OPTICAL PROPERTIES OF SUPERNOVA REMNANTS

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INTRODUCTION

Over the past decade there has been an increasing tempo of detailed optical and UV spectroscopy of SNR leading to comparisons with prevailing models of radiative shocks.

In these endeavours there have been reports of great success, for example with IC 443 (Fesen and Kirshner 1980) and SNR's in the LMC in the framework of shocked cloudlets (Dopita 1979), of moderate success, for example with the Cygnus Loop (Miller 1974), and of serious discrepancies, for example with Cygnus (Fesen et al. 1982), Vela (Danziger 1982) and RCW 86 and RCW 103 (Leibowitz and Danziger 1982). Since a new generation of models will appear in the very near future, if not at this symposium, and will be discussed in detail by those who have done this work, it seems more profitable to discuss other more general areas.

SOME INDIVIDUAL SNR

Reference is made to Table 1, where one finds a highly selective listing of SNR's from our Galaxy and from external galaxies. The emphasis here has been placed on objects where there has been some evidence for abundance effects (i.e. variations from solar-type abundances that may not be part of a galactic abundance gradient). Note that objects such as Tycho and SNR 1006 and similar objects in the Magellanic Clouds have not been discussed, even though, with an emission spectrum due only to hydrogen, they are certainly not normal SNR's. Objects above the double line in Table 1 are those in which I believe it is impossible at this stage to conclude that increased abundances of some heavy elements are not present. Below the double line there are objects where there is room for doubt. Indeed the last group of 3 are probably only representative of a bigger group which are not carefully defined here.

The outstanding characteristic of this table is that with the exception of the Crab, oxygen overabundances always appear in high velocity (~ thousands of km/sec) filaments, and therefore in presumably

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young objects (⩽2000-3000 years). Nitrogen overabundances occur in low velocity filaments, but in objects that can be extremely young as well as of moderate age. These properties have led to the formulation of models involving some form of low velocity mass loss of nitrogen-enriched material prior to the SN explosion. The oxygen-enriched material is apparently consistent with the remnants formed from material in the interior of a $25M_{\odot}$ star prior to collapse and explosion.

Table 1. Some Properties of SNR

SNR	RV Km/s	Abundances	Comment
CRAB	⩾1200 - 1500 (6000?)	Variable He N, O, Ne, S Low x 2-3	
CasA HVF QSF	5000 ~100	O Var. S, Ar, Ca N + He	
LMC N132D	2200	O	similar to CasA?
G292.0 + 1.8	1600	O	
LMC 0540-69.3	1500	O	
SMC 0102-72.3	2000	O	
NGC 4449	3500	O	
Puppis A	300	N + He O?	WN Star?
W 50	Small	N	
Kepler	300	N	Dense, [FeII] strong
3C58	100	N	AD1181
LMC 0525-66.0	Small?	N	
RCW 86	200	N (Variable?)	AD185?
RCW 103	300	N	
RCW 89	Small?	N	[FeII] strong

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Comments are made on individual objects:

Crab. An analysis using photoionisation models and recent optical (Fesen and Kirshner 1982) and UV (Davidson et al. 1982) data has been made by Henry and MacAlpine (1982). There is no large inconsistency with earlier published work and the carbon abundance seems normal. These authors give a warning that "the strong [SII] lines originate in the H° zone, and their strength is indicative of a large volume of gas which is relatively unionized, instead of an overabundance of sulphur". This might serve as a warning for the interpretation of some of the spectroscopic features of Cas A.

Cas A. While the oxygen overabundance in the high velocity knots seems certain, one could be more sceptical about S, Ar, Ca. If the ionisation structure of sulphur is difficult to model, this is surely true also of calcium. The forbidden and allowed transitions of CaII are seen in great strength in some but not all much older and more conventional SNR's, where one would be less willing to interpret it as an effect of overabundance in the absence of more sophisticated models and where oxygen is not apparently overabundant. The case for an overabundance of argon would be enhanced if it could be measured against another ion of similar excitation and ionisation properties.

LMC N132D. Danziger and Dennefeld (1976) first suggested this was identical to Cas A. Recently I have become less convinced of this exact identity. There are two major differences. The quasi-stationary flocculi of Cas A enriched in nitrogen are not apparent in N132D. The high velocity oxygen knots are very distinct and separate in N132D even at a distance of 55 kpc. If Cas A (or G292.0 + 1.8, the other oxygen rich SNR in the galaxy) was at the distance of the LMC, with our method of observing them through apertures 2 - 4 arcseconds in diameter, the resulting spectra would resemble the spectrum of the object in NGC 4449, i.e. oxygen lines with broad wings and no separate identity. This difference may be reflecting a difference in the environments of the two SNR's rather than in the natures of the exploding stars.

