two seconds and being spectrally softer than their shorter counterparts (Kouveliotou *et al.* 1993). It has been well established that most, if not all, long GRBs originate from massive star collapse due to observational evidence linking these events to broad-lined supernovae of type Ic. However, short GRBs were theorized to result from the merger of two neutron stars or a neutron star and a black hole (BH) (Eichler *et al.* 1989, Narayan *et al.* 1992) and the evidence for these scenario has remained indirect until the detection of GW170817A.

A 2014 review paper (Berger 2014) lists four characteristic signatures expected from a NS-NS or NS-BH merger scenario. Prior to GW170817, short GRBs have indeed been detected in both early- and late-type galaxies, consistent with a wide range of delay times between the formation of the binary pair and their eventual merger. Also, these detections often revealed an offset between the GRB and its host galaxy, as expected from natal kicks imparted to the binary system by the supernova explosions preceding the formation of the neutron stars (or black hole). What GW170817 added was the direct evidence of a gravitational wave signal clearly identifiable as being due to two neutron stars merging as well as the direct detection in the optical and infrared of a *kilonova*, powered by the radioactive decay of neutron-rich ejecta expelled during the merger.

Both short and long GRBs are produced during a cataclysmic process resulting in a compact remnant (typically a BH). The gamma rays are either attributed to the emergence of a relativistic jet from the photosphere, internal collisions between shells of plasma within the jet or some other physics related to the jet (for example a magnetic reconnection cascade in a magnetized outflow). Once the jet emerges as a forward shock into the circumburst medium, it will decelerate towards a non-relativistic and ultimately quasi-spherical blast wave akin to a supernova remnant. During this stage, synchrotron emission is produced by shock-accelerated electrons interacting with locally generated small-scale magnetic fields at the shock front, leading to an *afterglow* visible across the broadband spectrum from X-rays to radio waves. The theory and dynamical modelling of this stage has been well established. When afterglow jets are pointed directly towards the observer, it is typically sufficient at a qualitative level to assume a single laterally expanding shell of relativistic plasma. For cosmically distant sources it is indeed those jets that are observed straight-on that will be sufficiently bright to stand out as GRBs against the background across the sky.

The dynamics of the plasma shell will be guided by energy conservation and trans-relativistic shock-jump conditions; synchrotron emission can be modelled at various levels of complexity, typically assuming a post-shock non-thermal power-law distribution of electrons in energies. Prior to GRB 170817A, tweaks to models of the long-term behaviour of afterglow jets (days, weeks and beyond in observer time) and their emission have concentrated on more accurate numerical modelling of the jet dynamics, jet-environment interaction and on accounting for the observable signatures of thermal electrons and inverse-Compton processes. Following the first results of the Neil Gehrels Swift Observatory (launched in 2004), investigations of the afterglow light curves at the hours to days timescale have often focused on afterglow plateau stages often seen in Swift-XRT X-ray light curves and X-ray flares. Both have been argued to be indicative of the physics of the engine of the burst, showing direct late-engine activity (requiring e.g. fallback accretion or a remnant that is still capable of intrinsic activity, such as a magnetar) or dynamics of an ejecta still capable of producing emission before emission from the forward shock into the external medium takes over completely.

1.2. *Some toy model considerations*

As mentioned previously, a basic afterglow shell model can be built from an energy conservation argument, $E = \tau V$, where E the energy of the explosion, V the volume of the shell in the lab frame and τ the energy density (internal plus kinetic, excluding rest mass) of the plasma. If an initial mass M_{ej} of the ejecta is accounted for, a term $(\gamma - 1)M_{ej}c^2$ for the kinetic energy of a cold shell can be added to the energy budget, where γ the Lorentz factor of the plasma. When modelled as a 'point explosion' (Taylor 1950, Sedov 1959, Blandford & McKee 1976), the initial radius of the fireball can be ignored. This assumption is not unreasonable, given that the initial energy release takes place within a compact region of radius 10^{6-7} cm, the characteristic width of a shell launched over the course of 2 seconds or less is $\sim 5 \times 10^{10}$ cm, the prompt dissipation radius for the internal shock model lies around 10^{12-13} cm and the afterglow emission is produced at radii of $\sim 10^{14}$ cm and beyond.

