SN2015L: a rotating black hole losing its charm?

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ABSTRACT

The super-luminous event SN2015L shows a total energy $E_{rad} \simeq 1.1 \times 10^{52}$ erg in black body radiation on par with its kinetic energy in ejecta, that defies a nuclear origin and puts magnetars at the limit of their rotational energies even at ideal efficiencies. By an ample energy reservoir in angular momentum, E_{rad} can be accounted for by outflows from rotating black holes at canonical efficiences. Their theoretical light curve features a late-time plateau with a change in magnitude $\Delta m \simeq 1.15$ post-peak that accurately captures SN2015L. SN2015L appears to be the first genuine "failed GRB" in successfully dissipating a black hole outflow mostly into heat accompanied by a lesser amount in kinetic energy.

1. Introduction

With a total energy $E_{rad} \simeq 1.1 \times 10^{52}$ erg in black body (BB) radiation, SN2015L (Dong et al. 2016) represents an extreme case of super-luminous class of supernovae (Gal-Yam et al. 2012; Quimby et al. 2013), whose light curve is not powered by nuclear decay of ^{56}Ni, common to convential core-collapse supernovae. Instead, SN2015L turns convention on its head with E_{rad} at least as large as the kinetic energy E_k in the expanding envelope,

$$E_{rad} \sim E_k, \tag{1}$$

that points to a far more efficient process such as dissipation into heat of baryon-poor magnetic winds from a central engine. This process may be closely related to the explosion mechanism itself when powered by angular momentum extraction of a compact inner engine (e.g. Bisnovatyi-Kogan 1970).

E_{rad} of SN2015L then requires an energy budget that is close to or even exceeds the maximal rotational energy $E_c \simeq 3\times10^{52}$ of a neutron star at extremely optimistic efficiencies (e.g. van Putten et al. 2011; Dong et al. 2016), leaving minor energies in E_k and turbulent magneto-hydrodynamic motion. Alternatively, stellar mass black holes, widely considered in models of extreme events associated with long gamma-ray bursts (Woosley & Bloom 2006; Fryer et al. 2015), can have rotational energies larger by some orders of magnitude. A relatively minor fraction suffices for E_{rad}, while a major fraction is radiated unseen in MeV neutrinos and gravitational waves from high density matter at the Inner Most Stable Circular Orbit (ISCO) defined by the Kerr metric (Kerr 1963) and setting the evolution of black hole mass and spin (van Putten 1999; van Putten & Levinson 2003). The latter may be probed by the gravitational wave observatories LIGO-Virgo and KAGRA (Abramovici et al. 1992; Acernese et al. 2006, 2007; Somiya et al. 2012).

SN2015's light curve shows a remarkably slow exponential decay post-peak followed by a plateau, seen neither in conventional core-collapse supernovae (e.g. Bufano et al. 2012) nor in broad lined SNe Ic (Turatto et al. 1990). At the exceptional luminiosity of SN2015L extending over several months, the Kelvin-Helmholtz time scale of the envelope is negligible. Consequently, the light curve of the observed BB radiation closely tracks the luminosity of such wind, providing a real-time signature of the "light bulb" within: the activity of the putative inner engine. While $E_{rad} \gtrsim E_c$ does not rule out a magnetar, the algebraic time decay $\propto (1+t/t_s)^{-2}$ of its light curve with characteristic spindown time t_s is woefully at odds with aforementioned unconventional temporal behavior.

Here, identify the light curve of SN2015L with a newly formed black hole, releasing its angular momentum in a baryon poor outflow. At an angular velocity $\Omega_H = (1/2M)\tan(\lambda/2)$ $(-\pi/2 \leq \sin\lambda < \pi/2)$, a $10M_\odot$ Kerr black hole (Kerr 1963) possesses a rotational energy

$$E_{rot} \simeq 6\times10^{54}\,\mathrm{erg}\left[\frac{\sin\left(\frac{\lambda}{4}\right)}{\sin\left(\frac{\pi}{4}\right)}\right]^2 \tag{2}$$

that amply accounts for E_{rad} by dissipation of a baryon-poor outflow into heat in the remnant stellar envelope at canonical efficiencies, possibly accompanied by further emissions unseen in MeV neutrinos and gravitational waves (van Putten & Levinson 2003).

2. SN2015L light curve and plateau

We consider the post-peak light curve of SN2015L marked by slow decay to an extended plateau, attributed to a relativistic baryon-poor wind from a newly formed black hole with initially rapid spin. The decay represents a relaxation of spacetime to that of a slowly spinning black hole with essentially exponential decay of Ω_H to an equilibrium $\Omega_H \simeq \Omega_{ISCO}$ to that of matter at the Inner Most Circular Stable Orbit (ISCO). The magnitude of this wind luminosity in the late-time plateau is about one magnitude higher than that at peak luminosity (van Putten 2016).

The original onset towards peak luminosity may be associated with hyper-accretion leading to a near-extremal black hole (van Putten 2015).

Fig. 1 show a match of the theoretical light curve derived from dissipation of a baryon poor outflow from a black hole losing angular momentum to the observed light curve of SN2015L, following a normalization of the peak luminosity and a scaling in duration. A theoretical change in magnitude $\Delta m \simeq 1.15$ in transition to the plateau from peak obtains by numerical integration of the equations of black hole evolution governed by angular momentum loss to high density matter at the ISCO (van Putten 2016). This prediction is in remarkable agreement with the observed change of about $\Delta m = 1.2$.

