Double-humped Super-luminous Supernovae

D. Leahy, R. Ouyed
University of Calgary, 2500 University Dr NW, Calgary, AB, T2N1N4, Canada

Super-luminous supernova (SLSN) are supernovae showing extreme properties in their light-curves: high peak luminosities (more than 10 times brighter than bright SN Ia), and long durations. Several mechanisms have been proposed for SLSN, such as pair instability SN of a massive progenitor, interaction of the ejecta with a massive circumstellar shell, and the dual-shock quark nova (dsQN) model. The dual-shock quark nova model is unique in that it predicts a normal SN event will be seen ∼10 days prior to the main SLSN event. The dsQN model is described here and shown that it is consistent with the light curve of the one currently known double-humped SLSN, 2006oz.

1. SUPER-LUMINOUS SUPERNOVAE

Super-luminous supernovae (SLSNe) have been discovered in significant numbers over the past decade. They have high peak brightness, with peak absolute magnitudes of -21 or brighter, and usually have long durations (up to 1 year) compared to normal type I or type II SN. Mechanisms proposed to produce such high luminosities for so long include: pair instability SN (which requires a massive progenitor, $> 100M_\odot$); the interaction of fast moving SN ejecta ($\sim 10M_\odot$) with a massive circumstellar shell (also with $\sim 10M_\odot$); and the dual-shock quark nova (dsQN) model. The quark nova (QN) was proposed as an explanation for SN 2006gy and other SLSNe including SN 2005ap Leahy & Ouyed [2008]. In Ouyed et al. [2009a], we emphasize that the lightcurve of the preceding SN gives a double-humped lightcurve.

In the dsQN model (see section 2 below for details), a normal core-collapse SN explodes to produce a high-mass neutron star. The neutron star converts to a quark star, with a delay of several days, in a violent explosion called a quark nova(QN). The shock produced by the QN then reheats the SN ejecta, which can radiate at high levels for extended periods of time- because the SN ejecta has already expanded so that adiabatic expansion losses are much slower than for the case of a normal SN. It is seen that the dual-shock quark nova model has unique signature: it predicts that a normal core-collapse SN event will be seen several days prior to the main SLSN event.

There is currently one known double-humped SLSN, namely 2006oz Leloudas et al. [2012]. Supernova (SN) 2006oz is a newly-recognized member of the class of H-poor, superluminous supernovae Quimby et al. [2011]. The bolometric light curve shows a precursor event with a duration between 6-10 days in the rest-frame, followed by a dip, after which the luminosity begins to rise. The subsequent rise has previously been fit using three different models: (i) input from radioactive decay; (ii) a magnetar spin-down model; (iii) a circum-stellar medium (CSM) interaction. The Nickel decay model has problems because it requires an unreasonably large amount ($10.8M_\odot$) of ^{56}Ni with a total ejecta mass of $14.4M_\odot$. Another problem is that the SN was not detected 9 months later, which is inconsistent with the standard decay curve for ^{60}Co. The magnetar and CSM lightcurve models were shown in Figure 7 of Leloudas et al. [2012]. None of these three models accounts for the precursor event. Yet the dsQN model for SLSN, predicts the existence of a precursor SN Ouyed et al. [2009a] very similar to the observed precursor of SN2006oz.

To show the precursor of SN2006oz is plausibly a normal SN, we estimate its energy be $\sim 10^{49}$ erg $\times$ $t_{\rm pre,10}$ where $t_{\rm pre,10}$ is the duration of the precursor in units of 10 days (limited by the observations from about 7 days to 12 days). This energy is typical of brighter Type-II SNe (e.g. Young [2004]).

In this paper we describe the dual-shock QN (dsQN) model, including the precursor SN. Then we show that the main peak and the precursor of SN2006oz are self-consistently fit by the dsQN model, and conclude with remarks including future work to be done.