The other oxygen rich objects in the Magellanic Clouds have broad oxygen lines. However SMC 0102 - 72.3 has its own peculiar dynamical pattern referred to later. An unidentified line near 4905 in N132D might be blue shifted [OIII]5007, indicative of velocities as high as 6000 km/sec.

G292.0 + 1.8. This SNR has recently been imaged at X-ray wavelengths by Tuohy et al. (1982) who suggest the morphology supports a model of an expanding ring of material ejected from the exploding star. An analysis of the motions of the optically visible material by Braun, Goss and Danziger (1983, reported later in this symposium) shows that the oxygen-rich material does not follow the pattern of an expanding ring.

Puppis A. This object has the strongest [NII] lines of any known SNR, and in some filaments the [NII]/Hα = 20. [NI] 5200 is also strong, reinforcing the conclusion that we are seeing an abundance effect. The [NII] electron temperatures are normal. The nitrogen line strengths vary from filament to filament. Although Danziger et al. (1982) have proposed that the precursor star might be a WN star, it is not yet clear whether the nitrogen enrichment occurred before the SN explosion or as a result of ejection at the time of the explosion. In its radio-optical properties it resembles a young SNR.

W50. Kirshner and Chevalier (1980) concluded that the remnant was not excited by particle beams from SS433, and certainly the [NII] electron temperature obtained from the [NII] 6584/5755 ratio for this SNR is normal (Danziger, unpublished material).

Kepler. Recently Leibowitz and Danziger (1982) published detailed spectra of the various filaments. It was not possible to find a published model to fit the spectra. One reason is that the indicated density is very high $Ne \geqslant 10^4$ cm^{-3}. Indeed plausible quantitative arguments were made that in some parts of the filament one is currently seeing a shock front "eating" its way into one of the dense clouds. Comparison with published models suggests that a successful model for Kepler will require at least a much denser medium for propagation of the shock, a higher shock velocity and an increased nitrogen abundance. The [FeII] lines are strong in Kepler, but we shall see later that this is probably a density effect.

3C58. It has been suggested by Kirshner and Fesen (1978) that 3C58 is similar to Kepler. It is, in the sense that high velocity filaments have not been detected in what are considered to be young remnants. However the [NII] lines are stronger and the densities are an order of magnitude greater in Kepler.

LMC 0525-66.0. This object is included here not because the [NII] lines and the nitrogen abundance are enhanced relative to conventional Galactic SNR's, because they are not, but because they are enhanced relative to other SNR's in the LMC (Dopita, Mathewson, Ford, 1977; Danziger and Leibowitz, 1982). The relative enhancement is not of the same order as is seen in Puppis A, posing for us the question: Are there any Puppis A type objects remaining to be discovered in the metal poor LMC or SMC? So far none have been found, which in itself may provide a clue as to what type of star can become a SN providing huge overabundances of nitrogen.

RCW 86, RCW 103, RCW 89. Ruiz (1981) analysed the spectra of filaments in RCW 86, and suggested that there were real variations of nitrogen abundance with position. Leibowitz and Danziger (1982) also analysed several positions with an advantage that electron temperatures were directly measurable for [OIII] rather than being inferred from [OII]/[OIII] ratios. Both found significant temperature variations although the Leibowitz and Danziger values were systematically and significantly lower. Because of these temperature fluctuations, one is inclined to doubt whether real nitrogen abundance variations are occurring. It is important to settle this question, because Ruiz has used the inferred variation as a sign of youth and consequent identification with the SN of AD 185. In any case if one is observing abundance effects in nitrogen in RCW 86, one must surely be seeing it in RCW 103, where the [NII] lines on average are twice as strong as observed in RCW 86 and comparable to those in Kepler. The [NII]/Hα ratio is also variable.

RCW 89 is included here because of the strong [NII] lines shown in Figure 1. The other interesting feature is the great strength of the [FeII] 5159 line which will be discussed later.

