SUPERNOVA REMNANTS AND THEIR SUPERNOVAE

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Abstract: Observing supernova remnants provides important clues to the nature of supernova explosions. Conversely, the late stages of stellar evolution and the mechanism of supernova explosions affect supernova remnants through circumstellar matter, stellar remnants, and nucleosynthesis. The elements of supernova classification and the connection between supernova type and remnant properties are explored. A special emphasis is placed on SN 1987a which provides a unique opportunity to learn the connection between the star that exploded (whose name we know) and the remnant that will develop in our lifetimes.

Introduction:

The bright supernova 1987a offers the unique opportunity to watch the development of a supernova into a supernova remnant, given moderate living and good health. It illuminates the intimate connection between supernova explosions and the remnants they create. The link to the young supernova remnants is clear: the composition depends on stellar interiors, the environment on stellar mass loss, and the energetics and the stellar remnant depend on the details of the collapse or explosion. The link to older remnants is less obvious, and we often act as if there is no shard of stellar history left to affect the remnant's behavior. But this may be misleading. Some remnants which are old enough to have swept up a large mass of interstellar matter may yet bear the signature of their stellar origin in unmixed debris, or in the structure of the surrounding interstellar medium.

Classifying Supernovae:

Supernovae are classified into two bins, based on their spectra near maximum light (Zwicky 1965). Type I supernovae(SN I) have no hydrogen lines in their optical spectra, and Type II supernovae (SN II) do. An unknown supernova can be classified by comparison to the prototypes for each class (Kirshner et al 1973, Oke and Searle 1974, Branch et al 1981, Branch et al 1983). This is a good

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empirical approach, although it does not guarantee that the types correspond to the stellar origins or to the physics of the explosion. The ideal classification scheme would describe whether a supernova results from a nuclear explosion or from a core collapse, and whether the star was of low mass or of high mass. The presence or absence of hydrogen on the surface may not be the ideal indicator for these more basic properties. Although the SN I probably do correspond to violent nuclear burning in low mass stars and SN II probably do correspond to high mass stars with core collapse, the other morphological boxes may be populated. For example, supernovae may result from core collapse in massive stars which have lost their surface hydrogen through stellar winds. The recent isolation of a subclass of SN I, the SN Ib, illustrates this point (Porter and Filippenko 1987). These explosions are widely (though not universally) thought to arise from core collapse in massive Wolf-Rayet stars, which could have a small amount of surface hydrogen, but the heart of a SN II.

<u>SN I:</u>

A successful picture of the SN I consists of exploding white dwarf stars, nudged over the Chandrasekhar limit by mass transfer from a binary companion. This fits the circumstantial evidence that they are the only supernovae seen in elliptical galaxies since they need not have very massive progenitors. It fits the interpretation of the spectrum at maximum light, which can be synthesized from the expected composition of a carbon/oxygen white dwarf and the observed colors at maximum. It fits the energetics of the late time photometry, too, with the long exponential decline (Doggett and Branch 1985), which is known to persist for at least two years (Kirshner and Oke 1975) powered by the radioactive decay of a few tenths of a solar mass of nickel which beta decays to cobalt and then to iron. The deflagration (subsonic burning) of a carbon/oxygen white dwarf is expected to produce this material as a result of the fusion reactions that disrupt the star. A model for the emission spectrum seen at late times in SN I is consistent with the excitation of this iron-peak material by the radioactive decay chain (Kirshner and Oke 1975, Axelrod 1980).

A serious problem with this picture is posed by the failure of X-ray observations to find large iron abundances in the remnants of supernovae that are widely thought to be from SN I (Hamilton et al. 1985). Of course, the spectroscopic evidence provided by Tycho on his 1572 event is no better than for SN 1006, so the classification is not really comparable to that for contemporary supernovae, but these two, along with Kepler's SN (SN 1604) are widely thought to

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be remnants of SN I. A solution to this riddle comes from the suggestion that the iron is too cold. (Hamilton, Sarazin, and Szymkowiak 1986). If the iron, slowly ejected from near the core, lies in the interior of the remnant, the reverse shock may not yet have reached that material, and may not yet have heated and ionized it to produce X-ray emission. Although such a picture may appear contrived, there is some direct evidence from UV observations that this may actually be the case.

