A UNIFIED PICTURE FOR LOW-LUMINOSITY AND LONG GAMMA-RAY BURSTS BASED ON THE EXTENDED PROGENITOR OF LGRB 060218/SN 2006AJ

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ABSTRACT

The relation between long gamma ray bursts (LGRBs) and low-luminosity GRBs (l/GRBs) is a long standing puzzle—on one hand their high energy emission properties are fundamentally different, implying a different gamma ray source, yet both are associated with similar supernovae of the same peculiar type (broad-line Ic), pointing at a similar progenitor and a similar explosion mechanism. Here we analyze the multi-wavelength data of the particularly well-observed SN 2006aj, associated with l/GRB 060218, finding that its progenitor star is sheathed in an extended ($>100R_\odot$), low-mass ($\sim0.01M_\odot$) envelope. This progenitor structure implies that the gamma ray emission in this l/GRB is generated by a mildly relativistic shock breakout. It also suggests a unified picture for l/GRBs and LGRBs, where the key difference is the existence of an extended low-mass envelope in l/GRBs and its absence in LGRBs. The same engine, which launches a relativistic jet, can drive the two explosions, but, while in LGRBs the ultra-relativistic jet emerges from the bare progenitor star and produces the observed gamma rays, in l/GRBs the extended envelope smothers the jet and prevents the generation of a large gamma ray luminosity. Instead, the jet deposits all its energy in the envelope, driving a mildly relativistic shock that upon breakout produces a l/GRB. In addition for giving a unified view of the two phenomena, this model provides a natural explanation to many observed properties of l/GRBs. It also implies that l/GRBs are a viable source of the observed extra-galactic diffuse neutrino flux and that they are promising sources for future gravitational wave detectors.

Key words: gamma ray burst: general – gamma ray burst: individual (GRB060218) – gravitational waves – neutrinos – supernovae: general – supernovae: individual (SN2006aj)

1. INTRODUCTION

The gamma ray emission of long gamma ray bursts (LGRBs) and low-luminosity GRBs (l/GRBs) show almost no similarities apart for being detected by the same instruments. LGRBs are luminous ($10^{50}–10^{52}$ erg s$^{-1}$), hard ($\geq100$ keV), highly variable, and narrowly collimated with a typical duration of 10–100 s (Piran 2004, and references therein). l/GRBs are fainter by about four orders of magnitude ($10^{46}–10^{48}$ erg s$^{-1}$), relatively soft ($\leq100$ KeV), not highly beamed, and show no significant temporal variability over their entire duration, which is often longer than 1000 s (Kulkarni et al. 1998; Campana et al. 2006; Soderberg et al. 2006; Kaneko et al. 2007).

To date there are only four well observed l/GRBs compared to hundreds of LGRBs. However, this is a result of their low luminosity, which limits the detection to a distance of $\sim$100 Mpc, compared to LGRBs which are seen throughout the entire universe. In fact, l/GRBs are much more common than LGRBs, and are the most abundant known relativistic explosions in the nearby universe (Pian et al. 2006; Soderberg et al. 2006). Thus, l/GRBs are of special interest, both for the understanding of GRBs and their connection to supernovae (SNe), and as sources of high energy non-electromagnetic signals, such as gravitational-waves (GWs) (e.g., Kotake et al. 2012; Ando et al. 2013; Bimholtz & Piran 2013), neutrinos (e.g., Murase et al. 2006; Murase & Ioka 2013), and cosmic rays (e.g., Budnik et al. 2008; Liu et al. 2011).

Based on high energy emission alone there is no reason to assume that LGRBs and l/GRBs are related. Moreover, theoretical considerations show that the gamma rays seen in l/GRBs cannot be produced in the same environment where the gamma rays in LGRBs are generated (Bromberg et al. 2011). It is therefore puzzling that these two apparently different GRB types are both associated with very similar peculiar SNe of the rare broad-line Ic type (e.g., Melandri et al. 2014). These SNe show no signs of H or He in their spectra, an indication of highly stripped progenitors. Their ejecta have unusually high velocities for SNe ($10,000–30,000$ km s$^{-1}$), their peak luminosities indicate a relatively large amount of synthesized $^{56}$Ni, and the total kinetic energy carried by these SNe is unusually high (Woosley & Bloom 2006, and references therein). The similarity of the associated SNe suggests that l/GRBs and LGRBs have similar progenitors and similar inner explosion mechanism. The natural question that arises is how similar explosions produce such different gamma ray signals.

Here we approach this puzzle by analyzing the early (first day) optical/UV light curve of SN 2006aj, which is associated with l/GRB 060218, in order to study its progenitor structure. l/GRB 060218/SN 2006aj has the best early observational coverage out of the four well observed l/GRBs and their associated SNe. It includes Swift continuous gamma ray, X-ray, UV, and optical observations ranging from $10^2–10^5$ s after the explosion (Campana et al. 2006), many optical spectra starting less than two days after the explosion (Mazzali et al. 2006; Mirabal et al. 2006; Modjaz et al. 2006; Pian et al. 2006; Sollerman et al. 2006) and radio observations starting a day after the explosion (Soderberg et al. 2006). In fact, SN 2006aj has probably the most detailed early optical/UV photometric coverage out of the thousands SNe observed to date.

The unique feature of the optical/UV light curve of SN 2006aj is that it shows two peaks. Using a recently
developed method for the analysis of double-peaked SNe (Nakar & Piro 2014) we constrain the progenitor properties. These properties are then used to learn about the physics of llGRBs and on their relation to LGRBs.

This paper is structured as follows. Section 2 presents the analysis of the optical/UV light curve and the resulting constraints on the progenitor structure of llGRB 060218/ SN 2006aj. These constraints strongly support the suggestion that llGRBs are generated by shock breakouts (Section 3). A unified picture for llGRBs and LGRBs that naturally explain the similarities and differences between them is presented in Section 4. This picture provides a simple explanation to the unique velocity profile of SNe associated with llGRB (Section 5). The implication of this picture for llGRBs’ neutrino and gravitational wave emission is discussed in Section 6.