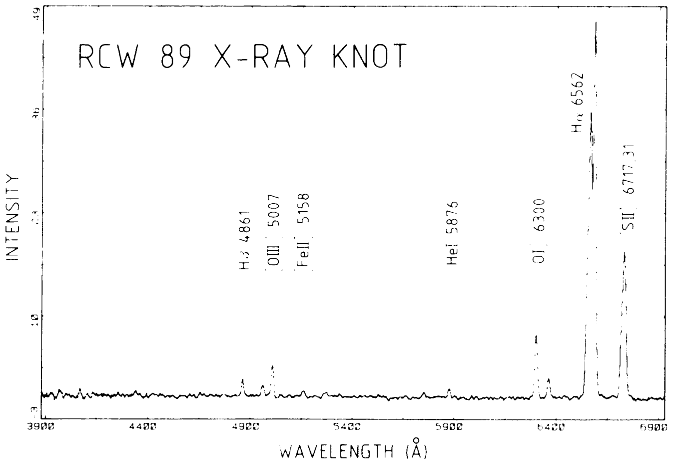

Figure 1. A spectrum of the optical knot in RCW89 showing strong [NII] lines and a strong [FeII] 5159 line.

NITROGEN AND HELIUM ABUNDANCES

Table 2 lists average line ratios for SNR's in various galaxies. Although this is a simplistic approach it contains valuable information.

Note the trend of decreasing [NII]/Hα towards less massive systems. A similar trend is apparent for the [OIII] and [SII] lines. This supports what is already known about the metallicity of these systems. Note also especially the dispersion and in particular the very low dispersion in the LMC. This suggests that [NII] lines if calibrated can give a very reliable determination of the abundance, a point already made by Dopita (1977). It also suggests that there is virtually no nitrogen abundance gradient nor variation in the interstellar medium of the LMC. The larger dispersions seen in the more massive galaxies are also consistent with what we know from more detailed studies of HII regions and SNR's.

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Table 2. Comparison of Average Line Ratios

	Galaxy	M31	M33	LMC	SMC
[OIII] 5007/Hβ	4.07 ± 2.75	2.63 ± 1.27	1.86 ± .83	1.70 ± 1.66	0.94
[NII] 6584/Hα	1.25 ± 0.63	0.83 ± .34	0.35 ± .14	0.21 ± .07	0.08
[SII] 6716,31/Hα	1.03 ± .36	1.03 ± .24	0.87 ± .23	0.72 ± .22	0.45

In Table 3 can be found a listing of ionised helium abundances obtained by Danziger and Leibowitz (1982) who have derived an average helium abundance $N(He^+)/N(H^+)$ using the HeI 4471, 5876 lines. For ten remnants in the LMC where we have a uniform set of data, we obtain $N(He^+)/N(H^+) \sim 0.079 \pm 0.013$. Also listed is the result for one SNR in the SMC obtained by Danziger and Dennefeld (1982).Since some models (Dopita 1977) show near coincidence of the H^+ and He^+ zones it may be that no correction for He^0 is necessary. This result would then support the results for the HII regions in the LMC of Peimbert (1975) and Shaver et al. (1982) who obtain values of 0.080 ± 0.005 and 0.083 respectively. Or the argument could be turned around to demonstrate that in real SNR the ionisation zones of the 2 species are on average very similar.

Table 3. Ionised Helium Abundances, $N(He^+)/N(H^+)$

	LMC
SNR	0.079 ± 0.013
HII (Peimbert)	0.080 ± 0.005 (0.084)
HII (Shaver et al.)	0.083 ± 0.008
	SMC
SNR	0.074 ± 0.017
HII (Peimbert)	0.077 ± 0.015 (0.081)
HII (Shaver et al.)	0.072 ± 0.008

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THE [FeII] SPECTRUM

It was intended to look for abundance effects in iron in the same empirical way as we discussed for nitrogen and helium. However it soon became clear that excitation effects were present and important, and would need to be understood before one could say anything about abundances. Figure 2 shows a plot of the density sensitive line ratio [SII] 6731/6717 versus the relative strength of [FeII] 5159. This line was chosen because it is generally one of the strongest [FeII] lines in spectra of SNR's. The data come from published sources and include both Galactic and LMC SNR's. Preference has been given to photoelectric measurements. It is possible that selection effects exist in this data. However a strong correlation exists, suggesting that [FeII] 5159 increases with electron density. It is not surprising then that one could not show a systematic difference in the [FeII] 5159/Hβ ratio, between the Galaxy and LMC. Clearly, modelling which reproduces this effect is necessary before conclusions concerning iron abundances can be drawn.