IUE observations of the SN 1006 remnant, originally carried out by Wu et al. (1983) suggested the presence of cold iron seen in absorption against the ultraviolet continuum of a background star. A painstaking analysis of the old and some new IUE spectra by Fesen et al (1987) makes this original suggestion convincing, and reveals several Fe II lines, presumably due to the cold iron in the interior of the remnant.

This combination of theoretical and observational work makes it quite plausible that the deflagrating white dwarf model for SN I is consistent with the observed remnants. The SN I light curves, especially their peak luminosities, are expected to have a narrow dispersion in this case, since the explosion takes place in a well-defined stellar setting by a sharply constrained physical mechanism (Arnett, Branch, and Wheeler 1984). The empirical evidence is that SN I do have very similar properties, and might make good standard candles for cosmology (Sandage 1985).

A second puzzle associated with SN I has been the optical spectra of the young remnants. Although they result from the violent disruption at 12 000 km s^{-1} of a star with no hydrogen, the spectra of SN 1006 and of SN 1572 show only hydrogen lines at zero velocity. The spectrum of H alpha for SN 1006 actually has two components, a narrow feature and a broad one with a FWHM of about 2600 km s^{-1} (Kirshner, Winkler, and Chevalier 1987). This type of structure was predicted by Chevalier, Kirshner and Raymond (1980) based on similar observations of SN 1572 and pursued, but not detected, by Lasker (1981).

The model for this emission is that the "non-radiative" supernova shock is overrunning neutral material in the neighborhood. Otherwise, the expected post-shock temperature would be so high that no optical emission would be seen. Of course, the very presence of neutral material close to a supernova puts a limit on the uv flash produced at the surface of the star when the supernova shock wave arrives. Whether the gas itself results from mass loss from the binary system is not known. Since the shock in the interstellar medium generated by the disrupted star is

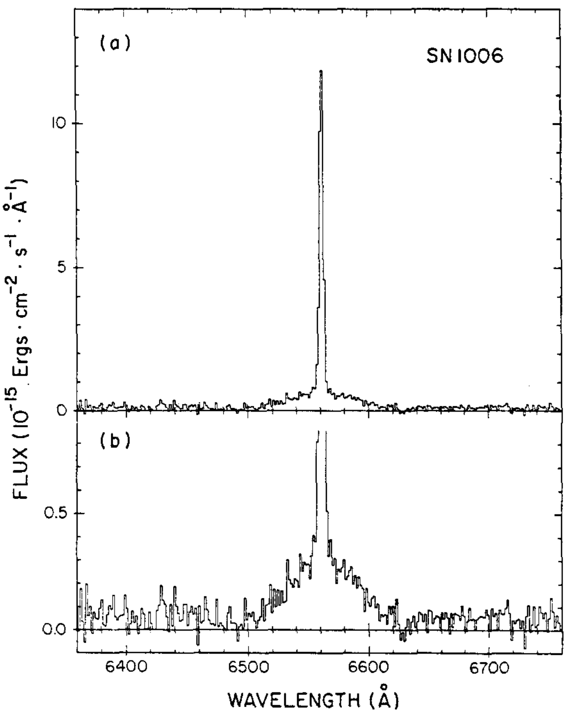

Fig. 1

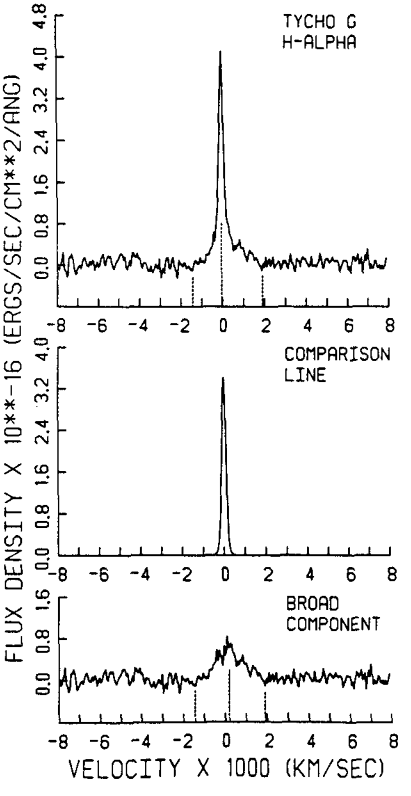

Fig. 2

Fig. 1-- The H alpha line of SN 1006. (a) Illustrates the strength of the narrow component relative to the broad. (b) Shows the width of the broad component.

