EARLY SPECTROSCOPIC IDENTIFICATION OF SN 2008D*

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ABSTRACT

SN 2008D was discovered while following up an unusually bright X-ray transient (XT) in the nearby spiral galaxy NGC 2770. We present early optical spectra (obtained 1.75 days after the XT) which allowed the first identification of the object as a supernova (SN) at redshift $z = 0.007$. These spectra were acquired during the initial declining phase of the light curve, likely produced in the stellar envelope cooling after shock breakout, and rarely observed. They exhibit a rather flat spectral energy distribution with broad undulations, and a strong, W-shaped feature with minima at 3980 and 4190 Å (rest frame). We also present extensive spectroscopy and photometry of the SN during the subsequent photospheric phase. Unlike SNe associated with gamma-ray bursts, SN 2008D displayed prominent He features and is therefore of Type Ib.

Key words: supernovae: individual (SN 2008D)

Online-only material: machine-readable table

1. OBSERVATIONS OF SN 2008D

On 2008 January 9.56 UT, while observing the supernova (SN) 2007uy in the nearby spiral galaxy NGC 2770 ($z = 0.007$), the X-Ray Telescope onboard Swift detected a bright X-ray transient (XT), with a peak luminosity of $6 \times 10^{33}$ erg s$^{-1}$ and a duration of about 10 minutes (Soderberg et al. 2008b). Its power-law spectrum and light-curve shape were reminiscent of gamma-ray bursts (GRBs) and X-ray flashes, but the energy release was at least two orders of magnitude lower than for gamma-ray bursts (GRBs) and X-ray flashes, but the energy release was at least two orders of magnitude lower than for Type Ia. These spectra were acquired during the initial declining phase of the light curve, likely produced in the stellar envelope cooling after shock breakout, and rarely observed. They exhibit a rather flat spectral energy distribution with broad undulations, and a strong, W-shaped feature with minima at 3980 and 4190 Å (rest frame). We also present extensive spectroscopy and photometry of the SN during the subsequent photospheric phase. Unlike SNe associated with gamma-ray bursts, SN 2008D displayed prominent He features and is therefore of Type Ib.

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* Partly based on observations made with ESO telescopes at the La Silla Paranal Observatory under program 080.D-0526, with the Nordic Optical Telescope, operated on the island of La Palma jointly by Denmark, Finland, Iceland, Norway, and Sweden, and with the United Kingdom Infrared Telescope, which is operated by the Joint Astronomy Centre on behalf of the Science and Technology Council of the UK.
Table 1  
Log of Spectroscopic Observations

| Epoch (UT) | Phase (days) | Telescope/Instrument | Exposure Time (s) |
|------------|--------------|----------------------|------------------|
| Jan 11.31  | 1.75         | VLT/FORS2+G300V      | 1 × 600          |
| Jan 11.32  | 1.76         | VLT/FORS2+G600B      | 1 × 900          |
| Jan 13.07  | 3.51         | NOT/ALFOSC+G4        | 3 × 1200         |
| Jan 15.17  | 5.61         | NOT/ALFOSC+G4        | 3 × 1200         |
| Jan 15.95  | 6.39         | NOT/ALFOSC+G4        | 1 × 1200         |
| Jan 16.26  | 6.70         | NOT/ALFOSC+G4        | 1 × 1200         |
| Jan 17.20  | 7.64         | NOT/ALFOSC+G4        | 3 × 1200         |
| Jan 18.22  | 8.66         | VLT/UVES+Disc#1      | 1 × 3600         |
| Jan 26.15  | 16.59        | WHT/ISIS+R300B/R316R | 6 × 600          |
| Jan 29.01  | 19.45        | NOT/ALFOSC+G4        | 3 × 1200         |
| Feb 01.02  | 53.46        | NOT/ALFOSC+G4        | 2 × 900          |
| Feb 04.05  | 56.49        | NOT/ALFOSC+G4        | 2 × 900          |
| Feb 18.15  | 70.59        | NOT/ALFOSC+G4        | 3 × 1200         |
| Feb 25.88  | 78.32        | NOT/ALFOSC+G4        | 2 × 1500         |
| Mar 02.18  | 112.62       | NOT/ALFOSC+G4        | 3 × 1200         |
| Mar 18.87  | 129.31       | NOT/ALFOSC+G4        | 3 × 900          |

Note. Phases are computed relative to the XT onset.

