The Peculiar Physics of GRB 170817A and Their Implications for Short GRBs

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Abstract

The unexpected nearby gamma-ray burst (GRB) GRB 170817A associated with the Laser Interferometer Gravitational-Wave Observatory binary neutron star merger event GW170817 presents a challenge to the current understanding of the emission physics of short GRBs. The event’s low luminosity but similar peak energy compared to standard short GRBs are difficult to explain with current models, challenging our understanding of the GRB emission process. Emission models invoking synchrotron radiation from electrons accelerated in shocks and photospheric emission are particularly challenging explanations for this burst.

Key words: gamma-ray burst: individual (170817A) – radiation mechanisms: non-thermal – radiation mechanisms: thermal

1. Introduction

The mystery of the origin of short gamma-ray bursts (GRBs), the most cataclysmic events in the universe, has been suddenly unraveled by the nearly simultaneous detection of gravitational waves and GRB 170817A by the Laser Interferometer Gravitational-Wave Observatory (LIGO), by INTEGRAL, ACS and the Gamma-ray Burst monitor (GBM) on board the Fermi satellite (Abbott et al. 2017). This detection confirms the long hypothesized scenario that some short GRBs have progenitors of binary neutron star mergers (Eichler et al. 1989; Narayan et al. 1992); for a review, see, e.g., Piran (2004), Gehrels et al. (2009), and Kumar & Zhang (2015). However, in the context of other known short GRBs with measured distances, the luminosity of GRB 170817A is ~1000 times dimmer than any previously measured short GRB (Gruber et al. 2011), challenging our understanding of the emission mechanism at work.

The theoretical framework commonly invoked for GRB emission is the fireball model (Paczynski 1986, 1990; Rees & Meszaros 1992, 1994; Piran et al. 1993). It assumes that an amount of energy comparable to the rest mass energy of the Sun is emitted within a small region, typically a few 10^6–7 cm, the size of a black hole of a few solar masses. The fireball is initially optically thick, trapping the radiation within the flow. The expansion of the fireball is triggered by its own internal thermal pressure or by magnetic stresses, forming a jet. As the plasma expands, it becomes transparent at a radius on the order of 10^{12} cm for typical GRB parameters (Goodman 1986; Paczynski 1986; Abramowicz et al. 1991), emitting (almost) thermal radiation. However, nonthermal processes dominate the signal in the X-ray and gamma-ray bands. In fact, it is widely believed that the spectrum is that of synchrotron radiation emitted by electrons accelerated in shocks or magnetic reconnection (Rees & Meszaros 1992, 1994; Daigne & Mochkovitch 1998; Zhang & Yan 2011).

The exact geometry of the relativistic outflow is subject to intense debate, but different assumptions can be made. On one hand, its expansion can be considered conical with little emitting material outside of the cone opening. Those outflows are commonly referred to as top-hat jets, as emission is only coming from the cone forming the jet. On the other hand, jets could also be structured, with a luminosity L and Lorentz factor Γ depending only on the angle between the center of the jet and the considered direction of expansion (Rossi et al. 2002; Zhang & Mészáros 2002). In this case, emission originates from the part of the jet expanding toward the observer. Indeed, Troja et al. (2007) interpret an off-axis afterglow for GRB 170817A via an observed delay in the X-ray emission. They estimated the observation angle to be around 30°, in agreement with the limit provided by radio observations (Alexander et al. 2017) and the analysis of the gravitational-wave signal (Abbott et al. 2017). Additionally, a slowly expanding cocoon can also be formed by the material pushed away during the propagation of the jet (Kathigamaraju et al. 2017; Lazazziti et al. 2017).

The observed low γ-ray luminosity of GRB 170817A can be either low intrinsic luminosity, or off-axis emission. The first case, low intrinsic luminosity, is very unlikely since we do not know a physical process that can produce the same spectral shape at a luminosity difference of 10^5. In this Letter, we investigate the feasibility of the previously favored emission mechanisms, but just seen from a large off-axis angle. We show that photospheric emission models and synchrotron radiation produced in shocks are particularly challenged mechanisms. After a brief description of our analysis of GRB 170817A, we consider in turn photospheric emission models, synchrotron radiation, and synchrotron self-Compton mechanisms.