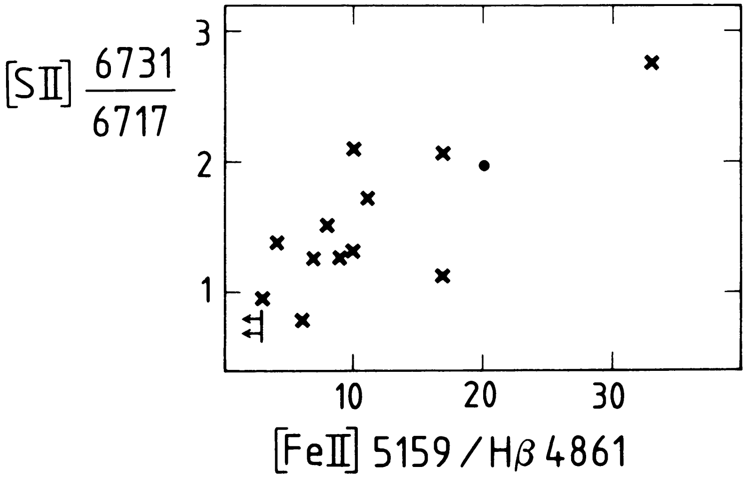

Figure 2. A plot showing the variation of [FeII]5159 with density indicated by the [SII]6731,17 doublet ratio. The dot is the point for the Herbig-Haro object HH-1 given by Dopita (1978). The point deviating most from the correlation results from a photographic measurement.

Since RCW 89 (bright X-ray knot) has a very strong [FeII] 5159 line, one might predict that the electron density is high ($Ne \sim 10^4$). Unfortunately our [SII] line measurements are of too low resolution to suggest whether a high density is present, but the spectroscopic results presented at this symposium by Murdin et al. (1983) do confirm this prediction.

CORONAL [Fe XIV]

Since the original report of the presence of [Fe XIV] 5303 in the spectrum of N49 by Danziger and Dennefeld (1976), I have been concerned about the interpretation of this feature. The resolved structure of the line seen in our original spectra and further elaborated by Murdin et al. (1978) shows components separated by 4 angstroms (or 240 km/s) in N49. This same structure can be seen in the spectra of N103B and probably N132D (Figures 3 and 4), where Danziger and Leibowitz (1982) have detected the feature for the first time. Thermal broadening alone at a temperature of 2 x 10^6K is not nearly sufficient to explain this structure. At present we know very little about the mass motion of the gas at these high temperatures, so this feature provides a possible means of learning more. One might also be tempted to speculate that [FeXIV] does not provide the only contribution to this feature, even though an alternative identification is not obvious.

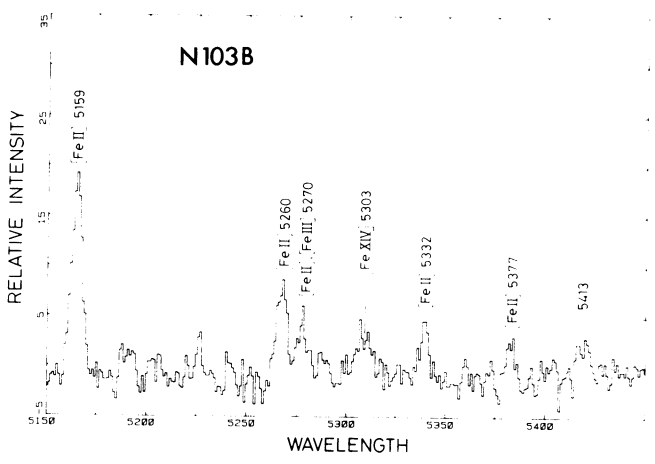

Figure 3. A spectrum of N103B showing the feature assumed to be [FeXIV]5303.

An attempt to detect spectroscopically [Fe XIV] 5303 in the LMC SNR N63A has not been successful. (Danziger and Dennefeld, 1982; Danziger and Leibowitz, 1982). The upper limit is about a factor 2 - 3 lower than a previously reported detection by Dopita and Mathewson (1979) using filter techniques. This applies to the main northern component of N63A and a separate cloudlet to the east.

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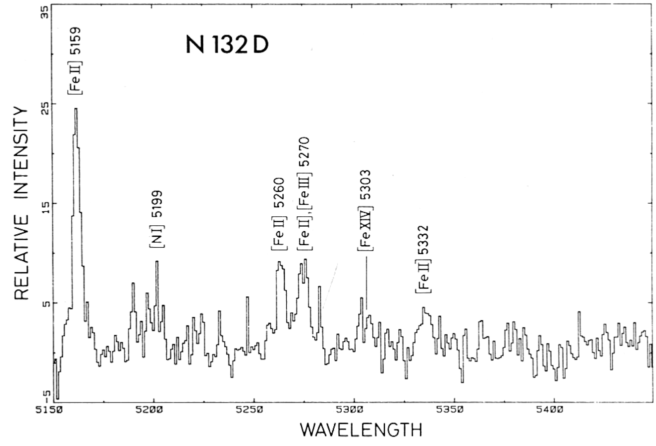

Figure 4. A spectrum of N132D showing a possible feature assumed to be [FeXIV]5303.