2. THE PROGENITOR OF LLGRB 060218/SN 2006AJ

Figure 1 depicts the optical/UV light curve of SN 2006aj as taken from Campana et al. (2006). It shows two peaks in the optical bands, at \( t \approx 10 \) hr and \( t \approx 10 \) days, where \( t \) is time since first detection of the gamma rays, estimated here as the explosion time. Such double-peaked light curves are very rare among SNe. In typical SNe, the light curve is dominated by one of two power sources: (i) the internal energy deposited by the SN shock, known as “cooling envelope emission,” or (ii) the radioactive decay of \( ^{56}\text{Ni} \). Each one of these power sources produces only a single peak in the optical and, in typical SNe, the timescales of the maximal contribution to the optical light from each of the two sources are comparable. Therefore, observed SN light curves usually contain only a single optical peak which is powered by the stronger power source at any given SN. This is cooling envelope in explosions of red supergiants, such as type II-P SNe, and \( ^{56}\text{Ni} \) in explosions of more compact progenitors, such as type I and 1987-like SNe.

Two peaks are observed in rare cases where at an early time the emission is powered by the cooling envelope, which then decays sharply on a timescale comparable to that of the rising \( ^{56}\text{Ni} \) contribution. This behavior requires an atypical progenitor structure of a compact massive core that is engulfed by extended low-mass material (Hofflich et al. 1993; Bersten et al. 2012; Nakar & Piro 2014). The second peak in these cases is similar to the main peak of a typical \( ^{56}\text{Ni} \) powered SNe, and thus its properties provide an estimate of the total ejecta mass and of the \( ^{56}\text{Ni} \) mass. In the case of SN 2006aj, the second peak is clearly powered by \( ^{56}\text{Ni} \) and it shows a total ejecta mass of \( \sim 2M_\odot \), out of which \( \sim 0.2M_\odot \) are \( ^{56}\text{Ni} \) (Mazzali et al. 2006). The only natural source of the first peak in SN 2006aj is the cooling envelope phase of an extended mass (see Appendix A) and thus its properties can provide a robust estimate of the radius and the mass of the extended material. Here the results of Nakar & Piro (2014) are used to derive these constraints.

The mass of the extended material can be estimated from the time of the first peak, \( t_p \) (Nakar & Piro 2014):

\[
M_{\text{ext}} \approx 0.01 \frac{v_{\text{ext}}}{0.2c} \left( \frac{t_p}{10 \text{ hr}} \right)^2 M_\odot
\]  

where \( c \) is the light speed and \( v_{\text{ext}} \) is the velocity to which the extended material is accelerated by the explosion. Spectroscopic observations limit \( v_{\text{ext}} > 0.1c \), the measured photospheric velocity at \( t = 2.89 \) days (Pian et al. 2006). On the high end it is most likely that \( v_{\text{ext}} < 0.3c \), since at higher velocities the kinetic energy carried by \( M_{\text{ext}} \) would be larger than the kinetic energy deposited by the explosion in the massive core (\( \sim 10^{51} \text{ erg} \); Mazzali et al. 2006).

The pre-explosion radius of the extended material, \( R_{\text{ext}} \), can be estimated by the bolometric luminosity at the first peak. The colors before and during the first peak are very blue and they are constant in time (Simon et al. 2010), as expected if the observed bands are on the Rayleigh–Jeans part of a blackbody spectrum during that time (i.e., with temperature \( T(t \leq t_p) \gtrsim 50,000 \text{ K} \); see consistency check below). This implies that the total luminosity seen in UV during the peak, \( \sim 3 \times 10^{44} \text{ erg} \), is only a lower limit on the true bolometric luminosity, which may be significantly higher. Since \( R_{\text{ext}} \) is linear in the bolometric luminosity (Nakar & Piro 2014), the available observations set a lower limit:

\[
R_{\text{ext}} \gtrsim 10^{13} \left( \frac{v_{\text{ext}}}{0.2c} \right)^{-2} \text{ cm.}
\]  

This is consistent with the lack of color evolution at \( t < t_p \) and the model prediction that temperature is dropping with time, reaching at the peak \( T(t_p) \approx 50,000(R_{\text{ext}}/10^{13} \text{ cm})^{1/4} \text{K} \) (Nakar & Piro 2014). Thus, the optical/UV light curve of SN 2006aj indicates that its progenitor had a relatively compact core of several solar masses, surrounded by \( \sim 0.01M_\odot \), which is extended to a radius of a supergiant. This structure is very different than the typically expected structure of a fully H stripped progenitor, based on stellar evolution models, yet it must be very common in GRB progenitors given that llGRBs are more common than LGRBs. This progenitor structure has several far reaching implications for the physics of llGRBs and their associated SNe, which are discussed in the following sections.
4. A UNIFIED PICTURE FOR LGRBS AND LLGRBS

If all LGRB progenitors have a similar structure to that of LGRB 060218 then it provides a natural solution to the puzzle why two explosions with similar inner workings produce such different gamma ray signals. According to the standard model for LGRBs the burst is powered by a central engine that launches a highly collimated ultra-relativistic bipolar jet. In order to produce a LGRB the jet must first punch its way through the star and then expand freely at ultra-relativistic velocities to radii where generated gamma rays can be seen by the observer. While the jet drills through the dense stellar matter its energy is dissipated and the engine must continue to supply power into the jet if it is to succeed punching through the star and produce the observed LGRB (Zhang et al. 2003; Morey et al. 2007; Mizuta & Aloy 2009; Bromberg et al. 2011). Thus, a necessary condition for the production of a LGRB is that the engine working time is long enough to allow the jet to drill through the star. Observations indicate that a typical LGRB engine launches a jet at a typical isotropic equivalent luminosity of $L_{\text{iso}} \sim 10^{51}$ erg s$^{-1}$ and a typical opening angle $\theta_j \sim 10^\circ$ over a typical duration of $\sim 20$ s (Piran 2004). The total energy carried by the jet, after correction for beaming, is $\sim 10^{51}$ erg. If the progenitor is a bare H stripped star of several solar masses and several solar radii it takes $\sim 10$ s for the jet to penetrate through the star (see Appendix B; Bromberg et al. 2011), implying that the jet can successfully emerge from the star and that the collapse of such a progenitor can lead to a LGRB.

