The Late Phase of SN 1998bw

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SN 1998bw is of exceptional interest. The time and position coincidence between the explosion of the SN and the explosion of GRB 980435 makes it likely that the two phenomena are related. The SN evolution has been extensively studied first with the 3.6-m/EFOSC2 during the first year, then was monitored with the VLT/FORS1 during the second year when the object became fainter than m_V = 21.

We report here on the late phase of SN 1998bw.

1. Introduction

Some supernovae are special. Supernova SN 1998bw was discovered when the optical counterpart of the γ-ray burst GRB980425 was sought in the BeppoSax error box. It became one of the most luminous stellar explosions ever observed in the optical (Galama et al. 1998), the brightest radio supernova at a time when most other supernovae are still deeply enshrouded in an ionised cocoon which blocks all radio emission (Kulkarni et al. 1998), and the temporal and positional coincidence make a connection to the γ-ray burst itself very likely (Galama et al. 1998). But SN 1998bw was peculiar in several other aspects as well. The spectrum looked different from any other known supernova and defied a clear classification for some time. Due to the lack of obvious hydrogen, helium or silicon lines near maximum light, each of these indicate a Type II, a Type Ib, and a Type Ia supernova, respectively, it was finally assigned a Type Ic classification.

The many deviations from known supernovae and the probable connection with the γ-ray burst triggered a substantial interest in SN 1998bw. It has been called the 'Rosetta stone' of γ-ray bursts and a detailed understanding of this explosion could provide insights into the nature of relatively close-by GRBs (the recession velocity of the parent galaxy is only 2550 km s^{-1}). The collapse of the core and subsequent explosion of massive stars had been proposed for GRBs before SN 1998bw (e.g. Woosley 1993). Supernovae from stars which have lost their hydrogen and even helium envelope can come from either massive stars which shed their upper layers in stellar winds (e.g. Wolf-Rayet stars) or binary stars which undergo a common envelope phase in which one star is stripped to the core. The connection of the γ-ray burst and the supernova explosion can be studied in detail for SN 1998bw.

The peculiarity of SN 1998bw was recognised almost immediately at ESO, and a dedicated follow-up programme initiated. These data map the evolution during the first observing season extensively and will appear soon (Patat et al. 2000). Here we present the data of a smaller programme that also monitored SN 1998bw into the second year. The main reason for the interest at these epochs is in the possibility to directly study the nucleosynthesis and the hydrodynamic properties of the explosion.

2. Observations

We followed the spectral and photometric evolution of SN 1998bw with the 3.6-m/EFOSC2 and UT1/FORS1 from 33 days until 504 days after the outburst (Sollerman et al. 2000). The decrease in brightness can be appreciated in Figure 1 where the images from the 3.6-m from 33 days and from UT1 414 days after explosion are shown. The supernova faded from V = 14.7 to V = 21.7 over the year. The FORS1 image shows the supernova also superposed on an HII region which makes the photometry at late phases very difficult.