2. GBM Analysis of GRB 170817A

Using the time-tagged Event GBM spectral data of GRB 170817A, we estimate the background emission from off-source regions by fitting an unbinned Poisson likelihood to all spectral channel count data. The source region of the light curve is determined via a Bayesian blocks analysis (Scargle et al. 2013) yielding a source region starting at T0 = 0.32 s with a dead time corrected duration of ΔT = 0.64 s. With the estimated background, we perform a Bayesian spectral fit of the source region spectrum assuming a cutoff power-law model Nγ = A(E/100 keV)^α exp(E/E_u), where A is the normalization, E_u is the cutoff energy, and α_u is the spectral index. MULTINEST (Feroz et al. 2009) was used for sampling the
posterior. Informative Gaussian priors from the GBM catalogs are used for the spectral index and the peak of the spectrum resulting in a spectral index $\alpha_p = -1 \pm 0.23$ and spectral peak $E_p = 240^{+130}_{-70}$ keV. The posterior distributions for the peak energy and the spectral slope are displayed in Figure 1. The entire analysis was performed with the Multi-Mission Maximum Likelihood framework (3ML Vianello et al. 2015).

The luminosity of the source given its distance at $\sim$40 Mpc is $9.1 \times 10^{46}$ erg s$^{-1}$. Those values are in agreement with the analysis of Abbott et al. (2017). An additional soft spectral component was reported after the main peak (Goldstein et al. 2017). However, the statistical significance of this emission interval is 1.4$\sigma$ (Burgess et al. 2017), far below the threshold required for proper spectral analysis. As such, it is not considered in this paper where we focus our effort in the understanding of the physical process that produced the bright 0.6 s long gamma-ray peak.

### 3. Constraints on Thermal Emission

We start our discussion by providing constraints on photospheric emission, produced when a structured jet becomes optically thin. It was initially proposed by Goodman (1986) and Paczynski (1986), and later considered as an alternative to the internal shock scenario, to palliate the low efficiency of this model. Indeed, photospheric emission can naturally achieve high efficiency for the energy release, see the detailed discussion in the review by Pe’er (2015), as well as the results based on relativistic hydrodynamical simulations by Chhotray & Lazzati (2017).

The theory is simple enough such that the observed temperature, linked to the peak energy by $E_p = 2.8T_{\text{obs}}^3$ and observed flux directly constrain the Lorentz factor of the outflow and the photospheric radius (Pe’er et al. 2007). For GRB 170817A, we estimate those properties to be $\Gamma \sim 65$ and $r_{\text{ph}} \sim 2.5 \times 10^8$ cm. Therefore, assuming a linear increase of the Lorentz factor with radius, valid if the fireball is thermally accelerated, we obtain an upper limit on the initial expansion radius $r_0 \sim 3.5 \times 10^9$ cm. This radius is on the order of the innermost stable circular orbit of a 3 solar mass black hole, putting tight constraints on the plausibility of photospheric emission. Indeed, if the jet is produced by neutrino anti-neutrino annihilation, it requires a volume of radius several times that of the black hole (Dessart et al. 2009).

To obtain these results, we assume that the radiative efficiency at the photosphere is 5%. Larger radiative efficiency leads to a lower limit on $r_0$, further reducing the possibility that the emission is of photospheric origin. We additionally note that a similar result holds in the case of an electron–positron pair jet, leading to a Lorentz factor of $\Gamma \sim 5$, $r_{\text{ph}} \sim 5 \times 10^6$ cm, and $r_0 \sim 10^6$ cm.