The picture, however, is very different if there is an additional extended envelope surrounding the massive core, similar to the one found here for LGRB 060218. Although the extended material mass is low its large radius makes it very hard for a jet to penetrate. In fact the time that the engine must work in order for the jet to drill through the entire extended mass is (Appendix B):

$$ t_{\text{eng}} \gtrsim 150 \left( \frac{L_{\text{iso}}}{10^{51} \text{ erg s}^{-1}} \right)^{-1/2} \left( \frac{R_{\text{ext}}}{3 \times 10^{13} \text{ cm}} \right)^{1/2} \left( \frac{M_{\text{ext}}}{10^{-2} M_\odot} \right)^{-1/2} \text{s} , $$

(4)

This time is considerably longer than the typical working time of a LGRB engine. Thus, a collapse of the progenitor of LGRB 060218 and the formation of a LGRB engine at its center will not lead to an observed LGRB. Instead, the launched jet, which penetrates the stellar core, is choked while still propagating in the extended material. The energy carried by the jet ($E_{\text{jet}} \sim 10^{51}$ erg) is then deposited in the extended mass accelerating it to high velocity

$$ v_{\text{ext}} \approx 0.3 c \left( \frac{E_{\text{jet}}}{10^{51} \text{ erg}} \right)^{1/2} \left( \frac{M_{\text{ext}}}{10^{-2} M_\odot} \right)^{-1/2} $$

and driving it into a strong shock. The shock accelerates further at the dropping density gradient near $R_{\text{ext}}$ and upon breakout produces a LGRB.
Note that while the energy deposition is done by a narrow jet and is therefore highly aspherical, the shock upon breakout can be quasi-spherical. The reason is that the jet is choked long before it approaches $R_{\text{ext}}$ and the resulting blast wave becomes much more spherical during its propagation before it breaks out at $R_{\text{ext}}$. A schematic sketch of the similarities and differences between $\nu$GRBs and LGRBs according this picture is illustrated in Figure 2.

5. THE UNCOMMON VELOCITY PROFILE OF SNe ASSOCIATED WITH LGRBs

This scenario resolves yet another puzzle related to SNe associated with $\nu$GRBs—why is the kinetic energy in their fast moving ejecta is so high compared to other SNe (Soderberg et al. 2006; see also Margutti et al. 2014c). In typical SNe the explosion energy is all deposited at the center of the progenitor. This drives a shock that crosses first the bulk of the mass and then accelerates at the sharp density drop near the stellar edge. This acceleration dictates a certain relation between the kinetic energy carried by slow and by fast moving material, where $E_k(v) \propto v^{-5}$ (Sakurai 1960; Matzner & McKee 1999).

This relation is seen in regular SNe, but not in $\nu$GRBs where the fast moving ejecta carries much more energy than it predicts (Soderberg et al. 2006). For example, in SN 2006aj about $2 \times 10^{51}$ erg are carried by the bulk of the mass at ~10,000 km s$^{-1}$ (Mazzali et al. 2006). In a regular SNe if a mildly relativistic (>150,000 km s$^{-1}$) ejecta exist, the relation $E_k(v) \propto v^{-5}$ dictates that it should carry ~$2 \times 10^{55}$ erg. Instead, in SN 2006aj radio observations indicate that the mildly relativistic material carries >$10^{48}$ erg (Soderberg et al. 2006; Barniol Duran et al. 2014). This observed property of SN 2006aj is naturally explained by the picture of $\nu$GRBs presented here. In this picture the energy in the slow moving material is deposited by the SN explosion mechanism at the center, while the observed >$10^{48}$ erg in the fast moving material is deposited directly by a GRB jet, thereby decoupling the amount of energy carried by each of the components.

6. NEUTRINOS AND GWS FROM LGRBS

An intriguing implication of the arising picture is the prospects for future detection of non-electromagnetic signal from $\nu$GRBs. The extreme energies and velocities involved in LGRB engines and jets make them a potential source of GWs, neutrinos, and high-energy cosmic rays. However LGRBs are very rare in the local universe and are typically seen at a distance >Gpc. Here we suggest that $\nu$GRBs harbor the same engine as LGRBs, which produces similar ultra-relativistic jets. The propagation of an $\nu$GRB jet is similar to that of a LGRB jet within the massive core. After the jet breaks out of the core and into the $\nu$GRB extended envelope the envelope density is low, so the pressure in the cocoon does not affect the jet (see Appendix B). Thus, at any location that is far from the jet head the jet is unaware of the extended envelope. Therefore, all the physical processes that take place during the formation of the engine, the launching of the jet and the jet propagation in LGRB also take place in $\nu$GRBs up to the radius where $\nu$GRB jets are choked in their progenitors’ extended envelopes, namely ~$10^{12}$–$10^{13}$ cm. Thus, the same emission generated by a LGRB engine and by its jet while it propagates up to a radius of ~$10^{12}$–$10^{13}$ cm are expected to be generated also by a $\nu$GRB. This includes photons, high energy particles (cosmic rays), neutrinos and GWs. The extended envelope has a Thompson optical depth $>100$ and therefore photons and cosmic rays cannot escape through the extended envelope (the cross-section for pp inelastic collision at ~TeV energies is ~0.1 Thomson). However, the envelope is transparent to neutrinos and GWs. It is therefore worth considering the implications of the model presented here for neutrino and GW emission from $\nu$GRBs, especially given that $\nu$GRBs are more common than LGRBs.

