SN 2006oz: rise of a super-luminous supernova observed by the SDSS-II SN Survey


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ABSTRACT

Context. A new class of super-luminous transients has recently been identified. These objects reach absolute luminosities of $M_r < -21$, lack hydrogen in their spectra, and are exclusively discovered by non-targeted surveys because they are associated with very faint galaxies.

Aims. We aim to contribute to a better understanding of these objects by studying SN 2006oz, a newly-recognized member of this class.

Methods. We present multi-color light curves of SN 2006oz from the SDSS-II SN Survey that cover its rise time, as well as an optical spectrum that shows the explosion occurred at $z \sim 0.376$. We fitted black-body functions to estimate the temperature and radius evolution of the photosphere and used the parametrized code SYNOW to model the spectrum. We constructed a bolometric light curve and compared it with explosion models. In addition, we conducted a deep search for the host galaxy with the 10 m GTC telescope.

Results. The very early light curves show a dip in the $g$- and $r$-bands and a possible initial cooling phase in the $u$-band before rising to maximum light. The bolometric light curve shows a precursor plateau with a duration of 6–10 days in the rest-frame. A lower limit of $M_r \sim -21.5$ can be placed on the absolute peak luminosity of the SN, while the rise time is constrained to be at least 29 days. During our observations, the emitting sphere doubled its radius to $\sim 2 \times 10^{15}$ cm, while the temperature remained hot at $\sim 15000$ K.

As for other similar SNe, the spectrum is best modeled with elements including O, Si, and Mg, and SNe II, while we tentatively suggest that Fe might be present. The host galaxy is detected in $g$ with $25.74 \pm 0.19$, $24.43 \pm 0.06$, and $24.14 \pm 0.12$, respectively. It is a faint dwarf galaxy with $M_r = -16.9$.

Conclusions. We suggest that the precursor plateau might be related to a recombination wave in a circumstellar medium (CSM) and discuss whether this is a common property of all similar explosions. The subsequent rise can be equally well described by input from a magnetor or by ejecta-CSM interaction, but the models are not well constrained owing to the lack of post-maximum observations, and CSM interaction has difficulties accounting for the precursor plateau self-consistently. Radioactive decay is less likely to be the mechanism that powers the luminosity. The host is a moderately young and star-forming, but not a starburst, galaxy.

Key words. supernovae: general – supernovae: individual: SN 2006oz – stars: massive
1. Introduction

Historically, supernovae (SNe) have usually been discovered by monitoring bright, nearby galaxies. With a few exceptions, the supernovae discovered in this targeted way fit well within the traditional SN classification scheme (e.g. Filippenko 1997). During the last few years, however, rolling searches, such as the Texas SN Search (Quimby et al. 2005) and the Catalina Real-Time Transient Survey (Drake et al. 2009) have changed our view of stellar explosions. In particular, it has been shown that interesting transients were previously missed exactly because they occur in environments different from those probed by the traditional SN searches. Remarkably, these include the brightest SNe ever recorded (hereafter super-luminous supernovae, SLSNe) with luminosities exceeding those of SNe Ia by 10–100 times.

Many of these SLSNe are associated with SNe IIn and have high luminosities attributed (at least partly) to the interaction of the ejecta with a dense H-rich CSM (e.g. Ofek et al. 2007; Smith et al. 2007, 2008). SN 2005ap, in contrast, showed only weak evidence for hydrogen and yet reached an absolute magnitude of $M_B < -22.5$ (Quimby et al. 2007). A seemingly unrelated object of peculiar nature was discovered by the Supernova Cosmology Project (SCP) with HST (Barbary et al. 2009). SCP06F6 had unprecedented spectra and light curves, but the lack of a robust redshift estimate left this study inconclusive with respect to its nature (see also Chatzopoulos et al. 2009; Gänsicke et al. 2009; Soker et al. 2010).

Significant progress was made when Quimby et al. (2011) showed that four objects detected by the Palomar Transient Factory (PTF; Rau et al. 2009; Law et al. 2009) could be grouped together with SN 2005ap and SCP06F6 to form a distinct class of H-poor SLSNe. The redshifts of these objects were identified by the detection of the Mg II λ2800 doublet and SCP06F6 was shown to be at a much higher redshift ($z = 1.189$) than originally estimated. All objects had similar spectra, blue colors, and relatively symmetric light curves. Their typical absolute magnitude is $M < -21.5$ and their explosion mechanism remains a mystery. Possible suggestions include pulsational pair-instability (Woosley et al. 2007), the powering of the ejecta by a magnetar (Kasen & Bildsten 2010; Woosley 2010), or interaction with an CSM (Chevalier & Irwin 2011; Blinnikov & Sorokina 2010; Moriya & Tominaga 2012). A third class of SLSNe, also H-poor, but different from those in Quimby et al. (2011), might be represented by SN 2007bi, which has been proposed (Gal-Yam et al. 2009) to be a pair-instability event, although this explanation is not unique (Young et al. 2010; Moriya et al. 2010).

