The dusty type IIn Supernova 1998S

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Abstract. The type IIn SN 1998S is one of the most remarkable core-collapse supernovae ever observed. It underwent a complex interaction with a substantial circumstellar medium, resulting in radiation at wavelengths from radio to X-rays. IR and optical observations have revealed a wide variety of broad and narrow emission lines. Examination of the SN/CSM interaction and of the ejecta spectra has allowed us to deduce that the supernova probably arose from a massive, RSG progenitor having a large (>3200 AU radius), dusty circumstellar disk. SN 1998S also developed one of the strongest, most persistent infrared excesses ever seen in a supernova. IR/optical monitoring of SN 1998S has been carried out to nearly 1200 days post-explosion. This includes coverage to wavelengths as long as 4.7 µm, making SN 1998S only the second supernova (after SN 1987A) to be observed in this spectral region. Fading of the central and redshifted components of the late-time H I and He I line profiles suggests strongly that dust condensed in the ejecta. However, it is less clear whether the strong late-time IR emission arose from this dust, or from an IR echo in the dusty CSM. One interesting possibility is that dust condensed in the cool dense shell between the outer and reverse shocks, thus simultaneously producing both the line obscuration and the IR emission.

1 Introduction

One of the challenges of supernova research is to obtain evidence about the nature and environment of the progenitor. For type IIn supernovae, the progenitors must have undergone one or more mass-loss phases before explosion. By using the ‘illumination’ of the resulting circumstellar medium (CSM) by the supernova explosion we can get clues about the progenitor, even at distances of tens of Mpc.

More than 30 years ago, it was suggested [1–3] that supernovae could be important sources of interstellar dust. More recent work [4–6] still invokes core-collapse SNe as significant dust contributors. However, the number of supernovae in which dust has been detected is relatively small and, prior to SN 1998S, only

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for SN 1987A had dust condensation been convincingly demonstrated [7–14].

An opportunity to address both the progenitor problem and the question of supernovae as dust sources has been provided by the occurrence of the type IIn SN 1998S. This has become the most intensively-studied type IIn event [15–30].

2 Early-time behaviour

2.1 Early-time optical spectral evolution

The earliest optical spectra of SN 1998S show a blue continuum with emission features superimposed. A rough blackbody fit yields $T \sim 25,000$ K, but with a blue excess [18, 24]. The emission lines are identified with H I (Balmer series), He I, He II, C III and N III. The high-ionisation carbon and nitrogen lines are also commonly observed in Wolf-Rayet stars [18]. The emission lines have a broad base (e.g. Hα FWZI $\sim 20,000$ km/s), but a narrow ‘peaked’ unresolved centre. The lines are symmetrical about the local standard of rest. This is quite surprising since at such an early phase most of the receding part of the supernova should be occulted by the photosphere. In fact, Chugai [23] has shown that this constitutes some of the earliest evidence of a strong ejecta-CSM wind interaction. The broadening results from Thomson scattering in a radiatively-accelerated CSM wind lying immediately above an opaque, relatively cool dense shell (CDS) at the ejecta-wind interface [31,32]. The blue excess can also be attributed to the CDS, since the significant optical depth can yield an increase in continuum absorptive opacity with wavelength, due to both bound-free (i.e. the Paschen Continuum) and free-free processes [18].

By about 2 weeks after the explosion, the emission lines had essentially disappeared. (Following Fassia et al. [24], we adopt JD 2450875.2 as zero epoch. This was probably a few days post-explosion.) This disappearance is attributed to the dense inner-CSM being overrun by the ejecta. Nevertheless, the CDS remained optically-thick in the Paschen continuum until around 40–50 days, and this accounts for the lack of strong broad lines from the ejecta during the $\sim 2$–6 weeks era. However, during this time we can see weak unresolved lines superimposed on the continuum. This is due to the flash-ionisation of the undisturbed wind (see below). After $\sim 40$–50 days, broad, square-shaped lines in Hα and the Ca II triplet formed. Such line profiles are characteristic of emission from a shocked ejecta/CSM shell.

2.2 Early-time infrared spectral evolution

SN 1998S is unique in that it allowed the first-ever good IR spectroscopic coverage of a type IIn event [17,24]. In the $J$-band, we see Paschen $\beta$, Paschen $\gamma$ and He I 1.083 $\mu$m lines. Their evolution was similar to that seen in the optical. At the earliest times broad-based, peaked profiles were present. These faded by
day 17, being replaced by broad, square-shaped profiles by day 44. Between days \( \sim 10 \) and \( \sim 60 \) a strong, unresolved He I 1.083 \( \mu \)m CSM line was superimposed on the ejecta/CSM broad lines.

