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The peculiar case of the "double-humped" super-luminous supernova SN 2006oz

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Abstract SN 2006oz is a super-luminous supernova with a mysterious bright precursor that has resisted explanation in standard models. However, such a precursor has been predicted in the dual-shock quark nova model of super-luminous supernovae – the precursor is the supernova event while the main light curve of the super-luminous supernova is powered by the Quark-Nova (explosive transition of the neutron star to a quark star). As the supernova is fading, the Quark-Nova re-energizes the supernova ejecta, producing a "double-humped" light curve. We show that the quark nova model successfully reproduces the observed light curve of SN 2006oz.

Key words: supernovae: general — supernovae: individual (SN 2006oz)

1 INTRODUCTION

The discovery of super-luminous supernovae (SLSNe) has challenged traditional models of core-collapse supernovae. SLSNe can be very bright (with peak absolute magnitude of -21 or higher in optical) and with long duration (exceeding hundreds of days). These include hydrogen-rich and hydrogen-poor events (Quimby et al. 2011). A variety of extreme models has been suggested to explain events in both classes. For example, for the hydrogen-rich SN 2006gy, Woosley et al. (2007) proposed a pulsational pair-instability supernova event; Smith et al. (2007) proposed a massive shell collision; and Leahy & Ouyed (2008) introduced the dual-shock quark-nova (hereafter, dsQN) model. However, later studies (Agnoletto et al. 2009) found that somewhat less extreme events could still reproduce the data: an explosion of a $\sim 30\ M_{\odot}$ star producing $\sim 3\ M_{\odot}$ of ^{56}Ni and ejecting $\sim 10\ M_{\odot}$ of material which collides violently with $\sim 10\ M_{\odot}$ of circumstellar material. In the hydrogen-poor class, one very rare event is SN 2007bi (Gal-Yam et al. 2009), which is only explainable as a pair-instability supernova (PISN) with a large mass of ^{56}Ni ($\sim 7\ M_{\odot}$) and with $\sim 100\ M_{\odot}$ of ejecta from a massive helium core explosion. Models for different events involve very different amounts of ^{56}Ni production. There is probably a genuine difference in explosion mechanisms for different events and some may require novel explanations.

Supernova (SN) 2006oz (Leloudas et al. 2012) is a newly-recognized member of the class of H-poor, super-luminous supernovae (i.e. SN 2005ap-like; Quimby et al. 2011). The bolometric light curve shows a precursor "plateau" with a duration between 6–10 d in the rest-frame and it is followed by a dip, after which the luminosity begins to rise. This subsequent rise was fit using three different models (see Chatzopoulos et al. 2012): (i) input from radioactive decay; (ii) magnetar spin-down model; (iii) interaction with circumstellar matter (CSM). The nickel decay model is least likely since it requires unreasonable amounts (10.8 $M_{\odot}$) of ^{56}Ni together with a total ejecta mass of only

14.4 $M_{\odot}$. In addition, the SN was not detected nine months later, which is inconsistent with the standard decay curve for ^{60}Co. The magnetar and CSM models present an approximate fit to the data (see fig. 7 in Leloudas et al. 2012). In general, to explain SN 2005ap-like objects (Chomiuk et al. 2011) the suggested models require rather extreme additional conditions. The magnetar model requires initial spin periods near break-up (1–2 ms). CSM interaction models require expelling several solar masses of H-poor material in the few years before the explosion, but this has never been observed from Wolf-Rayet stars (see Chomiuk et al. 2011 for details).

Existing models for the precursor (Dessart et al. 2011) are too dim to explain it. The only explanation offered by Leloudas et al. (2012) was a recombination wave in the oxygen around the progenitor star, with no physical cause suggested for the wave. None of the above models can account for the precursor. This begs for alternatives which can self-consistently explain the precursor and the main peak of SN 2006oz.

