

The type IIb SN 2011dh - 2 years of observations and modelling of the bolometric and photometric lightcurves.

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Submitted to Astronomy and Astrophysics

ABSTRACT

We present optical and near-infrared (NIR) photometry and spectroscopy of the Type IIb supernova (SN) 2011dh spanning 2 years, and modelling of the bolometric and photometric lightcurves. To model the 0-100 days bolometric lightcurves of SNe 2011dh, 1993J and 2008ax, we use the hydrodynamical model grid and the fitting procedure presented in Ergon et al. (2014a), which allows us to determine the errors in the derived quantities. Using this method we find a helium core mass of $3.4^{+0.6}_{-0.3} M_{\odot}$ for SN 2011dh and similar values for SNe 1993J and 2008ax. Using a bolometric correction determined with steady-state NLTE modelling we extend the temporal coverage of the model grid to 300 days and applied to SN 2011dh we obtain results in good agreement with those based on the 0-100 days bolometric lightcurve. We present 100-500 days bolometric and photometric lightcurves for the Jerkstrand et al. (2014) steady-state NLTE models and discuss the constraints derived from the those on the model parameters. The optimal $12 M_{\odot}$ model, presented and found to give a good agreement with observed nebular spectra in Jerkstrand et al. (2014), shows a good agreement with the observed lightcurves, although the evolution in the MIR is only partly reproduced. Time-dependent NLTE modelling shows that after 600 days a steady-state assumption is no longer valid. The radioactive energy deposition in this phase is likely dominated by the positrons emitted in the decay of ^{56}Co but what energy source is dominating the emitted flux is unclear. We find an excess in the MIR developing between 100 and 200 days, during which an increase in the optical tail decline rates is also observed. Steady-state NLTE models with a modest amount of dust ($\tau = 0.25$) added during this period partly reproduce this behaviour. A modest amount of CO first overtone band emission is detected at 89 and 202 days implying a contribution to the Spitzer 4.5 μm band from CO fundamental band emission. Examining the steady-state NLTE models neither complete CO cooling nor absence of CO cooling in the C/O zone well reproduce the observed Spitzer 4.5 μm flux suggesting an intermediate scenario. Estimates of the sizes of the line emitting regions, ranging from $\sim 3000 \text{ km s}^{-1}$ for the oxygen lines to $\sim 1500 \text{ km s}^{-1}$ for the iron lines, suggest partial mixing of the nuclear burning zones, and the sizes of these regions are in all compared cases smaller than for SNe 1993J and 2008ax. The profiles of the [O I] 6300 Å and Mg I 4571 Å lines show a remarkable similarity, suggesting these lines to be emitted by the same material and to originate from the O/Ne/Mg zone. We use repetitions of small scale fluctuations in the [O I] 6300 Å and [O I] 6364 Å lines to estimate a line ratio close to 3, consistent with optically thin emission, from 200 days and onwards. This paper concludes our extensive observational and modelling work on SN 2011dh presented in a series of papers. The results from hydrodynamical modelling, steady-state NLTE modelling and stellar evolutionary progenitor analysis presented in Maund et al. (2011), Bersten et al. (2012), Jerkstrand et al. (2014) and this paper are all consistent and suggest an initial mass of $\sim 13 M_{\odot}$ for the progenitor. The initial masses of $\leq 15 M_{\odot}$ found for SNe 2011dh, 1993J and 2008ax, by hydrodynamical modelling and steady-state NLTE modelling in Jerkstrand et al. (2014) and this paper suggest that all of these Type IIb SNe originates from binary systems, as previously established for SN 1993J.

Key words. supernovae: general — supernovae: individual (SN 2011dh) — galaxies: individual (M51)

1. Introduction

Type IIb supernovae (SNe) are observationally characterized by a transition from Type II (with hydrogen lines) at early times to Type Ib (without hydrogen lines but with helium lines) at later times. The physical interpretation is that these SNe arise from stars that have lost most of their hydrogen envelope, ei-

ther through stellar winds or interaction with a binary companion. Which of these production channels are dominating is still debated but for SN 1993J, the prime example of such an SN, a companion star was detected by direct observations (Maund et al. 2004). The evolution of this binary system has been successfully modelled (Podsiadlowski et al. 1993; Stancliffe & El-

dridge 2009) and it is widely accepted that the companion was responsible for the removal of the hydrogen envelope. Bright, nearby Type IIb SNe as 1993J, 2008ax and the recent 2011dh are essential to improve our understanding of this class. Observations of the progenitor star in pre-explosion images, a search for the companion star when the SN has faded and multi-method modelling of high quality data, all provide important clues to the nature of Type IIb SNe and their progenitor stars.

In this paper we present the extensive optical and near-infrared (NIR) dataset, covering nearly two years, that we have obtained for SN 2011dh. The first 100 days of this dataset have been presented in Ergon et al. (2014b, hereafter E14a). Detailed hydrodynamical modelling of the SN using those data were presented in Bersten et al. (2012, hereafter B12) and steady-state NLTE modelling of nebular spectra in Jerkstrand et al. (2014, hereafter J14). Identification and analysis of the plausible progenitor star was presented in Maund et al. (2011, hereafter M11) and confirmation of the progenitor identification through its disappearance in E14a.

SN 2011dh was discovered on 2011 May 31.893 UT (Griga et al. 2011) in the nearby galaxy M51 at a distance of 7.8 Mpc (E14a). The SN has been extensively monitored from X-ray to radio wavelengths by several teams. Most observations cover the 3-100 days period, but late time data have been published in Tsvetkov et al. (2012), Van Dyk et al. (2013), Sahu et al. (2013), Shivvers et al. (2013) and Helou et al. (2013). As in E14a we focus on the UV to MIR emission. The explosion epoch, the distance to M51 and the interstellar line-of-sight extinction towards the SN used in this paper, are all adopted from E14a.

The nature of the progenitor star has been a key issue since the identification of a yellow supergiant in pre-explosion images, coincident with the SN (M11; Van Dyk et al. 2011). Recent progress in modelling of the SN (B12; J14; Shivvers et al. 2013) and the disappearance of the progenitor candidate (E14a; Van Dyk et al. 2013) strengthens the hypothesis that the progenitor was a yellow supergiant of moderate mass, as was originally proposed in M11. In this paper we present further modelling in support of this hypothesis. As shown in Benvenuto et al. (2013) a binary interaction scenario that reproduces the observed and modelled properties of the yellow supergiant is possible. HST observations that could detect or set useful constraints on the presence of a companion star are scheduled for Cycle 21.

The paper is organized as follows. In Sect. 2 we present the observations and describe the reduction and calibration procedures and in Sect. 3 we present an observational analysis and comparison of the observations to SNe 1993J and 2008ax. In Sect. 4 we model the bolometric and photometric lightcurves and in Sect. 5 we review the results we have obtained for SN 2011dh so far and the implication for our understanding of Type IIb SNe. Finally, we conclude and summarize the paper in Sect. 6.

2. Observations

2.1. Software

As in E14a two different software packages have been used for 2-D reductions, measurements and calibrations of the data. The IRAF based QUBA pipeline (Valenti et al. 2011, hereafter V11) and another IRAF based package which we will refer to as the SNE pipeline. This package has been developed with the particular aim to provide the high level of automation needed for large sets of data.

2.2. Imaging

An extensive campaign of optical and NIR imaging was initiated for SN 2011dh shortly after discovery using a multitude of different instruments. The observations during the first 100 days have been described in E14a. The late time data were obtained with the Liverpool Telescope (LT), the Nordic Optical Telescope (NOT), Telescopio Nazionale (TNG), the Calar Alto 3.5m (CA 3.5m) and 2.2m (CA 2.2m) telescopes, the Asiago 67/92cm Schmidt (AS Schmidt) and 1.82m Copernico (AS 1.82m) telescopes, the William Herschel Telescope (WHT), the Albanova Telescope (AT) and the United Kingdom Infrared Telescope (UKIRT). The major contributors were the NOT, the AS Schmidt and the AT for the optical observations and the CA 3.5m, the WHT and the UKIRT for the NIR observations. The late time dataset includes 61 epochs of optical imaging and 9 epochs of NIR imaging which, together with the early time observations, gives a total of 146 epochs of optical imaging and 32 epochs of NIR imaging.

2.2.1. Reductions and calibration

The optical and NIR raw data have been reduced with the QUBA and SNE packages respectively as described in E14a, except for the optical LT and NIR UKIRT data for which reductions provided by the automated telescope pipelines have been used. Photometry was performed with the SNE pipeline as described in E14a. Comparison to photometry on template subtracted images shows that the background contamination is negligible before ~ 300 days after which we have used photometry on template subtracted images. The optical and NIR photometry was calibrated to the Johnson-Cousins (JC), Sloan Digital Sky Survey (SDSS) and 2 Micron All Sky Survey (2MASS) systems as described in E14a where we also discuss the related uncertainties. The photometry was transformed to the standard systems using S-corrections (Stritzinger et al. 2002) as described in E14a, except for the JC U and SDSS u bands which were transformed using the linear colour-terms tabulated in E14a. As discussed in E14a we find the calibration to be accurate to within five percent in all bands for the first 100 days. The accuracy of the late time photometry depends critically on the accuracy of the S-corrections. The late time JC and SDSS photometry were mainly obtained with the NOT but comparisons between S-corrected NOT, LT and CA 2.2m JC and SDSS observations at ~ 300 days show differences at the 5 percent level suggesting that this precision is maintained. We note that in this phase S-corrections are absolutely necessary. For example the difference between the NOT and CA 2.2m I band observations are almost one magnitude at ~ 300 days if these are not applied, mainly because of the strong [Ca II] 7291,7323 Å and Ca II 8498,8542,8662 Å lines. The late time 2MASS photometry was obtained with a number of different telescopes and although the sampling is sparse the shape of the lightcurves suggests that the errors in the S-corrections are modest. Note that we have used JC-like $UBVRI$ filters and SDSS-like gz filters at NOT whereas we have used JC-like BV filters and SDSS-like $ugriz$ filters at LT. The JC-like URI and SDSS-like uri photometry were then tied to both the JC and SDSS systems to produce full sets of JC and SDSS photometry.

!We probably add a discussion here, or possible a separate section, on the very late time observations and the uncertainties in these.!

2.2.2. Space Telescope Observations

We have also performed photometry on the Spitzer 3.6 and 4.5 μm imaging¹ using the *sNE* pipeline as described in E14a to calculate magnitudes in the natural (energy flux based) Vega system of IRAC. All Spitzer images were template subtracted as described in E14a and the photometry is in good agreement with that published in Helou et al. (2013) !quantify this!. Optical and UV SWIFT magnitudes were published in E14a.

2.2.3. Results

The S-corrected optical and NIR magnitudes and their corresponding errors are listed in Tables 4, 5 and 6 and the Spitzer 3.6 and 4.5 μm magnitudes and their corresponding errors in Table 7. For completeness we also include the magnitudes for the first 100 days already published in E14a. All magnitudes, including the SWIFT magnitudes published in E14a, are shown in Fig. 1 which also shows cubic spline fits using 3-5 point knot separation, error weighting and a 5 percent error floor or, when the sampling is sparse, linear interpolations as well as extrapolations assuming a constant colour to adjacent bands. All calculations in Sect. 3, including the construction of the bolometric lightcurve, are based on these spline fits, interpolations and extrapolations. In these calculations the errors in the fitted splines have been estimated as the standard deviation and then propagated.

2.3. Spectroscopy

An extensive campaign of optical and NIR spectroscopic observations was initiated for SN 2011dh shortly after discovery with data obtained from a multitude of telescopes. The observations during the first 100 days have been described in E14a. The late time data were obtained with the NOT, the TNG, the WHT, the CA 2.2m, the Asiago 1.22m Galileo telescope (AS 1.22m), and the Gran Telescopio Canarias (GTC). The major contributors were the NOT, the WHT and the GTC. Details of all spectroscopic observations, the telescope and instrument used, epoch and instrument characteristics are given in Table 8. The late time dataset includes 18 optical spectra obtained at 13 epochs and 2 NIR spectra obtained at 2 epochs which, together with the early time observations, gives a total of 73 optical spectra obtained at 39 epochs and 20 NIR spectra obtained at 12 epochs.

2.3.1. Reductions and calibration

The optical and NIR raw data were reduced and the flux extracted using the *QUBA* and *sNE* pipelines respectively as described in E14a. The optical and NIR spectra were flux and wavelength calibrated using the *QUBA* and *sNE* pipelines respectively as described in E14a. The absolute flux scale of all spectra has been calibrated against interpolated photometry using a least square fit to all bands for which the mean energy wavelength is at least half an equivalent width within the spectral range.

!Some spectra still has to be corrected for telluric absorption. The wavelength calibration of all spectra, with the important exception of the ~ 200 days NIR spectra, have been checked against skylines but some have not been shifted yet (but in all these cases the shift is very small)!.

2.3.2. Results

All reduced, extracted and calibrated spectra will be made available for download from the Weizmann Interactive Supernova data REpository² (WISeREP) (Yaron & Gal-Yam 2012). Figure 3 shows the sequence of observed spectra where those obtained on the same night using the same telescope and instrument have been combined. For clarity some figures in this and the following sections are based on time-interpolations of the spectral sequence as described in E14a. To further visualize the evolution, the spectra have been aligned to a time axis at the right border of the panels. Interpolated spectra were used in the calculations of the bolometric lightcurve (Sect. 3.2) and S-corrections. Figure 2 shows the interpolated optical and NIR spectral evolution of SN 2011dh for 5–425 days with a 20-day sampling. All spectra in this and subsequent figures have been corrected for redshift and interstellar extinction.

3. Analysis

In this section we provide an analysis of the data and a comparison of these to the Type IIb SNe 1993J and 2008ax. Besides SN 2011dh, these are the best monitored Type IIb SNe so far, which motivates a detailed comparison. Both occurred in nearby galaxies, have progenitor detections and well constrained explosion epochs. We keep the analysis of the photometric and bolometric evolution observational, as we return to the physical interpretation in Sect. 4, where we present steady-state NLTE and hydrodynamical modelling of these data. The analysis of the spectral evolution is complementary to the steady-state NLTE modelling of these data in J14, and we therefore frequently refer to this paper and the results obtained therein. The early (0-100 days) evolution of SN 2011dh, as well as comparisons in this phase to SNe 1993J and 2008ax, were discussed in E14a, and here we focus on the evolution after 100 days.

As discussed in E14a, the systematic errors stemming from the uncertainties in distance and extinction are large for all three SNe, which should be kept in mind when absolute quantities are compared. For SNe 1993J and 2008ax we adopt the same values and error bars for the distance and extinction as in E14a. The references for the photometric and spectroscopic data of SNe 1993J and 2008ax used in the comparison are the same as specified in E14a !not true, we use additional late time data!. We note that the lack of S-corrected photometry for SN 1993J complicates the comparison, whereas for SN 2008ax the S-corrected JC photometry by Taubenberger et al. (2011) agrees reasonably well with the JC photometry by Tsvetkov et al. (2009).

3.1. Photometric evolution

Absolute magnitudes were calculated as in E14a. In Fig. 4 we show absolute optical and NIR magnitudes for SN 2011dh as compared to SNe 1993J and 2008ax, and in Table 1 we tabulate the tail decline rates at 100, 200 and 300 days. Most striking is the similarity between the lightcurves, except for a shift towards higher luminosities for SNe 1993J and 2008ax, the shift being larger in bluer bands and negligible in the NIR and most pronounced for SN 2008ax. As discussed in E14a, this difference could be explained by an error in the adopted extinctions.

Given the caveat that SNe 1993J and 2008ax are only partly covered in *U* and NIR, we find the following general trends. At 100 days the *V*, *R* and *I* decline rates are roughly twice the de-

¹ Obtained through the DDT program by G. Helou.

² <http://www.weizmann.ac.il/astrophysics/wiserep/>

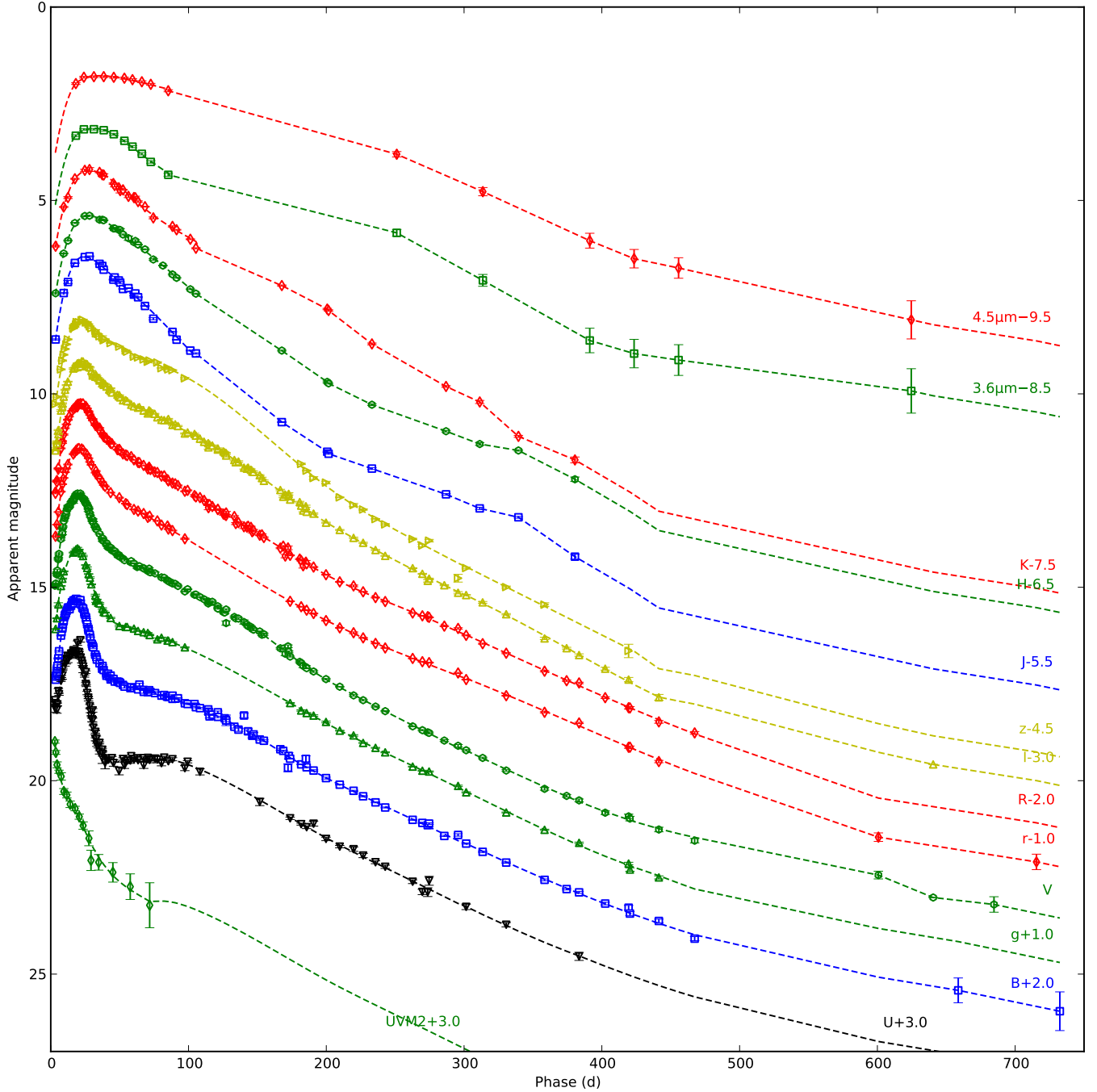


Fig. 1. Photometric evolution of SN 2011dh in the UV, optical, NIR and MIR. For clarity each band has been shifted in magnitude. Each lightcurve has been annotated with the name of the band and the shift applied. We also show combinations of spline fits, interpolations and extrapolations described in Sect 2.2.3 (dashed lines).

cay rate of ^{56}Co , and subsequently decrease towards 300 days. The U and B decline rates are significantly lower at 100 days, subsequently approach the other optical decline rates and then evolve similarly. The J and H band decline rates are considerably higher than the optical at 100 days, subsequently approaches those and eventually become considerably lower. For SNe 2011dh and 1993J the K band behaves quite differently than the other NIR bands. At 100 days the decline rate is significantly lower, but as it remains roughly constant, it subsequently approach the other NIR decline rates and eventually becomes considerably higher. As seen in Fig. 1, the optical lightcurves of

SN 2011dh flatten considerably after ~ 450 days, approaching a decline rate similar to, or lower than, the decay rate of ^{56}Co .

Both SNe 2011dh and 1993J were also monitored in the MIR, SN 2011dh in the Spitzer 3.6 and 4.5 μm bands and SN 1993J in the L band, which is similar to the Spitzer 3.6 μm band. For both SNe a strong excess in the MIR develops between ~ 100 and ~ 250 days. For SN 1993J the MIR coverage ends at ~ 250 days and for SN 2011dh the subsequent evolution is fairly similar to the evolution in the optical, and the considerable flattening seen in the optical lightcurves after ~ 450 days, is also seen in the Spitzer lightcurves.

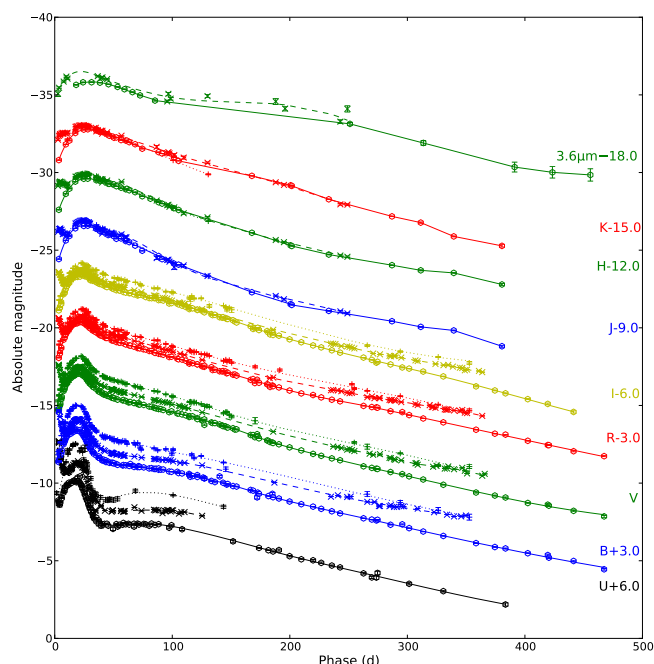


Fig. 4. Photometric evolution of SN 2011dh (dots) in the optical and NIR as compared to SNe 1993J (crosses) and 2008ax (pluses). For clarity each band has been shifted in magnitude. Each lightcurve has been annotated with the name of the band and the shift applied. We also show combinations of spline fits, interpolations and extrapolations described in Sect. 2.2.3 (dashed lines).

I have removed a discussion on the colour evolution here. Maybe this should be included, I'm not sure. It is a very long paper.!

3.2. Bolometric evolution

As in E14a we have used a combination of the spectroscopic and photometric methods, applied to wavelength regions with and without spectral information respectively, when calculating the pseudo-bolometric lightcurves. The details of these methods have been described in E14a. Combinations of spline fits, interpolations and extrapolations, as described in Sect. 2.2.3 and shown in Figs. 1 and 4, have been used to calculate the magnitudes.

Figure 5 shows the U to K (3300-24000 Å) pseudo-bolometric lightcurves for SN 2011dh as compared to SNe 1993J and 2008ax for the 0-500 days period as calculated with the photometric method, and in Table 2 we tabulate the decline rates at 100, 200 and 300 days. Given the caveat that SNe 1993J and 2008ax are not covered in NIR after ~ 250 and ~ 150 days respectively, their U to K pseudo-bolometric lightcurves are remarkably similar to the one of SN 2011dh, except for the shift towards higher luminosities discussed previously in Sect. 3.1. The decline rates decrease from ~ 0.020 mag day $^{-1}$, roughly twice the decay rate of ^{56}Co , at 100 days to ~ 0.015 mag day $^{-1}$ at 300 days. There is however a significant increase in the decline rate between ~ 150 and ~ 200 days for SN 2011dh, not seen for SNe 1993J and 2008ax. For SN 1993J the decline rate becomes increasingly lower towards 300 days as compared to SNe 2011dh and 2008ax, which is consistent with an increasing contribution from CSM interaction in this phase.

Figure 6 shows the UV to MIR (1900-50000 Å) pseudo-bolometric lightcurve for SN 2011dh, as calculated with the

Table 1. Tail decline rates at 100, 200 and 300 days for SN 2011dh compared to SNe 1993J and 2008ax as measured from cubic spline fits.