2. THE DUAL-SHOCK QUARK NOVA (dsQN) MODEL

A quark nova (QN) was proposed as an alternative explanation for SN 2006gy Leahy & Ouyed [2008], Ouyed et al. [2009a]. A QN is expected to occur when the core density of a neutron star reaches the quark deconfinement density and triggers a violent Ouyed et al. [2002] conversion to the more stable strange quark matter Itoh [1970], Bodmer [1971], Witten [1984]. During the spin-down evolution of the neutron star, accompanied by increasing central density, a detonative Niebergal et al. [2010], Ouyed et al. [2011] phase transition to up-down-strange triplets would result in ejection of the outer heavy element-rich and neutron-rich layers of the neutron star at ultra-relativistic velocities Keranen et al. [2005], Ouyed & Leahy [2009] (in Ouyed & Leahy [2009], see the first panel of Fig. 2). Follow-up studies of neutrino and photon emission processes during the QN Vogt et al.

[2004], Ouyed et al. [2009b] have shown that these outermost layers (of $\sim 10^{-4}$-$10^{-3} M_{\odot}$ in mass) can be ejected with up to 10^{53} erg in kinetic energy. Nucleo-synthesis simulations of the evolution of the neutron-rich QN ejecta were found to produce primarily heavy elements with mass number, A > 130 Jaikumar et al. [2007].

If the time delay($t_{\rm delay}$) between SN and QN explosions is too long the SN ejecta will have dissipated such that the QN essentially erupts in isolation. However, when $t_{\rm delay}$ is on the order of days to weeks a violent collision occurs reheating the extended SN ejecta Leahy & Ouyed [2008], Ouyed et al. [2009a]. The brilliant radiance of the re-shocked SN ejecta fades as the photosphere recedes, eventually revealing a mixture of the inner SN ejecta and the QN ejecta material.

3. A PLAUSIBLE CANDIDATE DOUBLE-HUMPED dsQN EVENT: SN2006oz

SN2006oz is the first known double-humped SLSN event Leloudas et al. [2012]. Ouyed & Leahy [2012] study this event is some detail. Here we use SN2006oz as an example of double-humped SNSNe, and argue that, in the dsQN model, we expect to see other similar examples in future.

Figure 1 (from Ouyed & Leahy [2012])) shows the observed SN2006oz light curve using the data from Leloudas et al. [2012]. The g-band data is used, which has the best time coverage and smallest errors for most times. Time is in days at the source using the known redshift ($z = 0.376$). Apparent g-band magnitudes were converted to absolute g-band magnitudes using the corresponding luminosity distance for the standard model Wright [2006]. The suggested extinction correction (B-V) from Leloudas et al. [2012] was included, even though it was small. The dsQN model is also shown in Fig. 1. For the SN lightcurve (the first hump), we use an observed light curve: the light curve of SN1999em from Bersten& Hamuy [2009] which has good time coverage in the first 50 days. Bersten et al. [2011] fitted hydrodynamic models to SN1999em and derived a progenitor mass of $19 M_{\odot}$ which is similar in mass to the SN progenitor we used in our QN model. Other parameters for the SN1999em model were progenitor radius of $800 R_{\odot}$, explosion energy of 1.25×10^{51} erg and ^{56}Ni mass of $0.056 M_{\odot}$. We scaled the bolometric magnitude by $+2$ to represent a more energetic SN, which is reasonable since the range in brightness of Type II SNe varies considerably with many models giving brighter SN than 1993em (e.g. Young [2004]).

In the QN model the progenitor initial mass is in the range of 20-40$M_{\odot}$ (see Leahy & Ouyed [2008], Ouyed et al. [2009b], Ouyed et al. [2010]) to create a massive neutron star with core density near the instability to convert to quark matter Niebergal et al. [2010]. This motivates our choice of SN ejected mass of $20 M_{\odot}$. Best fits from our previous studies of SLSNe yielded time delays of ~ 10 days which motivates the time delays that we explored. For SN2006oz the shown fit (see Figure 1) uses $t_{\rm delay} = 6.5$ days, $v_{\rm QN} = 5000$ km s^{-1} and a preceding SN ejecta with an average velocity of $v_{\rm SN} \simeq 1900$ km s^{-1}. The combined light from the SN and from the QN-reheated SN ejecta give a reasonable fit to the observations with a self-consistent model.

4. COMMENTS

Leloudas et al. [2012] notes the intriguing possibility of an intrinsic precursor event in SN 2005ap-like objects. In the dsQN model, there must be a normal SN ($20 <$ Mbol < 15) preceding the SLSN (if the delay is long enough, $>\sim 10$ days) which should be detectable for nearby SN 2005ap-like explosions. For short delays, the normal SN lightcurve would overlap with the brighter dsQN lightcurve and not give a distinct hump.