One of the objects studied by Quimby et al. (2011), SN 2010gx, was also extensively followed by Pastorello et al. (2010). By obtaining spectra at later phases, they managed to demonstrate that this SLSN transitioned to a SN Ic, showing that there is a possible link between these energetic explosions. Recently, two more SNe belonging to this intriguing class were discovered by Pan-STARRS1 at $z \approx 0.90$ (Chomiuk et al. 2011). These objects showed no signs of deceleration in their expansion velocities during observations observed over a period of about three weeks around maximum light.

A common characteristic for H-poor SLSNe is that they are systematically found in faint galaxies. Indeed, to date, only three of these hosts have been detected; there are only upper limits on the others (typically $M_B > -18$), suggesting that they are probably metal-poor (Neill et al. 2011). It has been speculated that low metallicity might be an indispensable ingredient to produce SLSNe.

One reason that our understanding of these objects is limited is that the available data are sparse and incomplete: observations are often obtained in 1 or 2 neighboring filters, and when multi-color light curves are available, they cover only part of the SN evolution. The study of SLSNe is a relatively new topic and any complementary dataset (especially covering the critical early phases) constitutes a valuable contribution to the field.

SN 2006gz was discovered by the SDSS-II SN Survey (Frieman et al. 2008) toward the end of the 2006 observing season at RA = 22°08′53″56, Dec = +00°53′50″4 (J2000). Labeled internally as a "strange hostless transient", it was initially classified (Stritzinger et al. 2006) as a possible SN Ib based on a spectrum obtained at the Nordic Optical Telescope (NOT). In the analysis by Östman et al. (2011), it was given a SN II designation, noting, however, that it matched less than five templates in SNID (Blondin & Tonry 2007). Today, we know that these misclassifications were due to the lack of suitable comparison spectra in the literature, and, here, we identify it as an H-poor SLSN, as defined by Quimby et al. (2011). Our observations and results are presented in the next section. Section 3 contains the discussion and Sect. 4 our concluding remarks.

2. Observations and results

Photometric observations were carried out with the SDSS telescope at Apache Point Observatory ( Gunn et al. 1998, 2006) in the SDSS ugriz filters (Pukugita et al. 1996). As for all SNe discovered by the SDSS SN survey, the identification was made according to Sako et al. (2008) and the photometry was performed in the way described in Holtzman et al. (2008), to which we refer the reader for more details. We just point out that these are "asinh" magnitudes, defined by Lupton et al. (1999) to be identical to the traditional astronomical magnitudes at higher signal-to-noise ratio, but which provide a well-behaved finite flux and error even in the low-flux regime. We have derived more traditional 3σ upper limits (see Table 3) for non-significant detections (error ≥0.5 mag), but used the asinh magnitudes for the construction of our bolometric light curve (Sect. 3.2).

The SDSS light curves are plotted in Fig. 1. As can be seen, our observations cover the rise of SN 2006gz, and end before or close to maximum light. Because of a six day gap in the observations, the explosion date is not very well constrained, but the $g$-band limit previous to our first detection suggests that the explosion occurred between MJD 54022 and 54028. Nevertheless, these ugriz light curves are very interesting: there are hints in our photometry that the SN initially faded in the u-band and re-brightened a few days later. This behavior has only been observed for a handful of stripped core-collapse SNe that were discovered at very early phases and is usually attributed to a phase of adiabatic cooling of the envelope following shock breakout (e.g. Richmond et al. 1994; Stritzinger et al. 2002). Our observations are only poorly constraining (because we are in the low-flux regime), but based on the error bars and upper limits we estimate that there is a probability of 78% that the SN faded between MJD 54028 and 54037 in the $g$-band. Additionally, a (significant) dip in the light curve is observed simultaneously in the $g$- and $r$-bands. Combining the $ug$-bands there is strong evidence ($>5\sigma$) for a non-standard, non-increasing luminosity evolution of this SN during the first ten days of observations.