LGRBs are expected to be bright sources of high energy neutrinos ($\sim 10^{14}$–$10^{16}$ eV). The most promising production site of neutrinos is internal shocks within the relativistic jet (Waxman & Bahcall 1997). At radii that are large enough $>10^{11}$–$10^{12}$ cm these shocks are collisionless and are therefore expected to efficiently accelerate protons (at smaller radii the shocks are radiation mediated and no efficient particle acceleration is expected; Levinson & Bromberg 2008). At radii that are small enough, $\leq 10^{14}$, the photon density is high enough to allow an efficient photo-pion production and thus a generation of high energy neutrinos. Current measurements limit the neutrino flux from LGRBs to $E_\nu \phi_\nu \lesssim 2 \times 10^{-10}$ GeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$ per flavor, where $E_\nu = 100$ TeV (Aartsen et al. 2014b). This upper limit is comparable to recent estimates of the flux expected from $\nu$GRBs if particles are accelerated efficiently in internal shocks at radii of ~$10^{12}$–$10^{14}$ cm (Hümmer et al. 2012) and it is about two order of magnitude lower than the measured diffuse neutrino flux (Aartsen et al. 2014a).

In the picture presented here $\nu$GRBs are expected to be a much stronger source of diffuse neutrino flux than LGRBs. First $\nu$GRBs are more numerous. The local rate of $\nu$GRBs, without correction for beaming, is ~$3 \times 10^{-7}$ Mpc$^{-3}$ yr$^{-1}$, while beaming correction is expected to be relatively small, <10 (Pian et al. 2006; Soderberg et al. 2006). This is compared to a LGRB local rate, uncorrected for beaming, of ~$10^{-8}$ Mpc$^{-3}$ yr$^{-1}$ (Wanderman & Piran 2010). Beaming correction increases the true rate of LGRBs by about two orders of magnitude. Thus, $\nu$GRBs are more frequent than LGRBs by about an order of magnitude. Second, the neutrino production of LGRBs depends on the fraction of high-energy protons that produce pions via interaction with the observed gamma rays. This fraction, denoted as $f_\pi$, depends strongly on the burst parameters and it vary between bursts. Under optimal conditions the estimates are $f_\pi \lesssim 0.1$ (Waxman & Bahcall 1997; Hümmer et al. 2012). In $\nu$GRBs however, the jet is buried in an envelope that is optically thick to high-energy protons. Thus, energy of protons that in LGRBs would have been released to the host galaxy as cosmic rays, is converted in large part to neutrinos via pp interactions. Thus, unlike LGRBs, $f_\pi \sim 1$ and the neutrino flux is rather insensitive the exact conditions in the jets. Instead it depends only on the energy that the jets deposit in accelerated protons. Thus, assuming that a large fraction of the LGRBs’ neutrinos are generated at radii $\lesssim 10^{13}$ cm, $\nu$GRBs are more efficient in producing ~100 TeV neutrinos by about two orders of magnitude, and possibly more (this is the product of the $\nu$GRB to LGRB rate ratio and $1/f_\pi$ in LGRBs).

2 This is similar to the scenario discussed by Murase & Ioka (2013) for ultra-long GRBs (another possibly distinctive type of GRBs), where the progenitors are assumed to be extended and $f_\pi \sim 1$ in shocks that take place during the jet propagation inside the progenitor.
As high-energy protons are accelerated within the ultra-relativistic narrowly collimated jets, the neutrino signal is narrowly beamed as well. Since the gamma ray emission from \( l/lGRBs \) is not highly beamed, most of observed bursts are not expected to be accompanied by a neutrino signal. Thus, \( l/lGRBs \) will contribute to the diffuse flux but they are not suitable for a targeted point-sources search, similar to the search conducted for LGRBs (Aartsen et al. 2014a). Can \( l/lGRBs \) be then the main source of the observed diffuse flux? Ahlers & Halzen (2014) find that the sources of the diffuse neutrino flux produce a total energy output of \( \sim 10^{43} \text{ erg Mpc}^{-3} \text{ yr}^{-1} \) in \( \sim 100 \text{ TeV} \) neutrinos and their volumetric rate, assuming transient sources, must be \( \gtrsim 10^{-8} \text{ Mpc}^{-3} \text{ yr}^{-1} \) (as inferred from the lack of neutrino clustering). Assuming that each \( l/lGRB \) harbor a relativistic jet with a typical energy of \( \sim 10^{51} \text{ erg} \) the total energy output in such jets is \( \sim 3 \times 10^{44} \text{ erg Mpc}^{-3} \text{ yr}^{-1} \). Thus, if \( \sim 10\% \) of this energy is converted to high-energy protons before the jet is choked (i.e., at radii \( \lesssim 10^{13} \text{ cm} \) then \( l/lGRBs \) are producing the observed diffuse flux. Assuming that the typical jet angle is \( \sim 10^\circ \) the rate of \( l/lGRBs \) for which the neutrino beam is pointed toward Earth is \( \sim 0.5 \times 10^{-8} \text{ Mpc}^{-3} \text{ yr}^{-1} \) consistent with the limit derived by Ahlers & Halzen (2014). Thus, \( l/lGRBs \) are certainly viable candidates for the origin of the observed extra-galactic neutrino flux!