Fig. 2-- The H alpha line of SN 1572. (a) The observations. (b) A comparison line profile observed with the identical equipment. (c) The observations with a suitably scaled instrumental profile subtracted.

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mediated by charged particles, the neutral hydrogen atoms suddenly find themselves surrounded by fast moving electrons and protons. These particles might excite the H atoms: the subsequent radiative decay would give rise to a narrow emission line at zero velocity. An alternative possibility is charge exchange, producing a fast-moving atom in an excited state. These decays create a broad line whose width reflects the velocity distribution. Since the ratio of the direct excitation to the charge exchange is a function of velocity, the relative strength of the two components, as well as the width of the broad line, reflect the shock velocity.

The interesting fact is that the velocity derived from the width and the velocity derived from the ratio of narrow lines to broad lines give consistent answers: 2300 km s^{-1} for SN 1572 and 3300 km s^{-1} for SN 1006. These velocities can be compared with the proper motions measured by Kamper and van den Bergh (1978) and by Hesser and van den Bergh (1981) to give distances to these two SN I: 1.4-2.1 kpc for SN 1006 and 2.0-2.8 kpc for SN 1572. The evidence is consistent with SN 1006 expanding into a lower density medium than SN 1572, just as required by the detailed models for the X-ray emission (Hamilton et al. 1986)

In principle it would be interesting to use this analysis of the remnant together with the contemporary accounts of the supernova explosion to establish the absolute magnitude of SN I explosions and calibrate the extragalactic distance scale. In practice, the uncertainties in the early records make this a precarious enterprise.

The follow-up to the Einstein X-ray survey of the LMC by Tuohy et al. (1982) revealed four LMC remnants with narrow-band images that showed H alpha, but not [S II]. Whether or not these are the remnants of SN I is not shown by the images or by spectra, but the resemblance to SN 1572 and SN 1006 is suggestive. Winkler and Kirshner have observed these four remnants at the CTIO 4m: we find that one has H alpha only, but no broad component, one has H alpha only with a broad component, one has H alpha with a broad component and weak [S II] emission, and one has H alpha with no broad component, [N II], and [S II]. It is possible that these represent the stages of evolution from the high velocity "non-radiative" shock down through the beginning of an ordinary cooling shock in ionized interstellar material. In any event, it may be possible to measure the shock velocity for some of these, for comparison with X-ray models. As a class, these Balmer-dominated remnants provide a strong warning that searches for extragalactic SNR's (such as that reported in this volume by Long et al) which depend on the [S II]/H alpha ratio will miss some remnants.

The other young SNR which is widely thought to result from a SN I is Kepler's SN 1604. There, the late stellar evolution and mass loss may be decisive in shaping the observed remnant. Spectroscopically, it shows strong [N II] lines, suggesting a high nitrogen abundance, such as might arise from the CNO-cycle hydrogen burning in a massive star. One way to account for this, the large distance from the galactic plane and the X-ray morphology has been suggested by Bandiera (1987) who considered extensive mass loss from a runaway star as a possible origin for Kepler's SNR. If that is correct, the usual classification as a SN I will have to be reconsidered.