At MJD 54061.87, we obtained a spectrum of SN 2006gz at the NOT equipped with ALFOSC. The spectrum spans the wavelength range 3200–9100 Å with a resolution of 20 Å and was reduced in the manner described by Östman et al. (2011).
The spectrum is displayed in Fig. 2 with a sample of comparison spectra from Quimby et al. (2011), obtained at comparable pre-maximum phases, to highlight their similarity. To obtain a redshift estimate, our spectrum was initially cross-correlated with the four objects presented in Quimby et al. (2011) by using SNID (Blondin & Tonry 2007). The constructed templates matched reasonably well, all within $0.365 < z < 0.397$ with a mean $z = 0.376 \pm 0.014$. It is possible, however, that there are intrinsic velocity differences between the features of SN 2006oz and the other SNe, which would influence our redshift estimate. We have searched in the wavelength window $\sim3500$–$4500$ Å for any absorption lines, in particular Mg 2795, 2802 (Quimby et al. 2011) that would allow us to determine the redshift more accurately. At the low resolution of our spectrum the doublet will appear blended, making the search more complicated. The only candidate line that we were able to identify is at $\sim3856$ Å. Although at low significance ($\sim2.7\sigma$), it appears consistently in all sets of extractions that we attempted and always with the same profile (Fig. 2; inset). Although this line is insufficient to derive a robust spectroscopic redshift (i.e. Mg at $z = 0.377$), it can be considered as supporting evidence for the redshift derived by cross-correlating the SN spectra.

Our best redshift estimate, used throughout the paper, is therefore $z = 0.376$. Assuming a cosmology with $H_0 = 71 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_m = 0.27$ and $\Omega_\Lambda = 0.73$, SN 2006oz reached an absolute (rest-frame) magnitude of $M_u = -21.5$ mag.
respectively. Their photometry is reported in Table 1. Both images are objects, including one that appears extended, labeled B, C, D and E, on their rest frame assuming $z = 0.376$ for SN 2006oz. The inset shows a zoom of the area around 2800 Å. At this redshift we identified the only probable line (although at low significance 2.7σ) consistent with the Mg doublet (which would appear blended at this resolution).

This calculation contains the assumption that maximum light occurred in our last epoch of observations and is, therefore, only a lower limit to the peak luminosity of the SN. In addition, owing to the uncertainty in the cross-correlation redshift, one needs to assign a 0.1 mag systematic error in all quantities that depend on the distance to the SN. Similarly, we are able to place a strict constraint on the (rest-frame) rise time of $\sim 1\, \text{day}$, resulting in $T_{\text{BB}} = 15540 \pm 430 \, \text{K}$. The or-

## Table 1. Host galaxy candidates for SN 2006oz.

<table>
<thead>
<tr>
<th>Id</th>
<th>$g$ (mag)</th>
<th>$r$ (mag)</th>
<th>$i$ (mag)</th>
<th>dist. (arcsec)</th>
</tr>
</thead>
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<tr>
<td>A</td>
<td>25.74 ± 0.19</td>
<td>24.43 ± 0.06</td>
<td>24.14 ± 0.12</td>
<td>0.47</td>
</tr>
<tr>
<td>B</td>
<td>&gt;26.47</td>
<td>25.62 ± 0.16</td>
<td>25.02 ± 0.25</td>
<td>2.97</td>
</tr>
<tr>
<td>C</td>
<td>&gt;26.47</td>
<td>25.81 ± 0.19</td>
<td>24.65 ± 0.18</td>
<td>6.26</td>
</tr>
<tr>
<td>D</td>
<td>25.18 ± 0.11</td>
<td>24.70 ± 0.07</td>
<td>24.32 ± 0.12</td>
<td>4.56</td>
</tr>
<tr>
<td>E</td>
<td>25.28 ± 0.15</td>
<td>23.71 ± 0.03</td>
<td>23.21 ± 0.06</td>
<td>6.56</td>
</tr>
</tbody>
</table>

Notes. The indexing follows the notation in Fig. 3. All magnitudes are given in the AB system. The last column contains the angular distance from the SN position (as determined by a geometrical transformation between images) and has an associated error of 0.35′.

Distances from the SN position are presented in Table 1. The error of these angular distances as determined from the rms of the IRAF task `geomap` was estimated to be 0.35′. Because of its spatial proximity, we identify galaxy A as the host of SN 2006oz. Assuming $z = 0.376$, the SN occurred at a distance of 2.40 ± 1.36 kpc from the galaxy center, while the distance to the nearest other candidate would exceed 15 kpc. At this redshift, the host of SN 2006oz is intrinsically faint with a (rest-frame) absolute magnitude of $M_g = -16.9$. We note that the photometric red-shift obtained for this galaxy (using the code `Le Phare`; Arnouts et al. 1999; Ilbert et al. 2006) is $z_{\text{phot}} = 0.37^{+0.32}_{-0.04}$. Although not constraining, this value is consistent with what was obtained for the SN.