SN	Band	Rate (100 d) (mag day $^{-1}$)	Rate (200 d) (mag day $^{-1}$)	Rate (300 d) (mag day $^{-1}$)
2011dh	U	0.013	0.019	0.018
2011dh	B	0.014	0.019	0.017
2011dh	V	0.018	0.021	0.018
2011dh	R	0.020	0.019	0.016
2011dh	I	0.019	0.021	0.017
2011dh	J	0.036	0.017	0.012
2011dh	H	0.029	0.019	0.011
2011dh	K	0.020	0.020	0.024
1993J	U	0.006	...	...
1993J	B	0.011	0.017	0.012
1993J	V	0.019	0.019	0.017
1993J	R	0.022	0.015	0.013
1993J	I	0.022	0.019	0.013
1993J	J	0.041	0.016	...
1993J	H	0.033	0.018	...
1993J	K	0.023	0.022	...
2008ax	U	0.013	...	...
2008ax	B	0.015	0.018	0.016
2008ax	V	0.022	0.018	0.017
2008ax	R	0.023	0.016	0.015
2008ax	I	0.018	0.021	0.013
2008ax	J	0.035	...	...
2008ax	H	0.032	...	...
2008ax	K	0.033	...	...

combined spectroscopic and photometric methods, and in Table 9 we tabulate the 3-300 days period (for which we have full UV to MIR coverage) for reference. As expected, the UV to MIR and U to K pseudo-bolometric lightcurves are very simi-

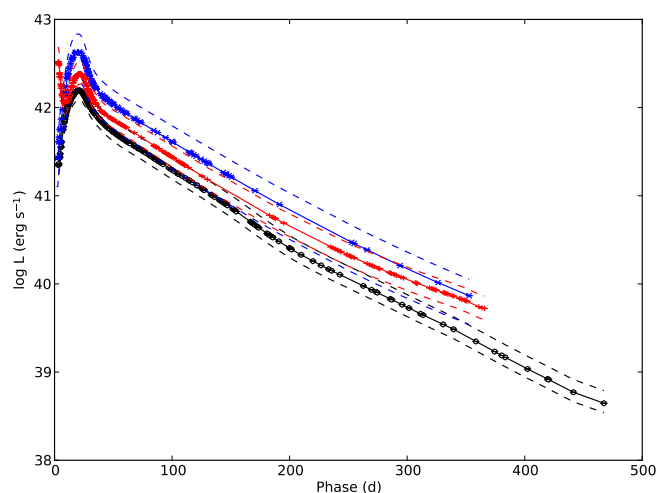


Fig. 5. Pseudo-bolometric U to K lightcurve for SN 2011dh (black circles and solid line) calculated with the photometric method as compared to SNe 1993J (red crosses and solid line) and 2008ax (blue pluses and solid line). The upper and lower error bars for the systematic error arising from extinction and distance (dashed lines) are also shown.

Table 2. Tail decline rates at 100, 200, and 300 days for the U to K bolometric lightcurve of SN 2011dh compared to SNe 1993J and 2008ax.

SN	Rate (100 d) (mag day ⁻¹)	Rate (200 d) (mag day ⁻¹)	Rate (300 d) (mag day ⁻¹)
2011dh	0.021	0.021	0.016
2008ax	0.020	0.017	0.015
1993J	0.021	0.017	0.013

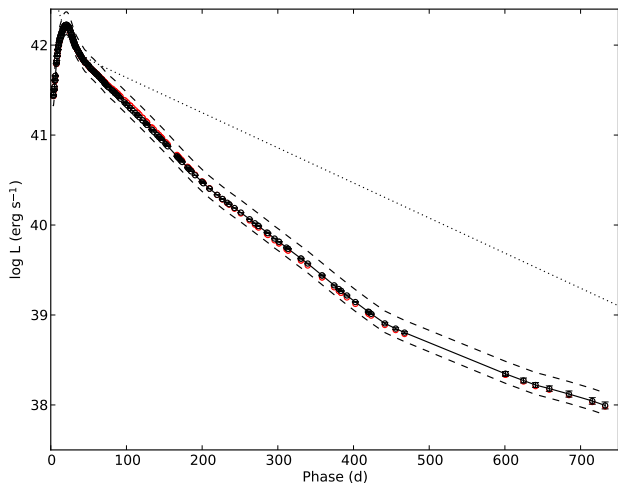


Fig. 6. Pseudo-bolometric UV to MIR lightcurve for SN 2011dh calculated with the spectroscopic (black circles and solid line) and photometric (red circles) method. The upper and lower error bars for the systematic error arising from extinction and distance (black dashed lines) and the radioactive decay chain luminosity of $0.075 M_{\odot}$ of ^{56}Ni (black dotted line) are also shown.

lar. The decline rates at 100, 200, 300 and 400 days are 0.021, 0.022, 0.015 and 0.016 mag day⁻¹, but the increase in decline rate between ~ 150 and ~ 200 days is not as pronounced as in the U to K pseudo-bolometric lightcurve. Given the caveats that the NIR coverage ends at ~ 350 days, and the sampling is sparse and the measurement errors large after ~ 500 days, the UV to MIR pseudo-bolometric lightcurve shows a significant flattening after ~ 500 days, when the decline rate decreases to a value similar to, but lower than, the decay rate of ^{56}Co .

Figure 7 shows the fractional UV (1900-3300 Å), optical (3300-10000 Å), NIR (10000-24000 Å) and MIR (24000-50000 Å) luminosities for SN 2011dh. The early evolution was discussed in E14a, and after 100 days the most notable is the strong increase in the MIR fraction between ~ 100 and ~ 250 days. The subsequent evolution becomes quite uncertain after ~ 350 days when the NIR coverage ends and ~ 500 days when the sampling and measurement errors become worse, but the optical, NIR and MIR fractions seems to be roughly constant during this period. Keeping these uncertainties in mind it is worth noting the dominance of the optical flux even at ~ 750 days.

Figure 8 shows the evolution of the SED as calculated with the photometric method, overplotted with blackbody fits to the V , I , J , H and K photometry as well as the observed (interpolated) spectra. The early evolution was discussed in E14a, and after 100 days the most notable is again the strong excess de-

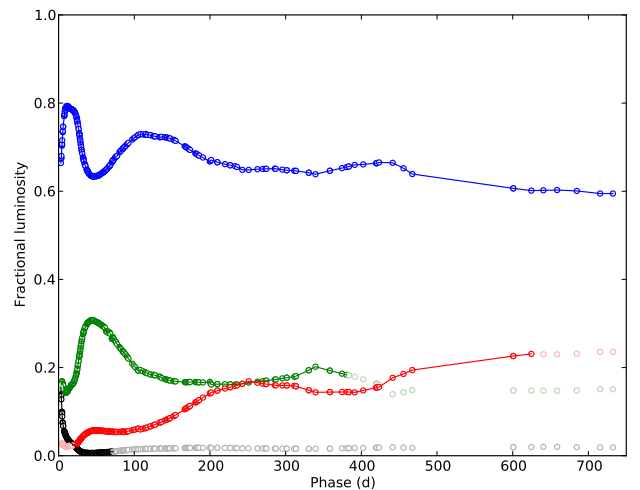


Fig. 7. Fractional UV (black dots), optical (blue dots), NIR (green dots) and MIR (red dots) luminosity for SN 2011dh. Luminosities based on extrapolated magnitudes are displayed in shaded colour.

veloping in the MIR between ~ 100 and ~ 250 days. There also seems to be a similar excess developing in the K band between ~ 100 and ~ 200 days, gradually fading away towards 300 days.

3.3. Spectroscopic evolution

The early spectral evolution was discussed in some detail in E14a and in this section we focus on the spectral evolution from 100 days and onwards. Steady-state NLTE modelling of this evolution as well as a detailed analysis of the formation of the identified lines and the evolution of their fluxes are presented in J14. In this section we summarize the findings in J14 and provide a complementary analysis, mainly related to the line profiles and what can be learned about the distribution of the material from the different nuclear burning zones. In doing this we refer to the subdivision of the (unmixed) ejecta described in J14 with a Fe/Co/He core surrounded by the Si/S zone, the oxygen-rich O/Si/S, O/Ne/Mg and O/C zones, the helium-rich He/C and He/N zones and the hydrogen-rich envelope. The amount of macroscopic mixing between these zones is determined by hydrodynamical instabilities in the explosion (Hammer et al. 2010) and is a free parameter in the steady-state NLTE modelling.

3.3.1. Line profiles and emitting regions

To characterize the line profiles in an observational way we calculate the typical wavelength and widths of the lines. The typical wavelength of the line is calculated as the first wavelength moment of the flux (center of flux) and the typical widths as the blue- and red-side regions containing 76 percent of the flux, corresponding to the half-width-half-maximum (HWHM) of a Gaussian profile. Both these quantities are quite insensitive to the continuum subtraction and are thus suitable for characterization and comparison to other SNe. The continuum level is determined by a linear interpolation between the minimum flux levels on the blue and red sides within a region set to ± 6000 km s⁻¹ for most of the lines, ± 10000 km s⁻¹ for the Ca II 8662 Å line and ± 3000 km s⁻¹ for the [Fe II] 7155 Å line.

Figure 10 shows the center of flux and blue- and red-side widths as compared to the rest wavelength for the [O I] 6300, 6364 Å, [O I] 5577 Å, Mg I] 4571 Å, Na I 5890, 5896 Å,

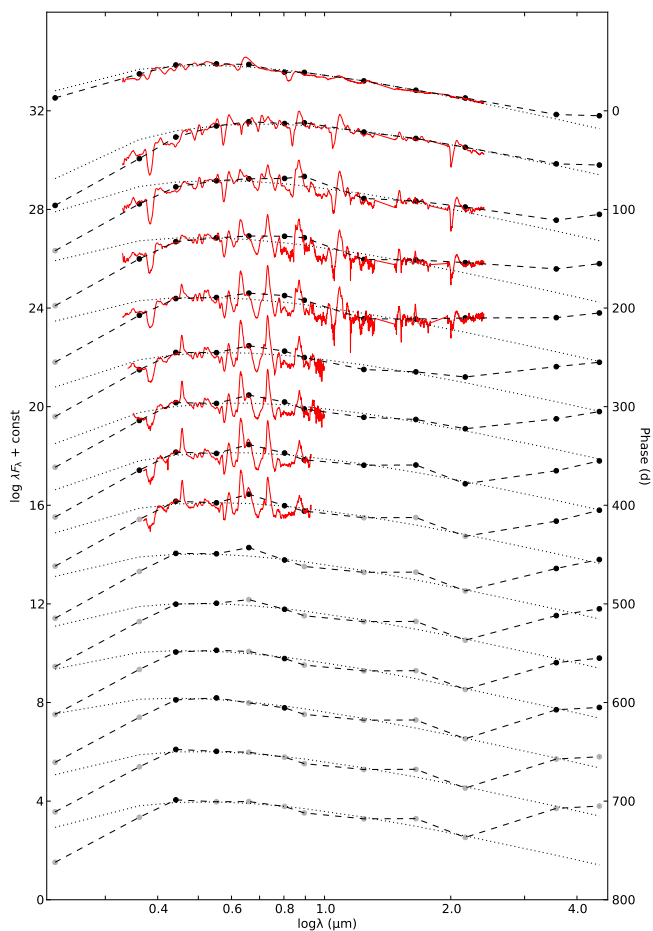


Fig. 8. The evolution of the SED as calculated with the photometric method (black dots and dashed lines) overplotted with blackbody fits to the V , I , J , H and K photometry (black dotted lines) as well as the observed spectra interpolated as described in Sect. 2.3.2 (red solid lines). Fluxes based on extrapolated magnitudes are displayed in shaded colour.

[Ca II] 7291,7323 Å, Ca II 8498,8542,8662 Å and [Fe II] 7155 Å lines calculated with this method. The rest wavelength is assumed to be 6316 Å for the [O I] 6300,6364 Å line as is appropriate for a line ratio of 3 and 5993 Å, 7307 Å and 8662 Å for the Na I 5890,5896 Å, [Ca II] 7291,7323 Å and Ca II 8498,8542,8662 Å lines respectively.

To estimate the sizes of the line emitting regions and the absorptive continuum optical depths required to cause the blue-shift of the typical wavelength seen in many lines we use a method based partly on the knowledge gained from J14. For lines found to be optically thin using the steady-state NLTE modelling, we fit the line profile of a spherically symmetric region of constant line emissivity, optically thin in the line and with a constant absorptive continuum opacity, to the observed line profile. This gives a rough estimate of the size of the region responsible for the bulk of the line emission.

Some lines arise as a blend of more than one line which has to be taken into account. The [O I] 6300 Å flux was calculated by iterative subtraction of the [O I] 6364 Å flux, from the left to the right, using $F_{6300}(\lambda) = F_{6300,6364}(\lambda) - F_{6300}(\lambda - \Delta\lambda)/R$, where $\Delta\lambda$ is the wavelength separation between the [O I] 6300 Å and 6364 Å lines and R the [O I] 6300,6364 Å line ratio. This ratio was assumed to be 3, as is supported by the steady-state

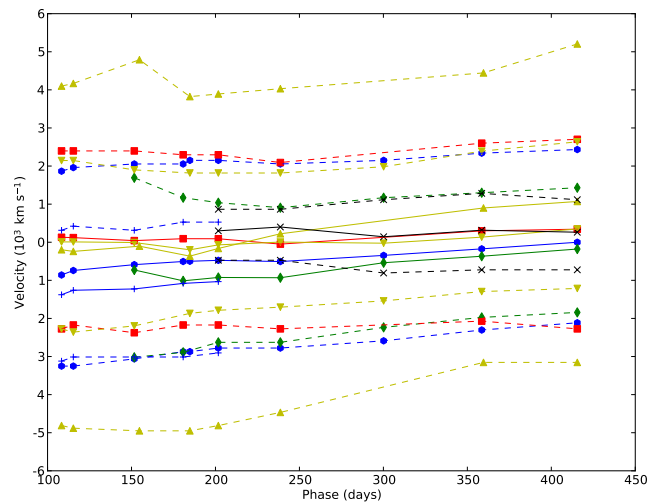


Fig. 10. Center of flux velocities (solid lines) and the blue- and red-side widths (dashed lines) as compared to the rest wavelengths for the [O I] 6300,6364 Å (blue dots), Mg I 4571 Å (green diamonds), Na I 5890,5896 Å (red squares), [Ca II] 7291,7323 Å (yellow downward triangles), Ca II 8498,8542,8662 Å (yellow upward triangles), [Fe II] 7155 Å (black crosses) and [O I] 5577 Å (blue pluses) lines.

NLTE modelling and estimates based on small scale variations (Sect. 3.3.10). In all other cases, where the line ratios of the blended lines are not known, we make a simultaneous fit assuming the same size of the emitting region for all of the blended lines.

3.3.2. Hydrogen lines

Summary of the findings in J14: No (isolated) hydrogen lines are identified. Some $H\alpha$ emission arising from the hydrogen-rich envelope is present, but is found to be increasingly dominated by [N II] 6548,6583 Å emission arising from the helium zone after ~150 days. No detectable absorption is found in $H\alpha$ or any of the other hydrogen lines.

Figure 9 shows the post 100 days (interpolated) spectral evolution centred on the $H\alpha$ line. There is a dip in the [O I] 6300,6364 Å line profile after ~150 days, that corresponds well to the early time $H\alpha$ absorption minimum at ~11000 km s⁻¹ (E14a). However, as discussed in Sect. 3.3.10, this feature repeats in a number of other lines and is rather due to clumping/asymmetries in the ejecta. There is also an emerging emission feature near the rest wavelength of $H\alpha$ after ~200 days which, given the findings in J14, is rather be due to [N II] 6548,6583 Å emission.

Using the method described in Sect. 3.3.1, we find the feature to be well fitted by emission from a region with a radius of 5500 km s⁻¹, emitting mainly in the [N II] 6583 Å line, although the wings of the observed line profile may extend to ~12000 km s⁻¹ on the red side. $H\alpha$ emission from the hydrogen-rich envelope is expected to result in a flat-topped line profile, at least 11000 km s⁻¹ wide (E14a). The size of the line emitting region, as well as the extent of the wings, is instead consistent with emission from the helium zone, in agreement with the results in J14.

!But the peak at late times is exactly at the rest wavelength of $H\alpha$. What does this mean?!

3.3.3. Helium lines

Summary of the findings in J14: The (isolated) helium lines identified are the He I 10830 Å and He I 20581 Å lines, although the He I 10830 Å line is found to be blended with the [S I] 10820 Å line. The helium lines arise mainly from the helium zone, but there is also some contribution from helium in the Fe/Co/He zone. Both lines are found to be optically thick, implying a significant contribution from line scattering.

Figure 9 shows the post 100 days (interpolated) spectral evolution for the identified helium lines. The He I 10830 Å and He I 20581 Å lines emerge at ~10 and ~15 days respectively (E14a) and remain until our spectral coverage ends, both in emission and absorption.

Both the He I 10830 Å and He I 20581 Å lines have P-Cygni like profiles, suggesting a significant contribution from scattering, in agreement with the results in J14. Although the unblended He I 20581 Å line has a quite broad peak it is not flat-topped, suggesting a contribution from helium at low velocities. This is again in agreement with the results in J14, where we find helium in the Fe/Co/He zone to contribute significantly at low velocities.

3.3.4. Oxygen lines

Summary of the findings in J14: The (isolated) oxygen lines identified are the [O I] 5577 Å, O I 7774 Å, O I 9263 Å, O I 11300 Å, O I 13164 Å and [O I] 6300,6364 Å lines, although the O I 9263 Å line is found to be blended with the [Co II] 9338,9344 Å line on the red side. All these lines are found to arise from the oxygen zones, the part arising from the O/C and O/Si/S zones depending sensitively on the amount of molecule (CO and SiO) cooling in these zones.

Figure 9 shows the post 100 days (interpolated) spectral evolution for the identified oxygen lines. The allowed oxygen lines emerge between ~25 and ~50 days (E14a) and, except for the [O I] 5577 Å line which disappears at ~300 days, remain until our spectral coverage ends. The [O I] 6300,6364 Å line emerges at ~100 days and remains until our spectral coverage ends.

We measure the radius of the [O I] 6300,6364 Å line emitting region to 3400, 3100 and 2900 km s⁻¹ at 202, 300 and 415 days respectively. The line profile fits (Fig.11) are quite good, but the observed emission is underestimated at low velocities and extends to at least ~5000 km s⁻¹, suggesting radially decreasing emissivity.

The center of flux of the [O I] 6300,6364 Å line shows a blue-shift of ~1000 km s⁻¹ at 100 days, decreasing towards zero at 400 days, whereas the center of flux of the [O I] 5577 Å line shows a blue-shift of ~1500 km s⁻¹ at 100 days, decreasing towards ~1000 km s⁻¹ at 200 days, when the line begins to fade away. We do not find any significant blue-shifts of the O I 11300 and 13164 Å lines. The blue-shifts are discussed further in Sect.3.3.11, where we compare to observation of other SNe, and in J14, where we suggest the physical cause to be line-blocking in the core.

3.3.5. Sodium lines

Summary of the findings in J14: The only (isolated) sodium line identified is the Na I 5890,5896 Å line. Observationally this line is hard to disentangle from the He I 5876 Å line, but the emission is found to arise mainly from the Na I 5890,5896 Å line (al-

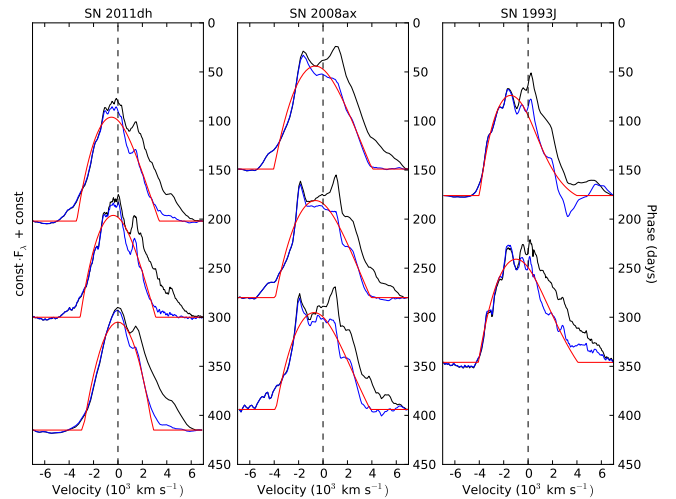


Fig. 11. [O I] 6300,6364 Å (black) and decomposed [O I] 6300 Å (blue) line profiles at selected epochs as compared to line profile fits (red) for SNe 2011dh (left panel), 2008ax (middle panel) and 1993J (right panel).

though absorption could be a blend), and to be a combination of recombination emission from the O/Ne/Mg zone and scattering throughout the ejecta.

Figure 9 shows the post 100 days (interpolated) spectral evolution for the Na I 5890,5896 Å line. The line has a P-Cygni like profile, suggesting a significant contribution from scattering, in agreement with the results from J14 and remains, both in emission and absorption, until our spectral coverage ends.

3.3.6. Magnesium lines

Summary of findings in J14: The (isolated) magnesium lines identified are the Mg I 4571 Å and Mg I 15040 Å lines, and both are found to arise mainly from the O/Ne/Mg zone.

Figure 9 shows the post 100 days (interpolated) spectral evolution for the identified magnesium lines. The Mg I 4571 Å line emerges at ~150 days whereas the Mg I 15040 Å line may emerge as early as ~40 days (E14a) and both remain until our spectral coverage ends.

We measure the radius of the Mg I 4571 Å line emitting region to 3600, 2800 and 2700 km s⁻¹ at 202, 300 and 415 days respectively, and the radius of the Mg I 15040 Å line emitting region to 3400 and 2900 km s⁻¹ at 89 and 205 days respectively. The line profile fits (Fig. 12) of the Mg I 4571 Å line are quite good, but the observed emission is underestimated at low velocities and extends to at least ~5000 km s⁻¹, suggesting radially decreasing emissivity.

The center of flux of the Mg I 4571 Å line shows a blue-shift of ~1000 km s⁻¹ at ~200 days, decreasing towards a few hundred km s⁻¹ at ~400 days. We do not find any significant blue-shift of the Mg I 15040 Å line. The blue-shifts are discussed further in Sect.3.3.11, where we compare to observation of other SNe, and in J14, where we suggest the physical cause to be line-blocking in the core.

The estimated radius of the Mg I line emitting region of 2700-3600 km s⁻¹ is similar to the estimated radius of the O I line emitting region of 2900-3400 km s⁻¹. As mentioned above the Mg I lines are found in J14 to arise from the O/Ne/Mg zone and the O I lines to arise from the O/Ne/Mg zone and, depending

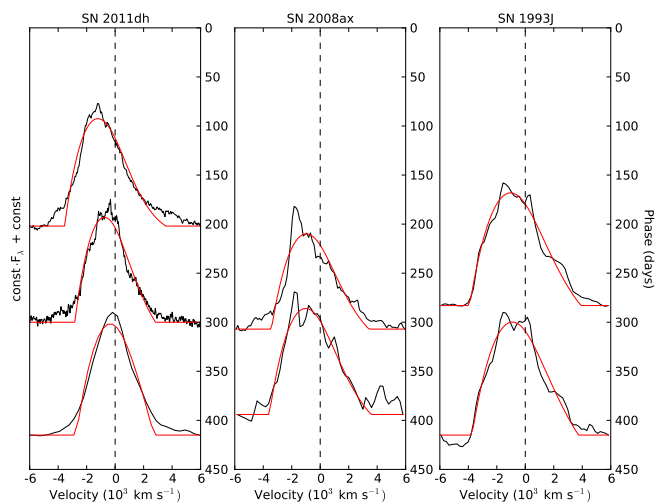


Fig. 12. Mg I 4571 Å line profiles (black) at selected epochs as compared to line profile fits (red) for SNe 2011dh (left panel), 2008ax (middle panel) and 1993J (right panel).

on the amount of molecule (CO and SiO) cooling, the O/C and O/Si/S zones. As is evident from Figs. 11 and 12 (but see also Fig. 16) the profiles of the [O I] 6300 and the Mg I 4571 Å lines are very similar, suggesting these to arise from the O/Ne/Mg zone. In Sect. 3.3.10 we find this to be true also for small scale variations in the line profiles in further support of this hypothesis.

3.3.7. Calcium lines

Summary of the findings in J14: The (isolated) calcium lines identified are the Ca II 3934,3968 Å, Ca II 8498,8542,8662 Å and [Ca II] 7291,7323 Å lines. Absorption in the Ca II 3934,3968 Å lines is found to occur throughout the ejecta and the Ca II 8498,8542,8662 Å lines to arise mainly from fluorescence in these lines. The [Ca II] 7291,7323 Å lines, on the other hand, is found to arise mainly from the Si/S zone, with a possible contribution throughout the ejecta from fluorescence in the Ca II 3934,3968 Å lines. The Ca II 8498,8542,8662 Å line is found to be blended with the [C I] 8727 Å line, arising mainly from the O/C zone, the amount of blending depending sensitively on the amount of molecule (CO) cooling in this zone.

Figure 9 shows the post 100 days (interpolated) spectral evolution for the identified calcium lines. The Ca II 3934,3968 Å line is present initially in absorption (E14a) and remains so until the spectral coverage ends. The Ca II 8498,8542,8662 Å line is present initially with a P-Cygni profile (E14a), but disappears in absorption at ~100 days. The Ca II 8498,8542 Å lines disappear in emission at ~300 days, whereas the Ca II 8662 Å line remains until the spectral coverage ends. The [Ca II] 7291,7323 Å line emerges at ~100 days and remains until the spectral coverage ends.

We measure the radii of a two-component [Ca II] 7291,7323 Å line emitting region to 2400/9900, 2100/9100 and 2400/9000 km s⁻¹ at 202, 300 and 415 days respectively. The line profile fits (Fig. 13) are good in the inner region but worse in the wings, which are quite asymmetric and also blended with the [Fe II] 7155 Å line on the blue side. The more pronounced red-side wing could indicate a P-Cygni like contribution from scattering.