The transition point between ballistic motion of a cold relativistic shell and a decelerating blast wave dominating the dynamics of the system can be found when the former has transferred about half its energy to the latter. In toy model terms, this happens around radius $R \sim 6.6 \times 10^{17} n_{-3}^{-1/3} E_{51}^{1/3} \gamma_2^{-2/3}$ cm, observable about 1000 seconds after the burst. Here E_{51} is the energy of the shell in units of 10^{51} erg. n_{-3} the circumburst number density in units of 10^{-3} cm^{-3} and γ_2 the shell Lorentz factor in units of 10^2. If the source itself is active for longer, this might impact the light curve, both directly by adding additional flux and indirectly by injecting additional energy into the system. In the latter case, this could postpone the transition to deceleration-driven mechanics and/or slow down the deceleration afterwards. The impact of the collision with the external medium will propagate through the initial shell by means of a reverse shock, which can serve as a second acceleration site of emitting particles that will remain hot for some time even after shock crossing before fading out even at radio frequencies.

Once the blast wave dynamics are driven by the external medium, the density profile of the medium will set the scale for deceleration. Unlike for long GRBs, this medium is not expected to be sculpted at large scales by outflows from the progenitor system of the burst. Instead, it can presumably be modelled adequately as homogeneous with a low number density reflecting the displacement of the progenitor system from its birth location in its host galaxy (hence the normalization in units of 10^{-3} particles per cm^3 above). The shape of the synchrotron spectrum produced by electrons in a power-law distribution of slope $-p \sim -2.2$ in energy is well known, which allows for formulating *closure relations* expressing the time evolution of the light curve in terms of p. For a homogeneous medium, we have $F_\nu \propto t_{obs}^{(3-3p)/4} \sim F \propto t_{obs}^{-0.9}$, for emission observed above the injection break of the synchrotron spectrum but below the synchrotron cooling break.

Once the jet begins to decelerate and rapidly spread out laterally, this slope steepens into $F \propto t_{obs}^{-p} \sim F \propto t_{obs}^{-2.2}$ (in reality, the picture is more complex since jet spreading is not as fast in the observer frame as is tacitly assumed to obtain this value, but a slope approximately this steep indeed follows from a combination of jet spreading and the jet edges coming into view, Van Eerten & MacFadyen 2013). Ultimately, the outflow will become non-relativistic and the slope will flatten again to $F \propto t_{obs}^{(21-15p)/10} \sim F \propto t_{obs}^{-1.2}$.

The picture as sketched in this section is well established in the literature and its details are covered by various reviews (e.g. Piran 1999, Nakar 2007, Van Eerten 2018). The calculations above were done based on the iteration of the shell model first presented by Van Eerten 2013 and Nava *et al.* 2013.

2. Lessons from the light curve of GRB 170817A

2.1. *Delayed detection*

It was not surprising that the first GW/EM multi-messenger event ever to be observed would not be seen directly on-axis. After all, gravitational wave emission is far less collimated than GRB emission, and any GW detection of a NS-NS merger would have been guaranteed to lead to an extensive global follow-up campaign chasing after EM emission regardless of its orientation. The odds of detecting a NS merger at a given angle are decided by a number of factors. On the one hand, the detection of prompt GRB emission nearly coincidental with the GW signal (GRB 170817A was delayed by 1.7 seconds relative to GW170817) helps to narrow down the position on the sky for further follow-up. And even though for GW170817 the contribution to the localization of the source by the GW signal from VIRGO was substantial, this in general favours a smaller jet orientation angle relative to the observer where the observer is positioned within the cone of the jet, or at least not too far out of it, in order to ensure that the GRB prompt signal stands out sufficiently to trigger satellites such as Fermi and Swift. On the other hand, the further off-axis, the more likely the orientation from a statistical perspective,