By day 44, the \( HK \)-band was dominated by Paschen \( \alpha \). By day 108, first-overtone CO emission was clearly present in the \( K \)-band. The presence of CO in core-collapse supernovae is increasingly regarded as ubiquitous. In all cases where \( K \)-band observations have been carried out in the period 3-6 months post-explosion, CO has been detected. There are now seven known cases: 87A (IIpec) [13,33-35], 95ad (IIP) [36], 98S (IIn) [17,24], 99d (IIP) [37], 99em (IIP) [37,38], 99gi (IIP) [38], 00ew (Ic) [38]. Modelling of the SN 1998S spectra suggests a CO velocity of \( \sim 2000 \) km/s [17,24]. From this, Fassia et al. [24] deduced a core mass of \( 4 \) M\( \odot \) implying a massive progenitor. The actual mass of CO derived was \( 10^{-3} \) M\( \odot \). The low-excitation rotation-vibration states of CO mean that it is a powerful coolant. Its presence is suspected to be a necessary condition for dust condensation to occur in the ejecta.

On day 130, Fassia et al [24] succeeded in measuring the IR flux out to a wavelength of 3.8 \( \mu \)m (\( L' \)-band). This revealed a remarkable IR excess of \( K - L' = +2.5 \). The most plausible interpretation of this is emission from warm dust. But where was the dust located? For dust condensing in the ejecta to produce such a large, early \( L' \) flux the lowest possible velocity of the dust-forming region would be 11,000 km/s, and that includes the assumption that the temperature is close to the dust evaporation temperature of \( \sim 1500 \) K. Such high velocities were seen only in the extreme outer zones of the H/He envelope. No metals were seen at such high velocities. Fassia et al. [24] concluded that the IR excess at this epoch cannot, therefore, have been due to grain condensation in the ejecta. It must instead have been produced by an IR echo of the maximum-light luminosity from pre-existing dust in the CSM.

### 2.3 Narrow lines

Of particular interest are the high-resolution echelle spectra of SN 1998S obtained at the WHT by Bowen et al. [15] and Fassia et al. [24] on days 17 and 36. These observations succeeded in resolving the narrowest CSM lines. From forbidden lines such as [OIII] 5007 \( \AA \), an undisturbed CSM velocity of about 40 km/s is obtained, which is characteristic of an RSG wind. Fassia et al. [24] also deduced a centre of mass redshift velocity of \( +847 \) km/s. Between day 17 and day 36 the [OIII] 5007 \( \AA \) profile changed from having a red deficit, to being quite symmetrical about the SN centre of mass. This is attributed to the effect of the finite light travel time across the CSM [24]. As the initial ionising flash from the supernova propagated across the CSM, it took longer for the resulting nebular emission to reach us from the far side. This allowed confirmation that the CSM really was expanding. Making some simple assumptions, the echo geometry indicates that the CSM extended to at least \( \sim 2100 \) AU.
The narrow [OIII] 5007 Å line persisted for at least a year [28]. Assuming a maximum ejecta velocity of 10,000 km/s [18,24], it can be deduced that the unshocked CSM must have extended to at least 2000 AU, which is consistent with the lower limit derived from the echo interpretation. In fact, later observations have shown that the CSM extended to at least 3200 AU (see below). From the intensity ratio of [OIII] (4959 Å + 5007 Å) to [OIII] 4363 Å, Fassia et al. [24] infer a wind density of at least $1.5 \times 10^6$ cm$^{-3}$, implying a CSM mass exceeding 0.005 $M_\odot$, and a mass-loss rate exceeding around $2 \times 10^{-5}$ $M_\odot$/yr. This is consistent with the radio/X-ray estimate of around $10^{-4}$ $M_\odot$/yr [30].

The behaviour of the allowed H I, He I CSM lines was more complex. Not only did they exhibit asymmetric P Cygni profiles, but there were clearly two velocity components. The slower component is attributed to the same origin as the forbidden lines viz. the photo-ionised, unaccelerated CSM. The profile of this component was probably a combination of emission from the recombination cascade together with a classical P Cygni line due to scattering from the populated excited levels (resulting from the recombination cascade). The broad absorption component is more difficult to explain. It extends to a velocity of around 350 km/s which is too fast for a red supergiant wind. It may be that, as in the case of SN 1987A, the SN 1998S progenitor went through a fast-wind phase prior to explosion [24]. An alternative explanation is that CSM close to the supernova was accelerated by photospheric photons, or by relativistic particles from the ejecta/CSM shock [26]. Another possibility is that the faster component arose in shocked clumps within the CSM wind [26].