We estimate the energy in the precursor to 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 d (limited by observations from about 7d to 12 d). This energy is typical of brighter Type-II SNe (e.g. Young 2004) suggesting that the precursor could in fact be the SN explosion proper. This would require the main peak to have a separate physical origin. The quark nova (QN) was proposed as an alternative explanation for SN 2006gy and other SLSNe including SN 2005ap (Leahy & Ouyed 2008). In Ouyed et al. (2009a), we emphasize the lightcurve of the preceding SN, which yields a “double-humped” lightcurve in the dsQN model. The lightcurve of SN 2006oz has just this expected shape.

In this paper, we focus on studying the lightcurve of SN 2006oz in the context of our model: the dsQN model. The paper is organized as follows: in Section 2 we give a brief review of the dsQN model. In Section 3 we show that the main peak and the precursor of SN 2006oz are self-consistently fit by the dsQN. We briefly conclude in Section 4.

2 OUR MODEL

A QN is expected to occur when the core density of a massive neutron star (NS; $M_{\rm NS} > 1.6\ M_{\odot}$; Staff et al. 2006) reaches quark de-confinement density and triggers a violent (Ouyed et al. 2002) conversion to the more stable strange quark matter (Itoh 1970; Bodmer 1971; Witten 1984). The novel proposition was made that during the spin-down evolution of the NS, a detonative (Ouyed et al. 2002; Niebergal et al. 2010) phase transition to up-down-strange triplets would eject the outer layers of the NS at ultra-relativistic velocities (Keränen et al. 2005; Ouyed & Leahy 2009). Studies of neutrino and photon emission processes during the QN (Vogt et al. 2004; Ouyed et al. 2005) have shown that these outermost layers (with $\sim 10^{-4}$–$10^{-3} M_{\odot}$ in mass) can be ejected with up to 10^{53} erg in kinetic energy.

If the time delay ($t_{\rm delay}$) between SN and QN explosions exceeds months, 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, resulting in a dsQN (Leahy & Ouyed 2008; Ouyed et al. 2009a). The emission from the re-shocked SN ejecta declines as the photosphere recedes, eventually revealing a mixture of the SN and QN material with unique chemical signatures (Jaikumar et al. 2007; Ouyed et al. 2009a; Ouyed et al. 2012; Ouyed et al. 2011).

The basic physical processes involved in our model are: (i) an SN explosion at time $t = 0$ producing homologously expanding ejecta with the outermost velocity at $v_{\rm SN}$; (ii) a QN explosion at time $t_{\rm delay}$ which launches a shock at velocity $v_{\rm QN}$ into the preceding SN ejecta. This second shock reheats the SN ejecta to $T_{\rm QN}$; (iii) the QN shock breaks out from the SN ejecta at time $t_{\rm delay} + t_{\rm prop}$, where $t_{\rm prop}$ is the time for the QN shock to propagate through the SN ejecta. The reheated SN ejecta expands while radiating and undergoing adiabatic expansion losses. We approximate the evolution of the photosphere using photon diffusion in a medium where pure Thompson scattering occurs (see Leahy & Ouyed 2008). A key feature of this model is that the shock reheating occurs at large radius (because of the time delay), so that standard adiabatic losses inherent to SN ejecta are far smaller. In effect, the SN provides the material at large radius and the QN re-energizes it, causing the large luminosity compared to a normal SN.