## 3. Discussion

### 3.1. Black-body fits

To estimate the photospheric temperature and radius of SN 2006oz, we fitted a black body (BB) function to the optical spectrum. We achieved a reasonable fit with $\chi^2_1 < 1$, although not

![Fig. 2. Spectrum of SN 2006oz (red) obtained at the NOT. For comparison we show 3 spectra from Quimby et al. (2011) at similar pre-maximum phases. The colored spectra are smoothed versions (moving average of 5 pixels) of the original gray spectra. All spectra were plotted in their rest frame assuming $z = 0.376$ for SN 2006oz. The inset shows a zoom of the area around 2800 Å. At this redshift we identified the only probable line (although at low significance 2.7σ) consistent with the Mg doublet (which would appear blended at this resolution).](image1)

SN 2006oz

![Fig. 3. Left: image of SN 2006oz obtained with the SDSS telescope (MJD 54061.17). Right: deep i image of the field, obtained almost 5yr after the SN with GTC/OSIRIS. The SN is coincident with the position of galaxy A. However, within a radius of 7′′, there are four more objects, including one that appears extended, labeled B, C, D and E, respectively. Their photometry is reported in Table 1. Both images are 72′′ × 72′′. North is up and east is to the left.](image2)

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1 IRAF is distributed by the National Optical Astronomy Observatory: http://iraf.noao.edu/iraf/web/.
3.2. Bolometric and absolute light curves

To construct a (pseudo-) bolometric light curve of SN 2006oz we integrated the flux included within the limits of our simultaneous $ugriz$ observations. To account for the epochs containing upper limits (in $u$ and $z$) we used the \textit{asinh} magnitudes provided by the SDSS photometry (Lupton et al. 1999; Holtzman et al. 2008), e.g. $2.6 \pm 1.5 \mu \text{y}$. for our $u$ observation at MJD 54037. This is the most reliable assumption and the high uncertainties are propagated to the final bolometric light curve. A correction of up to a factor of 2–2.5. This is the worst case, however, because the flux in the UV clearly deviates from a BB (see also Chomiuk et al. 2011). Determining a bolometric correction is not trivial. This experiment was made to show that it cannot be established whether SN 2006oz was a fainter event or whether we are probing earlier stages of its evolution (or a combination of both). Indeed, a reasonable match of the light curves can be obtained by shifting $t_{\text{max}}$ by $-10$ days (rest-frame, time-dilation corrected). It is certainly true that the very early data-points of SN 2006oz were below the sensitivity of the PanSTARRS1 observations of PS1-10awh at $z \sim 0.9$. This can also be seen in the lower panel of Fig. 5, which contains a comparison of absolute rest-frame light curves. In particular, the observed $u$ and $r$-bands of SN 2006oz are compared to the $g$ and $z$ observations of PS1-10awh, which correspond to the same rest-frame wavelengths. This comparison shows that (despite the uncertainty in $t_{\text{max}}$) the SDSS observations of SN 2006oz reach deeper limits in an absolute level and provide a window to the early evolution of an SLSN.

The shape of this very early bolometric light curve is very interesting. The individual band observations discussed in the previous section were translated into a plateau-like phase in the bolometric light curve. This plateau has a minimum duration of six days and is followed by a dip, after which the luminosity begins to rise. Owing to the uncertainty in the time of explosion, the duration of this initial phase can be up to 14 days. Such a...
The observed spectrum and two model spectra, with and without C ii, are plotted together in Fig. 6. The figure also contains the spectrum of SCP06F6 (Barbary et al. 2009) to illustrate a possible extension of the spectrum to the (rest-frame) UV. The contributions of the individual ions to the model spectrum are also shown. The “W”–like feature around 4200 Å nicely matches the O i feature that was also invoked by Quimby et al. (2011) to model other SLSNe. The strong feature around 2700 Å is probably due to Mg ii, although the spectrum is noisy in that region. Fe ii can explain the observed bump around 3180 Å (Fig. 6; inset), and none of the other ions considered here were able to model that feature. Si iii has a contribution around 3000 Å, but its presence was mostly motivated by the assumption that SN 2006oz is spectrally similar to other SLSNe. Indeed, the result will more probably be enhanced because the colors of SN 2006oz evolve from blue to red during this period, which reduces the fraction of missing flux with time. The nature of the plateau is discussed in more detail in Sect. 3.4.

