Supernova progenitor constraints from circumstellar interaction: Type II

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All types of supernovae (SNe), except Type Ia (see Lundqvist & Cumming, this volume) have been observed to interact with their immediate circumstellar medium (CSM). This interaction can reveal their progenitor's histories, and in a broader sense constrain our ideas about the evolution of massive stars. Progress in this direction has concentrated itself in three areas. First, radio emission has been detected from a variety of core-collapse SNe, and modelling according to the simple model of Chevalier (1982) has given estimates of progenitor mass loss rates. For some of these SNe, especially SN 1993J, complementary information comes from X-ray observations. Second, multiwavelength observations of SN 1987A in the LMC have shown that the progenitor star passed through a phase as a red supergiant with a highly asymmetric and nitrogen-enhanced wind. Third, optical observations of some core-collapse SNe show that their emission to a large extent comes from circumstellar interaction, indicating that they are surrounded by a dense CSM.

As examples of the latest progress in these areas, we present some new results on two SNe: the famous 1987A, and the less well-known but rather intriguing 1994W. In the process we introduce Type IIn supernovae (SN IIn; Schlegel 1990) as an important new probe of massive star evolution.

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1. SN 1987A: a 3D map of the triple-ring nebula

In Cumming *et al.* (1997a) we present and model high-resolution ($R \sim 50\,000$) spectra of SN 1987A's three circumstellar rings, taken with the échelle spectrograph UCLES at the Anglo-Australian Telescope between 1990 and 1993. We measure the expansion velocity for the inner ring to be 10.3 ± 0.4 km s^{-1}; here we present the most detailed measurements yet of the kinematics of the two outer rings (Figure 1).

The outer rings seem to be parallel to and equidistant from the inner ring. Each lies $0.4 \pm 0.1 (D_{\rm LMC}/50$ kpc) pc from the inner ring plane. Comparing with the continuum echo mapping of the dusty shell between the rings (Crotts, Kunkel & Heathcote 1995), we see that the separation of the rings is close to the distance to the polar edges of the shell, $0.6(D_{\rm LMC}/50$ kpc) pc. Given the errors, the rings coincide with the outermost edges of the dusty shell. Our results strengthen the picture of the nebula as an open-ended, hourglass-shaped shell and provide an important constraint for hydrodynamic and stellar evolution models (e.g., Arnett, this volume).

2. SN 1994W: a type IIn supernova

We present observations from the first 201 days of the remarkable narrow-line Type II supernova 1994W in NGC 4041, taken at the *WHT, INT, JKT* and *NOT* on La Palma. A full analysis will appear in Cumming *et al.* (1997b). In Figure 2 we show the available photometry for SN 1994W. Figure 3 shows the spectral development.

The presence of the narrow P-Cygni lines seems quite consistent with the clumpy wind model presented by Chugai & Danziger (1994) and Chugai, Danziger & Della Valle (1995) for SNe 1988Z and 1978K. In this scenario, the wind consists of dense clumps embedded in a rarefied interclump wind. The broad component in H I is most easily