Neutrinos from jets in \( l/lGRBs \) were discussed in the past by several authors (e.g., Murase et al. 2006; Gupta & Zhang 2007; Horiuchi & Ando 2008; Xiao & Dai 2014). All these authors assumed that the jet properties are directly related to the observed gamma ray emission, namely that the jets are of low power and wide opening angle. These conditions are very different than those considered here, where the jets, which are not directly related to the gamma ray emission, are similar to those of LGRBs.

In addition to the neutrino signal discussed above, which is generated before the shock breaks out, neutrinos are also expected to be generated by the external collisionless shock that is driven into the circum-burst medium following the shock breakout (Kashiyama et al. 2013). This signal is expected to be fainter than the pre-breakout one, since the external shock dissipates only a small fraction of the energy carried by \( M_{\text{ext}} \) at radii where neutrinos can be generated efficiently. However, post break-out neutrinos are not narrowly beamed and are expected to be accompanied by the gamma ray signal, enabling a targeted search for nearby \( l/lGRBs \) (Kashiyama et al. 2013).

Finally, if \( l/lGRBs \) harbor the same engine and relativistic jets as LGRBs then they produce the same GW signals (e.g., Kotake et al. 2012; Birnholz & Piran 2013). A difference is that while LGRBs are always observed close to the jet axis, the line of sight to \( l/lGRBs \) is typically away from that axis. The GW signal from the engine can be slightly stronger along the jet axis (up to a factor of 1.6 compared to an average line-of-sight observer), if its origin is quadrupole mass inhomogeneity in a rotating disk (Kochanek & Piran 1993). Other axisymmetric GW sources in the engine, such as mass motions and neutrino emission, vanish along the axis and are strong at the equator (Kotake et al. 2012). The signal from the jet acceleration is also anti-beamed and is strongest along the equator (Birnholz & Piran 2013). Thus, the off-axis viewing angle of typical \( l/lGRBs \) is probably an advantage for GW detection. The main advantage of \( l/lGRBs \) is their much higher rate. The volumetric rate of \( l/lGRBs \) is larger by about an order of magnitude than that of all LGRBs, including those that are unobservable since their gamma ray beam points away from the Earth. If only LGRBs that points toward Earth are considered then the \( l/lGRB \) rate is higher by almost three orders of magnitude. This is important since targeted GW search for GRBs (e.g., following a detection of gamma rays) is more sensitive than a blind search, increasing the detection volume by a factor of \( \sim 3 \) (Kochanek & Piran 1993). The various predicted GW signals from the engine and the jet are expected to be detectable by future gravitational wave detectors up to a distance of \( \sim 100 \text{ Mpc} \). The rate of LGRBs at that distance is too low to allow a reasonable probability for detection. However, about one \( l/lGRB \) take place every year within a distance of 100 Mpc, making it a promising GW source for future detectors.

7. CONCLUSIONS

This paper analyzes the first day optical/UV light curve of SN 2006aj/\( l/lGRB \) 060218 finding that its progenitor has a compact core engulfed by an extended low-mass material. When the information on this structure is combined with the high velocities inferred from the radio emitting material, it implies that the shock breakout form the extended material must produce a gamma ray signal that is consistent with the observed \( l/lGRB \) gamma ray emission. This indicates that the gamma rays in 2006aj/\( l/lGRB \) 060218 are generated by a mildly relativistic shock breakout and it strongly supports the suggestion that the origin of all \( l/lGRBs \)’ high energy emission is a shock breakout.

These results, which are directly based on the observations of SN 2006aj, naturally suggest a picture that unifies LGRBs and \( l/lGRBs \), explaining how two types of explosions that are so different in their gamma ray signature produce very similar SNe. In this picture \( l/lGRBs \) and \( l/lGRBs \) are two manifestations of a similar core collapse process that leads to a similar SN explosion mechanism and a similar GRB central engine, where the observational outcome depends only on the slight differences in the existence, or the lack of, a low-mass extended envelope. This model also provides a simple explanation to the peculiar velocity profile seen in SNe that are associated with \( l/lGRBs \). It also implies that \( l/lGRBs \) are more promising sources of high energy neutrinos and GWs than LGRBs. \( l/lGRBs \) are viable candidates as the source of the observed extra-galactic diffuse neutrino flux and are promising GW sources for the next generation GW detectors.

A final comment on the progenitor structure of SN 2006aj. While the SN light curve constrains \( M_{\text{ext}} \) and \( R_{\text{ext}} \) it does not strongly constrain its density profile. The only requirement is that most of the mass \( M_{\text{ext}} \) is concentrated near \( R_{\text{ext}} \) (Nakar & Piro 2014). This is consistent with any density profile \( \rho(r) \) where \( \rho r^3 \) increases with radius at \( r < R_{\text{ext}} \) and decreases at \( r > R_{\text{ext}} \). Thus, we cannot determine whether the inferred progenitor structure is in hydrostatic equilibrium or whether the extended material was thrown out to \( R_{\text{ext}} \) a short time before the explosion. The latter option may be more attractive given that no current stellar evolution model predicts a hydrostatic structure similar to that SN 2006aj for a fully H stripped star, while recently there are several lines of evidence that massive stars go through a strongly enhanced mass-loss episode a short time before they explode (Ofek et al. 2013, 2014; Gal-Yam et al. 2014; Margutti et al. 2014b; Svirski & Nakar 2014). Additionally, the very soft spectrum of the X-ray afterglow of
//GRB 060218 together with the very high intrinsic hydrogen absorption column density may support an extensive pre-explosion mass loss (Margutti et al. 2014a). Yet, another intriguing speculation is that the progenitor is affected by a binary, or maybe even by a binary merger (e.g., along similar lines to those suggested by Chevalier 2012), that put the extended material at place a short time before the explosion.