We now consider that the emission is produced by a top-hat jet and seen off axis. Because of the relativistic motion of the outflow, the peak energy roughly scales proportionally to the Doppler factor $\delta = 1/(\Gamma(1 - \beta \cos \theta))$, where $\beta$ is the speed of the jet in units of the speed of light and $\theta$ is the angle between the observer’s direction and the edge of the jet. One can show from energy and dynamics arguments that the observed temperature of the photospheric component cannot be larger than the temperature close to the black hole, which itself cannot be larger than few MeV (Goodman 1986; Paczynski 1986). Assuming a value for the on-axis observed peak energy (or equivalently of the temperature), the Lorentz factor of the outflow can be estimated. The observed temperature translates to a lower limit on the luminosity, which itself translates to a lower limit on the photospheric radius. Figure 2 shows the value of the Lorentz factor of the outflow and the photospheric radius $r_{\text{ph}}$ as a function of the observed angle for three values of the on-axis spectral peak energy: 300 keV, 1 MeV, and 3 MeV. Additionally, the duration of the burst cannot exceed the curvature time $\Delta t_{\text{curv}} = r_{ph}/(2\Gamma^2c)$, corresponding to the time delay between two photons emitted toward the observer separated by an angle 1/$\Gamma$, see Piran (1999). This translates to an upper limit for $r_{ph}$. Here, $c$ is the speed of light. Clearly, if the burst is seen off-axis, the angle cannot be larger than a few degrees for photospheric emission from a top-hat jet, the least stringent limit being obtained for a peak energy of 300 keV on-axis, implying a maximum observation angle of $\sim 8^\circ$.

Another possibility is that thermal emission is produced by a nearly spherical outflow, which expands at subrelativistic speeds, the so-called cocoon (Kasliwal et al. 2017; Lazzati et al. 2017). The peak energy and the luminosity constrain the size of the emitting region to be $l \sim 2 \times 10^7$ cm. However, the amount of thermal energy in the region of volume defined by this size is found to be $10^{44}$ erg, two to three orders of magnitude smaller than the total emitted energy. Thus, the possibility of the emission originating from a nonrelativistic cocoon is unlikely. This is in agreement with the results of Kasliwal et al. (2017), who also considered the emission from a

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3 Note that the factor 2.8 is for pure blackbody radiation. In the case of the relativistic photosphere of GRBs, the exact value could be slightly smaller, with little effect on the results (see Pe’er et al. 2007).

4 The observed temperature is given by $T_{\text{obs}} = \delta T$, while the on-axis temperature is given by $T_{\text{on-axis}} = 2T$. Given an angle between the observer’s direction and the direction of the jet, the Lorentz factor and the comoving temperature at the photosphere can be solved for.
that pairs are not substantially created in the dissipative process, the relation \( \xi < 1 \) holds. Therefore, we can write the observed luminosity as the product between the single particle emissivity and the number of radiating particles

\[
L_{\text{obs}} = \frac{4}{3} \sigma_T c \left( \frac{2 \pi m_e c^2}{q_e} \right)^2 \frac{E_p^2}{8 \pi \gamma_e^2 \Gamma m_p} \alpha \xi M_\odot. \tag{1}
\]

In shock acceleration physics, the Lorentz factor of accelerated electrons is estimated to be the ratio of the proton and electron masses \( \gamma_e = m_p/m_e \), where \( \kappa \) parameterizes the uncertainty of the acceleration mechanism. We can now estimate the product \( \alpha \xi \) in Equation (1) from the observed luminosity of GRB 170817A. Figure 3 displays the value of \( \alpha \xi \) as a function of the Lorentz factor \( \Gamma \) and \( \kappa \) for the observed luminosity of GRB 170817A. A comparison is provided for a GRB with luminosity \( L = 10^{52} \text{ erg s}^{-1} \) and the same peak energy \( E_p = 200 \text{ keV} \). Note that \( \alpha \xi \) has dependence \( E_p^{-2} \), and therefore increasing the peak energy implies a substantial decrease of \( \alpha \xi \).