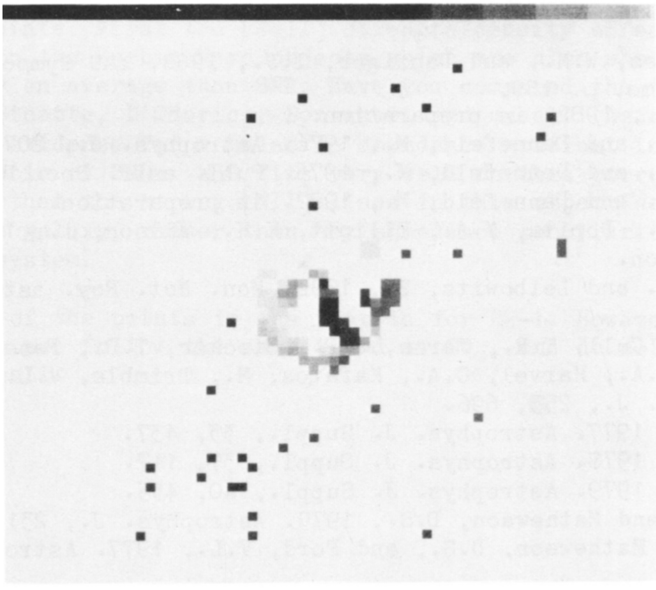

Figure 5. A grey scale map of all negative velocities in SMC 0102 - 72.3. The darkest levels represent velocities ~-2000 km/sec. The shell in this plot is ~30 arcseconds in diameter. North is to the top, east to the left.

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OTHER OXYGEN RICH SNR

In spite of my earlier remarks concerning the lumpy filamentry structure seen in N132D, and the lack of a coherent expanding optical ring in G292.0 + 1.8, it is worth noting that SMC 0102 -72.3, the oxygen rich SNR in the SMC discovered by Dopita, Tuohy and Mathewson (1981), has a distinctive coherent velocity pattern unlike those two. Figure 5 is a velocity map of 0102 - 72.3 shown as grey scale levels. This map results from TAURUS Imaging Fabry-Perot observations of [OIII] emission made at La Silla by Atherton, Taylor, Boksenberg, Baade and myself. This map shows all velocities that are negative relative to the systemic velocity (i.e. approaching material). The largest velocities of approach (shown by the darkest grey levels) tend to be near the centre of the object. What is most striking is the continuity of material expanding in various directions, and maintaining a certain cohesion over projected distances greater than 5 parsecs. While older SNR contain elongated filaments of some considerable dimensions that must be formed as a result of instabilities in the interstellar medium, it is worth examining whether in the case of these younger SNR the apparent toroidal structures are the imprint of this SN explosion itself and possibly of the structure of the exploding star.

Much of the new work reported here results from a fruitful collaboration with E. Leibowitz to whom I am grateful.

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DISCUSSION

CHEVALIER: I wish to comment on whether there are abundance effects in the Cas A fast knots. There are many lines observed in the brightest knots: three stages of ionization of O and Ar and two of S. The pattern of observed elements is compatible with heavy element nucleosynthesis. Oxygen and silicon group elements are present. It is unlikely that the pattern can be explained by atomic physics effects.

DANZIGER: Arguments based on atomic physics seem more reassuring than those based on possible complicated evolutionary nuclear physics scenarios.

DOPITA: Two points. First the [FeII] strength/density effect you mention is well known in the Herbig-Haro objects which are also shock-excited but somewhat denser on average than SNR. Have you compared the two sets of data? Second, Binette, D'Odorico, Benvenuti and myself (Astron. Astrophys, in press) give evidence for a galactic abundance gradient in the [NII]/Hα ratio of SNRs. W50 fits very well on this correlation which seems to argue that the strong [NII] lines in this object are the result of position in the galaxy, rather than any abundance peculiarity intrinsic to the SS433/W50 system.

DANZIGER: One of the points in the plot is for HH-1. However the Herbig-Haro objects do not follow the same trend as SNR, and do not show any clear correlation at all.