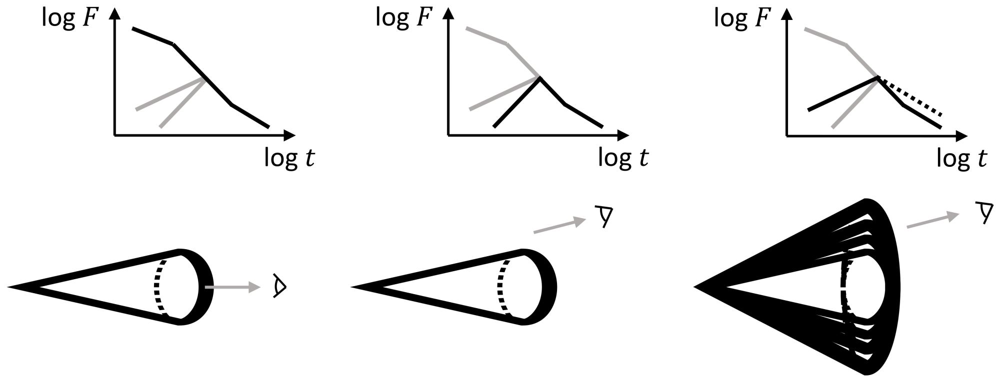

Figure 1. Implications for the light curve above the synchrotron injection break for different jet types seen at different angle. Left figure shows a top-hat jet seen on-axis, centre figure shows a top-hat jet where the direction to the observer is not within the cone of the jet, right figure shows a structured jet where the direction to the observer goes through the lower-energy wing of the jet. The dark lines in schematic light curve plots show the relevant light curve shape for the jet orientation figure underneath. The dotted line shows the downturn slope in case GRB 170817 was the product of a choked jet failing to break out and achieve collimated relativistic velocity.

given that we only have one option for looking straight into the jet but many possible off-axis orientations.

From the GW signal of GW170817 alone, the orientation of the jet relative to the observer was determined to be $< 55°$. Taking into account the distance to its associated host galaxy NGC 4993 (and therefore assuming a given cosmology) narrows this down to $< 28°$, since this serves to break the degeneracy that results from the correlation between distance measure and inclination angle (Abbott *et al.* 2017b). A substantial inclination angle was supported by the weakness of the prompt GRB (between 2-6 orders of magnitude weaker than regular short GRBs, Goldstein *et al.* 2017). Further support was provided by the absence of detectable afterglow emission for the first 9 days following the merger, whereas an on-axis observation would have yielded detectable and monotonically decaying X-ray emission straight-away (see Fig. 1).

The actual detections of afterglow emission in X-rays (Troja *et al.* 2017) and at radio frequencies (Hallinan *et al.* 2017) immediately posed a challenge for the default 'top-hat' jet model that simplified jet dynamics as (at least initially) a homogeneous release of energy truncated sharply at an angle. The energy of the prompt emission had been low, but not *that* low relative to its predicted value for an observer sufficiently far outside of the jet cone to align well with an afterglow light curve that appeared (at the time) to be close to peaking. Relativistic beaming of off-axis emission would have have rendered the prompt weaker than observed. The first papers on GRB 170817A therefore already included an alternative scenario to the top-hat jet, in the form of an outflow with energy decreasing more gradually with angle. This energy structure is readily modelled with a functional form (e.g. a Gaussian drop in angular energy, or a power law drop), and various such models have been available in the literature for a long time (Rossi *et al.* 2002, Kumar & Granot 2003). It was not so much that structured jet models were overlooked, but rather that they were too similar in their predictions for on-axis observers to be of much added value in a practical sense for modelling GRBs.

It should be noted however that even structured jets, while proven to be an exceedingly natural fit to the long-term aftermath of GRB 170817, are by themselves not sufficient to explain the prompt emission if the gamma rays are naively assumed to originate from a spot on the jet surface along the line of sight to the observer. Along the angle to the observer, the energy of the outflow (and therefore its Lorentz factor) would be so low that the prompt emission photons would struggle to outpace pair-production opacity issues and to get past the column depth of electrons still in between the photosphere and the expected prompt emission energy release radius (the latter being constrained by the delay time of the prompt burst relative to the GW signal, and by general considerations of the variability of prompt short GRB emission vis-a-vis its stretching over time due to the curvature of the emission front).

