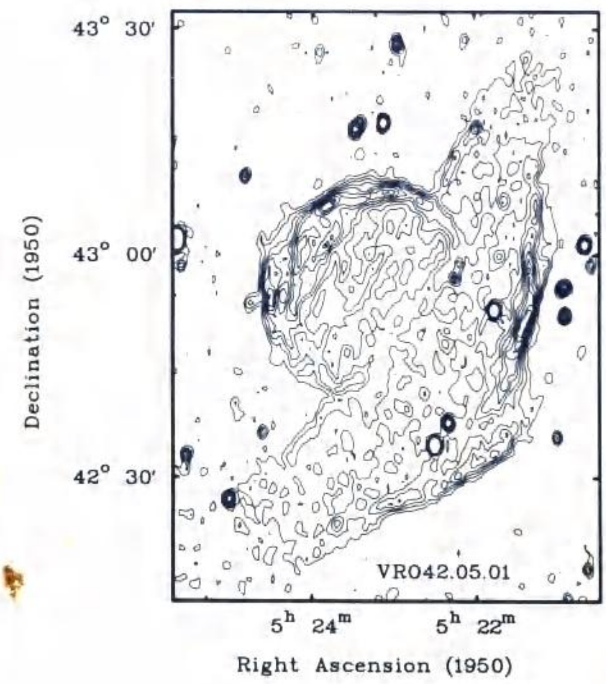
Supernova Remnants and the Interstellar Medium

IAU Colloquium 101

Edited by
R. S. ROGER and
T. L. LANDECKER



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SUPERNOVA REMNANTS AND THE INTERSTELLAR MEDIUM

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Edited by

R. S. ROGER AND T. L. LANDECKER

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PREFACE

Supernovae and their remnants play a vital role in the evolution of a galactic disk, both by injecting heavy elements and cosmic rays and by energizing the interstellar material through radiative and magneto-hydrodynamic processes. At the same time, the detailed state of the circumstellar and interstellar medium surrounding a supernova, sometimes modified by the progenitor star, determines the subsequent evolution of an individual remnant nebula throughout its lifetime. This mutual interaction was the theme for the International Astronomical Union Colloquium 101 held in Penticton, British Columbia from June 8 to 12, 1987.

One hundred and seventy thousand years ago a B3 supergiant exploded in the Large Magellanic Cloud. The light from SN1987a reached the Earth a mere three months before the Colloquium, with considerable effects on astronomy as a whole and on our meeting in particular. The results are plain to see in the proceedings that follow.

The Colloquium attracted 132 participants from 17 countries. Twelve invited review papers and 86 contributed papers were presented. All but five are published in this volume.

We are indebted to the members of the scientific organizing committee

Dr. S. van den Bergh - Canada	Dr. V.N. Fedorenko - U.S.S.R.
Dr. R.D. Blandford - U.S.A.	Dr. D.J. Helfand - U.S.A.
Dr. J.L. Caswell - Australia	Dr. H. Itoh - Japan
Dr. R.A. Chevalier - U.S.A.	Dr. S. D'Odorico - Germany
Dr. B.T. Draine - U.S.A.	Dr. I.R. Tuohy - Australia
Dr. R.A. Fesen - U.S.A.	Dr. H.W. Yorke - Germany

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Our organizing efforts were aided by the entire staff of the host institution, the Dominion Radio Astrophysical Observatory. We are particularly grateful to Lloyd Higgs, Erika Rohner, Cindy Furtado, David Lacey and Bette Jones for making everything happen. Serge Pineault, David Routledge and Fred Vaneldik came from far away to help run the show. Sidney van den Bergh organized and chaired the concluding panel discussion.

Tom Landecker and Rob Roger

TABLE OF CONTENTS

SUPERNOVA REMNANTS AND THEIR SUPERNOVAE

Robert P. Kirshner
Harvard-Smithsonian Center for Astrophysics
Cambridge, MA 02138, USA

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 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.