We find that the fraction \( \alpha \xi \) must be extremely tiny for GRB 170817A, several orders of magnitude smaller than what is expected for an average short GRB. This is expected because the luminosity of GRB 170817A is a factor of \( \sim 10^{-4} \) smaller than that of other short GRBs. There are two possibilities (and the combination of both). First, the number of particles accelerated in the dissipation event can be extremely small \( \xi \ll 1 \), leading to a small efficiency of the radiation process. Second, the total energy in the jet is small \( \alpha \ll 10^{-2} \), which is difficult to obtain simultaneously with a relativistic jet. Weaker constraints on \( \alpha \xi \) are obtained by increasing the Lorentz factor of the outflow, but this is difficult because of the high baryon pollution expected in the surrounding of the black hole immediately after the merger. Based on these arguments, we conclude that the GRB emission is unlikely to be synchrotron radiation from a structured jet or an on-axis top-hat jet.

We now turn to the possibility that the emission is synchrotron radiation from a top-hat jet, seen off-axis. However, the observed high peak energy would imply an inferred on-axis peak energy far too large even for a typical short GRB, see, e.g., Ramirez-Ruiz et al. (2005). Similarly to what we demonstrated for the photospheric case, we can assume an on-axis peak energy and compute the Lorentz factor as function of off-axis angle \( \theta \). For a 2 MeV on-axis peak

\[ \text{Figure 2.} \text{ Top: lower bound on the photospheric radius as a function of the angle for top-hat jets for several values of the on-axis (so not observed) spectral peak energy. The forbidden region is obtained from requiring the curvature time to be smaller than the duration of GRB 170817A. Bottom: Lorentz factor of the outflow at the photosphere.} \]

\[ \text{Figure 3.} \text{ (Left) Fraction } \alpha \xi \text{ required by the luminosity and the peak energy for GRB 170817A as a function of } \Gamma \text{ and } \kappa. \text{ (Right) Same but for a GRB of luminosity } 10^{52} \text{ erg s}^{-1} \text{ and a peak energy of 200 keV.} \]
(among the largest peak energies seen in a short GRB), we find that the Lorentz factor must drop below 20 around $10^7$. The compactness argument (Piran 1999) requires the Lorentz factor of the outflow to be at least in the order of a few tens to avoid excessive pair creation, thus requiring the observed angle to be small. We refer to the detailed analysis of Kasliwal et al. (2017) on the opacity to pair production in the context of GRB 170817A when seen off-axis. We conclude that the observed emission properties of GRB 170817A (luminosity and peak energy) cannot be explained as off-axis synchrotron emission from a top-hat jet.

5. Constraints on Synchrotron Self-Compton (SSC) Emission

We now investigate if the spectral peak at a few hundreds of kiloelectron volts can be the self-Compton component of synchrotron emission peaking near the optical-ultraviolet bands (Spada et al. 2000; Stern & Poutanen 2004). The peak frequency of inverse Compton is $\nu_{\text{peak}} = 2\gamma_{\text{acc}}^2 \nu_\infty$, where its flux is roughly estimated as $F_{\nu_{\text{peak}}} \sim \tau_\gamma \gamma_{\text{acc}}^2 F_\infty$, with $\tau_\gamma = \gamma_{\text{acc}} n l$ as an estimate of the opacity, $\nu_\infty$ as the synchrotron peak energy, and $F_\infty$ as the synchrotron flux, see, e.g., Sari & Esin (2001). Here, $l \sim c \Delta t \sim 2 \times 10^{10}$ cm is an estimate of the radial extension of the jet. In the expression of the SSC flux, we neglected several terms of the order of unity and assume that the scattering is not in the Klein–Nishina regime, which is valid at least for photons at the observed peak. In fact, the largest uncertainty comes from self-absorption of the synchrotron component, which requires a more advanced treatment. Keeping in mind these caveats, we proceed with our estimates.