SN 2005ap-like events are rare: they occur at a rate of less than one in 10^4 core-collapse SNe Quimby et al. [2011]. dsQNe are also expected to be rare events: the QNe rate is estimated to be $\sim$ one in 1000 core-collapse events with one tenth of them having time delays in the appropriate range to produce dsQNe (tdelay $\sim$ 5-30 days (Staff et al. [2006], Jaikumar et al. [2007], Leahy & Ouyed [2008], Leahy & Ouyed [2009], Ouyed et al. [2009a]). These two order of magnitude estimates of dsQN events and SN 2005ap-like events are consistent with eachother.

We note that the dsQN model applies to both H-rich and H-poor SLSNe, but these occur at similar rates. For both cases, the QN shock reheats the SN envelope to high temperature, so H-poor/H-rich progenitors would give H poor/ H-rich spectra. Because of mass-loss dependency on metallicity, we expect H poor SLSNe to occur in higher-metallicity environments. Low-metallicity progenitors would more likely be H-rich and should in principle have more massive envelopes.

We expect a number of SLSNe to have a double-humped character, as predicted by the dsQN model. The first hump is much fainter and has the brightness of a normal core-collapse SN, but should be observable in relatively nearby SLSNe. It is an for the dsQN model to find additional double-humped SLSNe beyond SN2006oz. We can model the precursor lightcurves to learn about the progenitors of SLSNe and of dsQN. The precursor SN is also a clear and unique signature of the dsQN model. Other properties predicted by the dsQN model include: the presence of

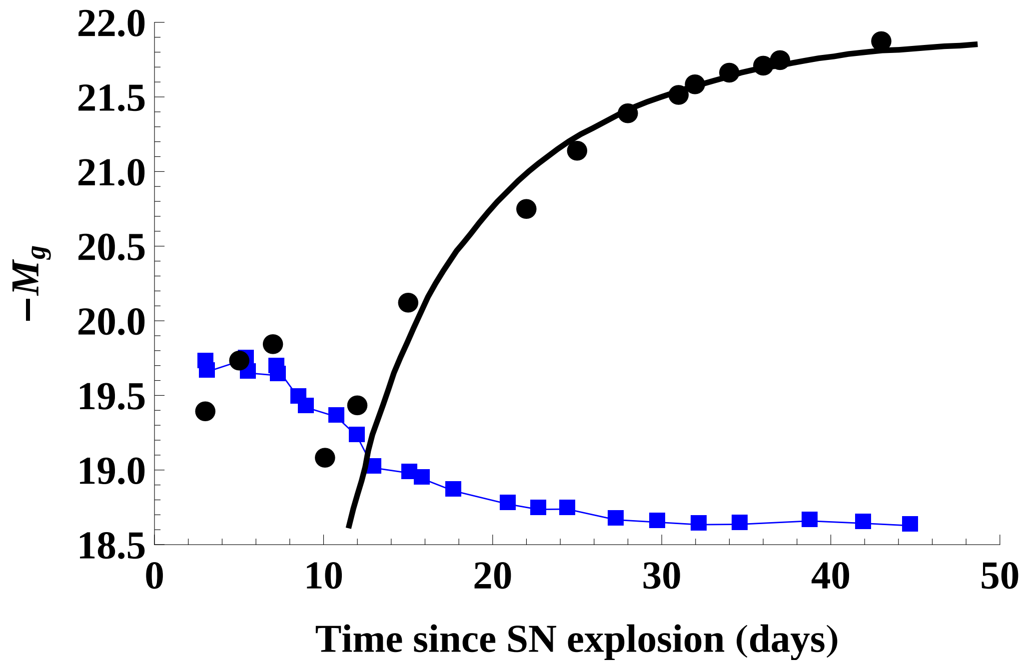

Figure 1: (reproduced from Ouyed & Leahy [2012]) SN2006oz r-band lightcurve (solid circles; upper limits shown as triangles). The dsQN model is calculated for $M_{\rm ejecta} = 20 M_{\odot}$ and $(t_{\rm delay}) = 6.5$ days.

heavy elements Jaikumar et al. [2007], and of spallation nuclei produced in the collision between the fast-moving QN ejecta and the inner parts of the SN ejecta Ouyed et al. [2011].

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