Table 2  
Log of Optical and Near-infrared Imaging Observations

| Epoch (UT) | Phase (days) | Filter | Magnitude | Instrument |
|------------|--------------|-------|-----------|------------|
| Jan 11.26528 | 01.70082 | U     | 18.60 ± 0.02 | NOT+StarCam |
| Jan 13.01426 | 03.49880 | U     | 19.16 ± 0.05 | NOT+ALFOSC |
| Jan 15.22931 | 05.66485 | U     | 19.40 ± 0.05 | NOT+ALFOSC |
| Jan 16.03116 | 06.46670 | U     | 19.29 ± 0.07 | NOT+ALFOSC |
| Jan 17.25019 | 07.68573 | U     | 19.19 ± 0.07 | NOT+ALFOSC |

Note. For the UBVR data, magnitudes do not include the zeropoint calibration error of 0.10, 0.03, 0.04, 0.03, and 0.04 mag, respectively.

This table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.

2. RESULTS

2.1. The Early Spectrum of SN 2008D

Our first optical spectrum of the transient source (Figure 1) exhibits Na I D absorption lines at $z = 0.0070$, thus establishing its extragalactic nature. Broad features are also apparent across the whole spectrum ($\text{FWHM} = (1-3) \times 10^4 \text{ km s}^{-1}$), which led us to identify the object as a core-collapse SN (Malesani et al. 2008). Soderberg et al. (2008a) describe nearly simultaneous spectra as featureless, probably due to their smaller covered wavelength range (4500–8000 Å). Modjaz et al. (2008b) report features consistent with those in our data.

We initially classified the SN as a very young Type Ib/c, based on the absence of conspicuous Si and H lines (Malesani et al. 2008). As the spectrum is among the earliest observed for any SN, comparable only to the very first spectrum of SN 1987A (Menzies et al. 1987), there is no obvious resemblance with known SN spectra. It is notable, however, that the earliest spectrum of the Type-Ic SN 1994I was essentially flat with broad, low-amplitude undulations (though the covered wavelength range was limited; Filippenko et al. 1995). Early spectra, also mostly featureless, are available for the H-rich Type-IIP SN 2006bp (Quimby et al. 2006). Dessart et al. (2008) interpret them in terms of high temperature and ionization.

A striking feature in the spectrum is a conspicuous W-shaped absorption with minima at 3980 and 4190 Å (rest frame). It was detected using two different instrument setups (Figure 1), and also reported by Modjaz et al. (2008b). If interpreted as due to P Cyg profiles, the inferred expansion velocity is $\sim 15,000 \text{ km s}^{-1}$, computed from the position of the bluest part compared to the peak. Its origin is unclear, although, following Quimby et al. (2007), Modjaz et al. (2008b) propose that it is due to a combination of C iii, N iii, and O iii. Interpreting the broad absorption at $\sim 5900$ Å as Si iii $\lambda\lambda 6347, 6371$, some ejecta reached $\sim 22,000$ km s$^{-1}$. Such large velocities have been seen only in broad-lined (BL) Type-Ic SNe, at significantly later stages (Patat et al. 2001; Hjorth et al. 2003; Mazzali et al. 2006).
Figure 3. Spectral evolution of SN 2008D from 1.75 days to seven weeks after explosion. On the left, the time in days since the XT is noted. The spectrum marked as “Jan 16” is the average of those taken on January 15.95 and 16.26 UT. Close to the January 29 track, we have indicated the most likely identification of the main features (HV H\(\alpha\) stands for “high-velocity H\(\alpha\)”). The narrow emission line at 6560 Å is residual H\(\alpha\) from the SN host galaxy. The He\(i\) feature around 6800 Å is affected by the B-band atmospheric absorption.

2.2. The Photospheric Phase

Figure 2 shows the optical and near-infrared light curves of SN 2008D. In the first days after the XT, the flux dropped faster in the bluer bands, with the color becoming progressively redder. This can be interpreted as due to the stellar envelope cooling after the shock breakout (Soderberg et al. 2008b). Our first spectra were taken during this stage, before energy deposition by radioactive nuclei became dominant; hence the physical conditions of the emitting material might be different than later. We note that the W-shaped absorption discussed in Section 2.1 was no longer visible from 3.5 days after the XT onward (Figure 3).