SN Ib :

Another complication in the SN I picture has arisen from the recent evidence that there is a distinct subclass of SN I, the SN Ib, which show no hydrogen (and are therefore SN I) but which do not have the strongest absorption feature (at about 6150 Å) that is seen in classical SN I (now called SN Ia). The observational situation has been summarized by Porter and Filippenko (1987). Several indirect lines of evidence converge to indicate that this spectroscopic difference is not just a detail, but that the SN Ib may come from a different type of star and may have distinct remnants. Those hints are (Uomoto and Kirshner 1985, Harkness et al 1987) that the SN Ib are fainter at maximum light, redder at maximum light, associated with H II regions, in Sc galaxies, and have some radio emission. These are generally taken to indicate that the progenitors of SN Ib are massive stars, but not very extended ones, with some circumstellar matter: a good possibility would be Wolf-Rayet stars. This view is strengthened by the analysis of late time spectra by Begelman and Sarazin (1986), which indicates a mass of oxygen in excess of 5 solar masses, and the models of Schaeffer, Casse, and Cahen (1987) which show that the light curve of an exploding W-R star would conform well with the observed properties of SN Ib.

A recent set of observations of Cas A by Fesen, Becker and Blair (1987) shows that the connection between this well-known remnant and W-R stars may be important. Cas A has fast moving knots which are oxygen and oxygen-burning products from the interior of a massive star (Kirshner and Chevalier 1977, Chevalier and Kirshner 1978, 1979) and quasi-stationary flocculi (QSF), which have hydrogen and strong nitrogen lines and low velocities, and are presumably the relics of mass loss from the star. What Fesen et al have found is fast moving material with composition like the

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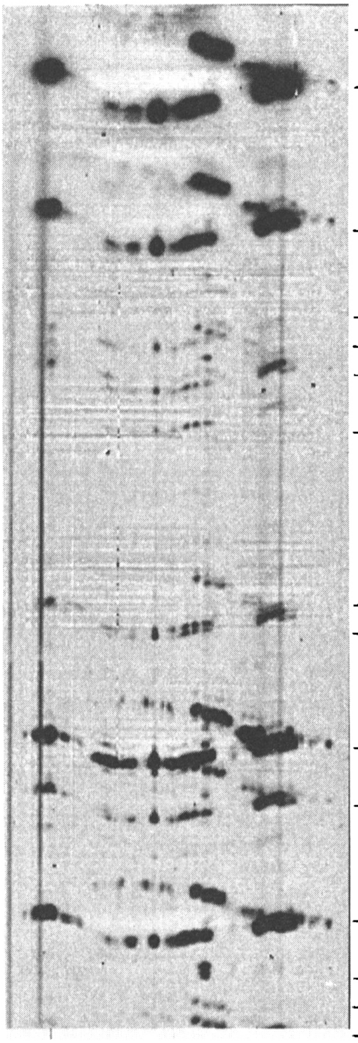

Fig. 3-- The near IR spectrum of Cas A. Note the large velocity range of the approaching and receding shells. The lines of [C I], [Cl II] and permitted O I are of special interest.