2.2. *Prolonged rise stage*

As we now know, the light curve of the afterglow of GRB 170817A maintained a rising slope for over 150 days since the merger, far longer than initially anticipated. For a structured jet model, which part of the jet is dominating the emission at a given time is set by the balance between relativistic beaming (increasingly suppressing flux from any region not moving along a line towards the observer for increasing Lorentz factor) and the jet energy at a given outflow angle (like Lorentz factor, increasing towards the jet tip, only now heightening the emission). In other words, between the onset of the rising light curve and its peak, the emission will be dominated by concentric rings increasingly closer to the jet tip.

The latter has a useful implication for the actual slope of the rising light curve, and for recovering meaningful closure relations relating light curve and spectrum, now that the model simplifications permitted for an on-axis orientation cease to be applicable. As shown by Ryan *et al.* 2020, the rising stage of the light curve above the synchrotron injection break can be modelled according to $F \propto t_{obs}^{3(1-2p+g)/(8+g)}$, where g encapsulates the change in energy of the outflow with outflow angle. For a jet with a Gaussian energy profile across outflow angle θ characterized by a core width θ_c, g can be approximated as $g = (\theta_{obs} - \theta) d \log E / d\theta \approx \theta_{obs}^2/(4\theta_c^2)$ when seen at an angle θ_{obs}. Given that the rising slope of the afterglow GRB 170817A in X-rays and radio was observed to follow $F \propto t_{obs}^{0.90\pm0.06}$, it follows that $g = 8.2$ and $\theta_{obs} = 5.7\theta_c$, a quickly accessible result that already lies close to the outcome of a full Bayesian model fit to the afterglow during its rising stage.

As pointed out by Takahashi & Ioka 2020, Takahashi & Ioka 2021, it is not even necessary to assume a particular functional form for the energy distribution with angle, and a process can be applied that effectively inverts the expression for g above in order to sample the energy of the jet as a function of angle. These authors also stress that concentric rings close to the actual tip of the jet have a diminishing solid area and therefore have little impact on the observed light curve even once it starts to turn over. It is therefore certainly consistent with the data if in reality the jet does not have an energy profile peaking at its tip (as dictated by e.g. a Gaussian or power law lateral energy profile), but instead a hollow core. Since this structure has been predicted by various jet simulations, in particular those with a large role for the magnetic field in collimating the jet (e.g. Kathirgamaraju *et al.* 2019, Sapountzis & Janiuk 2019, Nathanail *et al.* 2021), it is important not to let a good fit with a semi-arbitrary functional form that heuristically describes jet energy obscure this possibility.

With the lateral jet structure profile constrained by the jet rising stage, it is worthwhile to revisit the prompt emission, as done by Ioka & Nakamura 2019. These authors demonstrate that it is indeed possible to avoid any opacity issues when the observed prompt emission is predominantly produced at an angle $10^\circ - 20^\circ$ from the jet axis. This scenario, where the structured jet of GRB 170817A is not intrinsically different from other GRB jets, except viewed off-axis, is further supported by being able to reproduce the 'Amati' correlation (Amati *et al.* 2002) between prompt energy and prompt emission peak for GRB 170817A once the off-axis orientation of the system is corrected for.

2.3. *Turnover and decay*

Around 150 days after the event, the light curve (at this stage detected in radio, optical and X-rays) finally plateaued and turned over towards a decaying slope. The sharpness of this turnover in itself adds to the constraints on the jet geometry (Nakar & Piran 2021), but the actual decay slope held a bigger promise. Up until this point, it remained possible to maintain that GRB 170817A was not an ordinary short GRB viewed at an uncommon angle, but rather the intrinsically different quasi-spherical trans-relativistic outflow produced by the emergence of a shock wave from a choked jet that failed to make it through its initial dense environment (e.g. NS merger debris, Nagakura *et al.* 2014, or a dense neutrino-driven wind from the accretion disk, Murguia-Berthier *et al.* 2014) where it got stalled and dissipated its collimated energy. Such scenarios had been predicted beforehand (Nakar & Piran 2017, Lazzati *et al.* 2017) and their existence would not be unexpected in view of the range in initial Lorentz factors seen from jets in other astrophysical contexts (Lamb & Kobayashi 2016). Obtaining a prolonged rising stage would merely require that the initial choked jet / cocoon models be tweaked by allowing for a gradual catch-up of slower moving but still energetic material postponing the ultimate deceleration of the blast wave.