The later spectra, acquired during the radioactivity-powered phase and extending over more than two months in time, established SN 2008D as a Type-Ib SN (Modjaz et al. 2008a). From January 17 and onward unambiguous He lines are observed (Figure 3), consistent with other reports (Modjaz et al. 2008b; Valenti et al. 2008a; Soderberg et al. 2008b; Tanaka et al. 2008; Mazzali et al. 2008). In Figure 4, we plot the velocities at maximum absorption of a few transitions determined using the SYNOW code (Fisher et al. 1999). For comparison, we also plot the Si \(\text{ii}\) velocity of the BL SN 1998bw (Patat et al. 2001) and of the normal Type-Ic SN 1994I (Sauer et al. 2006), showing that the velocities of SN 2008D are lower than those of BL SNe.

Figure 4. Velocity at maximum absorption of several transitions computed with SYNOW. Diamonds indicate the velocity for the 6200 Å line if interpreted as Si \(\text{ii}\) (filled symbols) or HV H\(\alpha\) (open symbols). The latter interpretation is unlikely due to the lack of corresponding H\(\beta\) (see also Tanaka et al. 2008). SN 2008D shows velocities lower than the prototypical hypernova SN 1998bw (Patat et al. 2001) and comparable to SN 1994I (Sauer et al. 2006).

Figure 5. Bolometric light curves of SN 2008D (Type Ib), SN 1993J (Type IIb), and SN 1999ex (Type Ib). Extinctions corresponding to \(E(B − V) = 0.8, 0.19\), and 0.30 mag were assumed. The cooling envelope phase was visible only in the \(U\) band for SN 1999ex.

2.3. Dust Extinction

It follows from the detection of strong Na \(\text{i}\) D with an equivalent width (EW) of 1.3 Å that the extinction toward SN 2008D is substantial in NGC 2770. Our best estimate of the reddening comes from comparing the colors of SN 2008D with those of stripped-envelope SNe, which have \(V − R \approx R − I \approx 0.1\) around maximum (e.g., Folatelli et al. 2006; Richmond et al. 1996; Galama et al. 1998). The resulting reddening is \(E(B − V) = 0.8\) mag, corresponding to an extinction \(A_V = 2.5\) mag (using the extinction law of Cardelli et al. (1989) with \(R_V = 3.1\)).

A large dust content is supported by absorption features in our high-resolution spectrum (see also Soderberg et al. 2008b). The Na \(\text{i}\) D1 absorption line indicates a multicomponent system, spanning a velocity range of 43 km s\(^{-1}\), which sets a lower limit \(E(B − V) > 0.2\) mag (Munari & Zwitter 1997; their Figure 4).
The Na I D versus $E(B-V)$ relation for SNe (Turatto et al. 2003) suggests 0.2 mag $\lesssim E(B-V) \lesssim 0.6$ mag. Diffuse interstellar bands (DIBs) are also detected at 5781.2, 5797.8, and 6283.9 Å (rest frame). Their EWs suggest 0.5 mag $\lesssim E(B-V) \lesssim 2$ mag (Cox et al. 2005). A dusty environment has been directly revealed through millimeter imaging of NGC 2770 (Gorosabel et al. 2008). Last, the hydrogen column density in the X-ray spectrum of the XT is $N_H = 6.9^{+1.8}_{-1.5} \times 10^{21}$ cm$^{-2}$ (assuming Solar abundances; Soderberg et al. 2008b). The gas-to-dust ratio is $N_H/A_V = 2.8 \times 10^{21}$ cm$^{-2}$ mag$^{-1}$, close to the Galactic value $1.7 \times 10^{21}$ cm$^{-2}$ mag$^{-1}$ (Predehl & Schmitt 1995).

3. DISCUSSION

The precise explosion epoch is so far only known for a few Type-II SNe, thanks to either the detection of the neutrino signal (SN 1987A; Hirata et al. 1987; Bionta et al. 1987) or of the UV flash by Galaxy Evolution Explorer (Shawinski et al. 2008; Gezari et al. 2008), and for BL Type-Ic SNe associated with GRBs (e.g., Galama et al. 1998; Hjorth et al. 2003; Stanek et al. 2003; Campaña et al. 2006). SN 2008D is the first Type-Ib SN with a very early phase of ordinary SNe, which will provide an ordinary Type-Ib SN opens the possibility of addressing this issue will require theoretical modeling and an enlarged sample. The discovery of a short-lived XT associated with an ordinary Type-Ib SN opens the possibility of accessing the very early phases of ordinary SNe, which will provide new insights into SN physics. Future X-ray sky-scanning experiments, such as Lobster or eROSITA, may turn out, rather unexpectedly, ideally suited to examine this issue, alerting us to the onset of many core-collapse SNe.

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