3 APPLICATION TO SN 2006OZ

Figure 1 shows the observed SN 2006oz light curve from Leloudas et al.(2012; their table 3). We use the g-band data which have the best time coverage and also lowest errors for most times. The data are plotted in days at the source using the measured redshift of $z \sim 0.376$. We converted apparent g-band magnitudes to absolute g-band magnitudes using the corresponding luminosity distance for the standard model (Wright 2006). We converted the suggested extinction correction $(B-V)$ from Leloudas et al. (2012) to $(g-V)$ and included it, even though it was small. The dsQN light curve was computed as follows: The model produces an emitted spectrum at each epoch. We assume that the photosphere radiates like a blackbody (caveat: this is an approximation to a more realistic spectrum) at the temperature of the gas located at the photospheric radius. The photospheric radius is calculated using the diffusion approximation, including the losses due to blackbody radiation. This spectrum is then convolved with a g-band filter to obtain a g-band luminosity which is then converted to an absolute magnitude at each epoch. Specifically, luminosity in the g-band model was calculated using the approximation $\int_{\lambda_1}^{\lambda_2} g(\lambda) L_\lambda d\lambda / \int_{\lambda_1}^{\lambda_2} g(\lambda) d\lambda \simeq L_{\lambda_0} \delta\lambda$ with $L_\lambda = F_\lambda 4\pi R_{\rm ph}^2$ where F_λ is the model photospheric flux and $R_{\rm ph}$ is the photospheric radius. The central wavelength in the g-band filter is λ_0=4686 Å and the g bandpass is $\delta\lambda$=1260 Å (see, e.g. fig. 5 in Gunn et al. 1998); using the actual filter profile gives changes smaller than the errors in the photometry.

Our model also agrees with the early and late upper limits from Leloudas et al. (2012) although they are not plotted here because we chose to show the firm detections which are better. For the SN lightcurve (i.e. the first hump), we prefer to compare to an observed light curve. We use the light curve of SN 1999em from Bersten & Hamuy (2009) which has good time coverage in the first 50 d. Bersten et al. (2011) fitted hydrodynamic models to SN 1999em and derived a progenitor mass of $19\ M_\odot$ (similar in mass to the SN progenitor we used in our QN model), radius of $800 R_\odot$, explosion energy of 1.25×10^{51} erg and ^{56}Ni mass of 0.056 $M_\odot$. This gave a luminosity at 5 d of $10^{42.4}$ erg s^{-1}. We scaled the bolometric magnitude by +2 to represent a more energetic SN. This is not unreasonable 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 initial mass of the progenitor is in the range of 20–40 $M_\odot$ (Leahy & Ouyed 2009; Ouyed et al. 2009b; Ouyed et al. 2012). It creates a massive NS with core density near the instability needed for conversion to quark matter (Staff et al. 2006; Niebergal et al. 2010). A reasonable fit to the main peak of SN 2006oz was obtained for an SN with ejected mass of 20 $M_\odot$. Given current understanding of mass loss, the $20\ M_\odot$ approximately corresponds to an initial progenitor mass between 30–40 $M_\odot$ (e.g. De Loore et al. 1977; see also Langer 2012 and references therein for a recent review). This puts the progenitor mass in a range somewhat larger than in models of SLSNe driven by a magnetar (see the next paragraph). Best fits from our previous studies of SLSNe yielded time delays of ∼10 d, which motivates the range of time delays that we explored. For SN 2006oz, the fit shown (see Fig. 1) uses $t_{\rm delay}$=6.5 d, $v_{\rm QN}$= 5000 km s^{-1} and preceding SN ejecta with an average velocity of $v_{\rm SN}$ ≃1900 km s^{-1}. The combined light from the SN and from the QN-reheated SN ejecta gives a reasonable fit to the observations with a self-consistent model.

Here we note that events with similar but smaller initial masses have been reported: (i) Mazzali et al. (2006) studied SN 2006aj/GRB060218 (an X-ray flash) and concluded that the progenitor had an initial mass of $\sim 20\ M_\odot$ and that the SN ejected a mass of $\sim 2\ M_\odot$. For such a low-mass progenitor, formation of an NS is expected, thus they suggest that the X-ray flash could have been related to magnetar activity; (ii) Another event which seems to require a low-mass progenitor ($\sim 20-25\ M_\odot$) was SN 2005bf (Maeda et al. 2007). In this case, the lightcurve shows a second bright peak which