SN I:

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 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

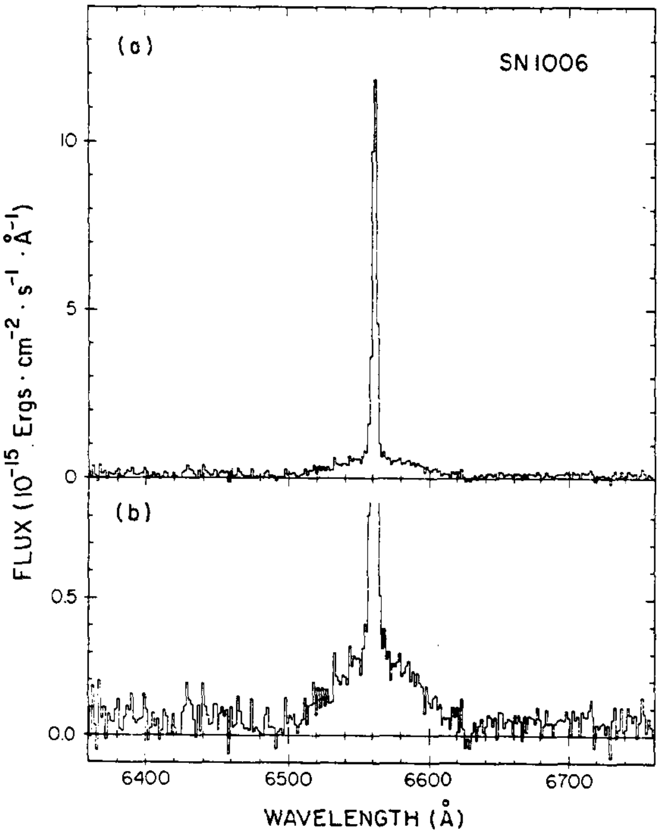

Fig. 1

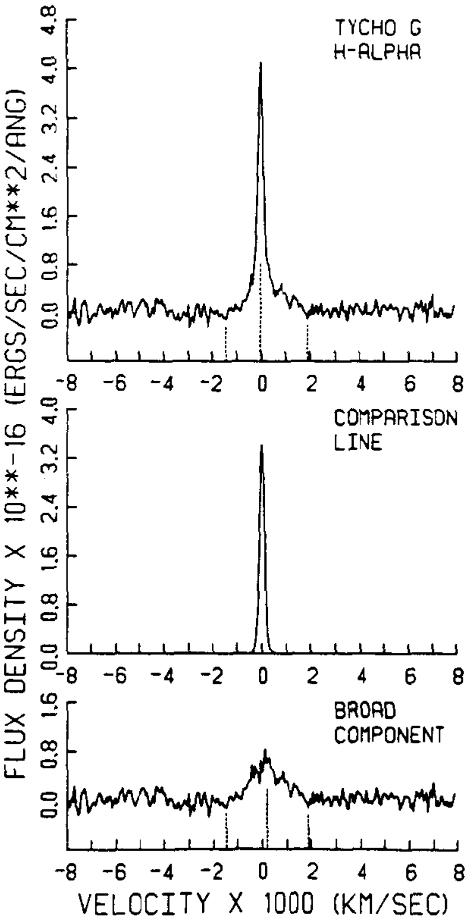

Fig. 2

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.

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 linesto broad linesgive 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

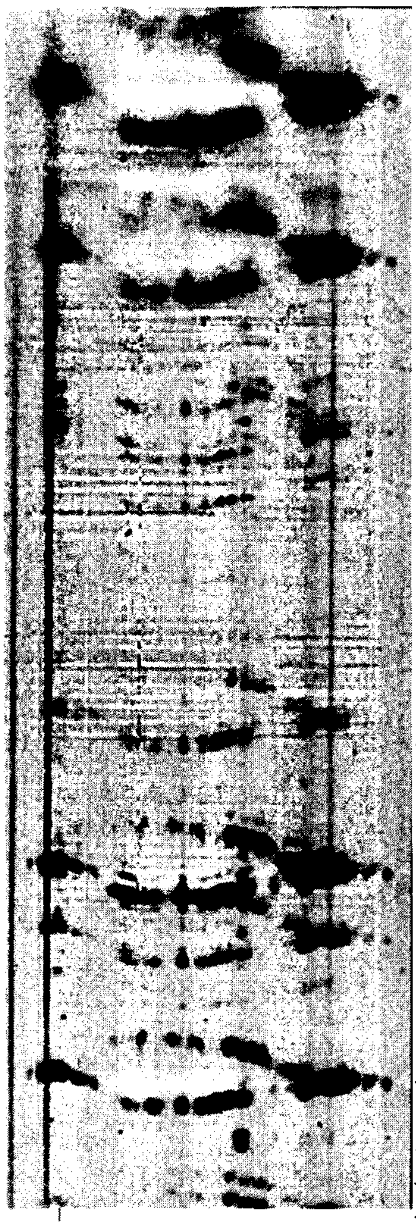

Fig. 3-- The near IR spectrum of Cas A. Note the large velocity range of the approaching and receding shells. The lines of [C I], [Cl II] and permitted O I are of special interest.