3.3. The spectrum

The lack of clear hydrogen features is an important clue to the nature of this event and the others in its class (Quimby et al. 2011). It is difficult to avoid the conclusion that the object is hydrogen-deficient, although the possibility that some hydrogen is present, but difficult to detect, cannot be rejected. The lack of clear signatures of helium is a more ambiguous clue. The prominent lines of He i in the optical and NIR arise in transitions to the $n = 2$ level from higher levels. Ambient conditions in SN photospheres are typically insufficient to populate these upper levels, consequently they must be populated by non-thermal (Harkness et al. 1987; Lucy 1991) or non-LTE (Dessart et al. 2011) processes. Relevant ionization energies are H – 13.6 eV, He i – 24.6 eV, C i – 11.3 eV and O i – 13.6 eV. From the absence of obvious helium lines, it is then much less obvious that an absence of helium can be firmly deduced. In addition, the wavelength range of the SN 2006oz spectrum (and most similar events), does not cover the most prominent He lines, with the exception of i5876, which is found in a noisy part of the spectrum. The question whether He might be expected requires additional investigation and better wavelength and temporal coverage.

We have applied the parametrized code SYNOW (Hatano et al. 1999; Branch et al. 2003) to model the spectrum of SN 2006oz. Although SYNOW is based on simplified physical assumptions, it is very useful for identifying spectral features that are strongly Doppler-broadened and sometimes heavily blended. Because SYNOW contains many adjustable parameters, we did not attempt an automated fitting via chi-squared minimization but instead looked for a reasonable agreement between the observed and the model spectra by eye, using the minimum number of different atoms/ions in the envelope. The photospheric expansion velocity and the temperature of the underlying blackbody radiation were initially set and kept fixed during the search for features. Adopting $v_{\text{phot}} = 12 000$ km s$^{-1}$ and $T_{\text{BB}} = 14 000$ K resulted in a good fit to most spectral features. A power-law atmosphere, where the optical depth as a function of velocity varies as $(v/v_n)^{-n}$ with $n = 7$, has been assumed for all atoms/ions. Our tests showed that there are no significant differences between the line profiles obtained by using either power-law or exponential optical depth profiles for the spectral features of SN 2006oz. The maximum velocity of the envelope $v_{\text{max}}$ was set to 40 000 km s$^{-1}$, but this parameter is only weakly constrained by our spectrum.
The chemical composition identified above (O Ⅱ, Mg Ⅱ, and maybe Fe Ⅲ, Si Ⅱ and S Ⅱ) is consistent with the “carbon-burned” SN atmosphere considered by Hatano et al. (1999). Although it is probably premature to conclude that SN 2006oz had such an atmosphere, it is interesting that together with the lack of H and He Ⅰ and maybe C Ⅱ in the spectrum, all identified features belong to the ions that are expected to be the strongest at an excitation temperature of ~14 000 K in an atmosphere containing elements that underwent carbon-burning.

3.4. Models for the light curve

The bolometric light curve can be divided into two parts: the initial precursor plateau and the subsequent smooth monotonic rise. As discussed above, it is not clear if the maximum of the light curve was observed, a handicap in constraining models.

We note that precursor plateaus, some similar in shape to that of SN 2006oz, were found by Dessart et al. (2011) in their models of helium star explosions. In their models, the plateau is associated with the shock breakout, fireball-cooling phase, before the rise to the peak powered by radioactive decay. The plateau arises when the temperature decrease at the photosphere slows down, an effect associated with the recombination of ejecta layers to their neutral state (primarily He, but also CNO elements in the helium-rich progenitor models). The plateau brightness is determined by the amount of energy initially deposited by the shock and the size of the progenitor envelope. The bolometric light curves of Dessart et al. (2011) typically have a plateau that lasts about ten days and is about a factor of 20 to 30 dimmer than the subsequent peak.

The physics explored by the precursor plateaus of Dessart et al. (2011) may be relevant to SN 2006oz and its kin, but the plateau these authors find seems to be too dim to directly correspond to that observed in SN 2006oz. In SN 2006oz, this plateau is dimmer than the subsequent peak by about a factor of 8–10 in luminosity (depending on tmax, Fig. 5). Because the plateau is brighter than in the models of Dessart et al. (2011), the material must be distributed at larger radii. The structures in the models of Dessart et al. (2011) are originally in hydrostatic equilibrium as dictated by the systematics of stellar evolution. A substantially larger radius suggests that the plateau we observe in SN 2006oz does not arise in a stellar envelope, but in a circumstellar medium. Consequently, the only likely explanation that we have found for the plateau is that it might represent a recombination wave in a CSM that surrounds the progenitor star. A possible case of shock breakout from a H-rich dense CSM was discussed by Ofek et al. (2010). For SN 2006oz, unlike for SNe II, this plateau cannot be caused by recombination of H, which occurs at much lower temperatures (5000–6000 K).