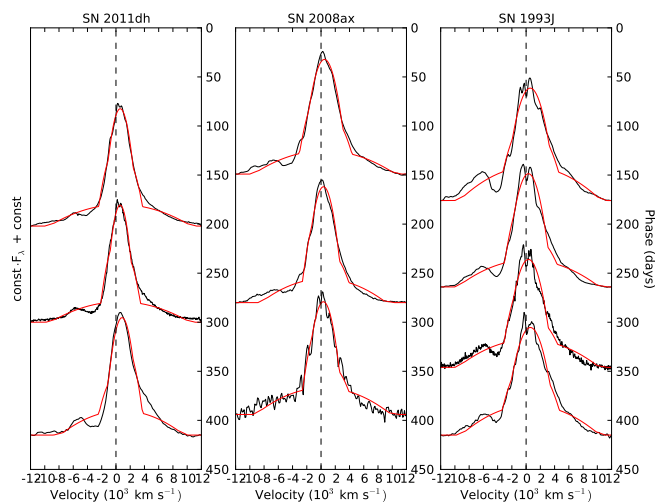


Fig. 13. [Ca II] 7291,7323 Å line profiles (black) at selected epochs as compared to line profile fits (red) for SNe 2011dh (left panel), 2008ax (middle panel) and 1993J (right panel).

The center of flux for the Ca II 8498,8542,8662 Å line shows a red-shift increasing towards ~1000 km s⁻¹ at 400 days. As the center of flux is calculated with respect to the rest wavelength of the Ca II 8662 Å line (Sect. 3.3.1) this suggests a significant contribution from the [C I] 8727 Å line to the flux, which is in agreement with the results from J14 if the amount of molecule (CO) cooling in the C/O zone is modest.

The size of the inner [Ca II] 7291,7323 Å line-emitting region of 2100-2400 km s⁻¹ is less than the 2700-3600 km s⁻¹ found for the Mg I and O I line emitting regions which, assuming this emission arises mainly from the Si/S zone (see above), suggests partial mixing of the Si/S zone and the surrounding oxygen zones. The size of the outer [Ca II] 7291,7323 line-emitting region of 9000-9900 km s⁻¹ implies a contribution from calcium in the helium zone.

3.3.8. Iron group lines

Summary of the findings in J14: The (isolated) iron lines identified are the [Fe II] 7155 Å, [Fe II] 12600 Å and [Fe II] 16400 Å lines. The (isolated) cobalt lines identified are the [Co II] 9338,9344 Å, [Co II] 10190,10248,10283 Å and [Co II] 15475 Å lines, although the [Co II] 9338,9344 Å line is found to be blended with the O I 9263 Å line on the blue side. All of the identified iron and cobalt lines are found to arise from the Fe/Co/He zone.

Figure 9 shows the post 100 days (interpolated) spectral evolution for the identified iron and cobalt lines. The [Fe II] 7155 Å line emerges at ~150 days and remains until our spectral coverage ends. The [Fe II] 12600 Å and [Fe II] 16400 Å lines are identified in our last NIR spectrum at ~200 days, although the identification of the former is a bit doubtful given the large offset from the rest wavelength. The [Co II] 9338,9344 Å line may emerge as early as ~50 days and remains until our spectral coverage ends, whereas the [Co II] 10190,10248,10283 Å and [Co II] 15475 Å lines are identified in our last NIR spectrum at ~200 days.

We measure the radius of the [Fe II] 7155 Å line emitting region to 1600 km s⁻¹ at 300 and 415 days, and the radius of the [Fe II] 16440 Å line emitting region to 2100 km s⁻¹ at 206 days.

We also measure the radius of the [Co II] 10190,10248,10283 Å line emitting region to 2000 km s⁻¹ at 206 days. The [Co II] 15475 Å line is noisy, but we find the radius of the line-emitting region to be 3200 km s⁻¹ at 206 days. As mentioned the [Co II] 9338,9344 Å line is blended with the O I 9263 Å line on the blue side, and also appears to be blended with other lines on the red side, so we do not attempt to estimate the radius of the line emitting region.

Except for the [Co II] 15475 Å line at 206 days, the estimates of the size of the Fe II and Co II line emitting region lie in the range 1600-2100 km s⁻¹, significantly smaller than the 2700-3600 km s⁻¹ estimated for the O I and Mg I line emitting region. This is consistent with a scenario where the Fe/Co/He core and the surrounding oxygen zones are only partially mixed. However, as discussed in Sect. 4.3, hydrodynamical modelling of the early lightcurve strongly suggests that some amount of Fe/Co/He core material has been mixed far out in the ejecta. This is not necessarily in conflict with the Fe II and Co II line profiles as this amount may be small enough not to be clearly visible.

3.3.9. CO emission

Figure 14 shows continuum subtracted observed *K* band spectra at 89 and 206 days compared to the synthetic *K* band spectrum at 200 days for the optimal steady-state NLTE model (Sect. 4.1). The region where we expect CO overtone emission is marked in the figure and is assumed to be 22750-24350 Å (reference). The continuum was estimated as a linear interpolation between the endpoint fluxes of the region averaged over 100 Å. As seen in Fig. 14 there is a clear excess in the region both compared to the continuum and the model spectrum and the shape and extent of the feature is similar at 89 and 202 days. Although other explanations cannot be excluded we find it reasonable to interpret this feature as CO overtone emission. The integrated continuum subtracted flux in the region was 3.1×10^{-14} and 8.1×10^{-15} erg s⁻¹ cm⁻² at 89 and 206 days respectively. These values should be taken with some caution as they depend sensitively on the method used to subtract the continuum.

The region where we expect CO fundamental band emission overlaps with the 4.5 μm band. As discussed in E14a, there is an excess in this band developing during the first hundred days, as compared to blackbody fits to the optical and NIR photometry. As seen in Fig. 8, this excess continues to develop after 100 days, and at 600 days the 4.5 μm band is ~100 times brighter as compared to such a blackbody fit. The total flux in the 4.5 μm band, calculated using the zeropoint flux and the equivalent width of the band, was 4.9×10^{-13} and 1.7×10^{-13} erg s⁻¹ cm⁻² at 89 and 206 days respectively. Note that the value at 206 days lies in the gap of the Spitzer observations and has been linearly interpolated between 85 and 251 days. If all of the flux in the 4.5 μm band was due to CO fundamental band emission this would correspond to fundamental to first overtone band flux ratios of ~15 and ~20 at 85 and 206 days respectively.

On the other hand the SiO overtone band and dust may also contribute to the 4.5 μm band so we cannot assume that all of the observed flux is due to CO fundamental band emission. Knowledge of the CO fundamental to first overtone band flux ratio would make an estimate of the contribution from CO fundamental band emission to the 4.5 μm flux possible. For SN 1987A this ratio was ~1 at 100 days, a few at 200 days, but increased dramatically to ~100 towards 500 days (Bouchet & Danziger 1993). So assuming the same flux ratios as for SN 1987A would suggest a minor contribution to the 4.5 μm flux from CO fundamental

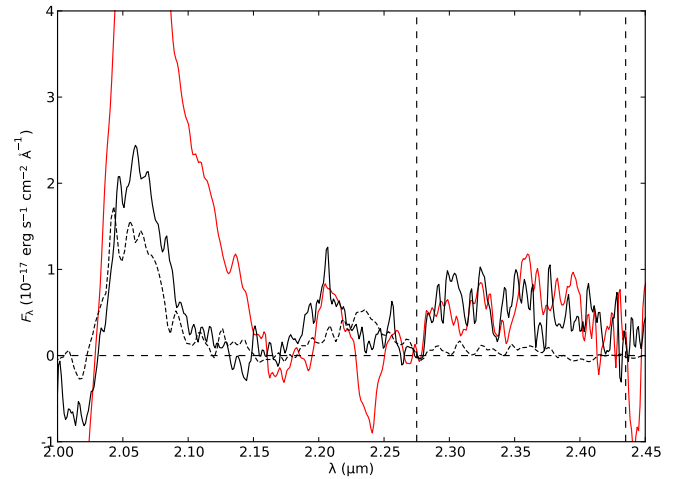


Fig. 14. Continuum subtracted observed *K* band spectra at 89 (red solid line) and 206 (black solid line) days compared to the continuum subtracted synthetic *K* band spectrum at 200 days (black dashed line) for the optimal steady-state NLTE model. The CO overtone region have been marked by black dashed lines and the observed flux at 206 days scaled with the ratio of the measured total CO overtone fluxes.

band emission at these epochs. However, this assumption is a bit dubious as the mass, density and composition of the ejecta are quite different for a Type IIb SN as compared to SN 1987A.

3.3.10. Small scale fluctuations

Figure 15 shows small scale fluctuations in the [O I] 6300,6364 Å, [O I] 5577 Å, O I 7774 Å, Mg I] 4571 Å and Na I 5890,5896 Å lines at 202 and 300 days. The resolution is ~600 and ~250 km s⁻¹ in the 202 and 300 days spectra respectively. A 1000 km s⁻¹ box average of the line profile was repeatedly (3 times) subtracted to enhance the small scale fluctuations. We have tested this method on the product of synthetic large and small scale structures and the small scale structure is recovered with reasonable accuracy. In the upper left panel we show a comparison of the [O I] 6300 Å line profiles at 202 and 300 days. These are very similar and there is not much evolution of the small scale fluctuations in the line profile during this period. We identify 8 features marked A-H with an FWHM between 300 and 600 km s⁻¹ present at both epochs.

However, features G and H interpreted as belonging to the [O I] 6364 Å line match very well with the E and F features interpreted as belonging to the [O I] 6300 Å line so these are likely to be repetitions. Minimizing the RMS (Root Mean Square) of the small scale fluctuations redwards 3000 km s⁻¹ (G and H), where the [O I] 6364 Å flux was subtracted from the [O I] 6300,6364 Å line profile using the method described in Sect. 3.3.1, we find a line ratio of 2.9 at 202 and 300 days to give a complete removal of features G and H. This ratio is in agreement with the value of 3 expected for optically thin emission and also with the results from J14.

In the upper right panel we show the corrected [O I] 6300 Å line profile and in the lower left panel we show a comparison to the Mg I] 4571 Å line profile at 300 days. All features except B are clearly identified and the agreement is good. The features on the red side are weaker for the Mg I] 4571 Å line, which is consistent with the larger red-side flux deficit for this line, but the relative (flux normalized) strength of all features are similar.

The good agreement suggests that the [O I] 6300 Å and Mg I 4571 Å lines arise from the same nuclear burning zones. Given that the Mg I 4571 Å line arises mainly from the O/Ne/Mg zone, as found in J14, it also suggests that the [O I] 6300 Å line arises mainly from this zone and that the contribution from the O/Si/S and O/C zones are modest.

In the lower right panel we show a comparison of the corrected [O I] 6300 Å line profile and the [O I] 5577 Å, O I 7774 Å and Na I 5890,5896 Å line profiles at 202 days. The E and F features are clearly identified in all of these line profiles, but none of the other features are seen. Since the E and F features are also the strongest it is not clear if the absence of the other features is real or if the other features are just too faint to be seen. The relative strength of the E and F features are similar for the [O I] 5577 Å, O I 7774 Å and [O I] 6300 Å lines, suggesting that all these lines arise mainly from the same nuclear burning zones, whereas the relative strength of these features for the Na I 5890,5896 Å line is a bit (~50 percent) weaker, suggesting contributions from other nuclear burning zones. This is in agreement with the results in J14, where all oxygen lines are found to arise from the oxygen zones and the Na I 5890,5896 Å line partly from the O/Ne/Mg zone.

The small scale fluctuations in the [Ca II] 7291,7323 Å line (not shown) do not match very well with those in the [O I] 6300 Å line and the relative strength of the features seen is weaker. We were not able to correct for blending as for the [O I] 6300,6364 Å line, which makes the interpretation less clear, but the result is in agreement with the results in J14, where we found this line to arise from other nuclear burning zones. This is also suggested by the different sizes of the line emitting regions discussed in Sect. 3.3.7.

Shivvers et al. (2013) presented an analysis of the line profiles of the [O I] 6300,6364 Å, O I 7774 Å and Mg I 4571 Å lines at 268 days. By decomposition of the [O I] 6300,6364 Å line profile into Gaussian profiles, assuming an [O I] 6300,6364 Å line ratio of 3, they found a good fit for one broad and two narrow profiles located at -400 and 1600 km s⁻¹. The two strongest features in our analysis, E and F, are located at ~0 and ~1500 km s⁻¹ and likely correspond to the two features found by Shivvers et al. (2013). They also find these features to repeat in the O I 7774 Å and Mg I 4571 Å lines, in agreement with our analysis. The difference in velocity for the E feature is likely explained by the different methods used.

Matheson et al. (2000) presented an analysis of the small scale fluctuations in the line profiles of SN 1993J. They found a good agreement between the fluctuations in the [O I] 6300 Å, [O I] 5577 Å and O I 7774 Å line profiles, which is in agreement with our results for SN 2011dh. However, they did not find a good agreement between the fluctuations in the [O I] 6300 Å and Mg I 4571 Å line profiles, which is a bit surprising since we find an excellent agreement between fluctuations in these lines for SN 2011dh. One possible explanation is that the [O I] 6300 Å line is dominated by flux from the O/Ne/Mg zone for SN 2011dh but not for SN 1993J, as we expect the Mg I 4571 Å line to emerge from this zone, whereas the oxygen lines could also have contributions from the O/Si/S and O/C zones.

The small scale fluctuations observed provide evidence for a clumpy ejecta as have been previously demonstrated for SNe 1993J (Matheson et al. 2000) and 1987A (Stathakis et al. 1991; Chugai 1994). In a simplified way we may represent the material of some nuclear burning zone by a number of randomly dis-

tributed clumps, having a typical size and occupying some fraction of the ejecta volume (filling factor). The small scale fluctuations in the line profiles then arise from statistical fluctuations in the distribution of the clumps, the RMS of the fluctuations increasing with decreasing number of clumps and/or filling factor and/or increasing size of the clumps. In the simplest case the ejecta is assumed to be a (globally) homogeneous sphere, which is in fact exactly how the core is represented in the steady-state NLTE modelling (Sect. 4.1).

Matheson et al. (2000) applied the statistical model by Chugai (1994) to their spectra of SN 1993J, giving a filling factor of ~0.06 for oxygen zone material, distributed within a sphere with 3800 km s⁻¹ radius. Using their estimated typical clump size of 300 km s⁻¹, this corresponds to ~900 clumps. The model requires the radius of the sphere containing the clumps, the typical size of the clumps and the RMS of relative flux fluctuations in lines originating from the clumps. In the case of SN 2011dh we adopt a radius of the sphere containing the bulk of the oxygen zone material of ~3500 km s⁻¹ based on the estimates of the O I and Mg I line emitting regions in Sect. 3.3.4 and 3.3.6. For SN 1987A a typical clump size of 120 km s⁻¹ was estimated from the power spectrum of the [O I] 6300 Å line by Stathakis et al. (1991) using high-resolution spectroscopy, but it is not clear how this was done by Matheson et al. (2000). As we do not have access to high-resolution spectroscopy for SN 2011dh we can only estimate an upper limit on the typical clump size taken to be 300 km s⁻¹, the smallest size of the features seen. The RMS of the relative flux fluctuations in the inner part (± 2000 km s⁻¹, see Chugai (1994)) of the sphere for both the corrected [O I] 6300 Å and the Mg I 4571 Å lines was ~0.09 at 300 days. Using these estimates and applying Chugai (1994, eq. 11), we find an upper limit on the filling factor of oxygen zone material within the sphere of ~0.07 and a lower limit on the number of oxygen zone clumps of ~900. These values are in good agreement with the values estimated by Matheson et al. (2000) for the clumping of oxygen zone material in SN 1993J.

3.3.11. Comparison to SNe 1993J and 2008ax

Figures 11, 12 and 13 show a comparison of the (continuum subtracted) [O I] 6300 Å, Mg I 4571 Å and [Ca II] 7291,7323 Å line profiles and fits using the method described in Sect. 3.3.1 for SNe 2011dh, 2008ax and 1993J respectively. The estimated radii of the line emitting regions are 4000-4100 and 3900-4000 km s⁻¹ for the [O I] 6300 Å line, 3700-3900 and 3400-3600 km s⁻¹ for the Mg I 4571 Å line and 3000-3400 and 2600-3000 km s⁻¹ for the [Ca II] 7291,7323 Å line for SNe 1993J and 2008ax respectively. These radii are in all cases significantly larger than the radii of the line emitting regions estimated for SN 2011dh (Sect. 3.3.4, 3.3.6 and 3.3.7), and are in all cases larger for SN 1993J than for SN 2008ax. The radius of the [Ca II] 7291,7323 Å line emitting region is in all cases smaller than the radii of the [O I] 6300 Å and Mg I 4571 Å line emitting regions, suggesting partial mixing of the Si/S zone and the surrounding oxygen zones as previously discussed for SN 2011dh in Sect. 3.3.7.

The shapes of the [O I] 6300 Å and Mg I 4571 Å line profiles for SNe 2008ax and 1993J differ from those of SN 2011dh and are significantly flatter at low velocities, most pronounced for SN 2008ax. This would in a spherically symmetric geometry suggest a lower fractional emissivity at low velocities as compared to SN 2011dh and possibly a decreasing emissivity or even a void at low velocities. The shape of the [Ca II] 7291,7323 Å line profiles on the other hand are similar and centrally peaked for all

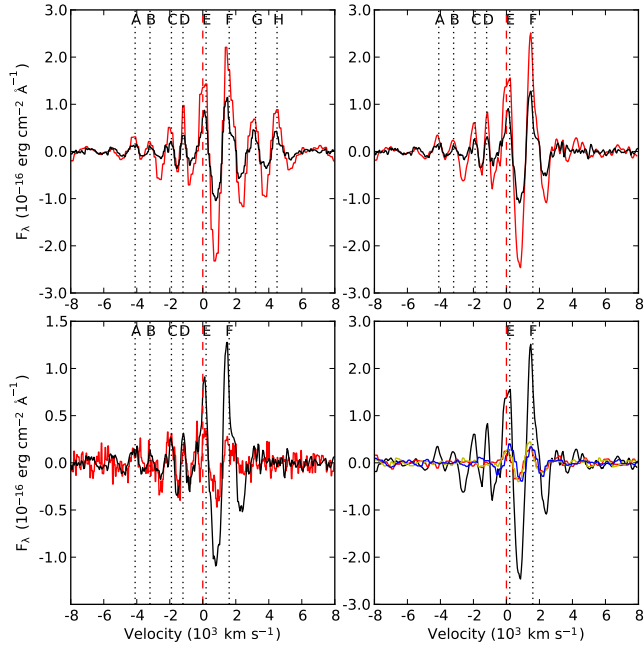


Fig. 15. Comparison of box average subtracted line profiles. The upper left panel shows the [O I] 6300 Å line profile at 202 (red) and 300 (black) days. The upper right panel shows the corrected [O I] 6300 Å line profile at 202 (red) and 300 (black) days. The lower left panel shows the corrected [O I] 6300 Å line profile (black) and the Mg I 4571 Å line profile (red) at 300 days. The lower right panel shows the corrected [O I] 6300 Å line profile (black) and the [O I] 5577 Å (red), O I 7774 Å (green) and Na I 5890/5896 Å (blue) line profiles at 202 days.

SNe. Note that the double peaks of the [O I] 6300,6364 Å line profile for SN 2008ax discussed by Taubenberger et al. (2011), Maurer et al. (2010) and Milisavljevic et al. (2010) seem to be well explained by a repetition of the blue peak in the [O I] 6364 Å line and that this blue peak also seem to repeat in the Mg I 4571 Å line.

Figure 16 shows the continuum subtracted mirrored blue-side profiles for the [O I] 6300 Å, Mg I 4571 Å, [Ca II] 7291 Å and [Fe I] 7155 Å lines for SNe 2011dh, 2008ax and 1993J at 300, 307 and 283 days respectively. This figure nicely illustrates the different sizes of the line emitting regions and shapes of the line profiles discussed above. The blue side is less affected by obscuration as compared to the red side and contamination from the [O I] 6364 Å and [Ca II] 7323 Å lines to the [O I] 6300 Å and [Ca II] 7291 Å lines is probably modest, although the [Ca II] 7291,7323 Å line ratio is uncertain. Note the remarkable similarity between the [O I] 6300 Å and Mg I 4571 Å line profiles seen for all SNe, previously discussed for SN 2011dh in Sect. 3.3.6 and 3.3.10.

Figure 17 shows the center of flux velocities for the [O I] 6300,6364 Å, [O I] 5577 Å, Mg I 4571 Å and [Ca II] 7291,7323 Å lines calculated as described in Sect. 3.3.1 for SNe 2011dh, 2008ax and 1993J. As discussed in Sects. 3.3.4 and 3.3.6 there is a blue-shift of the [O I] 6300,6364 Å, [O I] 5577 Å and Mg I 4571 Å lines for SN 2011dh which, as seen in Fig. 17, is also present, and even more pronounced for SNe 2008ax and 1993J. For SN 2011dh this blue-shift disappears towards 400 days but for SNe 2008ax and 1993J the blue-shift saturates at ~ 500 km s $^{-1}$ after 200 days. In J14 we provide a thorough discussion of these blue-shifts and suggest the cause to be line-blocking in

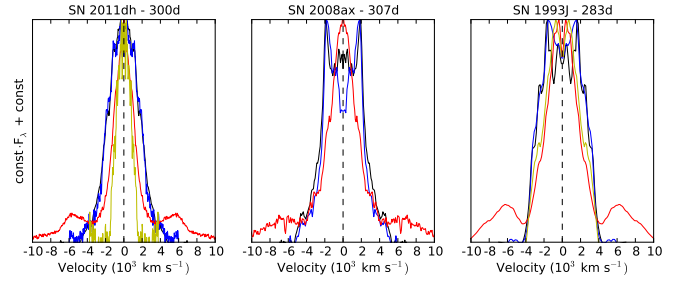


Fig. 16. Continuum subtracted mirrored blue-side profiles for the [O I] 6300,6364 Å (black), Mg I 4571 Å (blue), [Ca II] 7291,7323 Å (red) and [Fe I] 7155 Å (yellow) lines for SNe 2011dh, 2008ax and 1993J at 300, 307 and 283 days respectively.

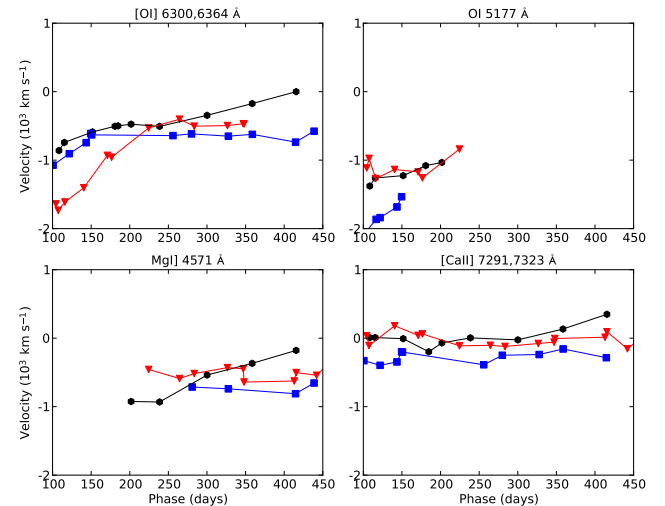


Fig. 17. Center of flux velocities for the [O I] 6300,6364 Å (upper left panel), [O I] 5577 Å (upper right panel), Mg I 4571 Å (lower left panel), [Ca II] 7291,7323 Å (lower right panel) lines for SNe 2011dh (black dots), 2008ax (blue squares) and 1993J (red triangles).

the core based on results from the steady-state NLTE modelling. There is no significant blue shift in the O I 11300 Å, O I 13164 Å and [Mg I] 15040 Å lines for SNe 2011dh (Sects. 3.3.4 and 3.3.6) and 2008ax in support of this hypothesis, as line-blocking is less effective in the NIR (J14). Milisavljevic et al. (2010) find the [O I] 6300,6364 Å, [O I] 5577 Å and Mg I 4571 Å lines to be either symmetric or asymmetric towards the blue for a sample of 18 stripped envelope SNe whereas Taubenberger et al. (2009) find a systematic blue-shift of the [O I] 6300,6364 Å line disappearing with time for another, partly overlapping, sample of 39 stripped envelope SNe. Both these results favours obscuration of the receding-side emission and disfavours ejecta asymmetries as the explanation, whereas the latter result is in agreement with our results for SN 2011dh and disfavours obscuration by dust.

4. Modelling

In this section we discuss modelling of the bolometric and photometric lightcurves with the steady-state NLTE code described in Jerkstrand et al. (2011, 2012) and J14 and HYDE, a hydrodynamical code described in E14b. HYDE, which is based on the diffusion approximation and Rossland mean opacities, can only produce bolometric lightcurves, whereas the steady-state NLTE code, which solves the frequency dependent radi-

tive transfer, is capable of producing photometric and pseudo-bolometric lightcurves. HYDE, on the other hand, has the hydrodynamical and time-dependent capabilities needed to evolve the SN through the explosion and the diffusion phase, whereas steady-state NLTE code has not and can only be used at times later than ~ 100 days. In the tail phase, where the diffusion time is short and steady-state is satisfied, both codes have the capability to produce bolometric lightcurves and in fact use the same radiative transfer model to calculate the deposition of the radioactive decay energy. So the advantage of the steady-state NLTE code is the capability to calculate pseudo-bolometric and photometric lightcurves or, equivalently, the corresponding bolometric corrections.