The choked jet scenario however would lack a stage akin to the post-jet break stage of a normal GRB and instead turn over directly into a decay consistent with an expanding quasi-spherical and non-relativistic blast wave (this is depicted schematically in Fig. 1 as well), and Troja *et al.* 2018 pointed out that this would serve to differentiate between the two scenarios. The subsequently observed decline of $F \propto t_{obs}^{-2}$ turned out indeed to be inconsistent with a choked jet, (Troja *et al.* 2019), which was later also confirmed by a more in-depth statistical comparison between the abilities of the two scenarios to accurately model the data (Troja *et al.* 2020)

Another striking feature of the light curve at at its turnover stage and beyond is the remarkable consistency of the slopes across a decade in frequencies from radio all the way to X-rays (which is why so far we did not really bother to distinguish between frequencies in this review). Throughout the observations of the long-term afterglow of GRB 170817A, the observed photons are all consistent with synchrotron emission from the spectral regime above the synchrotron injection break (set by the lower cut-off in energy of the power law distribution of accelerated electrons), but below the synchrotron cooling break (there maximum frequency for which accelerated electrons produce their radiation throughout the emission zone; higher frequencies only probe a hot zone closer to the acceleration site). This results in a very tightly constrained value for p around 2.2, fully consistent with default expectations for electrons that have undergone first-order Fermi acceleration at a relativistic shock front. It is indeed tempting to tie this directly to shock-acceleration theory and simulation (Kirk *et al.* 2000, Achterberg *et al.* 2001, Spitkovsky 2008) and even a particular shock front Lorentz factor for the acceleration site (Margutti *et al.* 2018), but that does leave a clear contrast to the wide range of p-values that has been determined for the larger sample of short and long GRBs accumulated over the past decades. Many bursts suggest p-values that lie well outside of the expected range of $2-2.4$ (with smaller values for less relativistic shocks) even when accounting for their error bars (Troja *et al.* 2019), and evidence for universality among bursts remains elusive (Shen *et al.* 2006, Curran *et al.* 2009, Curran *et al.* 2010).

2.4. *A flare around 155 days?*

The X-ray light curve has not been without features at shorter time scales, something which can potentially help to constrain the physics of the engine behind the explosion. In particular, Piro *et al.* 2019 draw attention to a potential X-ray flare occurring at 155 days. It is important here to define 'flare' in unambiguous terms, since differing definitions give rise to different statistical significances. Defined purely in terms of X-ray variability between the actual X-ray observations, the statistical significance lies around 2.2σ (Hajela *et al.* 2019). Defined in terms of a departure from the continuum as established from full broadband modelling (asking the question whether the X-ray signal is suggestive of physics not covered by the baseline model), the significance of the flare lies around $\geqslant 3.3\sigma$ (Piro *et al.* 2019).

When the flare is considered to be real, Piro *et al.* 2019 argue that this creates some tension with a BH remnant model. Any late time emission from a BH source must be triggered externally to the black hole, for example due to fragmentation of the accretion disk (Perna *et al.* 2006) or fall-back accretion (Rosswog 2007). However, the accretion disk is not expected to persist this long after the merger, while power for fall-back accretion is typically estimated to decline as $t^{-5/3}$, which too would put a flare around 155 days out of reach. The fallback accretion rate though is based on a number of idealizing assumptions (Rees 1988) and actual practice might be sufficiently different.