The derived temperature also makes a He recombination explanation unlikely, because most of the He atoms are singly ionized at $T > 10 000$ K, but double ionization starts above $T > 15 000$ K (Hatano et al. 1999). On the other hand, a recombination plateau could be consistent with the transition O Ⅱ to O Ⅰ (Hatano et al. 1999). This idea is also potentially consistent with the detection of O Ⅰ in the spectrum of H-poor SLSNe (Sect. 3.3). Interestingly, a precursor plateau was observed in the simulations of Blinnikov & Sorokina (2010) for SN 1a explosions in a C–O CSM, but, as the authors argue, it was an artifact of the arbitrary initial conditions. An early plateau is also present in the bolometric light curve of the 1987A-like SN 2006au (Taddia et al. 2012).

The subsequent smooth rise of the light curve represents a more normal SN behavior and could be satisfied by a variety of

![Fig. 6. SYNOW fit to the spectra of SN 2006oz and SCP06F6. The observed spectra were brought to the rest-frame by assuming $z = 0.376$ and $z = 1.189$, respectively, and their fluxes were scaled to match in the overlapping wavelength region. Two SYNOW models, with and without C Ⅱ, are overplotted. The inset shows a zoom in the spectrum of SN 2006oz around 3300 Å. The magenta line (inset only) shows a model without Fe Ⅲ that provides a worse fit in this region. The lower panel shows the contribution of the individual ions to the model spectra. The best-fitting model has $\tau$(O Ⅰ) = 0.02, $\tau$(Mg Ⅱ) = 0.05, $\tau$(Si Ⅱ) = 0.5, $\tau$(Fe Ⅲ) = 0.5 and $\tau$(Fe Ⅲ) = 0.4.](image-url)
The quoted limits are 3σ. For the epochs after the SN discovery, where the SN was below the formal detection limit (u and z-band), we also provide, below the 3σ limits, the sinh magnitudes (Lupton et al. 1999; Holtzman et al. 2008), which were used as the best approximation in the construction of the bolometric light curve. Observation mid-point and magnitude limits from stacking all observations from the first 5 weeks of the 2007 season. Observation mid-point and magnitude limits from stacking all observations from the 2007 season.

Table 3. SDSS photometry of SN 2006oz (AB magnitudes).

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<tr>
<th>MJD</th>
<th>u</th>
<th>g</th>
<th>r</th>
<th>i</th>
<th>z</th>
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<tr>
<td>54022.23</td>
<td>&gt;22.228</td>
<td>&gt;23.674</td>
<td>&gt;22.898</td>
<td>&gt;22.772</td>
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<td>54028.17</td>
<td>21.391 (0.198)</td>
<td>22.280 (0.112)</td>
<td>22.314 (0.237)</td>
<td>22.359 (0.388)</td>
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</tr>
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<td>54030.18</td>
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<td>21.940 (0.067)</td>
<td>21.926 (0.116)</td>
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Fig. 7. Bolometric light curve of SN 2006oz shown along with models describing the rise to maximum (ignoring the precursor plateau). Models include the following power sources for the luminosity: radioactive decay (red, dashed), input from a magnetar (green, dotted dashed) and CSM interaction (blue, solid). Details concerning the model parameters are given in the text.

The red dashed curve shows a model driven by radioactive decay with $M_{\text{Ni}} = 10.8 \ M_{\odot}$ and a diffusion time $t_d = 36$ days, determined by the time scale of the rise of the light curve. The SN ejecta mass, $M_{\text{ej}} = 14.4 \ M_{\odot}$, is derived from the diffusion time, $t_d$, assuming a velocity, $v = 12000 \ \text{km} \ \text{s}^{-1}$, and opacity $\kappa = 0.05 \ \text{cm}^2 \ \text{g}^{-1}$. The ejecta mass scales as $\kappa^{-1}$ and consequently would be lower for higher opacity values. The fact that such a big fraction of $M_{\text{ej}}$ has been burned to $^{56}\text{Ni}$, unlike in most observed SN types, shows that a radioactive decay model has difficulties to account for the rise of SN 2006oz to maximum. Furthermore, the SN was not detected in the next observing season that started nine months later. By stacking the images from the first five weeks, we deduce a limit $r > 24.2$ (Table 3) implying a decay rate $>2.03 \ \text{mag} \ 100^{-1} \ \text{d}^{-1}$. This is steeper than the radioactive decay of $^{56}\text{Co}$ (0.98 mag $100^{-1} \ \text{d}^{-1}$), assuming semi-analytic models of these processes have been constructed by Chatzopoulos et al. (2012), and will be applied to a range of superluminous events in Chatzopoulos, Wheeler & Vinko (in prep.). Figure 7 shows a sample of models compared with the observed bolometric light curve of SN 2006oz, ignoring the precursor plateau. The models all peak at a time around the last observed data point, but the lack of a measured maximum (and subsequent decline) means the models are not well constrained. The models were not fitted in any formal sense, but constructed to be reasonable “by eye”. The ejecta masses derived may be somewhat underestimated as discussed by Chatzopoulos et al. (2012).
complete γ-ray and positron trapping. The radioactive model for H-poor SLSNe has also been seriously challenged by the observations of Quimby et al. (2011), Pastorello et al. (2010), and Chomiuk et al. (2011). We stress, though, that an assumption involved in these calculations is that 56Ni is centrally condensed (Arnett 1982). It is therefore possible that a configuration where 56Ni is substantially mixed into the outer envelope, thereby allowing γ-rays to escape freely, cannot be ruled out.