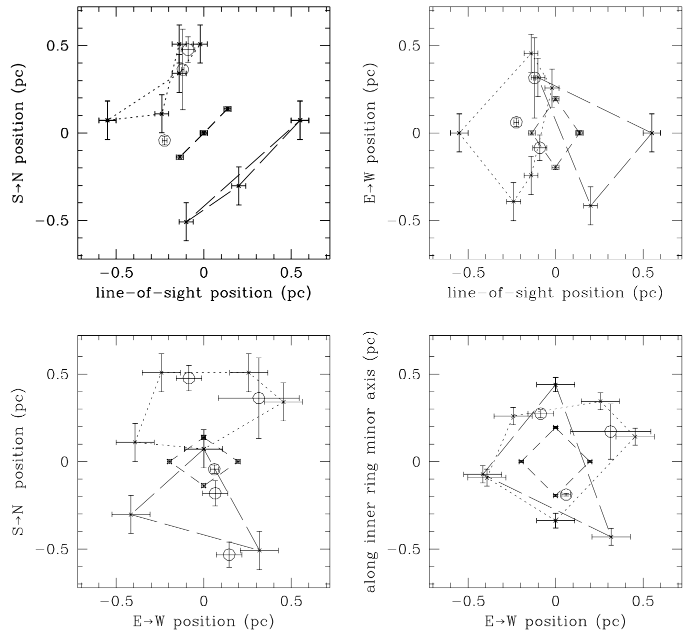

Figure 1. Four views of the three-dimensional structure of the triple-ring nebula, assuming homologous expansion. The morphology of the [N II] nebula hardly changed between 1036-1790d (Wang & Wampler 1992) and the ~2550-d *HST* imaging (Burrows *et al.* 1995). Using these images as a guide, we measured the velocities in different parts of the nebula from our position-velocity plots for days 1344 and 1397 together with the day 1402 observations of Crotts & Heathcote (1991). Then, assuming homologous expansion, we mapped each measured point to a position along the line of sight according to its velocity. Hydrodynamic models presented so far for the SN 1987A CSM have velocity fields not too different from this (e.g., Blondin & Lundqvist 1993). We followed the same procedure for the short-lived H I and He I blobs (Cumming & Meikle 1993 and references therein; open circles). Broken lines join points connected to each other in *HST* imaging.

explained using the shock model of Chevalier & Fransson (1985), in which the line wing emission comes from the cool, shocked ejecta close to the contact discontinuity between the shocked ejecta and the shocked circumstellar wind. In the clumps, the shock is slowed down, and high column density in the clouds can account for the observed narrow P-Cygni profiles. As long as the SN is covered by the clouds, we cannot see the broad Hα component normally seen in Type II SNe. The absence of normal ejecta lines in SN 1994W suggests both that the clumpy wind prevents us from seeing them, and that a substantial proportion of the SN's energy is reprocessed into circumstellar emission. We suggest that the drop of the light curve around day 120 marked the point at which the outgoing shock had passed most of the clumps. The simultaneous fading of the lines and the continuum indicates that *both* had a circumstellar origin.

SN 1994W's progenitor probably lost mass in a clumpy wind shortly before it exploded, a picture similar to the one suggested for SN 1984E (e.g., Gaskell & Keel 1988). However, SN 1984E showed normal ejecta lines both while its narrow lines were present and after they had disappeared. The resulting circumstellar shell round SN 1994W had, in contrast to 1984E, a clump filling factor high enough to conceal the SN ejecta entirely, and to reprocess most of its radiation.

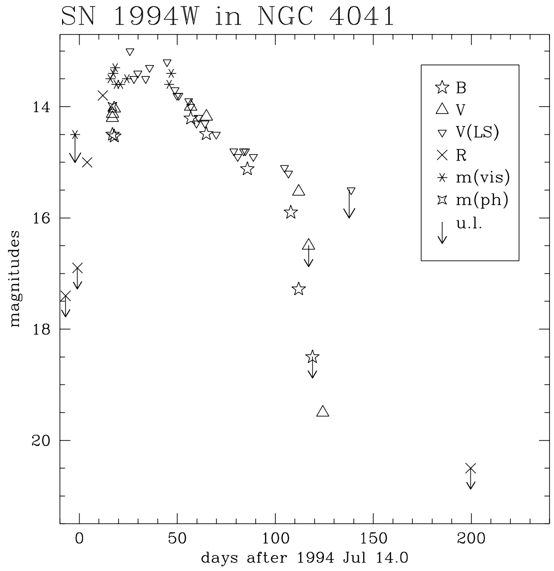

Figure 2. Light curve of SN 1994W. The inverted triangles are visual magnitude estimates by L. Szentasko which we have corrected to V by comparing a wide selection of his observations with contemporary photoelectric V measurements. The drop in the light curve after day 100 is the fastest ever seen in an SN, and is nicely bracketed by photometric points from Tsvetkov (1995) and our day 124 V point.