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APPENDIX A

THE POWER SOURCE OF THE FIRST OPTICAL PEAK

The analysis of the progenitor structure of SN 2006aj relies on the identification of the first optical/UV peak as a cooling envelope emission. Here this identification is justified by considering known and speculated emission power sources in SNe and GRBs. The conclusion is that while cooling envelope emission provides a natural explanation for the first peak (as discussed in length in Nakar & Piro 2014), all other sources are either ruled out or are highly unlikely.

Cooling envelope: the energy source of cooling envelope emission is the shock that crosses the star and any surrounding mass, if it exists, in regions where the diffusion time is longer than the expansion dynamical time. In these regions the internal energy deposited by the shock is trapped by the gas and it cools adiabatically during the gas expansion, hence the term “cooling envelope”. As the outflow expands its optical depth drop and so does the radiation diffusion time to the observer, while the expansion time grows. In regions where the two timescales become comparable the radiation escapes to the observer. As discussed in Nakar & Piro (2014), this source of emission provides a natural explanation for the first optical peak observed on a timescale of ∼day in case of a double peaked SNe. Important supporting evidence for that in the case of SN 2006aj is the very blue color of the first peak and the fact that the colors do not vary with time, which indicates that the band that we observe are most likely on the Rayleigh–Jeans part of a blackbody spectrum. This is expected for cooling envelope emission, where the optical depth at the source is high and the radiation has enough time to achieve thermal equilibrium before it escapes, even if the outflow is fast, after the ejecta expanded considerably (Nakar & Sari 2010).

Radioactive decay of 56Ni: this power source of energy, which dominates many SNe light curves, deposits energy at the known decay rate of 56Ni, first to 56Co and then to 56Fe. The observed luminosity form 56Ni is the energy deposited by radioactive decay in “exposed” regions, from where radiation can escape over a dynamical time. Since the total amount of mass in exposed regions depends on time and velocity, the evolution of luminosity generated by 56Ni for a given outflow is set by the fraction of 56Ni in that region (Piro & Nakar 2013). This sets, at any given time, a maximal luminosity that 56Ni can produce, which is the luminosity of an outflow that is composed purely of 56Ni. The exposed mass at the first peak is ~0.01 (v/0.2c)M⊙ implying that the maximal contribution of 56Ni to the luminosity at this time is ~1042 (v/0.2c) erg s⁻¹. This rules out 56Ni as the source of the first peak which show a luminosity >3 × 1044 erg s⁻¹.

Interaction (afterglow): another power source seen in some SNe is a continuous interaction with the circumstellar medium. In GRBs such interaction is the source of the afterglow. The difference between continuous interaction and cooling envelope emission is that in the former the shock takes place in a region with optical depth that allows for radiation to escape immediately over a dynamical timescale. Thus, if the first peak is generated by interaction then its luminosity is limited by the instantaneous strength of the interaction. Namely, the explosion ejecta must drive a strong shock into the circumstellar medium at least up to t ~ 10 hr, at which point either the interaction dies (e.g., due to a sharp drop in the circumstellar density) or the shock becomes radiatively inefficient. The radio emission at t = 1.89 day is presumably generated by such interaction and it shows that the interaction shock is propagating at a velocity close to the speed of light (Soderberg et al. 2006). The interaction at this point is much too weak to account for the optical emission at this epoch, but assuming that at t ~ 10 hr the interaction have been much stronger, could it then be the source of the optical/UV? Considering all the outcomes of the entire allowed phase space for interaction is beyond the scope of this paper, however several general considerations show that it is highly unlikely that interaction can produce the observed first optical/UV peak for two reasons—it predicts an optical/UV spectrum that is too red and an X-ray flux that is too bright compared to the observations.

As the interaction shock is mildly relativistic its radius at the first peak is r ~ 1015 cm. The circumstellar medium must be optically thin for Thomson scattering at this radius, otherwise the mildly relativistic shock breakout would have been taken place at ~1015 cm, resulting in a much brighter and longer signal in gamma rays then observed (Equation (3)). Emission from optically thin mildly relativistic shocks are seen in late stages of GRBs and in some SNe. In these cases the shock is collisionless and it generates strong magnetic fields and accelerates electrons to a power law distribution. As a result the dominant emission is synchrotron and the spectrum above the self absorption frequency (which is typically in the radio or mm bands) is a power-law that is spread over many orders of magnitude in frequency with a specific flux Fν ∝ να with α ~ −1. This is very different than the observed UV spectrum where α ~ 2, which requires the self-absorption frequency to be ≥1015 Hz. However, even the highest possible circumstellar density that is optically thin for Thomson scattering at ~1015 cm does not bring the synchrotron (or free–free) self-absorption frequency of a mildly relativistic shock into the UV. In addition, the synchrotron power law spectrum also predicts an X-ray luminosity that is comparable or larger than the UV luminosity, regardless of the location of the self-absorption frequency. In reality at the time of the first peak the X-ray luminosity is fainter than the UV by two orders of magnitude.

Continuous central engine activity: the last power source that is often considered in GRBs and sometimes also in SNe is a continuous energy supply by a central engine, possibly an accreting black hole or a long lived magnetar. The existence of such sources in SNe is still rather hypothetical, while in GRBs there is stronger evidence that the central engine can be active also on timescales of hour or days. Nevertheless, the optical emission is highly unlikely to be powered this way. The reason is that the bulk of the SN ejecta mass, ~2M⊙, lies between the center of the explosion and the observer. The photons observed in the first optical peak must be generated at larger radius than
that of the bulk of the ejecta. If the energy from the central engine is deposited first in the $\sim 2M_\odot$ ejecta it is converted to kinetic and thermal energy of the ejecta before radiated away after the ejecta optical depth drops, over timescale of weeks. Thus, similarly to LGRBs, the energy generated by the central engine must “penetrate” through the bulk of the mass before being dissipated to optical/UV photons. Again, like in LGRBs, this may be done if the engine continuously launches relativistic jets. However, based on GRB observations, the expected optical/UV/X-ray emission from relativistic jets suffers from the same problems of interaction emission. It usually show a power-law spectrum with $\alpha \ll 2$, which does not fit the observed optical/UV spectrum and the faint X-ray emission. More importantly, a relativistic jet must open a cavity in the SN ejecta inducing strong spherical asymmetry in the slow moving material, which is ruled out by the lack of polarization and by the spectral line profiles seen in the SN nebular phase (Mazzali et al. 2007).