For the same velocity, opacity, and rise time, a magnetar model yields the same ejecta mass, 14.4 $M_\odot$, as the radioactive decay model, but requires two more parameters, $E_p$ and $t_p$, where the decay model requires only one, $M_{csm}$, to fit the rise and peak. The green dot-dashed curve shows a magnetar spin-down model with initial rotational energy $E_p = 1.45 \times 10^{51}$ erg and a characteristic spin-down time of $t_p = 13$ days, giving an initial rotational period 3.7 ms and a magnetic field $B = 2.24 \times 10^{14}$ G.

The blue curve shows a model with SN ejecta and CSM interaction (including both forward and reverse shocks) for again the same velocity, opacity, rise time and ejecta mass as the previous models. This CSM model was designed to give both a reasonable fit to the rise time and a reasonable formal black-body temperature at maximum. The other parameters used are (see Chatzopoulos et al. 2012, for detailed definitions): $E_{sn} = 2.5 \times 10^{51}$ erg, the density slope of the SN ejecta $n = 12$, the progenitor radius $R_p = 2.5 \times 10^{14}$ cm, the density slope of the CSM $s = 0$, the density scale at the base of the CSM $\rho_{csm,1} = 5 \times 10^{-13}$ g cm$^{-3}$ (determined at $R_p$ and equal to the constant density of the CSM shell), $M_{csm} = 6.5 M_\odot$, and $M_{Ni} = 0.02 M_\odot$. The constant CSM photospheric radius of this model is $R_{ph} = 1.8 \times 10^{15}$ cm, virtually the same as the radius of the shell itself, giving an optical depth of $\tau_{csm} = 327$. For these parameters and for $E_{bol} = 1.3 \times 10^{44}$ erg s$^{-1}$ at peak, the formal black-body temperature at maximum light is $T_{BB} = 15,300$ K. This model, with several free parameters, can also provide a decent fit to the data.

The uncertainty in the bolometric correction and $t_{max}$ has, of course, an impact on the models discussed above, although this is not easy to quantify because of parameter degeneracies. It is, however, almost certain that constructing a viable radioactive model will become increasingly difficult as these uncertainties can only increase the necessary $M_{csm}$ (and the ratio $M_{Ni}$ to $M_{csm}$) to power the light curve. Our experience shows that it will still be possible to obtain viable magnetar or CSM models by modifying parameters such as $E_p$, $t_p$, $\rho_{csm}$ and $M_{csm}$. More constraining for these models would be the availability of post-maximum data and decay rate.

We have shown that a range of models can explain the smooth rise to maximum. Combining these models with the pre-cursor plateau is less straightforward, as none of these models are presently able to numerically reproduce it. The possibility that the plateau is the result of a recombination wave in a (O-rich?) CSM, the only reasonable suggestion we have come up with, gives a rationale for considering that the same shell might be responsible for the rise. This picture is not perfectly self-consistent, however, because the first part requires the shock to have broken out of the CSM, while the second part requires the shock to still be interacting with it. It is therefore difficult to understand how the CSM was heated in the first place, i.e. before the ejecta-CSM interaction provides the rise to the peak. A possible answer could be by energy deposition to the CSM by the SN blast wave, although this possibility remains to be studied. Another alternative solution could be provided by a hybrid model with a CSM recombination accounting for the plateau and a magnetar for the rise to the peak. Additional observations of similar events, including more multi-color light curves from very early to very late phases, will be required to resolve this problem.

3.5. Host galaxy

The host of SN 2006oz is only the fourth out of nine similar H-poor SLSNe to have been identified (Neill et al. 2011; Chomiuk et al. 2011). Very little information is available on the hosts of these events, and many of them are detected in only one filter, so that a study of the properties of the host of SN 2006oz is warranted.

