Double-humped Super-luminous Supernovae

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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⊙); the interaction of fast moving SN ejecta (~10M⊙) with a massive circumstellar shell (also with ~10M⊙); 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 2006ap [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 due to the long ejecta duration. 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 QN [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 QN [Niebergal et al. 2009, Ouyed et al. 2011] phase transition to 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., 2009; 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.].
Ouyed et al. [2009b] have shown that these outermost layers (of $\sim 10^{-2}$–$10^{-3} M_\odot$ 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 ($t_{\text{delay}}$) between SN and QN explosions is too long the SN ejecta will have dissipated such that the QN essentially erupts in isolation. However, when $t_{\text{delay}}$ is on the order of days to weeks a violent collision occurs re-heating 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 $1.25 \times 10^{51}$ erg and 56Ni 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. [2009a], Ouyed et al. [2014]) 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 $\sim 10$ days which motivates the time delays that we explored. For SN2006oz the shown fit (see Figure 1) uses $t_{\text{delay}} = 6.5$ days, $v_{\text{QN}} = 5000$ km s$^{-1}$ and a preceding SN ejecta with an average velocity of $v_{\text{SN}} \sim 1900$ 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 ($20 < M_{\text{bol}} < 15$) preceding the SLSN (if the delay is long enough, $> 10$ 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 ($t_{\text{delay}} \sim$ 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 $M_{\text{ejecta}} = 20 M_\odot$ and $(t_{\text{delay}}) = 6.5$ 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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References

Bersten, M. C., & Hamuy, M. 2009, ApJ, 701, 200
Bersten, M. C., Benvenuto, O., & Hamuy, M. 2011, ApJ, 729, 61
Bodmer, A. R. 1971, Phys. Rev. D, 4, 1601
Itoh, N. 1970, Prog. Theor. Phys. 44, 291
Jaikumar, P., Meyer, B. S., Otsuki, K., & Ouyed, R. 2007, Astronomy & Astrophysics, 471, 227
Keränen, P., Ouyed, R., and Jaikumar, P. 2005, ApJ, 618, 485
Leahy, D., and Ouyed, R. 2008, Mon. Not. Roy. Ast. Soc., 387, 1193
Leahy, D., & Ouyed, R. 2009, Advances in Astronomy, 2009

Leloudas, G., Chatzopoulos, E., Dilhay, B., et al. 2012, Astronomy & Astrophysics, 541, 129
Niebergal, B., Ouyed, R., & Jaikumar, P. 2010b, Phys. Rev. C 82, 062801 [arXiv:1008.4806 [nucl-th]]
Ouyed, R., Dey, J., & Dey, M. 2002, A&A, 390, L39
Ouyed, R., & Leahy, D. 2009, ApJ, 696, 562
Ouyed, R., Leahy, D., & Jaikumar, P. 2009a, Proceedings for "Compact stars in the QCD phase diagram II (CSQCD II)", May 20-24, 2009, KIAA at Peking University, Beijing - P. R. China, [http://vega.bac.pku.edu.cn/rxxu/csqcd.htm], [arXiv:0911.5424]
Ouyed, R., Pudritz, R. E., & Jaikumar, P. 2009b, ApJ, 702, 1575
Ouyed, R., Kostka, M., Koning, N., Leahy, D., & Stefan, W. 2010, MNRAS, 423, 1652
Ouyed, R., Leahy, D., Ouyed, A., & Jaikumar, P. 2011, Physical Review Letters, 107, 151103
Ouyed, R., & Leahy, D. 2012, submitted [arXiv:1202.2400v1]
Quimby, R. M., et al. 2011, Nature, 474, 487
Staff, J. E., Ouyed, R., & Jaikumar, P. 2006, ApJ, 645, L145
Vogt, C., Rapp, R., & Ouyed, R. 2004, Nucl. Phys. A, 735, 543
Witten, E. 1984, Phys. Rev. D, 30, 272
Wright, E. L. 2006, The Publications of the Astronomical Society of the Pacific, 118, 1711
Young, T. R. 2004, ApJ, 617, 1233