If the remnant is not a BH but instead a long-lived magnetar, explaining the flare becomes easier. It does however immediately raise the question whether such a remnant is realistic, both for short GRBs in general and GRB 170817A in particular. Magnetar engines have been proposed at various times for GRBs (Duncan & Thompson 1992, Usov 1992, Dai & Lu 1998, Zhang & Mészáros), and have been modelled numerically by various groups over the years (e.g. Tchekhovskoy *et al.* 2008, Bucciantini *et al.* 2008). One strand of observational evidence for magnetars focuses on the early stage of the X-ray afterglow, which is often seen to plateau rather than decay in line with a decelerating blast wave closure relation (see e.g. Rowlinson *et al.* 2013). While the time scale of these plateaus (10^{2-3} s) is actually well in line with expectations for a massive ejecta that moves ballistically at first before conveying its energy to an external blast wave (as discussed above in section 1.2), the subsequent drop towards the deceleration stage has for some bursts been steeper then one would reasonably expect from a smooth transition between stages of the same blast wave (although with some tweaking, shell models can be made to work here as well, Van Eerten 2014). A recent work by Sarin *et al.* 2019 presents a direct Bayesian model comparison between magnetar and BH engine-based fits to X-ray data, but their argument does hinge on an unproven assumption about the sharpness of light curve turnover being different between magnetar-driven outflows and regular GRB jets in a particular manner.

The main obstacles to long-term survival of a magnetar remnant in the case of GW170817 are constraints on the maximum allowed mass of the NS and its magnetic field (Ai *et al.* 2018, Pooley *et al.* 2018, see also Sarin & Lasky 2021 for a recent review on the fate of merger remnants). Following Ai *et al.* 2018, a surviving NS is allowed for if the NS ellipticity is large and its dipolar poloidal magnetic field below $\sim 10^{12}$ G (its toroidal field, however, will be strong and responsible for the ellipticity of the NS).

2.5. *A late time flattening in the light curve*

The latest in the long-term aftermath of GRB 170817A appears to be a growing indication that the light curve might be decaying slower than would be expected for a collimated outflow with the energy profile as established from previous observations. The evidence for this tension is not yet statistically compelling, however, in large part due to uncertainty in the modelling of the long-term evolution of structured jets and their emission. A recently published analysis of the latest data and an assessment of the statistical significance of a potential rise in the X-ray signal is given by Troja *et al.* 2022, who conclude that as of now, the tension between model and data is not so much driven by an inability to fit the full data set with a structured jet model but rather by a difficulty to simultaneously satisfy the picture that emerges from other messenger channels, in particular the gravitational wave observations and very-large baseline interferometry (we will return to this below, in section 3). It should also be noted that, without getting once again caught in a attempt to assess the statistical significance of a potential flare, it is the next-to-latest, and not the latest, X-ray observation that is the biggest outlier relative to the continuum as expected from structured jet modelling.

There are two main sources of uncertainty in long-term modelling of GRB 170817A. On the one hand, semi-analytical models of spreading (trans-)relativistic jets are notoriously sensitive to the simplifying assumptions that are applied. This has been amply demonstrated numerically for top-hat jets (Van Eerten & MacFadyen 2012), while currently simulations for jets both containing structure and covering a sufficiently large range in scales are still rare (e.g. Xie *et al.* 2018). If jet spreading is not accounted for, then the working surface of the forward shock running into the external medium does not increase as fast as it otherwise would, which implies that 'non-spreading jets' (which are unphysical) would decelerate slower than spreading jets would. As a consequence, the light curve decreases less steeply over time in the absence of spreading and the emission stays artificially closer to the observed late-time data (Troja *et al.* 2020). This is the main cause for the apparent success of Nathanail *et al.* 2020 in modelling GRB 170817A in the long term, as these authors do not account for the inevitable spreading of the jet when extrapolating an otherwise sophisticated multi-dimensional relativistic magnetohydrodynamics simulations across scales to late times. Recent work by Nativi *et al.* 2022 avoids this pitfall to some extent, by accounting for jet spreading when extrapolating simulation results, but at the cost of reintroducing some of the uncertainty inherent in semi-analytical modeling of jet expansion.

On the other hand, there are various ways in which the emission itself could change its character in a manner not typically accounted for in afterglow modelling. For one thing, the synchrotron slope p might change over time (and move towards ~ 2, as discussed above in section 2.3). Because standard synchrotron modelling tends to include flux normalization factors of the form $(p-2)$ and $(p-1)$ and an implicit assumption $p > 2$, it is not automatically obvious how to account for a changing p value in a way that does not risk the prediction of the evolution of the flux to be driven by a potentially artificial toy-model assumption.