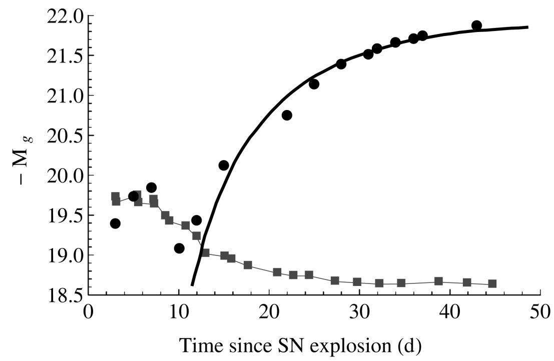

Fig. 1 SN 2006oz absolute magnitude light curve in g-band (*solid circles*). The dsQN model is calculated for $M_{\rm ejecta} = 20\ M_\odot$ and $t_{\rm delay} = 6.5$ d (see text for other parameters). The prototype SN light curve (*connected squares*) is a scaled version of that observed for SN 1999em (see text).

appears to have a separate origin from the first peak and late-time lightcurve. The second peak was best modeled by a magnetar energizing an $\sim 8\ M_\odot$ SN envelope (Maeda et al. 2007). The progenitor mass in our model (30–40 $M_\odot$) is higher than those inferred for SN 2006aj/GRB060218 and SN 2005bf and should produce a more massive NS, closer to the instability limit needed for conversion to a quark star. Since the magnetar model for SN 2006oz seems to require extreme parameters (unlike the models for SN 2006aj and SN 2005bf), our model is a good alternative hypothesis for the much more luminous SN 2006oz.

4 DISCUSSION AND CONCLUSIONS

Recent observations (such as the Texas SN search; Quimby et al. 2005 and the Catalina Real-Time Transit Survey; Drake et al. 2009) have revealed a new class of supernovae, the SLSNe. Among these are the SN 2005ap-like (H-poor) SLSNe. These events have proven challenging to explain. SN 2006oz was the first to have clearly shown a bright precursor with absolute magnitude of ~ -19 to -20. We suggest this precursor is a type II SN, and the main event is the dsQN (i.e. the SN envelope re-heated by the QN).

Leloudas et al. (2012) point out the intriguing possibility of an intrinsic precursor event in SN 2005ap-like events. In our model, there must be a normal SN ($-20 < M_{\rm bol} < -15$) preceding the SLSN if the delay is long enough that the SN light curve is not buried in the QN lightcurve. The precursor SN should be detectable in sensitive and early enough observations of SN 2005ap-like explosions.

SN 2005ap-like objects occur at a rate of less than one in 10^4 core-collapse SNe (Quimby et al. 2011). dsQNe are expected to be rare: the QNe rate is estimated to be $\sim 1/1000$ of the core-collapse rate with 1/10 of them having time delays in the appropriate range to produce dsQNe ($t_{\rm delay} \sim$ 5–30 d; Staff et al. 2006; Jaikumar et al. 2007; Leahy & Ouyed 2008; Leahy & Ouyed 2009; Ouyed et al. 2009b). This order of magnitude estimate is consistent with the rate of SN 2005ap-like events.

Our model applies to both H-rich and H-poor SLSNe – the key ingredient is a progenitor in the right mass range to produce a massive enough NS but not a black hole. We note that in both cases, the QN shock reheats the SN envelope so H-poor (H-rich) progenitors would give H-poor (H-rich) spectra. In this context, we expect H-poor SLSNe to occur in higher-metallicity environments because of higher stellar mass loss-rates. Low-metallicity progenitors would lose less mass and would more likely be H-rich and should in principle have more massive envelopes.

Upcoming observations from the large SN surveys should reveal more SLSNe and more of these with precursors. In our model, these precursors are type II SNe which should be recognized with sufficient photometry and/or spectroscopy. In addition, the overall shape of the SLSN lightcurve should vary from a single hump to a double hump depending on the time delay between the SN and the QN explosions.

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