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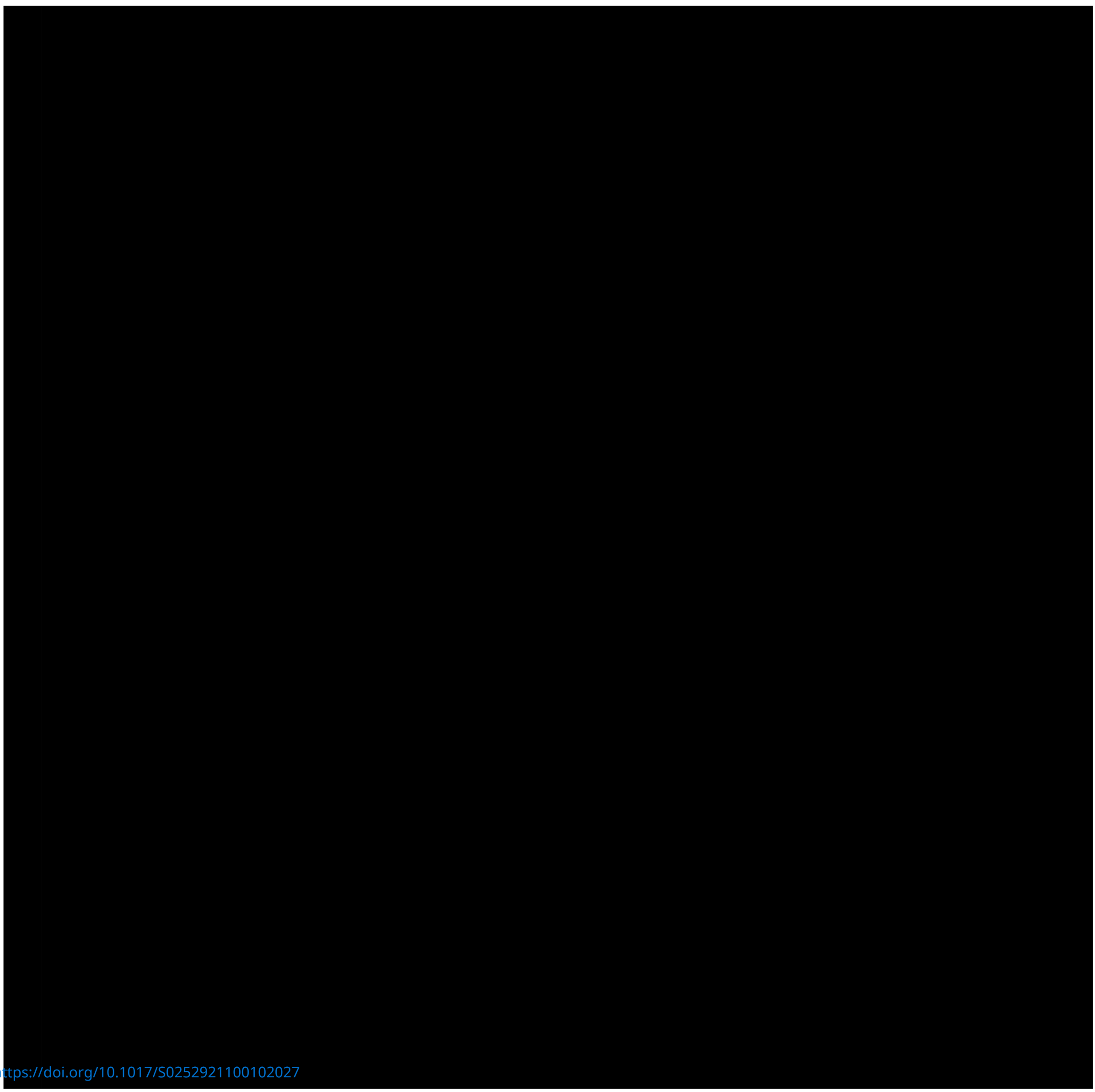
QSFs. They suggest that this nitrogen-rich, hydrogen rich material must have been on the surface of the massive star when it exploded, following an episode of mass loss, and that the star would have resembled a WN 7, a Wolf Rayet star

Gilmozzi et al (1987) shows that the separation, magnitude, and spectra of the two stars seen is consistent with the identification of the survivors as stars 2 and 3 of the Sanduleak -69° 202 trio. The clear implication is that Star



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1, the 12th magnitude B3 I star, has disappeared, and it may be identified as the progenitor of SN 1987a.

The fact that SN 1987a brightened exceptionally rapidly, was intrinsically fainter than other SN II, and changed in color so quickly (Blanco et al 1987) can all be attributed to the fact that the star, plausibly a 15 - 20 solar mass object when on the main sequence, was blue, and hence more compact than a red supergiant, when it exploded.

An important question is whether the star was a red giant before it became a blue one. Recent evidence from ultraviolet spectra show that SK -69° 202 probably did have an episode of substantial mass loss before the explosion, plausibly as a red supergiant wind. This evidence comes from short wavelength IUE spectra (1100-1900Å). This is the region where the supernova itself has little detectible flux. However, narrow emission lines, principally of nitrogen have been detected in this region (Wamsteker et al 1987, Kirshner et al 1987) and are growing in strength. These lines would be absorbed if formed in the debris of the supernova itself, and are probably coming from a circumstellar shell at a distance of order a light year. This shell has been excited by UV emission from the supernova emitted in the first few hours as the shock wave from the interior hit the surface of the blue supergiant. The material is nitrogen rich, with $N/C > 10$, and N/O also high. This is the type of composition expected in the atmosphere of a red giant which has converted its carbon and oxygen to nitrogen as a by-product of hydrogen burning in the CNO cycle. The quantitative question associated with the mass loss: how much hydrogen was on the star when it exploded? probably will be answered by modelling the supernova's spectral evolution and the supernova's light curve.