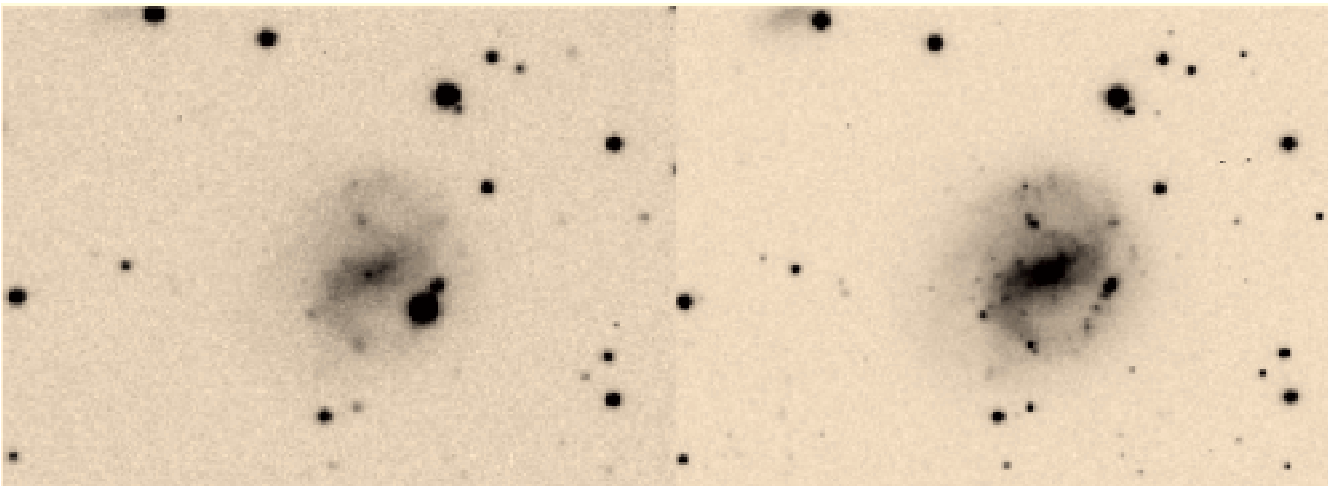

Figure 1: SN 1998bw in May 1998 (3.6-m with EFOSC2; left panel) and June 1999 (UT1 with FORS1; right panel). The supernova is superposed on a faint HII region.

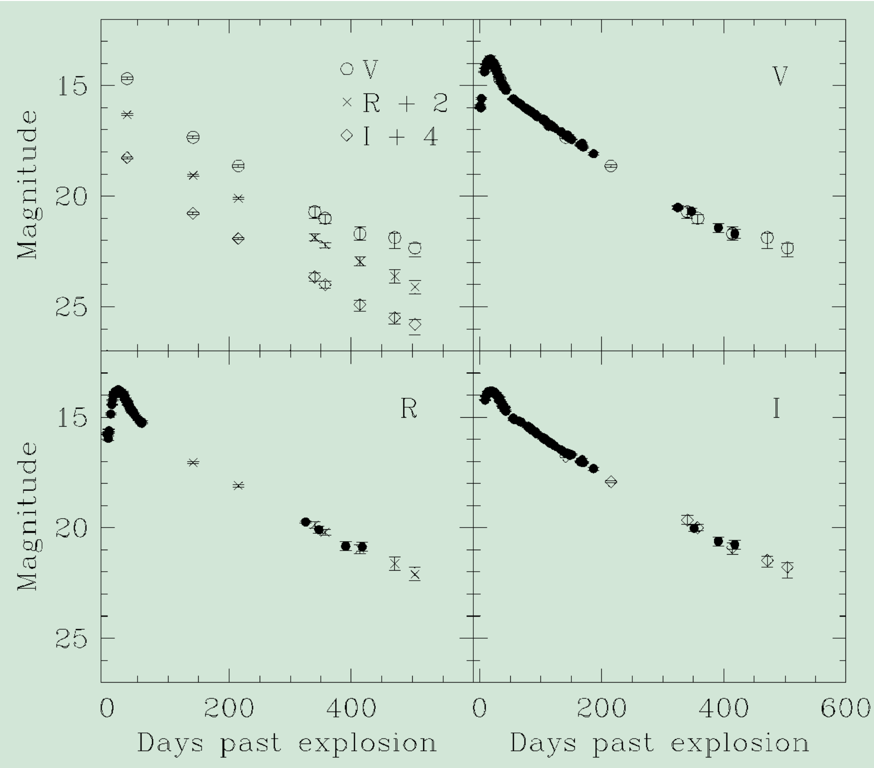

Figure 2: The V, R and I light curves of SN 1998bw. Our photometry (Sollerman et al. 2000) is plotted in the upper left panel. The other panels also include data from Galama et al. (1998; days 1–57), McKenzie & Schaefer (1999; days 63–187), and Patat et al. (2000; days 324–417).

The light curve of SN 1998bw shows an exponential decline in luminosity from about 50 to 400 days after explosion in *V*, *R* and *I* (Fig. 2). Only the last few points after 500 days start to show a deviation from this decline. A slight flattening of the light curve can be perceived at this epoch. We believe that the uncertainties in the background subtraction are not entirely responsible for this flattening and the supernova may be entering a new phase of its evolution.

The spectroscopic evolution of SN 1998bw is displayed in Figure 3. At early times, only very broad and not-well defined features can be seen. The lack of sharp lines is an indication of the high velocities in the ejecta and blending of many lines (e.g. Iwamoto et al. 1998). At late phases the regular features of Type Ib/c supernovae in their nebular phase, i.e. once the supernova ejecta have become optically thin, are observed. The familiar emission lines of Mg I] (λ 4571Å) or [Fe III], [Na I] (λλ 5890, 5896Å), [O I] (λλ 6300, 6364Å), [O II] (λλ 7320, 7330Å), [Ca II] (λλ 7292, 7324Å), and the Ca II IR triplet (λλ 8498, 8542, 8662Å) are all present and change little in shape, but fade away continuously.