### 2.4 Bolometric Light Curve

SN 1998S was exceptionally luminous, reaching a de-reddened $M_B = -19.6$ [16]. This is around $\times 10$ the typical luminosity of a type II SN. The excellent coverage achieved in the optical and IR allowed Fassia et al. [16] to examine the bolometric light curve. Both blackbody and UVOIR fits indicate that the total energy radiated in the first 40 days exceeded $10^{50}$ ergs, which is again $\times 10$ the typical value for type II SNe. Between days 90 and 130, the bolometric light curve is well-reproduced by the radioactive decay luminosity of 0.15 $M_\odot$ $^{56}$Ni. However, by this era the ejecta/CSM shock energy must also have contributed a minor contribution.

### 2.5 Polarisation

Spectropolarimetry by Leonard et al. [18] and Wang et al. [25] indicate asymmetry in the material responsible for the observed radiation. Leonard et al. favour a highly flattened CSM, with possibly some asymmetry in the ejecta. In contrast, Wang et al. favour ejecta asymmetry as the main cause of the polarisation.
3 SN 1998S at late times

Most of the observed features described in the previous section can be attributed to the interaction of the supernova with a pre-existing, dusty, possibly flattened CSM. SN 1998S remained observable from X-rays to radio for over 3 years [30,39]. This persistence was due to the ongoing conversion of the SN kinetic energy to radiation via the ejecta/shock interaction. To obtain further insights into this phenomenon, regular observations continued during this phase. In this section, I shall consider two aspects of this viz. the IR emission and the nature and evolution of the line profiles.

3.1 The infrared spectral energy distribution at late times

Infrared monitoring of SN 1998S continued at UKIRT up to day 1191 [39]. Observations were extended as far as the $M$-band (4.7 $\mu$m). Other than SN 1987A, this is the only time that such longwave IR radiation has been detected from a supernova. The IR excess persisted throughout this period. Between days 326 and 819, plausible blackbody fits to the de-reddened $HKLM'$ photometry (1.6–4.7 $\mu$m) are obtained. (We exclude the $J$-band to avoid contaminating the analysis with the very strong He I 1.083 $\mu$m emission.) The derived temperature and velocity declined from around 1400 K and 4000 km/s on day 326, to 930 K and 2000 km/s on day 819. However, for the latest photometry (days 1042 and 1191) it was not possible to achieve a single-temperature fit. On day 328, IR spectroscopy to 2.5 $\mu$m was acquired at UKIRT. This revealed that, while there was a small contribution due to Paschen $\alpha$, the IR excess was due primarily to a smooth continuum rising to longer wavelengths. We conclude that the late-time IR excess was due to thermal emission from warm dust.

We can now pose two, possibly connected, questions: what powered the IR emission from the dust, and where was the dust located? The total energy emitted by the dust in the 1.6–4.7 $\mu$m region between days 300 and 1200 was about $10^{49}$ ergs. This is a factor of $\times 10$ more than could be supplied by the decay of the daughter products of 0.15 $M_\odot$ $^{56}$Ni over the same period. We can therefore immediately rule out radioactivity as the source of the IR energy. There are two other possible energy sources. We know that the energy of the early light curve amounted to $\sim 10^{50}$ ergs. Thus, one possibility is that 10% of this was channeled into the IR emission via an IR echo from CSM dust. On the other hand, it is likely that of order $10^{51}$ ergs was stored in the kinetic energy of the ejecta. It would take only 1% of this to account for the IR emission, through the heating of either pre-existing (CSM) or newly-condensed (ejecta) dust. At 130 days, the huge $L'$-band flux argues strongly in favour of emission from pre-existing dust i.e. an IR echo. However, such an argument is less convincing at the later times being considered here. The blackbody fits produce velocities of 4000–2000 km/s which could, just conceivably, have arisen from dust condensation in the ejecta. To try to distinguish between the IR echo and dust condensation scenarios, we now examine the line profiles at late times.
3.2 H\textalpha and He I 1.083 \mu m profiles