Given the extensive coverage for SN 2011dh, both in time and wavelength, consistent modelling of the bolometric and photometric lightcurves, throughout the evolution, is highly desirable. Ideally, HYDE would be used to evolve a grid of initial stellar models through a parametrized explosion and the photospheric phase, and the resulting ejecta models then fed into the steady-state NLTE code and subsequently evolved. The resulting grid of SN models could then be fitted to observations and the degeneracy of the solution and the errors in the parameters quantified. For the 0-100 days evolution we use the grid of SN models, constructed with HYDE and MESA STAR, presented in E14b, but to evolve this $15 \times 10 \times 9 \times 9$ grid further with the steady-state NLTE code is not computationally feasible. We are therefore forced to use the hydrodynamical grid for the early evolution (0-100 days) and a highly restricted set of steady-state NLTE models, presented in J14, for the late evolution (100-500 days). To partly circumvent this problem we try two different approaches. First, to extend the temporal coverage of the J14 models to early times, we evolve these through the 0-100 days period using HYDE in homologous mode. Secondly, to extend the temporal coverage of the hydrodynamical model grid to 300 days, we apply a bolometric correction determined with the steady-state NLTE code. Finally, as discussed in Sect. 4.2, after 500 days time-dependent effects becomes important and a steady-state assumption is no longer valid, so in this phase neither code apply.

4.1. NLTE modelling of the 100-500 days bolometric and photometric lightcurves

Here we compare the pseudo-bolometric and photometric lightcurves for the J14 steady-state NLTE models to the observed 100-500 days pseudo-bolometric and photometric lightcurves. Contrary to the hydrodynamical model grid used in Sects. 4.3 and 4.4, these models spans a restricted volume of parameter space and the degeneracy of the solution and the errors in the model parameters can not be quantified. The optimal model, presented in J14, have been chosen to give the best agreement with both nebular spectra and the bolometric and photometric lightcurves. In J14 we discuss the constraints on the model parameters provided by the nebular spectra and here we discuss the constraints provided by the bolometric and photometric lightcurves. The set of models, listed in table 2 in J14, varies in at least one of the following parameters, initial mass (12, 13 or 17 M_{\odot}), degree of macroscopic mixing (medium or strong), positron trapping (local or free-streaming), molecule cooling (yes or no), dust absorption/emission (yes or no) and oxygen zone filling factor (small-large). The optimal model (12C) has an initial mass of 12 M_{\odot} , strong macroscopic mixing, local positron trapping, no molecule cooling, dust absorption/emission and an oxygen zone filling factor of 0.043. The meaning of each param-

eter and the different configurations used are described in detail in J14.

The underlying 12, 13 and 17 M_{\odot} ejecta models are described in detail in J14 and are constructed using abundances from Woosley & Heger (2007), a constant density core, a helium envelope density profile from B12 and a $\rho \propto v^{-6}$ hydrogen envelope density profile. The velocities of the core, the helium and hydrogen envelopes have been fixed based on observations and modelling of SNe 2011dh, 2008ax and 1993J in this and other works. This provides a rough constraint on the quantity E/M and corresponds to the fitting of photospheric velocities in Sects. 4.3 and 4.4. The mass of ejected ^{56}Ni has been fixed to 0.075 M_{\odot} as determined by hydrodynamical modelling in B12 and this paper. As the J14 models have been artificially constructed and have not been evolved through the 0-100 days evolution, we use HYDE in homologous mode to produce bolometric lightcurves for this phase and compare to the observed U to 4.5 μm pseudo-bolometric lightcurve. When doing this the J14 models are first rescaled to day one and then evolved using an initial temperature profile adopted from a hydrodynamical model similar to the He4R270 model in B12. In this model homology is reached and the thermal explosion energy gets exhausted at ~ 3 days, so the assumptions made are not critical for the subsequent evolution.

Figure 18 shows the 100-500 days U to 4.5 μm , U to K and U to z optimal model and observed pseudo-bolometric lightcurves. The optimal model U to z pseudo-bolometric lightcurve, for which we have full observational coverage, shows a good agreement with observations and the differences are at the ~ 10 percent level. The optimal model U to K and U to 4.5 μm pseudo-bolometric lightcurves shows a similar good agreement until ~ 300 days, where our NIR coverage ends, and then the differences slowly increase to ~ 50 and ~ 20 percent for the U to K and U to 4.5 μm pseudo-bolometric lightcurves, respectively. Given the uncertainty in the extrapolations of the NIR photometry these differences are not too worrying. Fig. 19 shows the 0-100 days bolometric lightcurves for the J14 models calculated with HYDE compared to the observed U to 4.5 μm pseudo-bolometric lightcurve. The bolometric lightcurve for the optimal model shows an overall agreement, although the peak is overproduced by ~ 20 percent. Finally, Fig. 20 shows the U to 4.5 μm lightcurves for the J14 models compared to the observed lightcurves. The lightcurves for the optimal model show an overall agreement with observations but there are some notable exceptions, in particular the MIR bands, which we discuss further in Sect. 4.1.5.

The pseudo-bolometric luminosity consists of the product of the bolometric luminosity, depending only on the deposition of radioactive decay energy, and the fractional luminosity within the wavelength range, depending on how this energy is processed. In terms of bolometric corrections we may write $L = L_{\text{Bol}} 10^{0.4BC}$. As mentioned, the first factor could as well be calculated with HYDE, and it is the ability to determine the second factor that is the strength of the steady-state NLTE code. The split of the pseudo-bolometric lightcurves in two factors that depend in different ways on the model parameters is also very useful for the analysis. Fig. 21 shows the 100-500 days bolometric lightcurves, calculated with HYDE, and Fig. 22 the U to 4.5 μm , U to K and U to z bolometric corrections for the J14 models. The bolometric lightcurves depend only on the energy deposition and are therefore independent of molecule cooling, dust emission/absorption and the filling factors, which only affects the processing of the deposited energy. As we discuss below, in the J14 models, the positron trapping has no effect on the energy deposition as well. Therefore the bolometric lightcurves

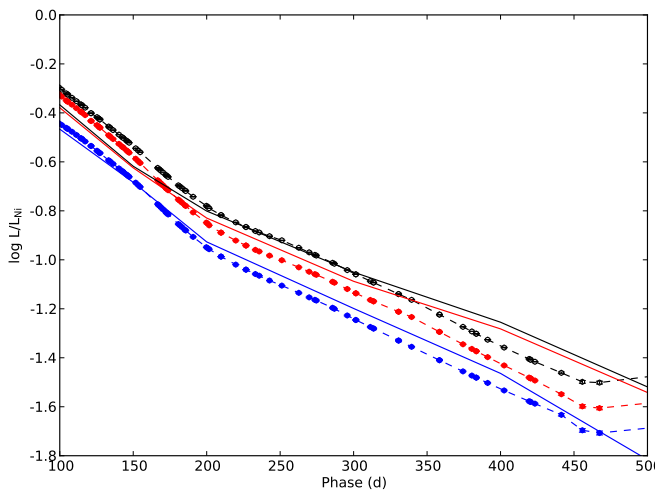


Fig. 18. 100-500 days U to $4.5 \mu\text{m}$ (black lines), U to K (red lines) and U to z (blue lines) bolometric lightcurves for the optimal model (12C) as compared to the observed U to $4.5 \mu\text{m}$ (black circles), U to K (red circles) and U to z (blue circles) bolometric lightcurves. The lightcurves have been normalized to the radioactive decay chain luminosity of $0.075 M_{\odot}$ of ^{56}Ni .

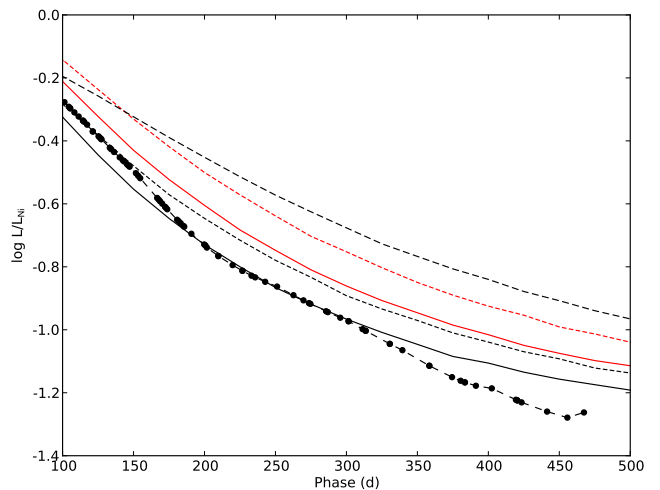


Fig. 21. 100-500 days bolometric lightcurves for the J14 models calculated with HYDE as compared to the observed bolometric lightcurve (black circles), calculated from the observed U to $4.5 \mu\text{m}$ pseudo-bolometric lightcurve using the bolometric correction for the optimal model (12C). The bolometric lightcurves have been normalized to the radioactive decay chain luminosity of $0.075 M_{\odot}$ of ^{56}Ni and the displayed models are as follows; 12A (red solid line), 12BCD (black solid line), 13AB (red short-dashed line), 13CDEFG (black short-dashed line), 17A (black long-dashed line).

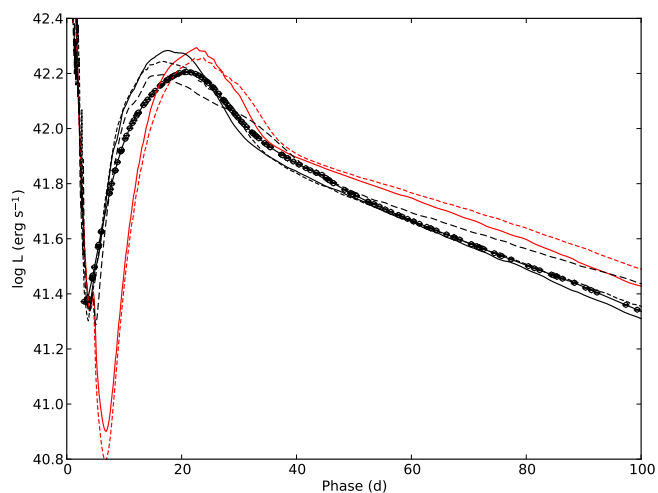


Fig. 19. 0-100 days bolometric lightcurves for the J14 models calculated with HYDE as compared to the observed U to $4.5 \mu\text{m}$ bolometric lightcurve for the first 100 days. The models are displayed as in Fig. 21.

depend only on the initial mass and the degree of macroscopic mixing, whereas the bolometric corrections may depend on all model parameters. The U to $4.5 \mu\text{m}$ bolometric corrections show very small differences (~ 0.05 mag) during the 100-300 days period, but these subsequently increase towards ~ 0.5 mag at 500 days. The U to K and U to z bolometric corrections, on the other hand, show much larger differences, mainly because molecule cooling and dust absorption/emission affects the distribution of the flux between these wavelength ranges and the MIR. Below we discuss the effects of the model parameters on the bolometric lightcurves and bolometric corrections as well as the photometric lightcurves and the constraints these provide on our choice of optimal model.

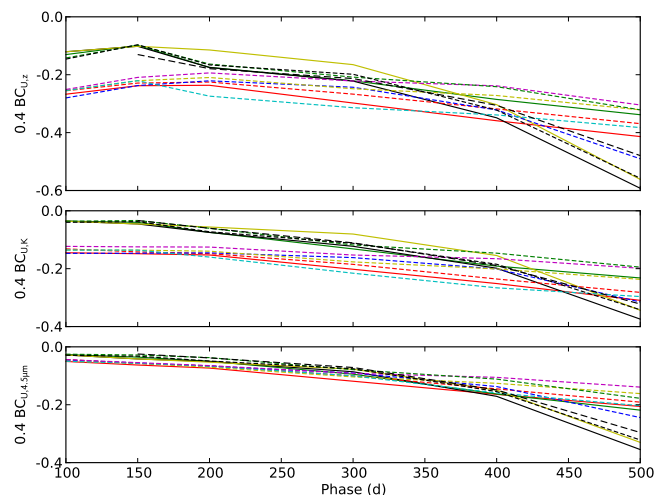


Fig. 22. 100-500 days U to $4.5 \mu\text{m}$, U to K and U to z bolometric corrections for the J14 models. The bolometric corrections have been multiplied with 0.4 to be on the same scale as the bolometric lightcurves in Fig. 21 and the displayed models are as follows; 12A (red solid line), 12B (green solid line), 12C (black solid line), 12D (yellow solid line), 13A (red short-dashed line), 13B (blue short-dashed line), 13C (yellow short-dashed line), 13D (cyan short-dashed line), 13E (magenta short-dashed line), 13F (green short-dashed line), 13G (black short-dashed line), 17A (black long-dashed line).

4.1.1. Initial mass

The initial mass may affect both the energy deposition (bolometric lightcurve) and the way this energy is processed (bolometric correction). Comparing the bolometric lightcurves and bolometric corrections for the optimal model (12C) and models 13G and 17A, which differs only in the initial mass, we find that the effect on the bolometric lightcurve, and thus on the energy deposition, is by far the most important. The effect of the initial mass on

the bolometric lightcurve is better investigated using the hydrodynamical model grid and is discussed in Sects. 4.3 and 4.4 and E14b. There we also discuss the issue of degeneracy between the model parameters, which can not be constrained by the restricted set of steady-state NLTE models. The choice of the initial mass is mainly motivated by the agreement with nebular spectra discussed in J14, but it is clear that compared to the 17 M_{\odot} model (17A) the optimal 12 M_{\odot} model (12C) gives a considerably better fit to the bolometric lightcurve.

4.1.2. Macroscopic mixing

The degree of macroscopic mixing may affect both the energy deposition (bolometric lightcurve) and the way this energy is processed (bolometric correction). Comparing models 13A and 13C, which differs only in the degree of macroscopic mixing and the oxygen filling factor, we find that the effect on the bolometric lightcurve, and thus on the energy deposition, is by far the most important. The mixing of the Fe/Co/He zone, containing the ^{56}Ni and its decay products, determines the overall deposition of the radioactive decay energy in the ejecta. The mixing of the other zones determines the distribution of this energy in each of these zones, which does not affect the bolometric lightcurve. We have used two configurations, one where all core zones are randomly mixed within 3500 km s^{-1} (medium), and one that differs only in that 50 percent of Fe/Co/He material have been mixed into the helium envelope within $3500\text{-}6000 \text{ km s}^{-1}$ (strong). The effect of the mixing of Fe/Co/He material on the bolometric lightcurve is better investigated using the hydrodynamical model grid and is discussed in Sects. 4.3 and 4.4 and E14b. The choice of strong mixing is mainly motivated by the lightcurve and in particular the rise to peak luminosity which is much better reproduced by models with strong mixing. Clearly there is a large number of possible configurations that have not been investigated, e.g. a configuration with partial mixing of the core zones, as we found evidence for in Sect. 3.3.

4.1.3. Filling factors

The filling factors only affects the way the deposited energy is processed (bolometric correction). This is because the average optical depths to γ -rays and positrons are independent of the filling factors. However, there is reasons to suspect that the differences in the bolometric corrections are small as well. In the optically thin limit, the energy deposition in each zone does not depend on the filling factors, as the total cross section of each zone remains the same. Furthermore, as shown by Kozma & Fransson (1992), the fraction of the deposited energy going into heating, ionization and excitation is not particularly sensitive to the density. We have used a number of configurations, where the filling factor of the oxygen zones ranges from small (0.043) to large (0.19), and adjusted the filling factors of the other zones accordingly. Comparing the pseudo-bolometric lightcurves of models 13C and 13E, which differ only in the oxygen zone filling factor, these are indeed very similar, but show a small difference increasing to ~ 10 percent towards 500 days. The choice of a small oxygen zone filling factor is motivated by the agreement with nebular spectra discussed in J14 and is also consistent with the upper limit of ~ 0.07 derived from small scale fluctuations in the [O I] 6300 and Mg I] 4571 Å lines in Sect. 3.3.10. Again there is a large number of possible configurations that have not been investigated.

4.1.4. Positron trapping

The positron trapping may affect both the energy deposition (bolometric lightcurve) and the way this energy is processed (bolometric correction). However, in the J14 models the energy deposition does not depend on the positron trapping as the optical depths to free-streaming positrons are always $\gg 1$. Positron trapping only affects the bolometric corrections when the fraction of radioactive decay energy deposited by the positrons becomes significant, and before this models with locally trapped or free-streaming positrons are indistinguishable. Comparing the optimal model (12C) and model 12B, which differs only in the positron trapping, the bolometric corrections for the optimal model gets increasingly larger after ~ 300 days, when the contribution from positrons to the energy deposition starts to become significant. The reason for this is that in the optimal model all positrons are trapped in the Fe/Co/He zone, and do not contribute to the heating of other zones, resulting in a lower luminosity in lines arising from these zones, in particular the strong [O I] 6300,6364 Å and Mg I] 4571 Å lines. The Fe/Co/He zone also has a lower temperature than other zones because of efficient cooling from the large number of iron lines, and the emission arising from this zone is redder. Not surprisingly, the effect on the U to z bolometric correction is strongest and begins earliest. The choice of local positron trapping for the optimal model (12C) is mainly motivated by the better fit to the pseudo-bolometric lightcurves after 300 days. As discussed in J14, the constraints obtained from nebular spectra are not conclusive. However, further evidence is gained from the 678 day spectrum of SN 2011dh presented by Shivvers et al. (2013), which shows a dramatic change as compared to our last spectrum. Many strong lines arising from other core zones than the Fe/Co/He zone, as the [O I] 6300,6364 Å and [Ca II] 7291,7323 Å lines, have disappeared or diminished dramatically, which is consistent with a scenario where all the positrons are being trapped locally in the Fe/Co/He zone. !Move to J14?!

4.1.5. Molecule emission

As discussed in Sect. 3.3.9 there is an excess in the $4.5 \mu\text{m}$ band, developing already during the first hundred days, but increasing dramatically between 100 and 250 days. The $4.5 \mu\text{m}$ band overlaps with both the CO fundamental band and the SiO first overtone band (see below) so molecule emission is a possible explanation. As also discussed in Sect. 3.3.9, we detect a modest amount of CO first overtone emission at 89 and 206 days, which implies at least some contribution from CO fundamental band emission to the $4.5 \mu\text{m}$ flux. Below we discuss how molecule cooling is treated in the J14 models, how it affects the lightcurves and which constraints could be obtained from comparisons with observations.

Molecule cooling only affects the way the deposited energy is processed (bolometric correction). It is included in the modelling in a simplified way, and is represented as the fraction of the deposited radioactive decay energy emitted as molecule (CO and SiO) emission in the O/C and O/Si/S zones. This energy is then emitted as CO and SiO fundamental and first overtone band emission, represented as box line profiles between 2.25-2.45 (CO first overtone), 4.4-4.9 (CO fundamental) and 4.0-4.5 (SiO first overtone) μm . The CO first overtone band overlaps with the K band and the CO fundamental and SiO first overtone bands with the $4.5 \mu\text{m}$ band whereas the SiO fundamental band lies outside the U to $4.5 \mu\text{m}$ wavelength range. The fundamental to first overtone band flux ratios are assumed to be the same

as observed for CO in SN 1987A (Bouchet & Danziger 1993). We have used two configurations, one where the fraction of deposited radioactive decay energy emitted as molecule emission has been set to one, and one where this fraction has been set to zero. Comparing models 13D and 13F, which only differs in the amount of molecule cooling, the U to z and U to K bolometric corrections for model 13D (complete cooling) are 20-25 percent larger throughout the evolution. The U to $4.5 \mu\text{m}$ bolometric corrections, on the other hand, are similar. This reflects the fact the most of the molecule emission falls within the U to $4.5 \mu\text{m}$ wavelength range and the flux is mainly redistributed within this wavelength range. The effect of molecule cooling is very evident in the $4.5 \mu\text{m}$ lightcurve which is a factor of 100-10000 brighter for model 13D (complete cooling) as compared to model 13F (no cooling).

Molecule cooling is an important parameter in the modelling, not only because it affects the flux in the K and $4.5 \mu\text{m}$ bands. It also determines the fraction of the deposited radioactive decay energy available for line emission and the temperature in the O/C and O/Si/S zones. The observed CO first overtone emission at 89 and 206 days, implies some molecule cooling in the O/C zone. Models with complete molecule cooling overproduce the $4.5 \mu\text{m}$ flux with a factor of ~ 10 whereas models without molecule cooling but with dust, as the optimal model, underproduce it with a factor of ~ 10 . Models without both molecule cooling and dust underproduce the $4.5 \mu\text{m}$ flux with a factor of 100-1000 and seem to be excluded. The strong similarity of the [O I] 6300 and Mg I] 4571 Å line profiles suggests the contribution from the O/C and O/Si/S zones to the [O I] 6300 Å emission to be modest, in turn suggesting the amount of molecule cooling in these zones to be significant. The redshift of the Ca II 8662 Å lines suggests a significant contribution from the [C I] 8727 Å line, found to arise mainly from the O/C zone in J14, in turn suggesting the amount of molecule cooling in the O/C zone to be modest. We have chosen no molecule cooling for our optimal model, but in the O/C zone an intermediate amount of cooling seems to be more likely.

4.1.6. Dust absorption and emission

As discussed in Sect. 3.2 there is a strong increase in the fractional MIR luminosity between 100 and 250 days during which an increase in the decline rate of the U to K pseudo-bolometric lightcurve is also observed. The increase in the decline rate is even more pronounced in the U to z pseudo-bolometric lightcurve (Fig. 18) and the increase in fractional luminosity affects both MIR bands as well as the K band (Fig. 8). This suggests that some process is re-distributing flux from the optical to the MIR during this period. One example of such a process is formation of dust in the ejecta, which would absorb the still quite hot radiation from the SN and re-emit it at a much lower temperature. Below we discuss how dust emission/absorption is treated in the J14 models, how it affects the lightcurves and which constraints could be obtained from comparisons with observations.

Dust emission/absorption only affects the way the deposited energy is processed (bolometric correction). It is included in the modelling in a simplified way, and is represented as a gray absorptive opacity in the core zones. The absorbed luminosity is re-emitted as blackbody emission from a homologously expanding surface, representing a number of optically thick dust clouds. The fractional area of this surface x_{dust} , as compared to the area of the core, is a free parameter in the modelling, and determines the temperature of the emitted blackbody radiation. Comparing

the optimal model (12C), for which dust has been added from 200 days and onwards, to model 12D the U to z bolometric correction for the former increases with ~ 20 percent at 200 days, roughly corresponding to the optical depth of the added dust (see below). The U to K bolometric correction is marginally affected at 200 days but then slowly increases whereas the U to $4.5 \mu\text{m}$ bolometric correction is unaffected until ~ 350 days and then slowly increases, both of which reflects the decreasing temperature of the dust (see below). The effect of dust (emission) is very evident in the K and the MIR lightcurves which increase with factor of a ~ 10 and ~ 100 , respectively, at 200 days and then slowly evolve according to the decreasing temperature.

Using our simplified dust model, we find a value of 0.25 for the optical depth of the dust to match the behaviour of the U to z pseudo-bolometric lightcurve. The value of x_{dust} was derived by minimization of the sum of squares of the relative flux differences of model and observed K , 3.6 and $4.5 \mu\text{m}$ photometry at 200, 300, 400 and 500 days (excluding K when the NIR coverage ends). This gives a value of x_{dust} of 0.01, which corresponds to temperatures of 2000, 1100, 666 and 416 K at 200, 300, 400 and 500 days respectively. However, assuming a large number of dust clouds and a small filling factor, it is possible to show from the assumptions made that $\tau = 3/4x_{\text{dust}}$, so this value of x_{dust} is not consistent with our assumptions. Furthermore, as seen in Fig. 20, the MIR lightcurves are not well reproduced by the optimal model (12C), although the discrepancy is much worse for the same model without dust (12D). The discrepancy in the $4.5 \mu\text{m}$ band could be explained by additional flux from molecule emission, but the discrepancy in the 3.6 μm band can not. On the other hand, the optimal model (12C) gives a good fit to the U to z pseudo-bolometric lightcurve and does improve the discrepancy in the MIR considerably as compared to the same model without dust (12D).

As a further complication there might also be a contribution from heated CSM dust to the MIR emission. Helou et al. (2013) show that such a model could explain the early evolution, whereas they fail to reproduce the late evolution. It is possible that a combination of emission from ejecta dust, CSM dust and molecules could well explain the MIR evolution. Comparing model 12D, which has neither dust absorption/emission nor molecule cooling, to observations, there is a huge discrepancy in the MIR bands but also a considerable discrepancy in the K band. This strongly suggest that at least one and probably a number of these processes are contributing. However, as the observational constraints are limited, it is not clear how to disentangle the contributions from each other.

!We probably need to add an discussion of the absence of blue-shifted line peaks at late times here!

4.2. Time dependent effects and the 500-750 days bolometric lightcurve

Figure 23 shows the observed U to MIR and U to z pseudo-bolometric lightcurves compared to the bolometric lightcurve, deposited ^{56}Co γ -ray and positron luminosity and deposited ^{57}Co luminosity for the optimal steady-state NLTE model (12C). The optimal hydrodynamical model produces very similar results. It is evident from the figure, that the deposited ^{56}Co luminosity is dominated by the positron contribution after ~ 450 day, and that the observed 500-750 days pseudo-bolometric lightcurves are unlikely to be powered by the γ -rays emitted in this decay. Shivvers et al. (2013) suggested that the SN has entered a phase powered by the positrons emitted in the ^{56}Co decay after 300-350 days. Given our results, this suggestion seems

to be roughly correct in the sense that the positron contribution dominates the deposited luminosity after ~ 450 days. However, as we will discuss below, it is not clear that the positron contribution dominates the emitted luminosity, because there is a number of processes that could provide additional energy sources.