**APPENDIX B**

**JET PROPAGATION IN THE CORE AND IN THE EXTENDED MATERIAL**

The general physics of a relativistic hydrodynamical jet that propagates in a surrounding medium is described at length in Bromberg et al. (2011). Here we provide a brief outline of this system, focusing on the time that the engine must work for the jet to penetrate through the core and through the extended material. A jet that propagates in surrounding media forms a forward-reverse shock structure at its head. The high pressure plasma in the jet head spills sideways continuously as the jet propagates forming a hot cocoon that engulfs the jet. This cocoon may or may not collimate the jet, depending on the jet and the external medium properties. Since energy is leaving the jet head into the cocoon continuously, the head propagation depends on a continuous supply of energy, which is injected into the head by the jet via the reverse shock. Thus, in order for the jet to propagate a given distance the engine that launches the jet must work for a duration that is long enough so a fresh jet material will continue to cross the reverse shock during the entire propagation. Thus, if the head propagates up to a distance $r$ at a velocity $\beta_h c$ the jet working time must be:

$$t_{\text{eng}}(r) \approx \frac{r}{c \beta_h}(1 - \beta_h)$$  \hspace{1cm} (5)

where the term $1 - \beta_h$ includes the relative velocity between the relativistic jet and the head. This term is $\approx 1$ for a Newtonian head, implying that the engine working time is simply the jet propagation time. However, if the head is relativistic then by the time that the engine stops working the head is at a distance $\approx c t_{\text{eng}}$ from the center and the last jet element that was launched by the engine will catch up with the head only after $t_{\text{eng}}/(1 - \beta_h)$. During that time the jet will continue to drive the head forward. Thus, the engine working time needed for a relativistic head to propagate a distance $r$ is much shorter than $r/c$.

The evolution of the jet is determined by finding the properties of the various components (e.g., head, cocoon, etc.) of that system. The propagation velocity of the head is set by the balance of the jet luminosity per unit area into the head and the ram pressure of the ambient medium. It is therefore useful to define a dimensionless parameter which is the ratio between the energy density of the jet and the rest-mass energy density of the ambient medium (Matzner 2003)

$$L = \frac{L_j}{\Sigma_j \rho c^3}$$  \hspace{1cm} (6)

where $L_j$ is the total jet luminosity, $\Sigma_j$ is the jet cross-section at the head, and $\rho$ is the ambient medium density at the head location. The propagation velocity of the jet head is:

$$\beta_h = \frac{1}{1 + L^{-1/2}}.$$  \hspace{1cm} (7)

Thus, the head is relativistic when $L \gg 1$ and Newtonian for $L \ll 1$. The collimation of the jet depends also on the half opening angle at which the jet is launched, $\theta_0$, where for $L < \theta_0^{-4/3}$ the jet is collimated by the cocoon pressure. The jet collimation affects the value of $\Sigma_j$ and thus also the value of $L$.

For a given set of parameters Bromberg et al. (2011) obtain

$$\tilde{L} = \begin{cases} \frac{L_j}{\rho \beta_0^2 \zeta^2} \left( \frac{\rho_0 c^3}{\rho c^3} \right)^{2/5} & L < \theta_0^{-4/3} \text{ (Collimated)} \\ \frac{L_j}{\rho_0 c^3} & L > \theta_0^{-4/3} \text{ (Uncollimated)} \end{cases}$$  \hspace{1cm} (8)

where $t$ is the time since the jet launching started and $\rho$ is the external density near the jet head location. Equations (7) and (8) together can be solved to find the jet location at time $t$.

The isotropic equivalent luminosity of a typical GRB jet is $L_{\text{iso}} \sim 10^{51}$ erg s$^{-1}$ and its opening angle is $\theta_0 \sim 10^\circ$. The beaming corrected jet luminosity is then $L_j = L_{\text{iso}} \theta_0^2/2$. In a massive ($M_{\text{core}} > M_\odot$) and compact ($R_{\text{core}} \sim 10^{11}$ cm) core the density is high and $\tilde{L} \lesssim 1$, resulting in a Newtonian (or at most a mildly relativistic) collimated jet. Thus, the engine working time must be comparable to the time needed for the jet to cross the core:

$$t_{\text{eng, core}} \sim \frac{L_{\text{iso}}}{10^{51} \text{ erg s}^{-1}} \left( \frac{\theta_0}{10 \text{ deg}} \right)^{-1/3} \left( \frac{M_{\text{core}}}{10 M_\odot} \right)^{1/3} \frac{R_{\text{core}}}{10^{11} \text{ cm}} \text{ s.}$$  \hspace{1cm} (9)

Here we used the approximation $\beta_h \approx L^{1/2}$ which is appropriate for Newtonian heads.

The density of the extended material is much lower than in the core. As a result, for a typical GRB jet $\tilde{L} > \theta_0^{-4/3}$, resulting in an uncollimated relativistic jet. The minimal engine working time for a successful jet penetration is shorter than the extended material light crossing time, but it is still much longer than the time it takes the jet to cross the core:

$$t_{\text{eng, ext}} \sim 150 \left( \frac{L_{\text{iso}}}{10^{51} \text{ erg s}^{-1}} \right)^{-1/2} \left( \frac{M_{\text{ext}}}{10^{-2} M_\odot} \right)^{1/2} \frac{R_{\text{ext}}}{3 \times 10^{13} \text{ cm}} \frac{1}{s.}$$  \hspace{1cm} (10)
Where we used the approximation for a relativistic head
\[ \gamma_h \approx \frac{L_{14}^2}{\sqrt{2}} \] where \( \gamma_h \) is the head Lorentz factor.