The plateau in the light curve of SN2015L is hereby a key feature in distinguishing inner engines harboring rotating black holes or magnetars, since the latter allow spin down all the way to essentially zero angular velocity even in isolation.

Similar evidence for black hole inner engines derives from analysis of light curves of long gamma-ray bursts (LGRBs). Low variability light curves of long gamma-ray bursts, for instance, show so-called Fast Rise Exponential Decay (FRED) light curves (Reichert et al. 2001), that closely match the proposed light curve of baryon-poor black hole winds (van Putten & Gupta 2009). Viewed as ab initio light curves underlying typical LGRBs, the same remains in normalized light curves obtained by averaging (van Putten & Gupta 2009).

3. Conclusions and outlook

With (1), SN2015L presents a major departure from existing super-luminous events that provides strong evidence for an origin in dissipation in baryon-poor outflows from a rapidly rotating compact object. SN2015L sets itself apart also by featuring a late-time plateau. A plateau is expected from outflows produced by rotating black holes but not magnetars. A remarkably accurate quantitative agreement is found in the change in magnitude post-peak in a model of black hole evolution dominated by angular momentum loss to surrounding high density matter at the ISCO.

It appears that SN2015L is the first genuine “failed GRB,” in delivering on wind power but failing to produce a successful break-out of an ultra-relativistic jet through the stellar envelope. Further confirmation may derive from a non-detection of a late-time radio-afterglow.

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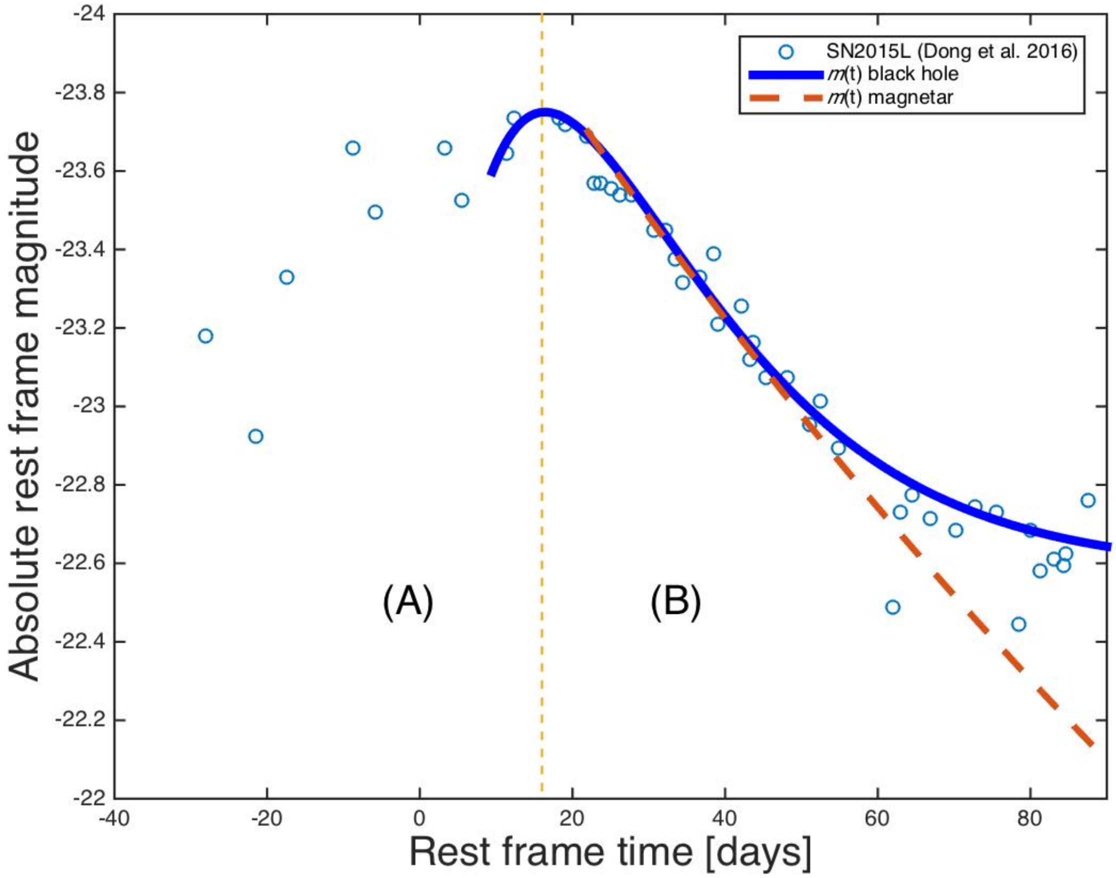

Fig. 1.— Following the formation of a central engine (A), shown is a theoretical light curve fits $m(t)$ of baryon-poor outflows from black holes and magnetars to the restframe absolute magnitude light curve of SN2015L by scaling of peak magnitude and duration (B). For outflows from black holes, the theoretical increase in magnitude $m_{pl} - m_p = 1.15$ agrees with the data. Prior to peak luminosity, the onset is associated with the formation of the central engine, here a near-extremal black hole during a phase of core-collapse and hyperaccretion.