A slight narrowing of the emission lines with time can be observed. Of interest is further the blue continuum below 5500Å which is likely to be due to many blended Fe II and Fe III transitions. The narrow lines of Hα, Hβ, [O III], and [S II] are from the underlying HII region.

The late-epoch spectroscopy hence confirms that SN 1998bw indeed comes from a massive star that has lost its envelope and we can observe the exposed core of the progenitor.

3. Interpretation

The large luminosity and the high velocities in the ejecta have been interpreted as due to an extremely powerful explosion (Iwamoto et al. 1998, Woosley et al. 1999) of carbon-oxygen stars of 6 to 13 $M_\odot$ (note that this is the mass at explosion and not the main-sequence mass which is more than about 40 $M_\odot$) and the production of about 0.5 to 0.7 $M_\odot$ of ^{56}Ni. This ^{56}Ni mass is about 5 to 10 times higher than what is observed in other core-collapse supernovae. Other interpretations have proposed asymmetric explosions (Höflich et al. 1999) with less nickel synthesised in the explosion. We have modelled the light curve at late epochs and find that a large amount of nickel is indeed required to sustain the observed luminosity. Since asymmetries play a minor role at late phases, this measurement argues for a Ni mass around 0.7 $M_\odot$, within a factor of two.

The late-phase spectrum shows rather high velocities still, at least 10,000 km s^{-1}. Models based on the massive explosions proposed to fit the early spectrum and light curve do not fare too well at these late phases. Strong macroscopic mixing has to be applied to the models to obtain the rather peaked line shapes observed. Without the mixing, the lines would basically trace the mass shells in the ejecta and with a stratified composition, they would produce flat-topped line shapes. But the models also predict velocities that are too high to fit the observations.

Since the energy input into the ejecta is down-scattering of the γ-rays coming from the decay of ^{56}Co, the daughter nucleus of the original ^{56}Ni, it depends directly on the column density of matter in the ejecta. The optical depth to γ-rays is proportional to M_{ej}/v^2_{exp}. A higher expansion velocity will thin out the ejecta faster, produce a steeper

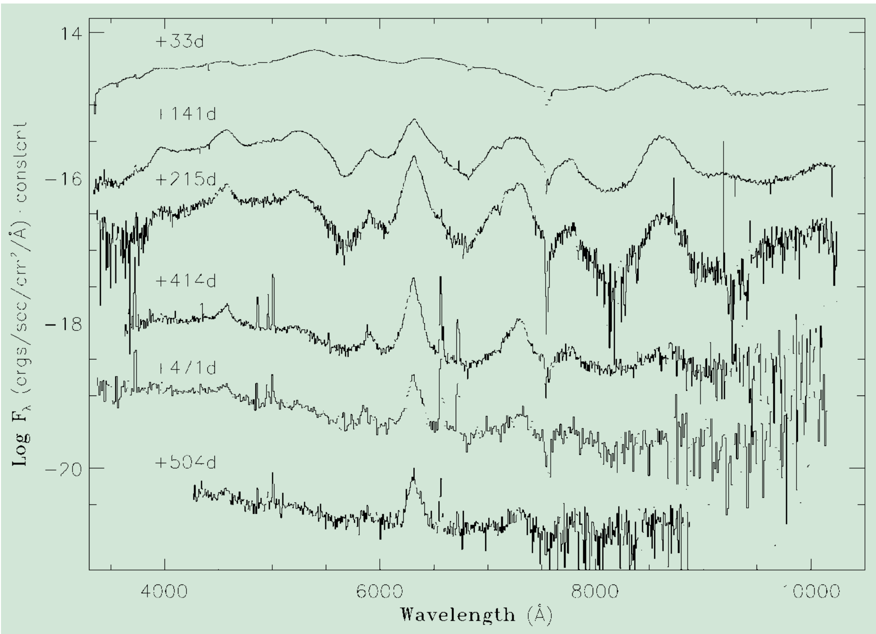

Figure 3: Spectral evolution of SN1998bw. For clarity, the spectra have been shifted by a constant factor. The wavelength scale has been corrected for the velocity of the parent galaxy (2550 km s^{-1}).

slope of the light curves, and hence require more nickel to power the late light curve. Decreasing the velocity boosts the late luminosity, and can reproduce the observed line shapes. However, these velocities were not predicted by the models that fit the early spectrum and light curve.