REFERENCES

Aartsen, M. G., Ackermann, M., Adams, J., et al. 2014a, PhRvL, 113, 101101
Aartsen, M. G., Ackermann, M., Adams, J., et al. 2014b, PhRvD, 85, 1401
Ahlers, M., & Halzen, F. 2014, PhRvD, 90, 043005
Ando, S., et al. 2013, RvMP, 85, 1401
Barniol Duran, R., Nakar, E., Piran, T., & Sari, R. 2014, arXiv:1407.4475
Bersten, M. C., Benvenuto, O. G., Nomoto, K., et al. 2012, ApJ, 757, 31
Birnholtz, O., & Piran, T. 2013, PhRvD, 87, 123007
Bromberg, O., Nakar, E., & Piran, T. 2011, ApJL, 739, L55
Bromberg, O., Nakar, E., Piran, T., & Sari, R. 2011, ApJ, 740, 100
Budnik, R., Katz, B., MacFadyen, A., & Waxman, E. 2008, ApJ, 673, 928
Campana, S., Mangano, V., Blustin, A. J., et al. 2006, Natur, 442, 1008
Chevalier, R. A. 2012, ApJL, 752, L2
Gal-Yam, A., Arcavi, I., Ofek, E. O., et al. 2014, Natur, 509, 471
Gupta, N., & Zhang, B. 2007, APh, 27, 386
Hoflich, P., Langer, N., & Duschinger, M. 1993, A&A, 275, L29
Horiuchi, S., & Ando, S. 2008, PhRvD, 77, 063007
Hümmer, S., Baerwald, P., & Winter, W. 2012, PhRvL, 108, 231101
Kaneko, Y., Ramírez-Ruiz, E., Granot, J., et al. 2007, ApJ, 654, 385
Kashiyama, K., Murase, K., Horiuchi, S., Gao, S., & Mészáros, P. 2013, ApJL, 769, L6
Katz, B., Budnik, R., & Waxman, E. 2010, ApJ, 716, 781
Kochanek, C. S., & Piran, T. 1993, ApJL, 417, L17
Kotake, K., Takiwaki, T., & Harikae, S. 2012, ApJ, 755, 84
Kulkarni, S. R., Frail, D. A., Wieringa, M. H., et al. 1998, Natur, 395, 663
Levinson, A., & Bromberg, O. 2008, PhRvL, 100, 131101
Li, L. 2007, MNRAS, 375, 240
Liu, R. Y., Wang, X. Y., & Dai, Z. G. 2011, MNRAS, 418, 1382
Margutti, R., Guidorzi, C., Lazzati, D., et al. 2015, ApJ, 85, 159
Margutti, R., et al. 2014a, ApJ, 780, 21
Margutti, R., et al. 2014b, ApJ, 797, 107
Matzner, C. D. 2003, MNRAS, 345, 575
Matzner, C. D., & McKee, C. F. 1999, ApJ, 510, 379
Mazzali, P. A., Deng, J., Nomoto, K., et al. 2006, Natur, 442, 1018
Mazzali, P. A., Foley, R. J., Deng, J., et al. 2007, ApJ, 661, 892
Melandri, A., Pian, E., D’Elia, V., et al. 2014, A&A, 567, A29
Mirabal, N., Halpern, J. P., An, D., Thorsten, J. R., & Temdrup, D. M. 2006, ApJL, 643, L99
Mizuta, A., & Aloy, M. A. 2009, ApJ, 699, 1261
Modjaz, M., Stanek, K. Z., Garnavich, P. M., et al. 2006, ApJL, 645, L21
Morsony, B. J., Lazzati, D., & Begelman, M. C. 2007, ApJ, 665, 569
Murase, K., & Ioka, K. 2013, PhRvL, 111, 121102
Murase, K., Ioka, K., Nagataki, S., & Nakamura, T. 2006, ApJL, 651, L5
Nakar, E., & Piro, A. L. 2014, ApJ, 788, 193
Nakar, E., & Sari, R. 2010, ApJL, 725, 904
Nakar, E., & Sari, R. 2012, ApJ, 747, 88
Ofek, E. O., Sullivan, M., Cenko, S. B., et al. 2013, Natur, 494, 65
Ofek, E. O., Sullivan, M., Shaviv, N. J., et al. 2014, ApJL, 789, 104
Pian, E., Mazzali, P. A., Masetti, N., et al. 2006, Natur, 442, 1011
Piran, T. 2004, RvMP, 76, 1143
Piro, A. L., & Nakar, E. 2013, ApJL, 769, 67
Sakurai, A. 1960, CPAM, 13, 353
Soderberg, A. M., et al. 2006, Natur, 442, 1014
Sollerman, J., Jaunsen, A. O., Fynbo, J. P. U., et al. 2006, A&A, 454, 503
Svirski, G., & Nakar, E. 2014, ApJL, 788, L14
Tan, J. C., Matzner, C. D., & McKee, C. F. 2001, ApJ, 551, 946
Simon, V., Pizzichini, G., & Hudec. R. 2010, A&A, 523, A56
Wanderman, D., & Piran, T. 2010, MNRAS, 406, 1944
Waxman, E., & Bahcall, J. 1997, PhRvL, 78, 2292
Waxman, E., Meszáros, P., & Campaña, S. 2007, ApJL, 667, 351
Woosley, S. E., & Bloom, J. S. 2006, ARA&A, 44, 507
Xiao, D., & Dai, Z. G. 2014, ApJL, 790, 59
Zhang, W., Woosley, S. E., & MacFadyen, A. I. 2003, ApJ, 586, 356