There is observational evidence for additional energy sources from the observed pseudo-bolometric lightcurves. The decline rates of the pseudo-bolometric lightcurves between 500 and 750 days is $0.0065\text{--}0.0070 \text{ mag s}^{-1}$, significantly lower than the decay rate of ^{56}Co . As discussed in Sect. 4.1, the optimal steady-state NLTE model requires the positrons to be locally trapped to fit the 300-500 days U to z pseudo-bolometric lightcurve. This implies an increasing contribution from the low temperature Fe/Co/He zone (Sect. 4.1), in turn implying an increasing bolometric correction. However, the ratio of the observed U to z pseudo-bolometric luminosity and the bolometric luminosity of the optimal steady-state NLTE model, increases from ~ 0.3 to ~ 0.5 between 450 and 750 days, in contradiction with this expectation.

If the recombination time scales become longer than the time scale of the ^{56}Co decay, the steady-state assumption required for the NLTE modelling is no longer valid. Some fraction of the deposited radioactive decay energy will then build up a reservoir of ionization energy, which through recombination emission could eventually dominate the emitted luminosity. This process is called freeze-out and, as discussed in J14, approximate calculations suggest that in the hydrogen-rich envelope freeze-out occurs already at 100-200 days and in the helium envelope at ~ 500 days [is this correct!]. The contribution from the hydrogen envelope, which absorbs a negligible fraction of the radioactive decay energy, is likely to be small whereas the contribution from the helium envelope could very well be substantial. We use a time-dependent NLTE code (Kozma & Fransson 1992, 1998a,b) to test the steady-state assumption for our optimal steady-state NLTE model. Figure 24 shows the synthetic B , V , r and I band photometry, with and without a steady-state assumption, as modelled with this code. It is clear from the figure, that time-dependent effects start to become important at ~ 600 days, and after ~ 700 days recombination emission from the helium envelope provides a dominant and increasing contribution to the flux in these bands. To determine if the additional energy source provided by freeze-out in the helium envelope can fully explain the late-time evolution of the pseudo-bolometric lightcurves is outside the scope of this paper, but it is clear that this contribution is likely to be substantial. The 678 day spectrum of SN 2011dh presented by Shivvers et al. (2013) [Is this date correct, there is 2 spectra!], shows features not present in our last optical spectra that could be identified as the He I 6678 Å and 7065 Å lines, whereas the strong feature identified as Na I 5890,5896 Å by the authors could have a significant contribution from, or be fed by, the He I 5876 Å line. This is consistent with a substantial contribution from helium envelope recombination emission at this epoch.

CSM interaction became the dominant energy source at ~ 300 days for SN 1993J [reference!], giving rise to broad box-like H α and Na I 5890,5896 Å lines and a considerable flattening of the lightcurves. The 678 day spectrum of SN 2011dh presented by Shivvers et al. (2013) [Is this date correct, there is 2 spectra!], shows a feature that is interpreted as broad box-like H α emission by the authors, but no broad box-like Na I 5890,5896 Å emission is seen. The interpretation of the broad feature as H α emission is far from clear, as a number of other lines may contribute in this wavelength range (including the He I 6678 Å line

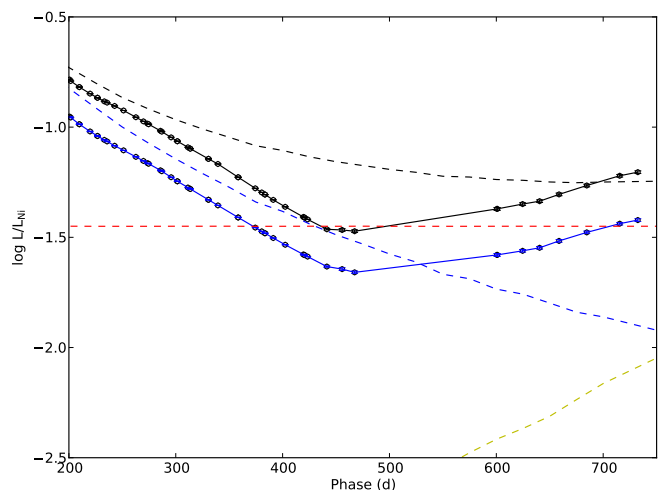


Fig. 23. U to MIR (black dots) and U to z (blue dots) pseudo-bolometric lightcurves compared to the bolometric lightcurve (black dashed line), deposited ^{56}Co decay gamma-ray (blue dashed line) and positron (^{57}Co decay luminosity and deposited ^{57}Co decay luminosity (yellow dashed line) for the optimal steady-state NLTE model (12C). The lightcurves have been normalized to the radioactive decay chain luminosity of $0.075 M_{\odot}$ of ^{56}Ni .

discussed above), and the feature is also much weaker than for SN 1993J at a similar epoch. It is hard to exclude a contribution from CSM interaction to the emitted luminosity, but as the flattening of the lightcurve is seen in all optical bands as well as the MIR bands, and is actually least pronounced in the r band, we do not find it likely to be dominant.

Additional energy sources could also be provided by the decay of radioactive isotopes other than ^{56}Co . In the optimal steady-state NLTE model, the fractional luminosity deposited by the ^{57}Co decay is ~ 10 percent at 700 days and increasing. A higher mass of ejected ^{57}Co than assumed in the optimal steady-state NLTE model, can not be excluded, and could help explain the observed evolution. The fractional luminosity deposited by the decay chain of ^{44}Ti in the optimal steady-state NLTE model is negligible, but contributions from other isotopes not included in the modelling can not be excluded.

4.3. Hydrodynamical modelling of the 0-100 days bolometric lightcurve

In B12 we presented a hydrodynamical model for SN 2011dh that well reproduced the observed 0-100 days bolometric lightcurve and photospheric velocity evolution. Here we use the grid of SN models constructed with HYDE and MESA STAR presented in E14b and the procedure described therein to fit the 0-100 days bolometric lightcurves and photospheric velocities of SNe 2011dh, 1993J and 2008ax. The strength of this method as compared to previous hydrodynamical modelling is the ability to determine the errors in the model parameters arising from the observed quantities and the degeneracy of the solutions, issues previously discussed in E14a from approximate considerations. The progenitor and SN parameters are the helium core mass (M_{He}), the explosion energy (E), the mass of ejected ^{56}Ni (M_{Ni}) and the distribution of it (Mix_{Ni}). The total parameter space spanned is $M_{\text{He}}=2.5\text{--}7.0 M_{\odot}$, $E=0.4\text{--}2.2 \times 10^{51}$ erg, $M_{\text{Ni}}=0.05\text{--}0.250 M_{\odot}$ and $\text{Mix}_{\text{Ni}}=0.6\text{--}1.4$ using a $15 \times 10 \times 9 \times 9$ grid. The stellar models consists of bare helium cores without a hydrogen envelope and, as discussed in E14b, this is sufficient to determine the ex-

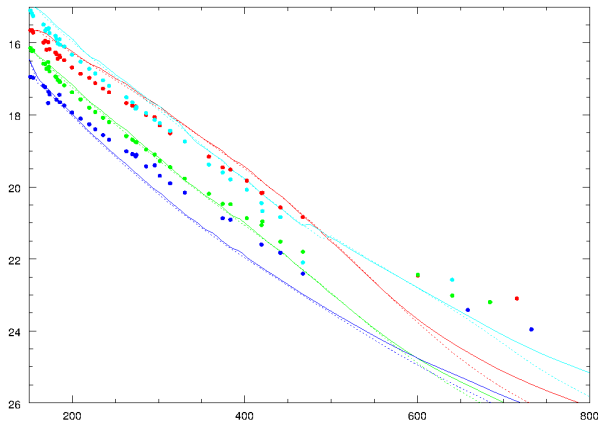


Fig. 24. Synthetic B (blue), V (yellow), r (red) and I (cyan) magnitudes for the optimal steady-state NLTE model (12C) as calculated with the time dependent NLTE code with (dashed lines) and without (solid lines) a steady-state assumption compared to the observed magnitudes (dots). !This figure has to be remade and does not show model 12C (but a similar model)!

plosion energy, helium core mass and mass and distribution of the ejected ^{56}Ni . To estimate the radius, as we did in B12, modelling of the early cooling phase, which depends on the hydrogen envelope, is necessary. As described in E14b equal weight is given to the diffusion phase lightcurve (5-40 days), the early tail lightcurve (40-100 days) and the early photospheric velocity evolution (5-40 days). To compare with the model bolometric lightcurves we use UV to MIR pseudo-bolometric lightcurves, in turn constructed from U to K bolometric lightcurves for SN 2008ax and 1993J, assuming the same UV and MIR fractions as for SN 2011dh. As seen in Fig. 22 the U to $4.5 \mu\text{m}$ bolometric correction for the optimal steady-state NLTE model of SN 2011dh is ~ 0.05 mag at 100 days, and not more than ~ 0.1 mag for any model, so the assumption that the bolometric correction is negligible seems justified.

Figure 25 shows the model bolometric lightcurve and photospheric velocity evolution compared to the observed UV to MIR pseudo-bolometric lightcurve and velocity evolution for the absorption minimum of the $\text{Fe II } 5169 \text{ \AA}$ line for the optimal models of SNe 2011dh, 2008ax and 1993J. Table 3 gives the helium core mass, explosion energy, mass of ejected ^{56}Ni and the distribution of it for the optimal models and the corresponding errors, calculated as described in E14b. A systematic error of 15 percent in the photospheric velocities has been assumed. As shown in E14b the helium core mass and explosion energy are mainly sensitive to errors in the photospheric velocities whereas the mass of ejected ^{56}Ni is mainly sensitive to errors in the distance and extinction. The derived parameters for SN 2011dh are in good agreement with the results in B12. The helium core mass and explosion energy derived for SNe 1993J and 2008ax are similar to what is derived for SN 2011dh, whereas the mass of ejected ^{56}Ni differs significantly. The mixing of the ^{56}Ni is strong for all three SNe and for SN 2011dh the fraction of ^{56}Ni outside 3500 and 6000 km s^{-1} is 53 and 8 percent respectively. This is in rough agreement with the optimal steady-state NLTE model, although in this model the ^{56}Ni is confined within 6000 km s^{-1} . We note that the velocity evolution of SN 2008ax is not well fitted, which could be explained by a worse correspondence between the absorption minimum of $\text{Fe II } 5169 \text{ \AA}$ and the photosphere as compared to SNe 2011dh and 1993J.

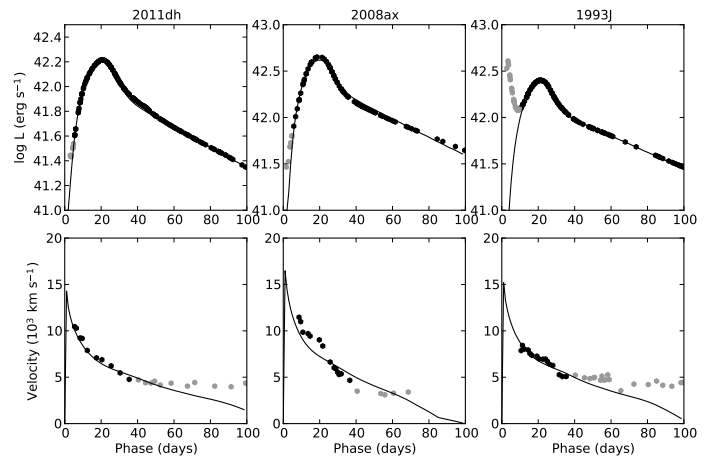


Fig. 25. Bolometric lightcurve (upper panels) and photospheric velocity evolution (lower panels) for the optimal models as compared to the observed UV to MIR pseudo-bolometric lightcurve and velocity evolution for the absorption minimum of the $\text{Fe II } 5169 \text{ \AA}$ line for SNe 2011dh (left panels), 2008ax (middle panels) and 1993J (right panels). Observations not included in the fit are displayed in gray.

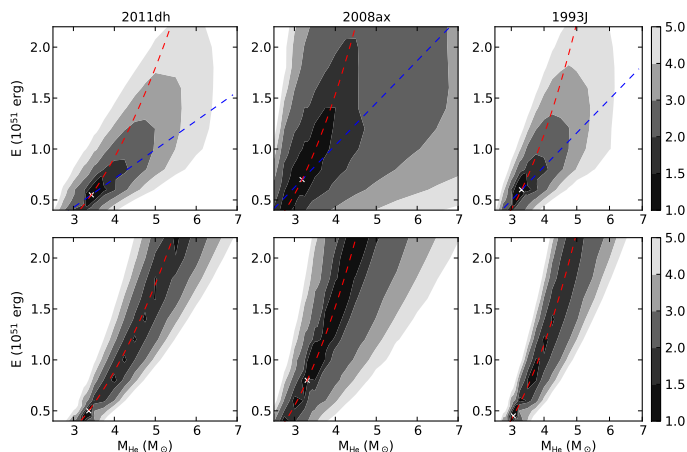
In E14b we discuss in detail the effects of the progenitor and SN parameters on the model bolometric lightcurves and the degeneracy between these parameters. The ejecta mass and explosion energy affects the width of the diffusion peak and the evolution of the tail luminosity, which provide the single constraint $M_{\text{ej}}^2/E = \text{const}$. In constant opacity models the diffusion phase provides an independent constraint (E14a), but in the hydrodynamical models this is not true and the bolometric lightcurve is degenerate in the ejecta mass and explosion energy. The mass of ejected ^{56}Ni affects the overall luminosity of the lightcurve, which provides the constraint $M_{\text{Ni}} = \text{const}$. The distribution of the ejected ^{56}Ni affects both the rise to peak luminosity and the evolution of the tail luminosity where the former effect provides the strongest constraint. The photospheric velocity evolution, which provides the constraint $M_{\text{ej}}/E = \text{const}$, allows the degeneracy in ejecta mass and explosion energy to be broken and is essential to determine these parameters. This is well illustrated by Fig. 26 where we show contour plots of the standard deviation in the fit, normalized to that of the optimal model, as a function of helium core mass and explosion energy. Apparently there is an almost complete degeneracy in the helium core mass and explosion energy along the $M_{\text{ej}}^2/E = \text{const}$ curve if the fitting is done using the bolometric lightcurve alone. When the photospheric velocity evolution is used this degeneracy disappears and the fit becomes quite robust. If we assume a good fit to correspond to a normalized standard deviation of < 2 and also take into account the errors arising from the observed quantities (Table 3) we find an upper limit on the helium core mass for all three SNe of $\leq 4 M_{\odot}$, corresponding to an upper limit on the initial mass of $\leq 15 M_{\odot}$.

4.4. Hydrodynamical modelling of the 0-300 days bolometric lightcurve

Here we extend the temporal coverage of the hydrodynamical model grid to 300 days (which is the period for which we have full U to $4.5 \mu\text{m}$ coverage), and make a fit of the observed U to $4.5 \mu\text{m}$ pseudo-bolometric lightcurve of SN 2011dh to this extended model grid. The 100-300 days bolometric lightcurves are calculated using HYDE whereas the 100-300 days U to 4.5

Table 3. Helium core mass, explosion energy, mass of the ejected ^{56}Ni and the distribution of it for the optimal models of SNe 2011dh, 1993J and 2008ax.

SN	E (10^{51} erg)	M_{He} (M_{\odot})	M_{Ni} (M_{\odot})	Mix_{Ni}
2011dh	0.55 (+0.40,-0.15)	3.44 (+0.70,-0.26)	0.075 (+0.028,-0.020)	1.10 (+0.06,-0.00)
2008ax	0.70 (+0.50,-0.30)	3.19 (+0.56,-0.39)	0.175 (+0.087,-0.099)	0.93 (+0.04,-0.00)
1993J	0.60 (+0.45,-0.20)	3.31 (+0.60,-0.25)	0.106 (+0.034,-0.028)	0.90 (+0.24,-0.08)


Fig. 26. Contour plots showing the standard deviation in the fits, normalized to that of the optimal model, projected onto the E - M_{He} plane for the case where the photospheric velocities were used (upper panels) and not used (lower panels) for SNe 2011dh (left panels), 2008ax (middle panels) and 1993J (right panels). We also show the constraints $M_{\text{ej}}/E=\text{const}$ (blue) and $M_{\text{ej}}^2/E=\text{const}$ (red) provided by the photospheric velocity evolution and the bolometric lightcurve, respectively.

μm bolometric corrections are determined with the steady-state NLTE code. As in Sect. 4.3 we assume the bolometric correction to be negligible during the 0-100 days period. The fitting is done by minimization of the square of the relative residuals, giving equal weight to the diffusion phase lightcurve (5-40 days), the early tail lightcurve (40-100 days), the late tail lightcurve (100-300 days) and the early photospheric velocity evolution (5-40 days). This weighting scheme gives less weight to the photospheric velocities, which makes some sense as we have additional information about the lightcurve.

To use the method we need to know how the bolometric correction varies in the parameter space of the hydrodynamical grid. Calculating the bolometric correction for all hydrodynamical models with the steady-state NLTE code is not computationally feasible so we have to seek another solution. As discussed in Sect. 4.1 and shown in Fig. 22 the U to $4.5 \mu\text{m}$ bolometric correction varies within ~ 0.05 mag between the J14 steady-state NLTE models during the 100-300 days period. We take advantage of this fact and use the correction for the optimal model for all hydrodynamical models, but as the J14 models cover a restricted volume of parameter space we need to justify this choice further. It is reasonable to assume that the bolometric correction depends mainly on the energy deposition per unit mass (determining the heating rate) and the density (determining the cooling rate). Furthermore, we know beforehand, that models giving a bad 0-100

days fit will not give a good 0-300 days fit. In Fig. 27 we have plotted the mass averaged density and the energy deposition per mass calculated as $L_{\text{Bol}}/M_{\text{ej}}$ at 200 days for the J14 models and the hydrodynamical models with a normalized standard deviation in the 0-100 days fit less than 3. It is clear from this figure that the hydrodynamical models that could possibly give a good fit do not span a wide range in density or energy deposition per mass and that the NLTE models cover about half of this region. Therefore the use of the U to $4.5 \mu\text{m}$ bolometric correction from the optimal steady-state NLTE model seems justified.

We also need to know that the steady-state NLTE model parameters that do not map onto the hydrodynamical model grid, i.e. filling factors, positron trapping, molecule cooling and dust emission/absorption, do not appreciably affect the results. Strictly speaking, this not possible, as a full scan of parameter space using the steady-state NLTE code is not computationally feasible. The small differences in the U to $4.5 \mu\text{m}$ bolometric correction for the J14 models during the 100-300 days period make this caveat less worrying though. As discussed in Sects. 4.1, 4.1.6 and 4.1.5, the reason for this is that molecule cooling and dust emission/absorption mainly redistributes the flux within the U to $4.5 \mu\text{m}$ wavelength range, the dependence on the filling factors is weak and the fraction of the energy deposited by the positrons is low. As discussed in Sect. 4.1 the filling factors, molecule cooling and dust emission/absorption do not affect the bolometric lightcurve whereas the positron trapping does if the ejecta is optically thin to free-streaming positrons. This requires a density much lower than in any of the hydrodynamical models shown in Fig. 27! check this! so the choice of this parameter is not important. Therefore, with respect to the bolometric lightcurve, the choice not to vary these steady-state NLTE-parameters seems justified.

Figure 28 shows the model U to $4.5 \mu\text{m}$ pseudo-bolometric lightcurve and photospheric velocity evolution compared to the observed U to $4.5 \mu\text{m}$ pseudo-bolometric lightcurve and velocity evolution for the absorption minimum of the Fe II 5169 Å line for the optimal model. The parameters of the optimal model are $E=0.55^{+0.40}_{-0.15} \times 10^{51}$ erg, $M_{\text{He}}=3.38^{+0.58}_{-0.27} M_{\odot}$, $M_{\text{Ni}}=0.075^{+0.028}_{-0.017} M_{\odot}$ and $\text{Mix}_{\text{Ni}}=1.00^{+0.00}_{-0.00}$, in close agreement with the results from the 0-100 days bolometric lightcurve. Figure 28 also shows contour plots of the standard deviation in the fit, normalized to that of the optimal model, as a function of helium core mass and explosion energy. The solution is slightly better constrained in helium core mass and slightly worse constrained in explosion energy, which probably just reflects the less weight given to the photospheric velocities. As expected, the fit using the lightcurve alone is still completely degenerate in helium core mass and explosion energy along the $M_{\text{ej}}^2/E=\text{const}$ curve. In the end, the main achievement is to prove that we get a good fit and similar best

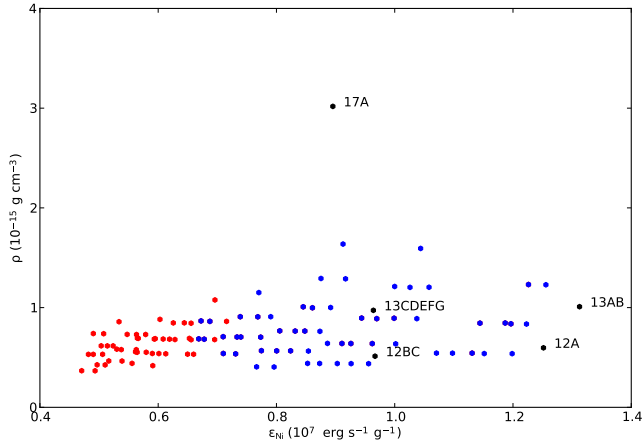


Fig. 27. Mass averaged density and energy deposition per mass calculated as $L_{\text{Bol}}/M_{\text{ej}}$ at 200 days for the J14 models (black circles) and the hydrodynamical models with a normalized standard deviation in the 0-100 days fit less than 3 for the case where the photospheric velocities were used (blue circles) and not used (red circles).

fit values using the 0-300 days U to $4.5 \mu\text{m}$ pseudo-bolometric lightcurve.

5. Discussion

5.1. The nature of the progenitor star

In M11, B12, E14a, J14 and this paper we investigate the nature of the progenitor star using a number of different and, at least partially, independent methods. In M11 we analyse direct observations of the star by comparison of the observed magnitudes to predictions from stellar atmosphere and evolutionary models. The best match is found to be a yellow supergiant with an initial mass of $13 \pm 3 M_{\odot}$ and a radius of $\sim 270 R_{\odot}$. In E14a we present observations of the disappearance of this star, thus confirming that it was the progenitor of SN 2011dh. In this paper we present hydrodynamical modelling, which shows that a star with a helium core mass of $3.3^{+0.6}_{-0.2} M_{\odot}$, exploded with an energy of $0.50^{+0.42}_{-0.10} \times 10^{51}$ erg and ejecting $0.075^{+0.028}_{-0.013} M_{\odot}$ of ^{56}Ni mixed out to high velocities, gives the best fit to the observed 3-300 days bolometric lightcurve and the photospheric velocity evolution. The use of a model grid allows us to determine the errors in the SN and progenitor parameters arising from the errors in the observed quantities and to constrain the degeneracy of the solution. Given this we find an upper limit on the initial mass of $\lesssim 15 M_{\odot}$. In B12 we present hydrodynamical modelling, which shows that a low-mass ($\sim 0.1 M_{\odot}$) and extended (200-300 R_{\odot}) hydrogen-rich envelope seems to be required to reproduce the observed g band lightcurve during the first 3 days. In E14a we estimate a hydrogen mass of 0.01-0.04 M_{\odot} using a Monte-Carlo atmosphere code. This hydrogen mass is consistent with the B12 ejecta model, and we also find the interface between the helium core and the hydrogen rich envelope to be located at a velocity consistent with this model. In J14 and this paper we present steady-state NLTE modelling, which shows that a star with an initial mass of 12 M_{\odot} well reproduces the observed 100-500 days spectral evolution and pseudo-bolometric and photometric lightcurves. The evolution in the MIR however, which is complex and depends on both dust and molecule (CO and SiO) emission, is not well reproduced. Particular attention is paid to the [O I] 6300,6364 \AA line, which is very sensitive to the ini-

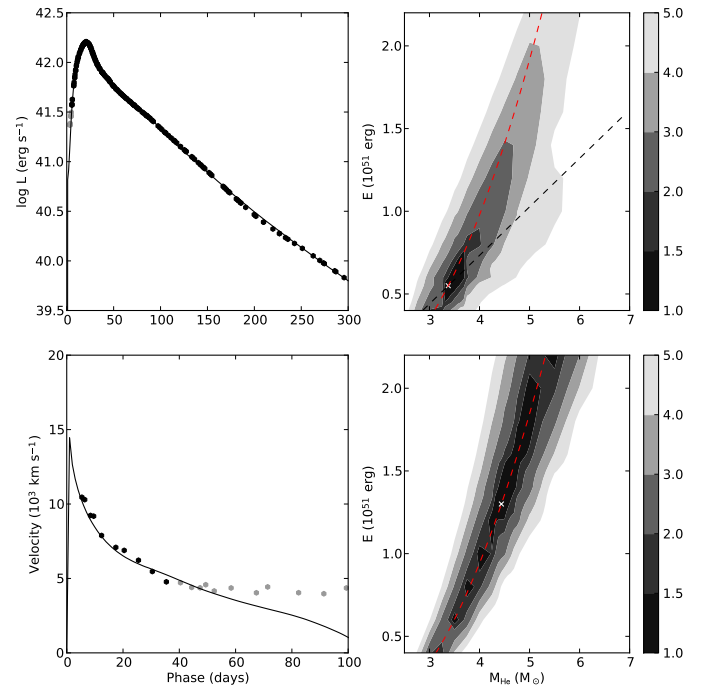


Fig. 28. Right panels: U to $4.5 \mu\text{m}$ pseudo-bolometric lightcurve (upper right panel) and photospheric velocity evolution (lower right panel) for the optimal model as compared to the observed U to $4.5 \mu\text{m}$ pseudo-bolometric lightcurve and velocity evolution for the absorption minimum of the Fe II 5169 \AA line. Observations not included in the fit are displayed in grey. Left panels: Contour plots showing the standard deviation in the fit, normalized to that of the optimal model, projected onto the E- M_{He} plane for the case where the photospheric velocities were used (upper left panel) and not used (lower left panel). We also show the constraints $M_{\text{ej}}/E=\text{const}$ (blue) and $M_{\text{ej}}^2/E=\text{const}$ (red) provided by the photospheric velocity evolution and the bolometric lightcurve, respectively.

tial mass of the star. To reproduce the flux in this line an initial mass of $< 17 M_{\odot}$ seems to be required. After 500 days modelling using a time-dependent NLTE code (Kozma & Fransson 1992, 1998a,b), shows that freeze-out in the helium envelope becomes important and the assumption of steady-state is no longer valid.