On top of uncertainty around a potentially changing p-value, the blast wave will also at some point enter into a *Deep Newtonian* emission regime, where another of the default assumptions in afterglow synchrotron modelling gets compromised: given enough time, it is possible for the assumption that all accelerated particles are ultra-relativistic to break down. Instead of a power law in energies, the particles are expected to form a power-law in momentum after shock-acceleration. The result again is a light curve that decays less steeply than it would otherwise (Sironi & Giannios 2013). Although this has been considered by Hajela *et al.* 2022 and dismissed by these authors as an explanation for the late-time X-ray flattening of GRB 170817A, it nevertheless will help to bridge the divide between model and data.

If we assume for the sake of argument that the discrepancy is real and points at additional physics not currently modelled for, then various possibilities emerge. A full statistical assessment of the different scenarios that can give rise to a late time excess is

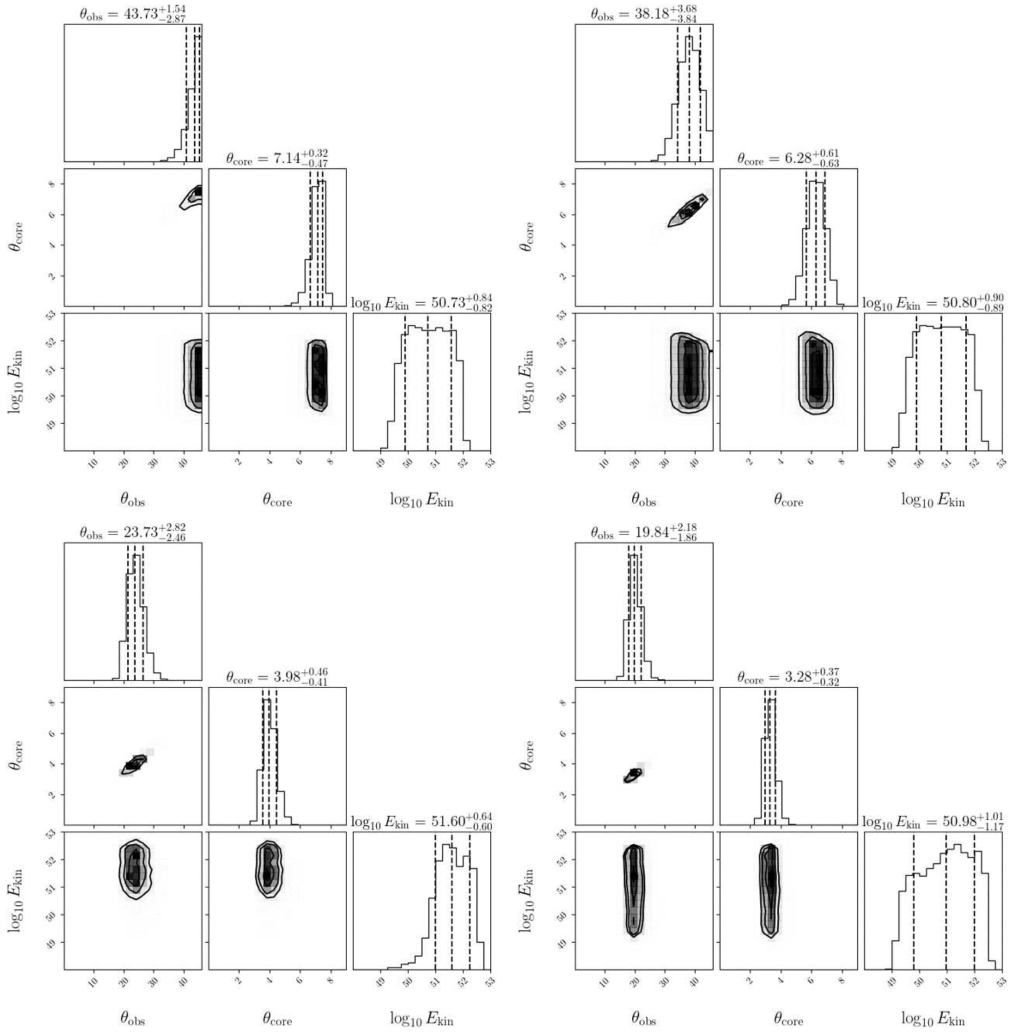

Figure 2. —Posterior distribution functions for a fit to the broadband data of GRB 170817A up to 1250 days. All but the bottom right assume a Gaussian structured jet. Top left assumes a random orientation on the sky for the prior on observer angle. Top right takes the posterior of the GW analysis as a prior for the observer angle. Bottom left co-fits for broadband emission and the positions of the centroid as from VLBI observations. Bottom right expands the model to include an additional flat X-ray luminosity component. All model fits were for the full set of model parameters (including circumburst environment density, p and efficiency factors for magnetic field generation and particle acceleration, but for clarity of presentation only jet observer angle θ_{obs}, Gaussian structured jet core angle θ_{core} and ejecta kinetic energy E_{kin} are displayed in this figure (Ryan, Van Eerten et al., unpublished).

however best done when other sources of information than the broadband light curve are taken into account.

3. Multi-messenger analysis

GW170817 / GRB 170817A has heralded an era of multi-messenger astrophysics for high-energy astrophysical transients. A Bayesian model fit of the GW signal yields a posterior on jet orientation (assuming it is launched perpendicular to the binary inspiral plane), which was first included directly as a prior in the afterglow analysis by Troja *et al.* 2018. There is however an exciting potential for this type of analysis to be a two-way street, and GW170817 has provided us with a whole range of linked phenomena with overlapping physics: a gravitational wave signal, a prompt GRB, a kilonova, a broadband afterglow from radio to X-rays and a series of very-large baseline interferometry (VLBI) observations at 75, 207 and 230 days after the burst (Mooley *et al.