These issues are relevant to studying supernova explosions, supernova remnants, and the interaction with the interstellar gas because the state of the atmosphere and the circumstellar environment can have a substantial effect on the supernova event and on the early evolution of the remnant. This is clearly important for the SN II, which are thought to arise from red supergiants, which are stars with considerable mass outflow. The radio emission for these is thought to arise in the circumstellar matter (Chevalier 1982), but there is also direct evidence for circumstellar matter in the spectra of SN II. For example, the spectra taken before maximum light by Niemela et al. (1985) of SN 1983k showed strong emission lines of highly ionized C and N, similar to the lines seen in Wolf-Rayet stars. Dopita et al (1984) observed narrow emission lines of H and He which they attributed to a wind surrounding this SN II. The interpretation of the UV spectra of SN II by Fransson et al

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Fig. 4

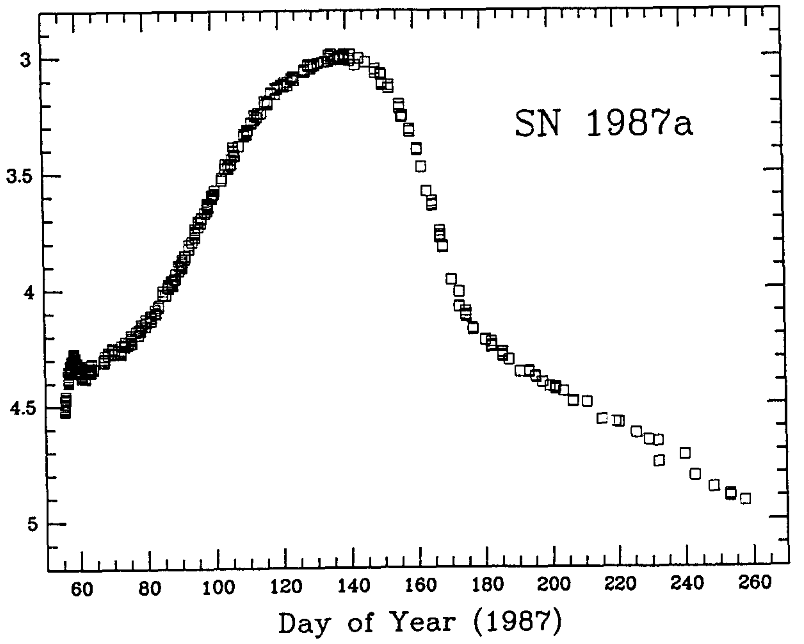

Fig. 4-- A V-like magnitude versus time for SN 1987a as measured with the IUE satellite fine error sensor. The exponential decline at late times is a strong clue that radioactive decay is important. The slope corresponds well with the 114 day decay of ^{56}Co, and the magnitude corresponds to about 0.07 solar masses of radioactive nickel.

Fig. 5

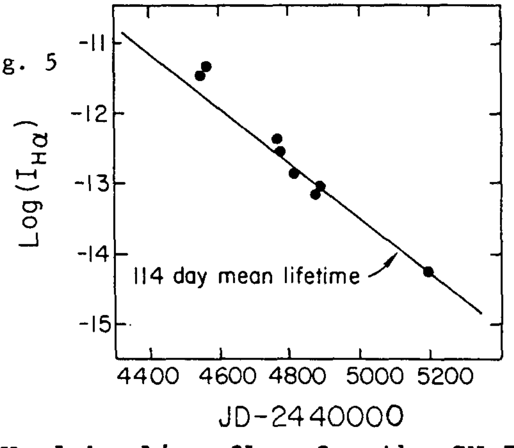

Fig. 5-- The H alpha line flux for the SN II 1980k. The straight line is not a fit to the data, but is a line with the 114 day e-folding time of ^{56}Co.