The H\textalpha profile of SN 1998S changed quite dramatically between day 97 and day 1086. On day 97 the profile had the form of a broad, steep-sided, fairly symmetrical line spanning \(\pm 7000\) km/s across the base [24]. This appearance persisted to at least day 140 [18]. However, by the time the supernova was recovered in the second season, the shape was remarkably different. The day 240 (relative to our adopted zero epoch) spectrum of Gerardy et al. [17] shows that the profile had developed a triple-peak structure, comprising a central peak close to the rest-frame velocity, and two outlying peaks at, respectively, \(\pm 4500\) km/s. Gerardy et al. suggest that the outermost peaks could have been produced by an emission zone having a ring or disk structure seen nearly edge-on, and resulting from the SN shockwave collision with the disk/ring. Following Chugai & Danziger [40] they also suggest that the central peak might have been due to shocked wind clouds. Spectra obtained on days 276 [17] and 288 [39] show a remarkable fading of the central and redshifted peaks with respect to the blueshifted peak. Subsequent spectra to day 640 show a continuation of this trend [ref. 39, R. Fesen private communication, A. Filippenko private communication]. In addition, the strong blue peak shifted in velocity to \(\sim 3500\) km/s, presumably due to a slowing of the shock as it encountered an increasing mass of CSM. Finally, when the supernova was recovered in the 4th season on day 1086, it was found that the profile had undergone another dramatic change [39]. While the blue-shifted peak at about \(\sim 3500\) km/s persisted, the central peak had grown in relative strength to about twice the height of the blue peak. An explanation for this latest behaviour is still being investigated. IR (J-band) spectra were obtained at UKIRT between days 225 and 1185 [39]. IR spectra were also acquired by Gerardy et al. on days 276 and 370 [17]. The form and evolution of the strong He I 1.083 \mu m profile was very similar to that of H\textalpha. The H\textalpha and He I 1.083 \mu m lines persisted to \(>1100\) days by which time their extreme blue limbs were still at a velocity of \(\sim 5000\) km/s. This indicates that the CSM must have extended to \(>3200\) AU.

3.3 Source of the IR emission and location of the dust

The relatively sudden fading of the central and redshifted components of the H\textalpha, He I lines immediately suggests dust condensation in the ejecta. This could have caused obscuration of the central and receding regions. A similar effect was observed in the ejecta line profiles of SN 1987A [12,41] and, more recently, in the type IIP SN 1999em [42]. The presence of CO emission from SN 1998S as early as 130 days lends credence to the dust condensation scenario. Moreover, the effect is comparably strong at 0.66 \mu m and 1.08 \mu m, suggesting that the dust quickly became optically thick. It is difficult to see how pre-existing dust in the CSM could have produced such an effect. Indeed, pre-existing dust would probably have been evaporated by the initial flash out to a radius of at least several thousand AU [43]. On the other hand, there may actually have been two dust zones present. In this more complicated scenario, the IR emission would be due to an IR echo of the SN peak luminosity from pre-existing dust in the CSM.
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The line-profile obscuration, however, would be due to possibly cooler dust condensing in the ejecta.

We note an interesting coincidence. Throughout the second year, the magnitude and evolution of the velocities of the blue-shifted H I, He I peaks were similar to those derived from the blackbody fits to the IR fluxes. It has been recognised for many years (e.g. ref. 31) that the interaction of the supernova ejecta with a dense CSM will produce outer and reverse shocks. When radiative cooling is important at the reverse shock front, the gas undergoes a thermal instability, cooling to \( \sim 10,000 \) K, thus forming a dense, relatively cool zone - the ‘cool dense shell’ or CDS. Line emission from low-ionisation species in the CDS will be produced [32]. We believe that this emission was responsible for the blueshifted and redshifted peaks of the H\( \alpha \) and He I line profiles. An exciting possibility, which still requires further study, is that dust may have formed in the CDS at the ejecta/wind interface. If cooling in the outer layer of the CDS, shielded from the reverse shock X-ray/UV radiation, brought the temperature below the condensation temperature, dust could have formed and survived there. In a similar process, suggested by Usov [44], dust may form in the colliding winds of Wolf-Rayet stars. Rayleigh-Taylor or convective instabilities [32] might have produced opaque clumps of dust, totally obscuring the central and receding parts of the supernova, while at the same time allowing some of the line radiation to escape from the approaching component of the CDS. Thus, this scenario can simultaneously account for the strong IR flux, the obscuration effect and the velocity coincidence with the line profiles.

4 Summary

The detailed study of the type IIn SN 1998S indicates that it probably arose from a massive, RSG progenitor having a large (>3000 AU), dusty circumstellar disk. The excess IR emission at early times was due to an IR echo from this disk. At late times the origin of the strong IR emission is less clear. It may be that a ‘double-dust’ scenario applies where the line obscuration was due to dust condensation in the ejecta, while the IR emission arose from an IR echo from the dusty CSM. Alternatively, dust condensation in the cool dense shell may account for both the line obscuration and the IR emission. More detailed modelling of the data will be required in order to test this ‘single-dust’ scenario.

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