Overall the results obtained with the different methods are consistent and, even given the caveats of each individual method, it is likely that the progenitor star is of moderate initial mass ($\lesssim 15 M_{\odot}$), and has a low-mass extended hydrogen rich envelope, most of which must have been lost either through stellar winds or interaction with a binary companion. The moderate mass suggests that interaction with a binary companion is needed, as stellar winds of stars in this mass range are not strong enough to expel the hydrogen envelope before core-collapse. As we show in J14 and in this paper, using steady-state NLTE modelling of nebular spectra and hydrodynamical modelling of the bolometric lightcurves, SNe 2008ax and 1993J are likely to be of similar initial mass and have similar explosion energy as SN 2011dh, although the mass of the ejected ^{56}Ni may differ significantly depending on the adopted distance and extinction. In particular, the upper bound on the initial mass for all three SNe is found to be $\lesssim 15 M_{\odot}$. For the same reason as discussed above, this suggests that interaction with a binary companion have taken place. In the case of SN 1993J, this conclusion is supported by direct observations of the binary companion (Maund et al. 2004). Observations, that could detect or set useful constraints on the presence of a companion star for SN 2011dh, are scheduled for Cycle

21 at HST, whereas similar observations for SN 2008ax would not be feasible, due to the longer distance. Clearly there is growing evidence that the main production channel for Type IIb SNe are stars whose hydrogen envelope has been stripped by interaction with a binary companion. Modelling of the nebular spectra and hydrodynamical modelling of the bolometric lightcurves for a larger sample of Type IIb SNe, could provide further evidence for this hypothesis.

6. Conclusions

We present two years of optical and NIR photometric and spectroscopic observations for the Type IIb SN 2011dh. Together with SWIFT and Spitzer observations the data cover the UV to MIR wavelength range although the photometric coverage ends at ~ 100 days in UV and at ~ 350 days in NIR, and the spectral coverage ends at ~ 200 days in NIR and at ~ 450 days in the optical. Particular attention is paid to the bolometric and photometric lightcurves where we use steady-state NLTE modelling and hydrodynamical modelling to put constraints on the SN and progenitor parameters. We also provide a spectral analysis, mainly related to the line profiles, complementary to the steady-state NLTE modelling of nebular spectra presented in J14.

The 0-100 days UV to MIR pseudo-bolometric lightcurve and the photospheric velocities of SN 2011dh are analysed using the grid of the hydrodynamical SN models presented in E14b and the fitting procedure described therein. To extend the temporal coverage of the model grid to 300 days we apply a U to $4.5 \mu\text{m}$ bolometric correction determined with the steady-state NLTE modelling. The method used allows us to determine the errors in the model parameters arising from the observed quantities and the degeneracy of the solution. The results for the 0-300 days period are very similar to those for the 0-100 days period and we find a helium core mass of $3.4_{-0.3}^{+0.6} M_{\odot}$, an explosion energy of $0.55_{-0.16}^{+0.40} \times 10^{51}$ erg and a mass of ejected ^{56}Ni of $0.075_{-0.017}^{+0.028} M_{\odot}$, in good agreement with our results in B12. The 0-100 days bolometric lightcurves and photospheric velocities of SNe 2008ax and 1993J are also analysed and the best fit values of the helium core mass and explosion energy are similar to those of SN 2011dh. We find an upper limit on the helium core mass for all three SNe of $\leq 4 M_{\odot}$, corresponding to an upper limit on the initial mass of $\leq 15 M_{\odot}$. Strong mixing of the ejected ^{56}Ni is required for all three SNe to fit the rise to peak luminosity.

The 100-500 days pseudo-bolometric and photometric lightcurves of SN 2011dh are analysed using the restricted set of steady-state NLTE models presented in J14. To extend the temporal coverage of these models we construct 0-100 days bolometric lightcurves using HYDE (E14b) in homologous mode. The optimal $12 M_{\odot}$ model, presented in J14 and chosen to give the best agreement with both spectra and lightcurves, shows a good overall agreement with the observed pseudo-bolometric lightcurves. The initial mass and the mixing of the Fe/Co/He material mainly affect the bolometric lightcurve and constraints on those are better obtained using the hydrodynamical model grid. The other model parameters only affects the bolometric corrections and constraints on those requires the steady-state NLTE modelling. Local trapping of the positrons emitted in the ^{56}Co decay gives the best fit the 300-500 days U to z pseudo-bolometric lightcurve and the amounts of dust and molecule cooling are strongly related to the evolution in the MIR. As compared to models without dust and molecule cooling we find a huge excess in the MIR and a considerable excess in the K band developing between 100 and 250 days, during which an increase

in the decline rates of the U to z and U to K pseudo-bolometric lightcurves is also observed. Models with a modest amount of dust ($\tau = 0.25$) formed in the ejecta during this period reproduce this behaviour although the MIR fluxes are underproduced by a factor of ~ 10 . CO first overtone band emission is detected in NIR spectroscopy at 89 and 202 days implying a contribution to the $4.5 \mu\text{m}$ band flux from CO fundamental band emission at these epochs. Neither complete molecule cooling nor absence of molecule cooling well reproduce the $4.5 \mu\text{m}$ magnitudes. In the C/O zone an intermediate amount of molecule cooling is supported by the observed CO first overtone emission and the similarity of the [O I] 6300 Å and Mg I] 4571 Å lines (see below).

The 500-750 days lightcurves are harder to analyse and modelling with a time-dependent NLTE code (Kozma & Fransson 1992, 1998a,b) shows that, in this phase, the steady-state assumption is no longer valid. In the optimal steady-state NLTE model the positron contribution dominates the ^{56}Co energy deposition after ~ 450 days. However, there is both observational and theoretical evidence that the 500-750 days lightcurves are dominated by additional energy sources. The decline rates are significantly lower than the decay rate of ^{56}Co and the observed U to z pseudo-bolometric luminosity is ~ 50 percent of the bolometric luminosity in our optimal model, in contradiction with a scenario with locally trapped positrons. Modelling with the time-dependent NLTE code shows that after ~ 600 days freeze-out in the helium envelope becomes important, and recombination emission from the helium envelope is likely to contribute substantially to the observed luminosity. We find a substantial contribution from CSM interaction and other radioactive isotopes less likely.

The line profiles of the important lines are analysed and we estimate the sizes of the oxygen, magnesium, iron and [Ca II] 7291,7323 Å line emitting regions to 2900-3400, 2700-3600, 1600-2100 and 2100-2400 km s^{-1} respectively, in all compared cases smaller than those of SNe 1993J and 2008ax. Given the findings in J14, these regions would correspond to the oxygen, O/Ne/Mg, Fe/Co/He and Si/S nuclear burning zones and suggest partial mixing of the core material. The profiles of the [O I] 6300 Å and Mg I] 4571 Å lines show a remarkable similarity, suggesting that these lines arise from the same nuclear burning zone. Given the findings in J14, this would be the O/Ne/Mg zone and contributions from the O/Si/S and O/C zones to the [O I] 6300 Å flux would be modest, in turn suggesting the amount of molecule (CO and SiO) cooling in these zones to be considerable. We use repetitions of small scale fluctuations in the [O I] 6300 Å and [O I] 6364 Å lines to find a line ratio close to 3, consistent with optically thin emission and in agreement with the results in J14, from 200 days and onwards. Applying the method of Chugai (1994) to these small scale fluctuations, we find an upper limit on the filling factor of the [O I] 6300 Å and Mg I] 4571 Å line emitting material of ~ 0.07 and a lower limit on the number of clumps of ~ 900 .

This paper concludes our observational and modelling work on SN 2011dh presented in M11, B12, E14a and J14. We have applied stellar evolutionary progenitor analysis, hydrodynamical modelling, SN atmosphere modelling and steady-state NLTE modelling to our extensive set of observational data. Although a number of issues remains unsolved, as the photometric evolution in the MIR and the late time flattening of the lightcurve, the main characteristics of the SN and its progenitor star found by the different methods are consistent. The progenitor star appears to have been of moderate ($12-15 M_{\odot}$) initial mass, and the $3-4 M_{\odot}$ helium core surrounded by a low-mass ($\sim 0.1 M_{\odot}$)

and extended (200-300 R_{\odot}) hydrogen-rich envelope. In particular we have found the initial masses of SNe 2011dh, 1993J and 2008ax to be $\lesssim 15 M_{\odot}$, from both hydrodynamical modelling of the early bolometric evolution and steady-state NLTE modelling of the late spectral evolution. This limit is also supported by stellar evolutionary progenitor analysis for SNe 2011dh and 1993J (Maund et al. 2004, 2011). Given that the mass-loss rates for stars in this mass range are probably not strong enough to expell the hydrogen envelope before core-collapse, a binary origin for these SNe is strongly suggested.

7. Acknowledgements

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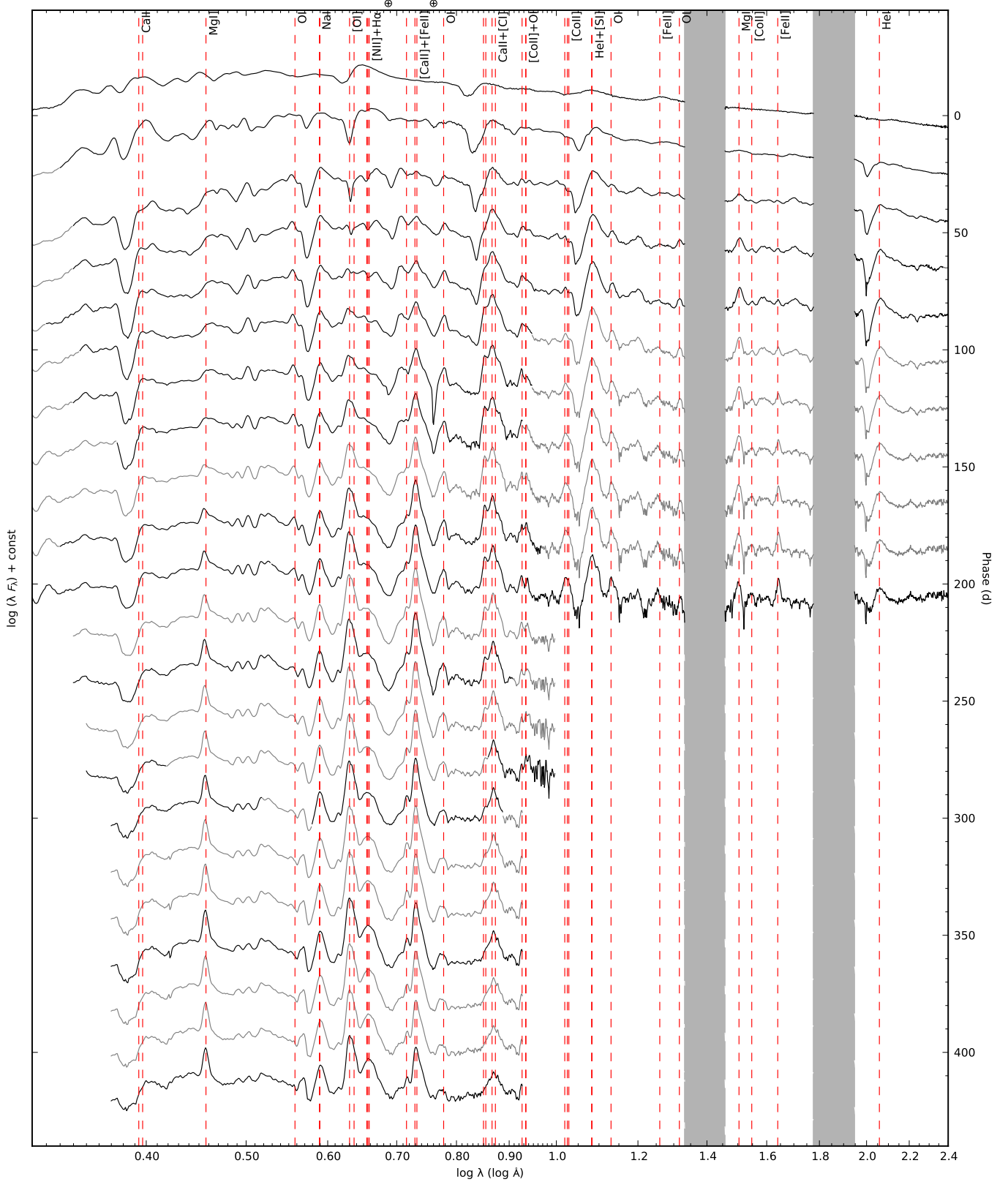


Fig. 2. Optical and NIR (interpolated) spectral evolution for SN 2011dh for days 5–425 with a 20-day sampling. Telluric absorption bands are marked with a \oplus symbol in the optical and shown as grey regions in the NIR.

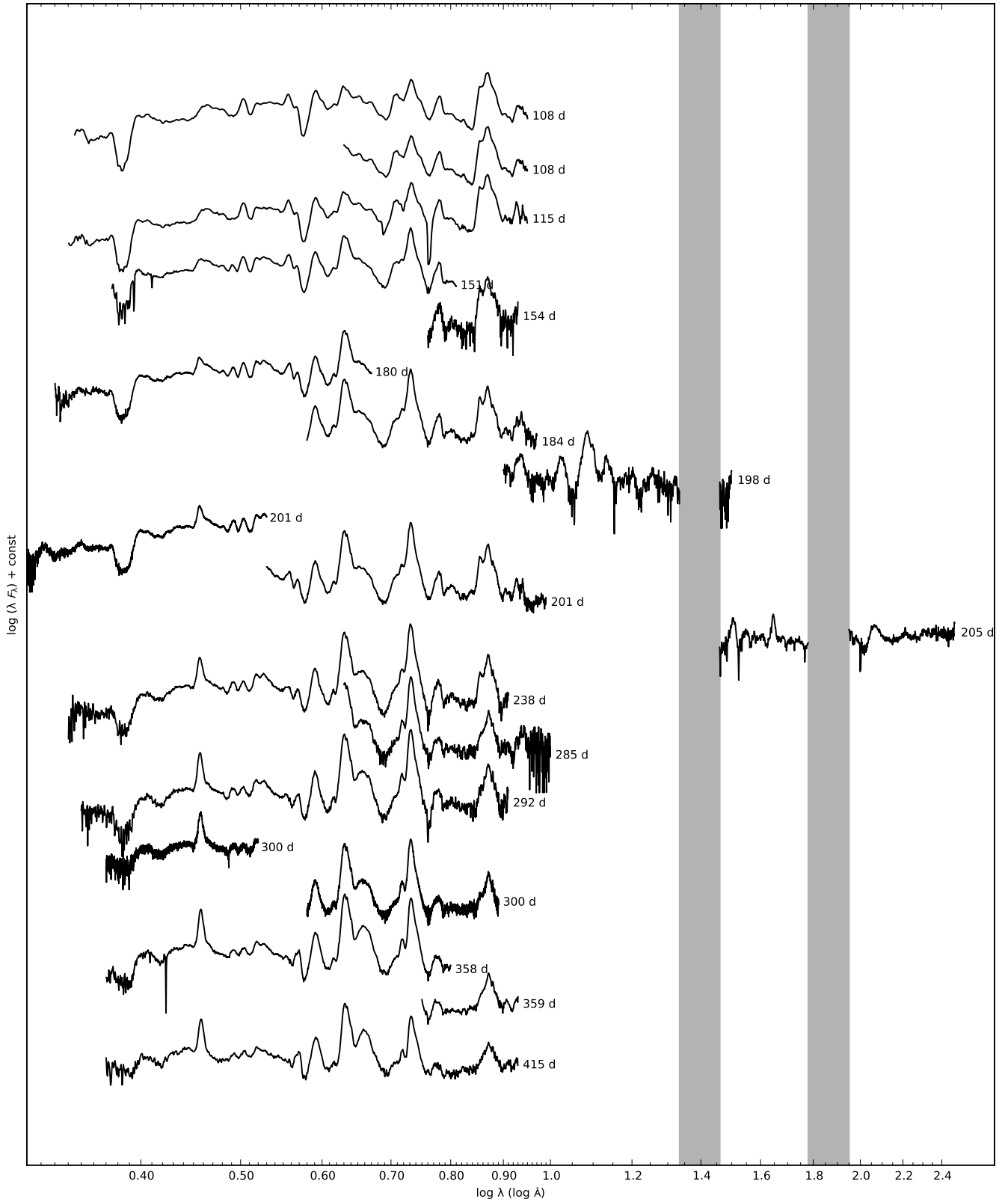


Fig. 3. Sequence of the observed late-time (100-415 days) spectra for SN 2011dh. Spectra obtained on the same night using the same telescope and instrument have been combined and each spectra have been labelled with the phase of the SN. Telluric absorption bands are marked with a ⊕ symbol in the optical and shown as grey regions in the NIR. !The AS-1.82/AFOSC spectra from 117 days is not yet included here.!

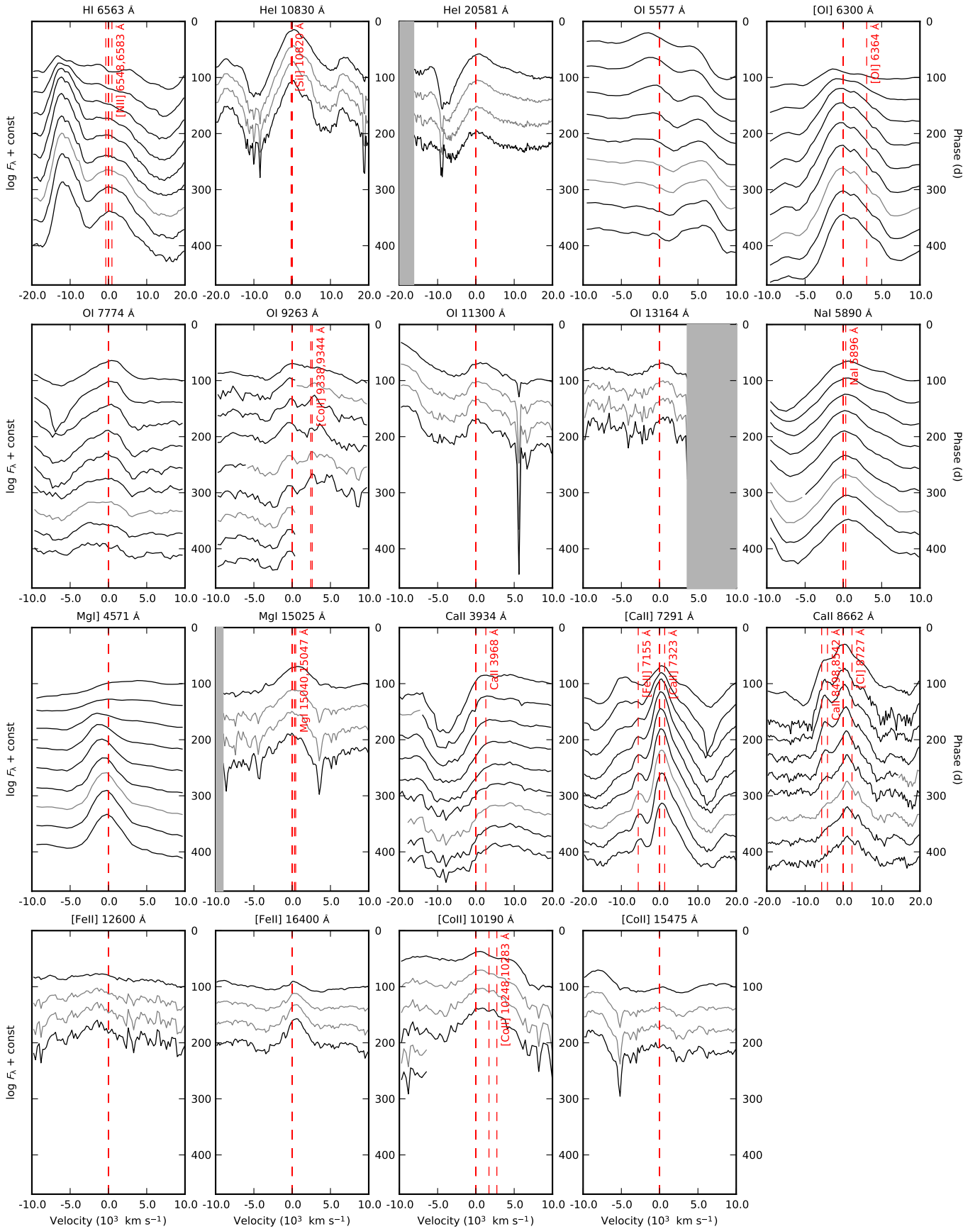


Fig. 9. Spectral evolution of all identified lines. Multiple or blended lines are marked with red dashed lines and telluric absorption bands in the NIR shown as grey regions.

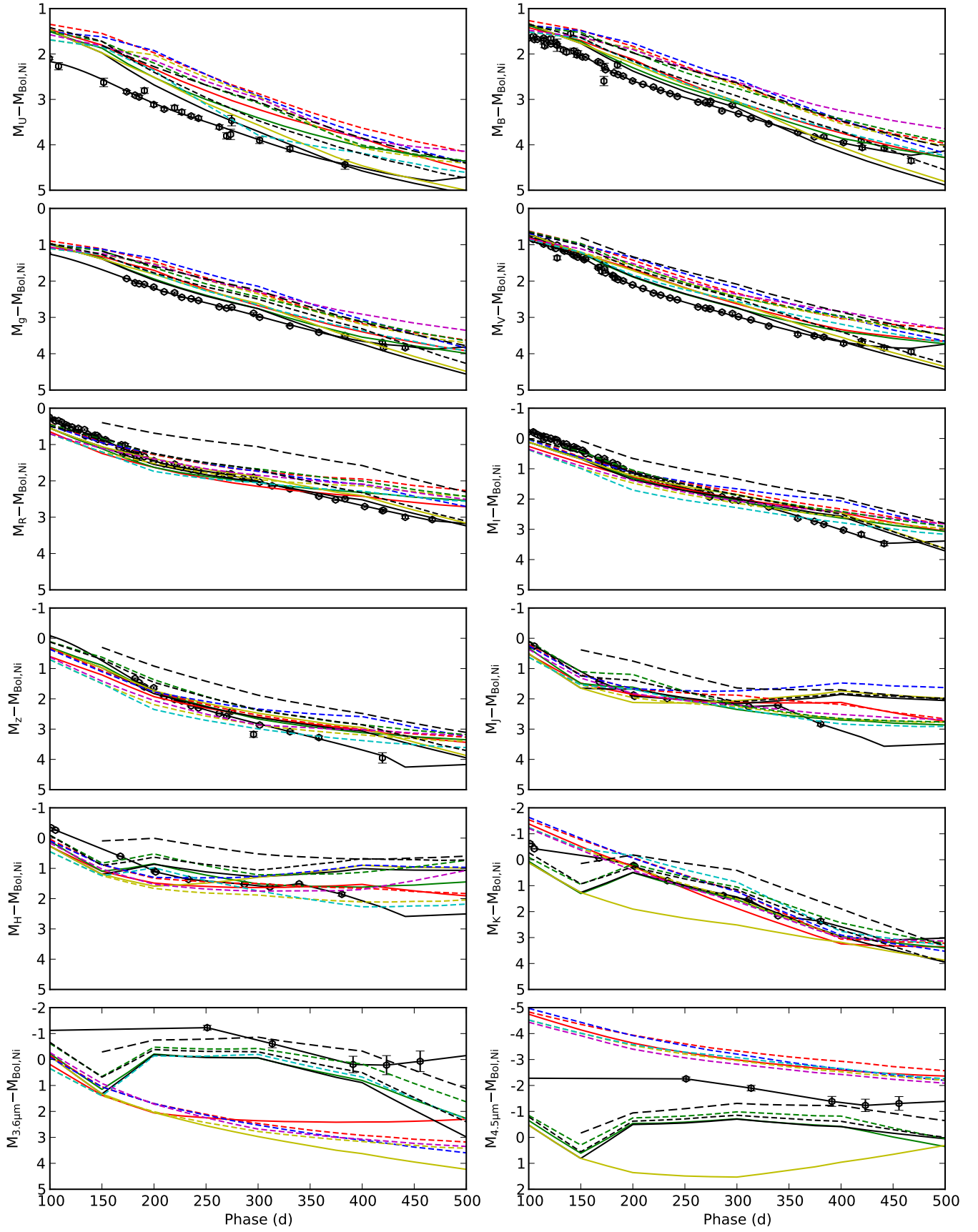


Fig. 20. 100-500 days Optical, NIR and MIR magnitudes for the J14 models as compared to the observed magnitudes. The lightcurves have been normalized to the radioactive decay chain luminosity of $0.075 M_{\odot}$ of ^{56}Ni and the models are displayed as in Fig. 22.