The colors $g - r = 1.26 \pm 0.20$ and $r - i = 0.26 \pm 0.13$ (after correcting for Galactic foreground extinction), suggest a significant break between the $g$ and $r$ filters. This can only be associated with the 4000 Å break, at a redshift consistent with the one we are examining. These colors are indeed consistent with an intermediate value $D_L(4000) = 1.4 \pm 0.1$ for the 4000 Å break, indicative of relatively old stellar populations and, possibly, of a burst of star formation within the last 1–2 Gyr (e.g. Kauffmann et al. 2003; Gallazzi et al. 2005). In Fig. 8, the host galaxy colors (K-corrected to $z = 0.1$) are compared to a set of galaxies, selected from the main spectroscopic sample of SDSS DR4 (Adelman-McCarthy et al. 2006) to have $0.08 < z < 0.12$, and to a set of dust-free model galaxies with different star-formation histories (Bruzual & Charlot 2003). Despite the high uncertainty, the galaxy position on this color-color diagram is more consistent with low-mass, star-forming galaxies and is far from the locus of elliptical, passive galaxies. It is not, however, a blue, starburst galaxy: by using the template of Kinney et al. (1996) and assuming the extinction law of Calzetti et al. (2000), it is not possible to reproduce these colors for any value of reddening.

2 The K-corrections were estimated from the model that best fits the observer-frame galaxy colors, as described below, and have an uncertainty of 0.13 mag in $g - r$ and 0.03 mag in $r - i$.

3 We used the MPA/JHU catalogs available at: http://www.mpa-garching.mpg.de/SDSS/
To gain a more quantitative understanding of the nature of the host galaxy, its observer-frame colors were compared to those predicted by a Monte Carlo library of model spectra, redshifted to $z = 0.376$, based on Bruzual & Charlot (2003) population synthesis models spanning a wide range of stellar population ages and metallicities. A direct metallicity measurement exists only for the host of SN 2010gx (Stoll et al. 2011), indicating a metallicity of $0.47 < Z < 0.57$. A129, page 10 of 11

With an absolute luminosity of $M_B = -16.9$, this galaxy is probably metal-poor. By using the mass-metallicity relation of Tremonti et al. (2004), we obtain an indicative value of $12 + \log(O/H) = 8.39 \pm 0.16$ for the oxygen abundance that corresponds to $0.5 < Z < 1.5$ (assuming the solar abundance of Asplund et al. 2009). A direct metallicity measurement exists only for the host of SN 2010gx (Stoll et al. 2011), indicating a metallicity of $0.47 < Z < 0.57$ (Kobulnicky & Kewley 2004; Asplund et al. 2009). These values are not particularly low, but the fact that all H-poor SLSNe have been found in faint galaxies suggests that metallicity might indeed play a role. The reason why this is interesting is that all viable models leading to H-poor SLSNe involve (one way or another) a very massive star that has suffered extensive mass loss. Since stellar winds are driven by metals (e.g. Vink & de Koter 2005; Puls et al. 2008) and are less efficient at low metallicity, it has been suggested that SLSN progenitors lose mass through episodic outbursts due to mechanisms that are not well understood, possibly involving pulsational pair instability (e.g. Woosley et al. 2007). On the other hand, a similar discussion has been going on about the preference of long GRBs, with optical afterglows, to be found in metal-poor galaxies, but it has been shown that this might be partly due to the fact that smaller galaxies have a higher SFR (Mannucci et al. 2010, 2011). It is therefore possible that the same bias exists for the SLSN hosts. The fundamental metallicity relation of Mannucci et al. (2011) for low-mass galaxies predicts $12 + \log(O/H) = 8.39$ for the host of SN 2006gz, i.e. again a value that is not very low.

4. Conclusions

We have studied SN 2006oz, an event belonging to the family of H-poor SLSNe identified by Quimby et al. (2011). The bolometric light curve shows a precursor plateau with a rest-frame duration of 6–10 days, while the bluest bands demonstrate a dip in the luminosity, before rising smoothly to maximum light. Our early observations are more sensitive than those of previous studies and it is therefore possible that this behavior might be common to more H-poor SLSN. If this is the case, it provides an important diagnostic for the nature of these events. We argued that the precursor plateau might be caused by a recombination wave in a H-deficient CSM. The subsequent rise in luminosity can be described by energy input from a magnetar or by ejecta-CSM interaction, but radioactive decay is less likely. Although the model parameters are not well constrained owing to the lack of post-maximum data, all models involve large ejected and CSM masses (if a CSM is required), pointing to a very massive progenitor.

Our deep observations with GTC have revealed the faint host galaxy of this event ($M_B = -16.9$). It is a moderately low-mass galaxy (log($M_*/M_\odot$) = 8.7), star-forming (0.17 $M_\odot$ yr$^{-1}$) galaxy with a luminosity-weighted age between 0.7–2.3 Gyr. It is not a blue, starburst galaxy and the metallicity, inferred indirectly, is not particularly low.

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