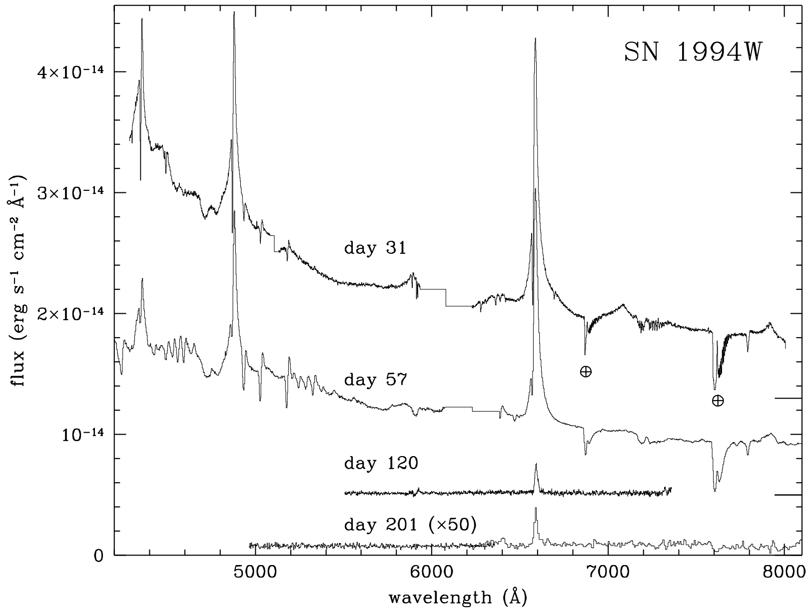

Figure 3. Spectral evolution of SN 1994W. On days 31 and 57 the spectrum was dominated by narrow ($\lesssim 10^3$ km sec^{-1}) H I lines with P-Cygni profiles and broad wings ($\sim \pm 10^4$ km sec^{-1}), which were accompanied by low-ionisation, mainly narrow P-Cygni lines — we identify He I (with triangular profiles), O I, Mg II Si II and Fe II, but no forbidden lines. The light curve drop coincided with a dramatic change in the spectrum. On day 120, just after the fading, Hα had narrowed and was present only in emission, accompanied by faint Na I and Ca II. By day 201, only Hα was left.

2.1. *The diversity of Type IIn supernovae: a picture emerges*

We suggest that the clumpy-wind model can be extended to account for the general features of *all* SN IIn, without abandoning spherical symmetry. It is the clumps that produce the narrow lines which distinguish these SNe as a class. The broad lines come from the SN ejecta's interaction with the interclump wind material. The prominence of the narrow lines relative to broad lines (either from the SN photosphere, as in SN 1984E, or from the interaction region, as in SNe 1988Z and 1994W) depends on the covering and filling factors of the clumpy wind, as well as the density ratio of the clump to interclump gas. Unlike SNe 1984E and 1994W (and probably SN 1987B; Schlegel *et al.* 1996), the progenitors of the slow SN IIn like SNe 1988Z, 1986J and 1978K (Leibundgut 1994, and references therein) had long-lived clumpy winds which still haven't been passed by the expanding shock.

In SN IIn, the flux evolution of the narrow lines measures the duration of clumpy mass loss ($\sim$500 yr for 1994W, for a 10- $\mathrm{km\,sec^{-1}}$ wind; much longer for 1988Z), while their widths measure the density contrast between the clumps and the interclump wind, if we know the original shock speed. That can be estimated from the width and evolution of broad lines at early times. From the early evolution of some SN IIn, like SN 1994W, we can probe the evolution of a massive star just prior to explosion. SN IIn are a whole class of supernovae that have the potential to provide us with just as detailed tests of stellar evolution as SN 1987A has.

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