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(1984) also requires the treatment of radiation reprocessed by the circumstellar gas.

Winds may have an important effect on the properties of remnants. One example is Puppis A, where the radio remnant is embedded in nitrogen-rich knots of material with low expansion velocities. This material is presumably analogous to that seen in SN 1987a, Kepler, and Cas A: the result of mass loss that includes the products of CNO cycling. At the same time, the chemical abundances of the stellar interior for Puppis A's progenitor are accessible to observation both through X-ray spectroscopy (Canizares and Winkler 1981) and optical spectroscopy (Kirshner and Winkler 1985). Both these lines of evidence suggest that Puppis A came from a star that produced large amounts of oxygen and neon: the stellar interior of a star around 15 solar masses. It is surprising, but true, that unmixed stellar debris is still present in Puppis A, even though the kinematic age is about 3700 years (see Winkler et al in this volume). Whether this is related to the interaction between the stellar wind and the more general interstellar medium is not yet clear.

There is a handful of cases where unmixed debris from deep within the star can be observed in the remnant: we ordinarily see high velocity gas with strong oxygen lines and no hydrogen emission. Those cases are: 1E0120 in the SMC, 0540-69 and N132D in the LMC, G292, Cas A, and Puppis A in our Galaxy, and the SNR in NGC 4449 (see Blair, Kirshner, and Winkler 1983). While this is strong evidence for massive progenitors, in most cases more detailed study of the remnants will be required to see whether an inference about the mass loss prior to the explosion can be supported. Those that exploded with a large hydrogen mass (presumably as red supergiants) would be the result of SN II, those which lost so much mass that they were compact at the moment of core collapse might correspond better to low luminosity SN II like SN 1987a or to exploding Wolf-Rayet stars such as Cas A might have been, and SN Ib might be.

<u>SN II:</u>

In discussing the evolution of massive stars with mass loss to become SN Ib, or SN 1987a, we have already alluded to the picture of SN II. In general, the core collapse to a neutron star in the red supergiant envelope of a massive star accounts for many of the observed features of the light curve near maximum light, the spectrum, and the circumstantial evidence that links SN II to regions of recent star formation. The observations of neutrinos from SN 1987a lends a satisfying note of reality to a picture in which the gravitational binding energy of a neutron star (of order

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10^{53} erg) is converted 99% to previously undetected neutrinos, and 1% to kinetic energy that we see in the disrupting star, and eventually in the supernova remnant.

While we are accustomed to considering the shock generated by the explosion as the source for energy in supernova remnants, other sources of energy are present and they may be of importance at early times. For example, the formation of a neutron star could have significant effects on the supernova remnant. The photoionization from the pulsar in the Crab Nebula is the principal source of excitation for the filaments we see there. In the past, the relativistic pressure may have played a role in the dynamics of the Crab. The pulsar in 0540-69 (Seward et al 1984) may play an important role there, while the pulsar in Vela probably is not an important factor in that much older remnant.

Other features of the explosion may be significant in the excitation of the very young remnant as it makes the transition from a star to a nebula. In particular, the inner zones of the star may be subjected to sufficient heating that nuclear burning takes place. Even though the principal energy source is the neutrino mediated shock, the fusion to the iron peak (especially the doubly magic nucleus ^{56}Ni) can be significant. This decays to ^{56}Co which decays to ^{56}Fe with an e-folding time of 114 days. Over the first months of an ordinary SN II, the diffusion of shock energy dominates the luminosity, but the radioactive energy input from 0.1 solar mass of Ni can become significant at later times. This effect can be seen in the light curve of SN 1987a, and in other SN II, where Uomoto and Kirshner(1986) have shown that the H alpha flux tracks the radioactive decay rate with surprising fidelity. Very young remnants are an especially interesting subject for study because they provide the links to stellar interiors and to the circumstellar surround that we seek to understand. The presence of an energy source to keep this material warm and visible in the first years after the explosion is a very useful circumstance that deserves further exploration.

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