Table 4. Optical colour-corrected JC U and S-corrected JC $BVRI$ magnitudes for SN 2011dh. Errors are given in parentheses. For completeness data for the first 100 days already published in E14a are included. !One AFOSC observations from 2011-11-20 is not yet included in the table.!

JD (+2400000) (d)	Phase (d)	U (mag)	B (mag)	V (mag)	R (mag)	I (mag)	Telescope (Instrument)
55716.43	3.43	14.99 (0.03)	15.35 (0.02)	14.92 (0.02)	14.54 (0.01)	14.41 (0.02)	LT (RATCam)
55716.43	3.43	15.15 (0.08)	15.39 (0.02)	14.94 (0.02)	14.57 (0.01)	14.46 (0.01)	TNG (LRS)
55717.43	4.43	15.03 (0.03)	15.14 (0.02)	14.67 (0.03)	14.25 (0.01)	14.26 (0.03)	LT (RATCam)
55717.48	4.48	15.17 (0.09)	15.21 (0.03)	14.63 (0.03)	14.24 (0.01)	14.23 (0.02)	AS-1.82m (AFOSC)
55717.48	4.48	...	15.12 (0.03)	14.63 (0.02)	14.27 (0.01)	14.28 (0.02)	CANTAB (BIGST8)
55718.48	5.48	...	14.84 (0.01)	14.28 (0.02)	13.94 (0.01)	13.94 (0.01)	LT (RATCam)
55718.57	5.57	14.68 (0.06)	14.84 (0.02)	14.24 (0.02)	13.91 (0.01)	14.04 (0.01)	CA-2.2m (CAFOS)
55720.42	7.42	14.42 (0.02)	14.25 (0.01)	13.75 (0.03)	13.41 (0.01)	13.43 (0.02)	LT (RATCam)
55721.42	8.42	14.28 (0.10)	14.02 (0.01)	13.48 (0.01)	13.22 (0.01)	13.24 (0.02)	LT (RATCam)
55721.43	8.43	14.07 (0.07)	14.06 (0.01)	13.60 (0.04)	13.27 (0.02)	13.34 (0.02)	NOT (ALFOSC)
55722.42	9.42	...	13.86 (0.01)	13.29 (0.01)	13.05 (0.01)	13.07 (0.01)	LT (RATCam)
55723.41	10.41	13.98 (0.06)	13.71 (0.01)	13.16 (0.01)	12.89 (0.01)	12.90 (0.01)	LT (RATCam)
55724.41	11.41	13.91 (0.08)	13.62 (0.01)	13.03 (0.01)	12.79 (0.01)	12.77 (0.01)	LT (RATCam)
55725.39	12.39	...	...	12.94 (0.02)	12.66 (0.01)	...	MONTCAB (BIGST8)
55725.43	12.43	13.88 (0.07)	13.52 (0.02)	12.92 (0.04)	12.68 (0.01)	12.68 (0.01)	LT (RATCam)
55726.36	13.36	...	13.52 (0.01)	12.91 (0.02)	12.59 (0.01)	...	MONTCAB (BIGST8)
55728.40	15.40	...	13.39 (0.01)	12.77 (0.01)	12.44 (0.01)	...	MONTCAB (BIGST8)
55729.39	16.39	13.65 (0.01)	13.35 (0.01)	12.77 (0.06)	12.39 (0.01)	12.35 (0.02)	LT (RATCam)
55730.40	17.40	13.64 (0.03)	13.33 (0.01)	12.66 (0.01)	12.36 (0.01)	12.32 (0.01)	LT (RATCam)
55731.41	18.41	13.74 (0.09)	13.30 (0.01)	12.60 (0.02)	12.31 (0.01)	12.27 (0.01)	LT (RATCam)
55731.82	18.82	...	...	...	12.33 (0.02)	12.25 (0.01)	FTN (FS02)
55732.40	19.40	...	13.35 (0.03)	12.61 (0.01)	12.27 (0.01)	12.21 (0.01)	CANTAB (BIGST8)
55732.41	19.41	13.44 (0.06)	13.36 (0.02)	12.64 (0.02)	12.33 (0.02)	12.31 (0.02)	NOT (ALFOSC)
55732.46	19.46	13.71 (0.07)	13.32 (0.01)	12.58 (0.01)	12.28 (0.02)	12.22 (0.01)	LT (RATCam)
55733.45	20.45	13.67 (0.07)	...	...	12.26 (0.01)	12.20 (0.02)	LT (RATCam)
55734.52	21.52	13.37 (0.05)	13.33 (0.01)	12.58 (0.01)	12.25 (0.01)	12.29 (0.01)	CA-2.2m (CAFOS)
55735.44	22.44	13.91 (0.04)	...	...	12.26 (0.01)	12.16 (0.01)	LT (RATCam)
55736.44	23.44	14.13 (0.08)	...	...	12.26 (0.01)	12.16 (0.01)	LT (RATCam)
55737.39	24.39	...	13.65 (0.01)	12.72 (0.01)	...	...	LT (RATCam)
55738.42	25.42	14.50 (0.04)	13.79 (0.02)	12.81 (0.01)	12.32 (0.02)	12.22 (0.01)	LT (RATCam)
55738.51	25.51	14.20 (0.04)	13.77 (0.02)	12.82 (0.01)	12.38 (0.01)	12.26 (0.01)	NOT (ALFOSC)
55739.43	26.43	14.73 (0.04)	13.95 (0.02)	12.88 (0.01)	12.38 (0.01)	12.23 (0.01)	LT (RATCam)
55740.36	27.36	...	14.09 (0.04)	12.93 (0.01)	12.45 (0.01)	12.29 (0.01)	MONTCAB (BIGST8)
55740.43	27.43	14.91 (0.03)	14.12 (0.01)	12.97 (0.01)	12.48 (0.01)	12.30 (0.01)	LT (RATCam)
55740.44	27.44	...	...	12.97 (0.01)	12.47 (0.01)	...	TJO (MEIA)
55741.44	28.44	...	...	...	12.54 (0.01)	12.32 (0.01)	LT (RATCam)
55742.49	29.49	15.33 (0.01)	...	...	12.62 (0.01)	12.40 (0.01)	LT (RATCam)
55743.41	30.41	...	14.53 (0.01)	13.27 (0.02)	...	...	LT (RATCam)
55743.42	30.42	15.18 (0.05)	14.51 (0.02)	...	12.65 (0.01)	12.53 (0.01)	CA-2.2m (CAFOS)
55743.42	30.42	15.43 (0.05)	14.53 (0.01)	13.26 (0.03)	12.68 (0.01)	12.49 (0.01)	NOT (ALFOSC)
55745.39	32.39	15.74 (0.03)	14.74 (0.01)	13.44 (0.01)	12.77 (0.01)	12.56 (0.01)	NOT (ALFOSC)
55745.44	32.44	15.93 (0.04)	...	...	12.81 (0.01)	12.53 (0.01)	LT (RATCam)
55745.80	32.80	...	...	...	12.80 (0.01)	12.51 (0.01)	FTN (FS02)
55746.45	33.45	16.07 (0.04)	14.87 (0.03)	13.51 (0.01)	12.83 (0.01)	12.55 (0.02)	LT (RATCam)
55747.44	34.44	16.12 (0.04)	...	...	12.89 (0.01)	12.59 (0.01)	LT (RATCam)
55748.43	35.43	16.02 (0.02)	14.97 (0.01)	13.62 (0.01)	12.88 (0.01)	12.65 (0.01)	NOT (ALFOSC)
55748.44	35.44	16.27 (0.04)	...	...	12.94 (0.01)	12.62 (0.01)	LT (RATCam)
55750.40	37.40	16.20 (0.04)	15.10 (0.01)	13.73 (0.01)	13.03 (0.01)	12.73 (0.01)	NOT (ALFOSC)
55750.42	37.42	16.41 (0.14)	15.11 (0.02)	13.78 (0.03)	13.03 (0.01)	12.73 (0.02)	LT (RATCam)
55751.41	38.41	...	15.14 (0.01)	13.81 (0.01)	13.08 (0.01)	12.73 (0.01)	TJO (MEIA)
55751.43	38.43	...	...	...	13.11 (0.01)	12.77 (0.01)	LT (RATCam)
55752.45	39.45	16.54 (0.16)	...	...	13.13 (0.01)	12.75 (0.01)	LT (RATCam)

Table 3. Continued.

JD (+2400000) (d)	Phase (d)	<i>U</i> (mag)	<i>B</i> (mag)	<i>V</i> (mag)	<i>R</i> (mag)	<i>I</i> (mag)	Telescope (Instrument)
55753.42	40.42	...	15.29 (0.01)	13.90 (0.02)	...	...	LT (RATCam)
55753.46	40.46	16.45 (0.05)	15.24 (0.01)	13.86 (0.01)	13.15 (0.01)	12.81 (0.01)	NOT (ALFOOSC)
55755.40	42.40	16.42 (0.04)	15.30 (0.01)	13.96 (0.01)	13.23 (0.01)	12.89 (0.01)	NOT (ALFOOSC)
55756.44	43.44	...	15.28 (0.02)	13.98 (0.02)	13.28 (0.02)	12.86 (0.01)	AS-Schmidt (SBIG)
55756.45	43.45	...	15.38 (0.02)	13.98 (0.01)	13.27 (0.03)	12.92 (0.01)	LT (RATCam)
55757.43	44.43	16.42 (0.04)	15.38 (0.01)	14.05 (0.01)	13.29 (0.01)	12.97 (0.01)	NOT (ALFOOSC)
55759.45	46.45	...	15.44 (0.01)	14.06 (0.02)	...	...	LT (RATCam)
55761.40	48.40	...	15.44 (0.01)	14.17 (0.01)	13.44 (0.01)	13.02 (0.01)	AS-Schmidt (SBIG)
55762.41	49.41	...	15.45 (0.01)	14.16 (0.01)	13.44 (0.01)	13.06 (0.01)	NOT (ALFOOSC)
55762.78	49.78	...	...	...	13.44 (0.01)	13.03 (0.01)	FTN (FS02)
55763.44	50.44	...	15.47 (0.01)	14.22 (0.01)	13.47 (0.01)	13.09 (0.01)	AS-Schmidt (SBIG)
55765.43	52.43	16.44 (0.03)	15.52 (0.01)	14.26 (0.01)	13.55 (0.01)	13.17 (0.01)	NOT (ALFOOSC)
55767.43	54.43	16.50 (0.05)	...	...	13.58 (0.01)	13.16 (0.02)	LT (RATCam)
55768.45	55.45	16.48 (0.04)	...	...	13.60 (0.02)	13.19 (0.02)	LT (RATCam)
55771.40	58.40	16.37 (0.03)	15.58 (0.01)	14.32 (0.01)	13.62 (0.01)	13.28 (0.01)	CA-2.2m (CAFOS)
55773.39	60.39	16.45 (0.04)	15.60 (0.01)	14.38 (0.01)	13.71 (0.01)	13.32 (0.01)	NOT (ALFOOSC)
55776.38	63.38	16.47 (0.04)	15.64 (0.01)	14.46 (0.01)	13.77 (0.01)	13.36 (0.01)	NOT (ALFOOSC)
55777.33	64.33	...	15.52 (0.03)	14.46 (0.02)	13.78 (0.02)	13.34 (0.02)	AS-Schmidt (SBIG)
55780.40	67.40	16.42 (0.03)	15.65 (0.01)	14.50 (0.01)	13.85 (0.01)	13.43 (0.01)	NOT (ALFOOSC)
55783.43	70.43	16.41 (0.03)	15.71 (0.01)	14.58 (0.01)	13.94 (0.01)	13.51 (0.01)	NOT (ALFOOSC)
55784.33	71.33	...	15.66 (0.02)	14.59 (0.01)	...	13.43 (0.02)	AS-Schmidt (SBIG)
55784.39	71.39	16.45 (0.04)	15.66 (0.01)	14.52 (0.02)	13.90 (0.01)	13.47 (0.02)	CA-2.2m (CAFOS)
55784.77	71.77	...	...	...	13.93 (0.02)	13.45 (0.01)	FTN (FS02)
55785.36	72.36	...	15.70 (0.02)	14.61 (0.01)	13.96 (0.01)	13.45 (0.01)	AS-Schmidt (SBIG)
55788.41	75.41	...	...	...	14.02 (0.02)	13.52 (0.01)	AS-Schmidt (SBIG)
55790.38	77.38	16.45 (0.09)	...	...	14.03 (0.01)	13.61 (0.01)	LT (RATCam)
55793.37	80.37	16.55 (0.07)	15.80 (0.01)	14.74 (0.01)	14.13 (0.01)	13.67 (0.01)	NOT (ALFOOSC)
55795.35	82.35	16.40 (0.04)	15.78 (0.01)	14.76 (0.01)	14.12 (0.01)	13.68 (0.01)	CA-2.2m (CAFOS)
55797.37	84.37	...	15.83 (0.02)	14.82 (0.01)	...	...	AS-Schmidt (SBIG)
55797.76	84.76	...	...	...	14.22 (0.01)	13.68 (0.01)	FTN (FS02)
55798.36	85.36	16.50 (0.03)	15.84 (0.01)	14.84 (0.01)	14.25 (0.01)	13.65 (0.02)	NOT (ALFOOSC)
55799.33	86.33	...	15.82 (0.01)	14.86 (0.01)	...	...	AS-Schmidt (SBIG)
55801.36	88.36	16.44 (0.04)	15.89 (0.01)	14.90 (0.01)	14.31 (0.01)	13.80 (0.01)	NOT (ALFOOSC)
55801.40	88.40	...	15.80 (0.02)	14.90 (0.01)	...	...	AS-Schmidt (SBIG)
55803.35	90.35	...	15.88 (0.02)	14.91 (0.01)	14.32 (0.01)	13.79 (0.01)	AS-Schmidt (SBIG)
55805.33	92.33	...	15.87 (0.02)	14.97 (0.02)	14.37 (0.01)	13.83 (0.01)	AS-Schmidt (SBIG)
55810.34	97.34	16.68 (0.06)	16.00 (0.01)	15.11 (0.01)	14.52 (0.01)	14.02 (0.01)	NOT (ALFOOSC)
55812.33	99.33	16.51 (0.03)	16.02 (0.01)	15.05 (0.01)	14.49 (0.01)	14.00 (0.01)	CA-2.2m (CAFOS)
55817.35	104.35	...	16.02 (0.03)	15.19 (0.02)	14.63 (0.02)	14.04 (0.02)	AS-Schmidt (SBIG)
55818.33	105.33	...	16.10 (0.02)	15.19 (0.02)	14.66 (0.01)	14.08 (0.01)	AS-Schmidt (SBIG)
55821.31	108.31	16.77 (0.08)	16.12 (0.02)	15.25 (0.01)	14.68 (0.01)	14.16 (0.01)	CA-2.2m (CAFOS)
55824.32	111.32	...	...	15.31 (0.02)	14.75 (0.03)	14.24 (0.03)	AS-Schmidt (SBIG)
55827.33	114.33	...	16.16 (0.03)	15.42 (0.01)	14.87 (0.02)	14.27 (0.01)	AS-Schmidt (SBIG)
55827.48	114.48	...	16.22 (0.07)	15.37 (0.03)	14.94 (0.05)	14.38 (0.05)	AT (ANDOR)
55828.27	115.27	...	16.34 (0.04)	15.39 (0.02)	14.86 (0.02)	14.31 (0.01)	AT (ANDOR)
55830.28	117.28	...	16.30 (0.02)	15.38 (0.01)	14.91 (0.01)	14.34 (0.01)	AS-1.82m (AFOSC)
55834.26	121.26	...	16.23 (0.03)	15.49 (0.02)	14.99 (0.02)	14.44 (0.02)	AT (ANDOR)
55834.31	121.31	...	16.35 (0.02)	15.55 (0.01)	14.99 (0.02)	14.41 (0.02)	AS-Schmidt (SBIG)
55838.34	125.34	...	...	15.64 (0.02)	15.11 (0.03)	14.49 (0.01)	AS-Schmidt (SBIG)
55839.28	126.28	...	16.39 (0.03)	15.65 (0.02)	15.12 (0.02)	14.52 (0.02)	AS-Schmidt (SBIG)
55840.26	127.26	...	16.44 (0.03)	15.57 (0.02)	15.15 (0.03)	14.53 (0.02)	AT (ANDOR)
55840.30	127.30	...	16.44 (0.14)	15.93 (0.06)	15.08 (0.04)	14.59 (0.04)	AS-Schmidt (SBIG)

Table 3. Continued.

JD (+2400000) (d)	Phase (d)	<i>U</i> (mag)	<i>B</i> (mag)	<i>V</i> (mag)	<i>R</i> (mag)	<i>I</i> (mag)	Telescope (Instrument)
55846.26	133.26	...	16.60 (0.03)	15.77 (0.02)	15.17 (0.02)	14.71 (0.02)	AT (ANDOR)
55847.30	134.30	...	...	15.81 (0.02)	15.35 (0.03)	14.77 (0.02)	AT (ANDOR)
55849.26	136.26	...	16.68 (0.05)	15.81 (0.02)	15.33 (0.03)	14.75 (0.02)	AT (ANDOR)
55853.27	140.27	...	16.32 (0.06)	15.90 (0.05)	15.44 (0.05)	14.91 (0.04)	AS-Schmidt (SBIG)
55855.38	142.38	...	...	15.96 (0.03)	15.44 (0.03)	14.93 (0.03)	AT (ANDOR)
55856.24	143.24	...	16.72 (0.06)	16.01 (0.03)	15.42 (0.02)	14.91 (0.02)	AT (ANDOR)
55858.29	145.29	...	...	16.02 (0.03)	15.45 (0.03)	14.96 (0.02)	AT (ANDOR)
55859.23	146.23	...	16.84 (0.05)	16.08 (0.02)	15.56 (0.03)	15.01 (0.02)	AT (ANDOR)
55860.22	147.22	...	16.80 (0.05)	16.10 (0.03)	15.53 (0.03)	15.02 (0.02)	AT (ANDOR)
55864.69	151.69	17.55 (0.09)	16.94 (0.02)	16.14 (0.01)	15.65 (0.01)	15.10 (0.01)	AS-1.82m (AFOSC)
55866.28	153.28	...	...	16.23 (0.02)	15.64 (0.03)	15.18 (0.02)	AT (ANDOR)
55867.70	154.70	...	16.97 (0.02)	16.21 (0.03)	15.71 (0.02)	15.25 (0.02)	CA-2.2m (CAFOS)
55879.66	166.66	...	17.19 (0.03)	16.58 (0.02)	15.99 (0.02)	15.49 (0.02)	AS-Schmidt (SBIG)
55881.74	168.74	...	17.23 (0.02)	16.59 (0.02)	15.94 (0.01)	15.66 (0.03)	CA-2.2m (CAFOS)
55883.24	170.24	...	...	16.72 (0.05)	16.19 (0.05)	15.61 (0.02)	AT (ANDOR)
55885.21	172.21	...	17.67 (0.10)	16.53 (0.03)	15.98 (0.05)	15.62 (0.03)	AT (ANDOR)
55885.73	172.73	...	17.36 (0.08)	16.67 (0.02)	...	15.59 (0.03)	AS-1.82m (AFOSC)
55886.75	173.75	17.97 (0.03)	17.43 (0.01)	16.79 (0.01)	16.17 (0.01)	15.73 (0.01)	NOT (ALFOSC)
55893.71	180.71	...	...	16.93 (0.02)	16.27 (0.01)	15.80 (0.02)	AS-Schmidt (SBIG)
55894.76	181.76	18.12 (0.03)	17.58 (0.01)	16.96 (0.01)	16.31 (0.01)	15.89 (0.01)	NOT (ALFOSC)
55896.20	183.20	...	...	17.03 (0.05)	16.44 (0.06)	16.01 (0.04)	AT (ANDOR)
55898.19	185.19	...	17.44 (0.08)	17.06 (0.04)	16.35 (0.04)	15.90 (0.03)	AT (ANDOR)
55898.73	185.73	18.20 (0.04)	17.65 (0.01)	17.09 (0.01)	16.39 (0.01)	16.05 (0.01)	NOT (ALFOSC)
55903.76	190.76	18.11 (0.06)	17.74 (0.02)	17.18 (0.02)	16.48 (0.01)	16.10 (0.02)	NOT (ALFOSC)
55912.79	199.79	18.51 (0.05)	17.93 (0.02)	17.37 (0.01)	16.68 (0.01)	16.33 (0.01)	NOT (ALFOSC)
55922.76	209.76	18.70 (0.03)	18.10 (0.01)	17.57 (0.01)	16.86 (0.01)	16.52 (0.01)	NOT (ALFOSC)
55932.79	219.79	18.77 (0.06)	18.26 (0.01)	17.80 (0.02)	16.97 (0.02)	16.72 (0.02)	NOT (ALFOSC)
55939.73	226.73	18.93 (0.05)	18.40 (0.02)	17.92 (0.02)	17.12 (0.01)	16.85 (0.01)	NOT (ALFOSC)
55948.73	235.73	19.11 (0.04)	18.56 (0.01)	18.08 (0.01)	17.27 (0.01)	17.04 (0.01)	NOT (ALFOSC)
55955.76	242.76	19.23 (0.04)	18.69 (0.01)	18.20 (0.01)	17.37 (0.01)	17.19 (0.01)	NOT (ALFOSC)
55975.69	262.69	19.61 (0.05)	19.01 (0.01)	18.59 (0.01)	17.67 (0.01)	17.51 (0.01)	NOT (ALFOSC)
55982.74	269.74	19.88 (0.07)	19.09 (0.02)	18.69 (0.02)	17.74 (0.01)	17.65 (0.01)	NOT (ALFOSC)
55986.62	273.62	19.88 (0.11)	19.15 (0.03)	18.75 (0.03)	17.76 (0.02)	17.83 (0.03)	CA-2.2m (CAFOS)
55987.62	274.62	19.59 (0.12)	19.11 (0.02)	18.76 (0.02)	17.78 (0.01)	17.78 (0.01)	LT (RATCam)
55998.67	285.67	...	19.43 (0.02)	18.96 (0.02)	18.00 (0.01)	17.95 (0.01)	NOT (ALFOSC)
56008.66	295.66	...	19.40 (0.03)	19.10 (0.03)	18.06 (0.02)	18.14 (0.03)	LT (RATCam)
56014.51	301.51	20.28 (0.07)	19.65 (0.01)	19.24 (0.02)	18.26 (0.01)	18.22 (0.01)	NOT (ALFOSC)
56026.49	313.49	...	19.86 (0.02)	19.44 (0.02)	18.47 (0.01)	18.41 (0.02)	NOT (ALFOSC)
56043.59	330.59	20.76 (0.06)	20.15 (0.02)	19.78 (0.02)	18.72 (0.01)	18.72 (0.02)	NOT (ALFOSC)
56071.42	358.42	...	20.61 (0.02)	20.28 (0.04)	19.20 (0.02)	19.36 (0.03)	NOT (ALFOSC)
56087.43	374.43	...	20.86 (0.02)	20.48 (0.03)	19.45 (0.02)	19.62 (0.02)	NOT (ALFOSC)
56096.48	383.48	21.62 (0.10)	20.95 (0.03)	20.60 (0.04)	19.51 (0.02)	19.81 (0.03)	NOT (ALFOSC)
56115.44	402.44	...	21.26 (0.03)	20.96 (0.05)	19.91 (0.02)	20.18 (0.04)	NOT (ALFOSC)
56132.43	419.43	...	21.38 (0.06)	21.07 (0.06)	20.19 (0.03)	20.49 (0.05)	NOT (ALFOSC)
56133.40	420.40	...	21.55 (0.05)	21.13 (0.06)	20.19 (0.03)	...	NOT (ALFOSC)
56154.39	441.39	...	21.76 (0.05)	21.46 (0.06)	20.58 (0.04)	21.01 (0.08)	NOT (ALFOSC)
56180.37	467.37	...	22.30 (0.05)	21.82 (0.06)	20.90 (0.04)	...	NOT (ALFOSC)
56313.73	600.73	...	...	22.44 (0.10)	...	...	NOT (ALFOSC)
56353.50	640.50	...	...	23.02 (0.00)	...	22.58 (0.00)	HST (ACS)
56371.69	658.69	...	23.42 (0.32)	...	...	...	NOT (ALFOSC)
56397.64	684.64	...	...	23.20 (0.20)	...	...	NOT (ALFOSC)
56445.43	732.43	...	23.96 (0.50)	...	...	...	NOT (ALFOSC)

Table 4. Optical colour-corrected SDSS *u* and S-corrected SDSS *griz* magnitudes for SN 2011dh. Errors are given in parentheses. For completeness data for the first 100 days already published in E14a are included.