4. Conclusions

The monitoring of SN 1998bw through its second year has provided important new clues on the nature of this object. The late spectrum very much resembles the ones of other Type Ib/c supernovae. Hence, SN 1998bw can be tied to a class of objects we know fairly well. We confirm the large nickel mass required to power the optical radiation of this event, but find discrepancies by fitting the late spectrum with the models which were used to interpret the early phases. The implied energies are still unique for any supernova ever observed.

The connection of SN 1998bw to GRB980425 is still unclear, but we do not expect to see any signature of the burst at these late phases. The radio observations have been linked to the γ-ray burst and the relativistic expansion of material (Kulkarni et al. 1998, Li & Chevalier 1999). The X-ray emission from the GRB afterglow is coincident with the supernova as well (Pian et al. 1999). SN 1998bw remains a fascinating and puzzling object.

The combination of two instruments and telescopes to follow SN 1998bw to late phases has been very useful. The 3.6-m/EFOSC2 provided the early coverage and only at the end was the supernova 'handed' to UT1/FORS1. We were therefore able to secure a spectrum about every month and could follow this object further than would have been possible with the 3.6-m.

It is unlikely that there will be a third observing season for SN 1998bw. Unless the luminosity becomes constant, it will be too faint to be recovered. There are known processes that could lead to such a constant flux, e.g. interaction with the circumstellar material or input from the accretion on a black hole. We have been following several such objects already and SN 1998bw will be worth at least a check in the next few months.

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MISTRAL: Myopic Deconvolution Method Applied to ADONIS and to Simulated VLT-NAOS Images

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1. Introduction

The performance of high-resolution imaging with large astronomical telescopes is severely limited by the atmospheric turbulence. Adaptive optics [1, 2, 3] (AO) offers a real-time compensation of the turbulence. The correction is however only partial [2, 4, 5, 6, 7] and the long-exposure images must be deconvolved to restore the fine details of the object.

Great care must be taken in the deconvolution process if one wants to obtain a reliable restoration with good photometric precision. Two aspects add to the difficulty: the fact that the residual point spread function (PSF) is usually not perfectly known [8, 9, 10], and the fact that astronomical objects are usually a mix of sharp structures and smooth areas. "MISTRAL" (Myopic Iterative STep Preserving ALgorithm) [11, 8] has been developed to account for these two points. It is based on a rigorous Bayesian approach which allows us to easily account for the noise in the image, the imprecise knowledge of the PSF, and the available *a priori* information on the object (spatial structure, positivity…). A specific edge preserving object prior is proposed, which is in particular well adapted for planetary-like objects.

The notion of AO partial correction is first discussed in Section 2. The principle of our deconvolution technique is briefly summarised in Section 3. In Section 4, the photometric accuracy of MISTRAL is first demonstrated on simulated AO images. The simulation parameters correspond to NAOS, the AO system of the VLT. MISTRAL is then applied to ADONIS images of Io taken at thermal wavelengths using the COMIC camera. This allows an accurate mapping of Io's surface volcanic activity. We also used our deconvolution method on broadband filter (J, H, K) images of Uranus taken with SHARPII+. The structures of the rings and its innermost satellites have been successfully detected.

2. Partially Corrected AO Images

Within the isoplanatic angle, the intensity i(r) at the focal plane of the system consisting of the atmosphere, of the telescope and of the AO bench is given by:

$$\mathbf{i}(r) = \mathbf{h}(r) * \mathbf{o}(r) + \mathbf{n}(r), \qquad (1)$$

where r is the spatial coordinate, $\mathbf{o}(r)$ is the observed object, $\mathbf{h}(r)$ *is* the system PSF and $\mathbf{n}(r)$ *is* an additive zero mean noise.

We consider here the case of AO corrected long exposure images. Such an image is presented in Figure 1. In this numerical simulation, we considered an 11th magnitude planetary-like object observed in the visible with the NAOS AO system [12] installed on the VLT. This system will provide high performance in the near IR ($SR \approx 70\%$ at high flux). Here we consider the case of observations at visible wavelength (λ = 0.5 μm). In such conditions, the image blur is very severe, the expected SR is only 2.1% for a 0.73 arcsec seeing. Neither the fine structures on the surface of the object, nor the stars in the background are apparent in the corrected image. A deconvolution is therefore required.

The deconvolution procedure needs a measurement of the PSF. The usual procedure consists in recording the corrected image of a nearby unresolved star shortly after observing the object of interest. Since the correction quality depends on the observing conditions (turbulence strength, magnitude of the source used for wavefront sensing), the unresolved star image is not a perfect measurement of the PSF associated with the image to be deconvolved [8, 11, 13, 14]. Actually, the main source of PSF variability is the seeing fluctuation.