* 2018, Ghirlanda *et al.* 2019). The latter is particularly promising for inclusion in a full fit to constraining the jet orientation and opening angle, and has been an important part of the argument in favour of a successful jet launch scenario for GRB 170817 (note however that Zrake *et al.* 2018 have demonstrated through simulations that centroid position alone cannot independently determine whether a collimated jet managed to emerge from the debris cloud).

The impact of co-fitting for centroid position on the posteriors for jet orientation (and thus core opening angle, given the close link between the two) are substantial, as shown in Fig. 2. The motion of the centroid serves to pull the fit back from emphasising strongly the late-stage X-ray data and towards a jet orientation closer to what GW observations and early data suggest. For this reason, the VLBI data are also directly relevant to the question whether this late X-ray excess is indeed indicative of additional physics. Shown in the Figure is a fit that includes an additional source of X-ray luminosity (possible completely unconnected to GRB 170817A, possibly linked; the fit is agnostic as to the origin of the X-ray flux). The extra term does help to alleviate the tension between model and data, but its impact next to that of the centroid motion is ultimately (still?) marginal. At this point it is not possible to disentangle from the existing data the signatures of the possible causes of the X-ray excess. An interesting option would be for the X-rays to be produced by an afterglow of the kilonova, and such a signal is certainly expected to exist (whether it will at some point outshine the GRB afterglow in a manner that can be detected is a different matter). After all, the kilonova too triggered a blast wave of fast-moving plasma with a shock front that can serve as an acceleration site for non-thermal particles. Alternatively, the X-ray excess is produced directly by a long-lasting NS remnant.

Finally, a multi-messenger approach to GW170817 / GRB 170817A holds a strong promise for cosmology (ie leaving cosmological parameters as actual fit parameters rather than assuming a cosmology, redshift and luminosity distance from the host galaxy and then fitting GW, kilonova and afterglow). With one event alone to work with, any cosmological constraints from this type are not competitive to other approaches, but an accumulating sample of multi-messenger observations has the potential to tip the balance and help resolve the apparent tension between supernova and background radiation observational cosmology results (Hotokezaka *et al.*2019).

Acknowledgments

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