JD (+2400000) (d)	Phase (d)	<i>u</i> (mag)	<i>g</i> (mag)	<i>r</i> (mag)	<i>i</i> (mag)	<i>z</i> (mag)	Telescope (Instrument)
55716.47	3.47	15.90 (0.03)	15.08 (0.01)	14.68 (0.01)	14.80 (0.01)	14.76 (0.02)	LT (RATCam)
55717.46	4.46	16.01 (0.03)	14.80 (0.01)	14.38 (0.01)	14.61 (0.01)	14.58 (0.02)	LT (RATCam)
55718.53	5.53	...	14.44 (0.04)	14.06 (0.01)	14.27 (0.01)	...	LT (RATCam)
55720.44	7.44	15.39 (0.02)	13.97 (0.01)	13.53 (0.01)	13.73 (0.02)	13.87 (0.01)	LT (RATCam)
55721.44	8.44	15.09 (0.01)	13.78 (0.01)	13.33 (0.01)	13.52 (0.01)	13.64 (0.01)	LT (RATCam)
55722.44	9.44	...	13.59 (0.01)	13.18 (0.01)	13.35 (0.01)	13.49 (0.01)	LT (RATCam)
55723.41	10.41	14.82 (0.03)	...	13.02 (0.01)	13.16 (0.01)	13.34 (0.01)	LT (RATCam)
55724.41	11.41	14.72 (0.02)	...	12.93 (0.01)	13.05 (0.01)	13.22 (0.01)	LT (RATCam)
55725.43	12.43	14.74 (0.04)	...	12.83 (0.01)	12.94 (0.01)	13.09 (0.01)	LT (RATCam)
55729.39	16.39	14.56 (0.03)	13.10 (0.01)	12.56 (0.01)	12.62 (0.01)	12.81 (0.01)	LT (RATCam)
55730.40	17.40	14.45 (0.03)	13.07 (0.01)	12.51 (0.01)	12.56 (0.01)	12.77 (0.01)	LT (RATCam)
55731.41	18.41	14.54 (0.03)	13.02 (0.01)	12.46 (0.01)	12.51 (0.01)	12.71 (0.01)	LT (RATCam)
55731.82	18.82	...	13.07 (0.01)	12.46 (0.01)	12.50 (0.01)	12.65 (0.01)	FTN (FS02)
55732.46	19.46	14.56 (0.01)	13.00 (0.03)	12.42 (0.01)	12.48 (0.01)	12.67 (0.01)	LT (RATCam)
55733.45	20.45	14.52 (0.05)	13.03 (0.01)	12.41 (0.01)	12.45 (0.01)	12.65 (0.01)	LT (RATCam)
55735.44	22.44	14.75 (0.04)	13.12 (0.01)	12.43 (0.01)	12.41 (0.01)	12.60 (0.01)	LT (RATCam)
55736.44	23.44	14.96 (0.03)	13.19 (0.02)	12.45 (0.01)	12.42 (0.01)	12.59 (0.02)	LT (RATCam)
55738.45	25.45	15.37 (0.02)	13.43 (0.01)	12.55 (0.01)	12.47 (0.01)	12.65 (0.01)	LT (RATCam)
55739.44	26.44	15.55 (0.02)	13.50 (0.03)	12.59 (0.01)	12.50 (0.01)	12.65 (0.01)	LT (RATCam)
55740.44	27.44	15.80 (0.01)	13.66 (0.01)	12.66 (0.01)	12.55 (0.01)	12.70 (0.01)	LT (RATCam)
55741.44	28.44	...	13.75 (0.02)	12.76 (0.01)	12.59 (0.02)	12.76 (0.01)	LT (RATCam)
55742.49	29.49	16.20 (0.02)	13.92 (0.01)	12.84 (0.01)	12.65 (0.01)	12.80 (0.01)	LT (RATCam)
55745.44	32.44	16.71 (0.05)	14.20 (0.02)	13.04 (0.01)	12.79 (0.01)	12.87 (0.03)	LT (RATCam)
55745.80	32.80	...	14.35 (0.04)	13.00 (0.01)	12.79 (0.01)	12.94 (0.01)	FTN (FS02)
55746.45	33.45	16.83 (0.04)	14.32 (0.01)	13.09 (0.01)	12.82 (0.01)	12.94 (0.01)	LT (RATCam)
55747.44	34.44	16.90 (0.04)	14.40 (0.02)	13.13 (0.01)	12.86 (0.01)	12.95 (0.01)	LT (RATCam)
55748.44	35.44	17.09 (0.04)	14.42 (0.02)	13.19 (0.01)	12.90 (0.01)	13.01 (0.01)	LT (RATCam)
55750.44	37.44	17.20 (0.10)	14.55 (0.02)	13.29 (0.01)	13.02 (0.02)	13.04 (0.04)	LT (RATCam)
55751.43	38.43	17.14 (0.03)	14.64 (0.03)	13.36 (0.01)	13.04 (0.01)	13.11 (0.01)	LT (RATCam)
55752.45	39.45	17.24 (0.07)	14.66 (0.01)	13.39 (0.01)	13.04 (0.01)	13.09 (0.01)	LT (RATCam)
55756.46	43.46	...	14.79 (0.01)	13.55 (0.01)	13.22 (0.01)	13.19 (0.01)	LT (RATCam)
55762.78	49.78	...	15.00 (0.02)	13.68 (0.01)	13.37 (0.01)	13.28 (0.01)	FTN (FS02)
55767.43	54.43	17.30 (0.02)	15.03 (0.01)	13.84 (0.01)	13.52 (0.01)	13.38 (0.02)	LT (RATCam)
55768.45	55.45	17.29 (0.02)	15.03 (0.01)	13.86 (0.01)	13.56 (0.01)	13.41 (0.01)	LT (RATCam)
55773.39	60.39	17.27 (0.04)	15.07 (0.01)	13.99 (0.01)	13.72 (0.01)	13.54 (0.02)	NOT (ALFOSC)
55776.38	63.38	17.36 (0.03)	15.13 (0.01)	14.03 (0.01)	13.76 (0.01)	13.56 (0.01)	NOT (ALFOSC)
55780.41	67.41	17.33 (0.03)	15.16 (0.01)	14.09 (0.01)	13.84 (0.01)	13.61 (0.01)	NOT (ALFOSC)
55783.44	70.44	17.26 (0.04)	15.18 (0.01)	14.19 (0.01)	13.93 (0.01)	13.67 (0.01)	NOT (ALFOSC)
55784.77	71.77	...	15.23 (0.02)	14.16 (0.01)	13.88 (0.01)	13.64 (0.01)	FTN (FS02)
55790.38	77.38	17.29 (0.03)	15.35 (0.04)	14.28 (0.01)	14.04 (0.01)	13.69 (0.02)	LT (RATCam)
55793.37	80.37	17.32 (0.03)	15.30 (0.01)	14.39 (0.01)	14.16 (0.01)	13.84 (0.01)	NOT (ALFOSC)
55797.76	84.76	...	15.38 (0.01)	14.42 (0.01)	14.18 (0.01)	13.82 (0.01)	FTN (FS02)
55798.37	85.37	17.35 (0.03)	15.38 (0.01)	14.50 (0.01)	14.26 (0.01)	13.87 (0.01)	NOT (ALFOSC)
55801.36	88.36	17.34 (0.01)	15.42 (0.01)	14.53 (0.01)	14.31 (0.01)	13.89 (0.01)	NOT (ALFOSC)
55810.34	97.34	17.49 (0.02)	15.55 (0.01)	14.75 (0.01)	14.56 (0.01)	14.10 (0.02)	NOT (ALFOSC)
55886.75	173.75	21.74 (1.97)	16.99 (0.01)	16.36 (0.01)	16.16 (0.01)	...	NOT (ALFOSC)
55894.76	181.76	18.89 (0.03)	17.19 (0.02)	16.50 (0.01)	16.28 (0.02)	16.31 (0.02)	NOT (ALFOSC)
55898.73	185.73	18.97 (0.03)	17.25 (0.01)	16.59 (0.01)	16.42 (0.01)	16.49 (0.01)	NOT (ALFOSC)
55903.76	190.76	19.07 (0.05)	17.32 (0.02)	16.68 (0.01)	16.47 (0.01)	16.68 (0.04)	NOT (ALFOSC)
55912.79	199.79	19.28 (0.04)	17.48 (0.02)	16.86 (0.01)	16.66 (0.01)	16.79 (0.03)	NOT (ALFOSC)

Table 5. Continued.

JD (+2400000) (d)	Phase (d)	<i>u</i> (mag)	<i>g</i> (mag)	<i>r</i> (mag)	<i>i</i> (mag)	<i>z</i> (mag)	Telescope (Instrument)
55922.77	209.77	19.44 (0.02)	17.71 (0.01)	17.05 (0.01)	16.83 (0.01)	17.18 (0.01)	NOT (ALFOSC)
55932.79	219.79	19.50 (0.05)	17.83 (0.02)	17.18 (0.02)	17.01 (0.02)	17.37 (0.04)	NOT (ALFOSC)
55939.74	226.74	19.74 (0.05)	18.02 (0.01)	17.31 (0.01)	17.11 (0.01)	17.49 (0.02)	NOT (ALFOSC)
55948.73	235.73	19.87 (0.03)	18.15 (0.01)	17.45 (0.01)	17.27 (0.01)	17.74 (0.01)	NOT (ALFOSC)
55955.76	242.76	20.01 (0.03)	18.27 (0.01)	17.57 (0.01)	17.40 (0.01)	17.87 (0.02)	NOT (ALFOSC)
55975.69	262.69	20.37 (0.04)	18.64 (0.01)	17.84 (0.01)	17.71 (0.01)	18.25 (0.02)	NOT (ALFOSC)
55982.74	269.74	20.64 (0.05)	18.74 (0.01)	17.92 (0.01)	17.86 (0.01)	18.42 (0.03)	NOT (ALFOSC)
55987.62	274.62	20.47 (0.11)	18.76 (0.01)	17.95 (0.01)	17.96 (0.01)	18.30 (0.03)	LT (RATCam)
56008.66	295.66	...	19.14 (0.02)	18.22 (0.01)	18.33 (0.03)	19.27 (0.10)	LT (RATCam)
56014.52	301.52	21.28 (0.04)	19.30 (0.01)	18.40 (0.01)	18.45 (0.01)	19.02 (0.02)	NOT (ALFOSC)
56043.60	330.60	21.73 (0.03)	19.82 (0.01)	18.82 (0.01)	18.96 (0.01)	19.52 (0.03)	NOT (ALFOSC)
56071.43	358.43	21.85 (0.06)	20.27 (0.02)	19.26 (0.02)	19.62 (0.03)	19.98 (0.05)	NOT (ALFOSC)
56096.49	383.49	22.35 (0.05)	20.61 (0.02)	19.55 (0.02)	20.09 (0.03)	...	NOT (ALFOSC)
56132.43	419.43	...	21.14 (0.03)	20.21 (0.03)	20.79 (0.05)	21.25 (0.17)	NOT (ALFOSC)
56133.41	420.41	...	21.30 (0.04)	20.21 (0.03)	20.95 (0.06)	...	NOT (ALFOSC)
56154.39	441.39	...	21.50 (0.04)	20.61 (0.03)	21.32 (0.07)	...	NOT (ALFOSC)
56313.75	600.75	...	...	22.46 (0.11)	...	...	NOT (ALFOSC)
56428.46	715.46	...	...	23.10 (0.20)	...	...	NOT (ALFOSC)

Table 6. NIR S-corrected 2MASS *JHK* magnitudes for SN 2011dh. Errors are given in parentheses. For completeness data for the first 100 days already published in E14a are included.

JD (+2400000) (d)	Phase (d)	<i>J</i> (mag)	<i>H</i> (mag)	<i>K</i> (mag)	Telescope (Instrument)
55716.51	3.51	14.09 (0.01)	13.90 (0.01)	13.68 (0.02)	TNG (NICS)
55722.40	9.40	12.89 (0.01)	12.87 (0.01)	12.67 (0.01)	TNG (NICS)
55725.50	12.50	12.61 (0.04)	12.54 (0.01)	12.43 (0.02)	NOT (NOTCAM)
55730.51	17.51	12.12 (0.01)	12.08 (0.01)	11.94 (0.01)	TNG (NICS)
55737.72	24.72	11.96 (0.01)	11.90 (0.01)	11.72 (0.03)	LBT (LUCIFER)
55741.13	28.13	11.94 (0.01)	11.90 (0.02)	11.70 (0.05)	TCS (CAIN)
55748.43	35.43	12.14 (0.01)	12.00 (0.02)	11.77 (0.01)	TCS (CAIN)
55750.42	37.42	12.19 (0.01)	12.00 (0.01)	11.84 (0.04)	TCS (CAIN)
55751.42	38.42	12.29 (0.01)	12.01 (0.01)	11.84 (0.03)	TCS (CAIN)
55758.45	45.45	12.55 (0.01)	12.22 (0.01)	12.06 (0.01)	TNG (NICS)
55759.41	46.41	12.49 (0.03)	12.22 (0.03)	12.11 (0.04)	TCS (CAIN)
55762.41	49.41	12.57 (0.01)	12.26 (0.01)	12.17 (0.03)	TCS (CAIN)
55763.42	50.42	12.62 (0.02)	12.27 (0.04)	12.25 (0.06)	TCS (CAIN)
55765.45	52.45	12.79 (0.01)	12.38 (0.01)	12.23 (0.01)	TNG (NICS)
55769.41	56.41	12.77 (0.01)	12.48 (0.06)	12.40 (0.03)	TCS (CAIN)
55773.37	60.37	12.94 (0.03)	12.58 (0.01)	12.42 (0.02)	TNG (NICS)
55774.40	61.40	12.90 (0.01)	12.55 (0.03)	12.43 (0.04)	TCS (CAIN)
55776.40	63.40	13.00 (0.01)	12.64 (0.01)	12.53 (0.02)	TCS (CAIN)
55781.41	68.41	13.23 (0.01)	12.76 (0.01)	12.66 (0.01)	WHT (LIRIS)
55787.44	74.44	13.56 (0.03)	13.03 (0.02)	12.95 (0.02)	NOT (NOTCAM)
55801.36	88.36	13.90 (0.02)	13.41 (0.02)	13.17 (0.01)	TNG (NICS)
55804.34	91.34	14.10 (0.01)	13.50 (0.01)	13.26 (0.01)	CA-3.5m (O2000)
55814.32	101.32	14.38 (0.01)	13.80 (0.01)	13.50 (0.01)	CA-3.5m (O2000)
55818.36	105.36	14.45 (0.02)	13.91 (0.01)	13.74 (0.01)	NOT (NOTCAM)
55880.72	167.72	16.23 (0.01)	15.38 (0.01)	14.70 (0.01)	CA-3.5m (O2000)
55913.68	200.68	17.00 (0.01)	16.19 (0.02)	15.31 (0.02)	CA-3.5m (O2000)
55914.66	201.66	17.05 (0.01)	16.23 (0.02)	15.35 (0.02)	CA-3.5m (O2000)
55946.13	233.13	17.43 (0.02)	16.78 (0.02)	16.21 (0.02)	UKIRT (WFCAM)
55999.91	286.91	18.10 (0.02)	17.47 (0.02)	17.31 (0.02)	UKIRT (WFCAM)
56024.38	311.38	18.46 (0.03)	17.80 (0.03)	17.71 (0.04)	WHT (LIRIS)
56052.47	339.47	18.69 (0.02)	17.96 (0.02)	18.60 (0.03)	WHT (LIRIS)
56093.48	380.48	19.71 (0.06)	18.71 (0.06)	19.21 (0.08)	WHT (LIRIS)

Table 7. MIR Spitzer 3.6 μm and 4.5 μm magnitudes for SN 2011dh. Errors are given in parentheses. For completeness data for the first 100 days already published in E14a are included.

JD (+2400000) (d)	Phase (d)	3.6 μm (mag)	4.5 μm (mag)	Telescope (Instrument)
55731.21	18.21	11.83 (0.02)	11.48 (0.02)	SPITZER (IRAC)
55737.06	24.06	11.66 (0.02)	11.31 (0.02)	SPITZER (IRAC)
55744.32	31.32	11.66 (0.02)	11.30 (0.02)	SPITZER (IRAC)
55751.46	38.46	11.68 (0.02)	11.30 (0.02)	SPITZER (IRAC)
55758.75	45.75	11.79 (0.02)	11.32 (0.02)	SPITZER (IRAC)
55766.45	53.45	11.96 (0.02)	11.34 (0.02)	SPITZER (IRAC)
55772.33	59.33	12.11 (0.03)	11.38 (0.02)	SPITZER (IRAC)
55779.12	66.12	12.30 (0.03)	11.43 (0.02)	SPITZER (IRAC)
55785.60	72.60	12.50 (0.03)	11.50 (0.02)	SPITZER (IRAC)
55798.28	85.28	12.84 (0.04)	11.66 (0.03)	SPITZER (IRAC)
55964.14	251.14	14.34 (0.09)	13.31 (0.07)	SPITZER (IRAC)
56026.63	313.63	15.57 (0.15)	14.27 (0.11)	SPITZER (IRAC)
56104.23	391.23	17.12 (0.32)	15.54 (0.19)	SPITZER (IRAC)
56136.41	423.41	17.46 (0.37)	16.01 (0.24)	SPITZER (IRAC)
56168.69	455.69	17.63 (0.40)	16.25 (0.26)	SPITZER (IRAC)
56337.59	624.59	18.42 (0.57)	17.59 (0.49)	SPITZER (IRAC)

Table 8. List of late-time (100-415 days) optical and NIR spectroscopic observations.

JD (+2400000) (d)	Phase (d)	Grism	Range (\AA)	Resolution	Resolution (\AA)	Telescope (Instrument)
55821.33	108.33	b200	3300-8700	...	12.0	CA-2.2m (CAFOS)
55821.33	108.33	r200	6300-10500	...	12.0	CA-2.2m (CAFOS)
55828.35	115.35	R300B	3200-5300	...	4.1	WHT (ISIS)
55828.35	115.35	R158R	5300-10000	...	7.7	WHT (ISIS)
55830.25	117.25	Grism 4	3500-8450	613	...	AS 1.82m (AFOSC)
55864.65	151.65	Grism 4	3500-8450	613	...	AS 1.82m (AFOSC)
55867.71	154.71	?	?-?	...	?	CA-2.2m (CAFOS)
55893.76	180.76	Grism 3	3200-6700	345	12.4	NOT (ALFOSC)
55897.76	184.76	Grism 5	5000-10250	415	16.8	NOT (ALFOSC)
55911.20	198.20	zJ	8900-15100	700	...	WHT (LIRIS)
55914.70	201.70	R300B	3200-5300	...	8.2	WHT (ISIS)
55914.70	201.70	R158R	5300-10000	...	15.4	WHT (ISIS)
55918.69	205.69	HK	14000-25000	333	...	TNG (NICS)
55951.64	238.64	Grism 4	3200-9100	355	16.2	NOT (ALFOSC)
55998.68	285.68	r200	6300-10500	...	12.0	CA-2.2m (CAFOS)
56005.63	292.63	Grism 4	3200-9100	355	16.2	NOT (ALFOSC)
56013.14	300.14	R600B	?-?	...	5.7	WHT (ISIS)
56013.14	300.14	R316R	?-?	...	3.0	WHT (ISIS)
56071.56	358.56	R500B	3440-7600	322	15.0	GTC (OSIRIS)
56072.61	359.61	R500R	4800-10000	352	20.8	GTC (OSIRIS)
56128.47	415.47	R300B	3600-7000	270	16.7	GTC (OSIRIS)

Table 9. Pseudo-bolometric 3-300 days UV to MIR lightcurve for SN 2011dh calculated from spectroscopic and photometric data with a 1-day sampling between 3 and 50 days and a 5-day sampling between 50 and 300 days. Random errors are given in the first parentheses and systematic lower and upper errors (arising from the distance and extinction) respectively in the second parentheses.

JD (+2400000) (d)	Phase (d)	L (log erg s ⁻¹)	JD (+2400000) (d)	Phase (d)	L (log erg s ⁻¹)
55717.00	4.00	41.465 (0.001) (0.098,0.186)	55773.00	60.00	41.670 (0.002) (0.093,0.160)
55718.00	5.00	41.553 (0.001) (0.097,0.181)	55778.00	65.00	41.627 (0.002) (0.093,0.160)
55719.00	6.00	41.653 (0.001) (0.097,0.179)	55783.00	70.00	41.585 (0.002) (0.093,0.161)
55720.00	7.00	41.747 (0.001) (0.097,0.178)	55788.00	75.00	41.544 (0.002) (0.093,0.161)
55721.00	8.00	41.835 (0.001) (0.097,0.178)	55793.00	80.00	41.502 (0.002) (0.093,0.161)
55722.00	9.00	41.909 (0.001) (0.097,0.178)	55798.00	85.00	41.460 (0.002) (0.093,0.162)
55723.00	10.00	41.970 (0.001) (0.097,0.177)	55803.00	90.00	41.417 (0.002) (0.094,0.162)
55724.00	11.00	42.019 (0.001) (0.097,0.176)	55808.00	95.00	41.375 (0.002) (0.094,0.163)
55725.00	12.00	42.057 (0.001) (0.097,0.176)	55813.00	100.00	41.333 (0.002) (0.094,0.163)
55726.00	13.00	42.089 (0.001) (0.096,0.175)	55818.00	105.00	41.291 (0.002) (0.094,0.163)
55727.00	14.00	42.118 (0.001) (0.096,0.174)	55823.00	110.00	41.249 (0.001) (0.094,0.164)
55728.00	15.00	42.142 (0.001) (0.096,0.174)	55828.00	115.00	41.208 (0.001) (0.094,0.164)
55729.00	16.00	42.164 (0.001) (0.096,0.173)	55833.00	120.00	41.166 (0.001) (0.094,0.164)
55730.00	17.00	42.182 (0.001) (0.096,0.173)	55838.00	125.00	41.124 (0.001) (0.094,0.164)
55731.00	18.00	42.198 (0.001) (0.096,0.173)	55843.00	130.00	41.081 (0.002) (0.094,0.164)
55732.00	19.00	42.209 (0.001) (0.096,0.172)	55848.00	135.00	41.038 (0.002) (0.094,0.165)
55733.00	20.00	42.214 (0.001) (0.096,0.172)	55853.00	140.00	40.995 (0.001) (0.094,0.165)
55734.00	21.00	42.216 (0.001) (0.096,0.171)	55858.00	145.00	40.953 (0.001) (0.094,0.165)
55735.00	22.00	42.211 (0.001) (0.095,0.171)	55863.00	150.00	40.909 (0.001) (0.094,0.165)
55736.00	23.00	42.201 (0.001) (0.095,0.170)	55868.00	155.00	40.863 (0.001) (0.094,0.165)
55737.00	24.00	42.186 (0.001) (0.095,0.169)	55873.00	160.00	40.817 (0.001) (0.094,0.165)
55738.00	25.00	42.165 (0.001) (0.095,0.167)	55878.00	165.00	40.772 (0.001) (0.094,0.165)
55739.00	26.00	42.142 (0.001) (0.094,0.166)	55883.00	170.00	40.726 (0.001) (0.094,0.164)
55740.00	27.00	42.117 (0.001) (0.094,0.165)	55888.00	175.00	40.681 (0.001) (0.094,0.164)
55741.00	28.00	42.091 (0.001) (0.094,0.164)	55893.00	180.00	40.637 (0.001) (0.094,0.164)
55742.00	29.00	42.064 (0.001) (0.094,0.163)	55898.00	185.00	40.594 (0.001) (0.094,0.164)
55743.00	30.00	42.039 (0.001) (0.094,0.162)	55903.00	190.00	40.552 (0.001) (0.094,0.164)
55744.00	31.00	42.016 (0.001) (0.093,0.162)	55908.00	195.00	40.512 (0.001) (0.094,0.164)
55745.00	32.00	41.996 (0.001) (0.093,0.161)	55913.00	200.00	40.472 (0.001) (0.094,0.164)
55746.00	33.00	41.977 (0.001) (0.093,0.161)	55918.00	205.00	40.432 (0.001) (0.094,0.164)
55747.00	34.00	41.959 (0.001) (0.093,0.160)	55923.00	210.00	40.396 (0.001) (0.094,0.164)
55748.00	35.00	41.943 (0.001) (0.093,0.160)	55928.00	215.00	40.362 (0.001) (0.094,0.164)
55749.00	36.00	41.928 (0.001) (0.093,0.160)	55933.00	220.00	40.327 (0.001) (0.094,0.164)
55750.00	37.00	41.914 (0.001) (0.093,0.159)	55938.00	225.00	40.294 (0.001) (0.094,0.164)
55751.00	38.00	41.900 (0.001) (0.093,0.159)	55943.00	230.00	40.262 (0.001) (0.094,0.164)
55752.00	39.00	41.887 (0.001) (0.093,0.159)	55948.00	235.00	40.230 (0.001) (0.094,0.164)
55753.00	40.00	41.874 (0.001) (0.093,0.159)	55953.00	240.00	40.200 (0.001) (0.094,0.163)
55754.00	41.00	41.861 (0.001) (0.093,0.159)	55958.00	245.00	40.169 (0.001) (0.094,0.163)
55755.00	42.00	41.848 (0.001) (0.093,0.159)	55963.00	250.00	40.137 (0.001) (0.094,0.163)
55756.00	43.00	41.836 (0.001) (0.093,0.159)	55968.00	255.00	40.104 (0.001) (0.094,0.163)
55757.00	44.00	41.823 (0.001) (0.093,0.159)	55973.00	260.00	40.071 (0.001) (0.094,0.163)
55758.00	45.00	41.812 (0.001) (0.093,0.159)	55978.00	265.00	40.039 (0.001) (0.094,0.163)
55759.00	46.00	41.802 (0.001) (0.093,0.159)	55983.00	270.00	40.006 (0.001) (0.094,0.163)
55760.00	47.00	41.792 (0.001) (0.093,0.159)	55988.00	275.00	39.973 (0.001) (0.094,0.163)
55761.00	48.00	41.782 (0.001) (0.093,0.159)	55993.00	280.00	39.940 (0.001) (0.094,0.163)
55762.00	49.00	41.773 (0.002) (0.093,0.159)	55998.00	285.00	39.907 (0.001) (0.094,0.163)
55763.00	50.00	41.763 (0.002) (0.093,0.159)	56003.00	290.00	39.873 (0.001) (0.094,0.163)
55768.00	55.00	41.716 (0.002) (0.093,0.159)	56008.00	295.00	39.838 (0.001) (0.094,0.163)