The electron number density $n$ is estimated from the total number of electrons $\alpha \xi M_\odot / (\Gamma m_p)$ divided by the volume of the fireball $V \sim 4\pi r^2 l$, where $r \sim 10^{13}$–$14$ cm is the typical radius of internal shocks (Rees & Meszaros 1994; Daigne & Mochkovitch 1998). As with the synchrotron process, we eliminate the unknown magnetic field by using the observed peak energy and arrive at the following estimate for the SSC luminosity

$$L_{\text{SSC}} = \frac{1}{24} \frac{\gamma_{\text{acc}}^2 m_p^3 c^3 \gamma_{\text{acc}}}{q_e^2 m_p^2} \frac{E_\gamma^2 (\alpha \xi M_\odot)^2}{l R} \left( \frac{R}{10^{13}} \right)^{12} \left( \frac{\tau}{10^7} \right)^{12} \left( \frac{l}{10^{10}} \right)^{-1},$$

where the strong dependencies on the Lorentz factor of the outflow $\Gamma$ and on $\kappa$ (characterizing the minimum Lorentz factor of the accelerated electrons) have to be noted. Equating this last result to the observed luminosity of GRB 170817A leads to values of the parameter $\alpha \xi$ on the order of a few per thousands, realistic considering the environment close to the black hole immediately after the merger. The detection or nondetection of the burst in the Fermi-LAT instrument (unoperational due to nearing the South-Atlantic anomaly; Fermi-LAT Collaboration 2017) or AGILE-GRID (occulted by the Earth for the first 900 s; Verrecchia et al. 2017) would have put additional constraints on the synchrotron self-Compton scenario. Indeed, a second-order SSC component should be produced and peak around few hundreds of giga-electron volts. Finally, we estimated the synchrotron absorption frequency and find that for a large set of parameter values, it is smaller than the synchrotron peak energy. Thus, SSC is a potential emission process for GRB 170817A.

As for synchrotron emission, similar constraints on the peak energy are obtained for synchrotron self-Compton if the emission is produced by a top-hat jet, strongly limiting the Lorentz factor of the outflow.

6. Conclusion

We explored different emission mechanisms to explain the unusually weak prompt emission of GRB 170817A. We have separately examined structured and top-hat jets, providing constraints in both cases. For structured jets, we find that photospheric emission is very unlikely, as it requires an initial expansion radius on the same order or even smaller than the innermost stable circular orbit of a 3 solar mass black hole, expected to have been created during the merger. For completeness, we also provided the estimate in the case of a pure electron–positron plasma, which led to a similar conclusion. Constraints on the synchrotron emission process are derived based on the assumption of high baryon pollution close to the black hole after the merger. The low luminosity of GRB 170817A requires either that only an extremely tiny fraction of the particles in the jet radiate, and thus, a very small radiative efficiency or that the jet be extremely clean of baryons. Both of these requirements are very difficult to fulfill. Indeed the first solution demands any form of dissipation to be suppressed, while the second one requires the environment in which the jet is created to be clear of baryons.

When considering top-hat jets seen off-axis, tight constraints on the Lorentz factor are obtained for both the photospheric emission and synchrotron radiation. Indeed, the sharp decrease in the Doppler boost with viewing angle and an upper limit on the peak energy of GRBs observed to-date lead to strict limits on either the Lorentz factor of the outflow or on the viewing angle: both are required to be small. Thus, if GRB 170817A is an ordinary burst as compared to other short GRBs with the exception of being observed off-axis, the observed properties of GRB 170817A exclude synchrotron radiation and photospheric emission in short-duration GRBs.

Only the estimates of the synchrotron self-Compton mechanism seem to lead to reasonable values in terms of the peak energy, Lorentz factor, and luminosity. A detailed study of this mechanism should be performed to take into account synchrotron self-absorption. To conclude, GRB 170817A is peculiar in many aspects and these peculiarities limit the typical emission processes within the standard fireball framework. We found that synchrotron self-Compton from a structured jet might explain the peculiar prompt phase of GRB 170817A. This is an alternative to the mildly relativistic cocoon (Kasliwal et al. 2017). In any case, if the emission of GRB 170817A is typical for short GRBs, in general, then our constraints imply that most previous suggestions concerning the on-axis emission of short GRBs need to be reconsidered. Alternatively, if GRB 170817A was atypical, the coincidence with the LVC trigger is amazing, and suggests the discovery of a new short GRB subclass.
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