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THE EXTRAORDINARY EXTRAGALACTIC SUPERNOVA REMNANT IN NGC 4449.
II. X-RAY AND OPTICAL INVESTIGATIONS

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ABSTRACT

X-ray observations with the *Einstein Observatory* show that the supernova remnant (SNR) in the galaxy NGC 4449 is the most luminous known X-ray SNR—a distinction it already holds at optical and radio wavelengths. New optical spectroscopy and the X-ray data indicate that the extraordinary luminosity is due to chemically enriched material at unusually high densities. A model in which the NGC 4449 remnant resulted from the explosion of a massive star in a medium of density near 25 cm^{-3} about 100 years ago is consistent with all of the data. In this picture the X-rays stem from chemically enriched supernova ejecta heated by a reverse shock. Models in which chemically processed material makes up less of the X-ray emitting plasma are also possible, but a blast-wave origin for the X-ray emission would require that the SNR be larger than upper limits from radio observations.

The detection of optical emission lines from [O II], [S II], and [Ne III] provides a refined picture of the physical conditions where the optical emission takes place and permits comparison of this remnant with others, such as Cas A, where fast-moving knots with peculiar abundances have been measured. The chemistry supports the picture that the remnant in NGC 4449 resulted from the explosion of a star of mass greater than 25 $M_\odot$.

Subject headings: galaxies: individual — nebulae: supernova remnants — X-rays: sources

I. INTRODUCTION

As part of a survey of the radio properties of nearby spiral and irregular galaxies, Seaquist and Bignell (1978) detected a strong, nonthermal point source (diameter $<2''$) approximately 1′ north of the nucleus of the irregular galaxy NGC 4449. This radio source is coincident with emission region number 187 from the H II region catalog of NGC 4449 by Sabbadin and Bianchini (1979; hereafter SB). Spectrophotometry of SB 187 by Balick and Heckman (1978) showed two components: narrow lines belonging to a conventional H II region and very broad features at [O III] $\lambda\lambda$4959, 5007 and [O I] $\lambda\lambda$6300, 6363 which they attributed to a young supernova remnant (SNR) similar to the galactic remnant Cassiopeia A. Subsequent spectra by Kirshner and Blair (1980; hereafter Paper I) confirmed and extended this interpretation and allowed a rough analysis of the physical conditions in the SNR and the associated H II region. They showed that the optical knots in the remnant are moving at 3500 km s^{-1} and emphasized the extremely low hydrogen abundance in the fast-moving material.

NGC 4449 is thought to be at a distance of about 5 Mpc (Sandage and Tammann 1975); the fact that the SNR is readily detected at radio and optical wavelengths attests to its large intrinsic brightness. Paper I suggested the remnant might be detectable with the *Einstein X-Ray Observatory*. We have now observed NGC 4449 with the High Resolution Imager (HRI) and have detected three X-ray sources, one of which is coincident with the SNR. The details of these observations will be reported elsewhere (Blair, Kirshner, and Winkler 1983; hereafter Paper III). Here we also report an optical spectrum of SB187 which shows additional emission lines belonging to the SNR. Combining these data allows us to constrain further the model of Paper I, to estimate an age for the SNR, and to compare the NGC 4449 event with other similar young remnants.

II. OBSERVATIONS

In Paper I, we reported several spectra of SB 187. In addition to the broad lines seen by Balick and Heckman (1978), lines of [O II] $\lambda\lambda$7320, 7330 and [O III] λ4363 belonging to the SNR were detected. However, because of poor blue response in the instrument used in Paper I, only an upper limit could be placed on a broad component of [O II] λ3727 and interesting limits on other possible broad lines in the blue were below the level of the noise.

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To obtain an improved blue spectrum of SB 187 and the embedded SNR, we have used the 2.1 m telescope and Intensified Image Dissector Scanner (IIDS) at Kitt Peak National Observatory. The spectrum was obtained 1980 April 11 with a total integration of 7200 s; the dual 6".1 apertures of the IIDS allowed simultaneous sky measurement. The total spectral coverage was from 3400 Å to 5300 Å with a resolution of 8 Å. The spectrum was placed on a linear wavelength scale and reduced to fluxes at KPNO using the standard IIDS data reduction techniques.

The resulting spectrum is shown in Figures 1*a* and 1*b*. Figure 1*a* clearly shows the narrow lines belonging to the H II region portion of SB 187 and the broad component of [O III] λλ4959, 5007 belonging to the SNR. Upon close inspection several other broad lines can be seen as shown in Figure 1*b*. In addition to the previously detected [O III] λ4363 line, broad components of [O II] λ3727, [Ne III] λλ3869, 3968, and [S II] λλ4069, 4076 have been detected for the first time. In Tables 1A and 1B we list the observed fluxes, $F(\lambda)$, and reddening corrected fluxes, $I(\lambda)$, for the H II region and SNR components of SB 187. These tables include the results of recalibration of the red spectra from Paper I and supersede the values listed there. The H II region fluxes are scaled to Hβ = 100 while the SNR fluxes are shown relative to [O III] λλ4959, 5007 = 100, since there is no broad component of Hβ. The reddening correction sets the narrow Balmer lines to their recombination values in the manner discussed by Miller and Mathews (1972). Following the recalibration discussed above, we find $A_v = 0.7$ mag. This correction has been applied to both

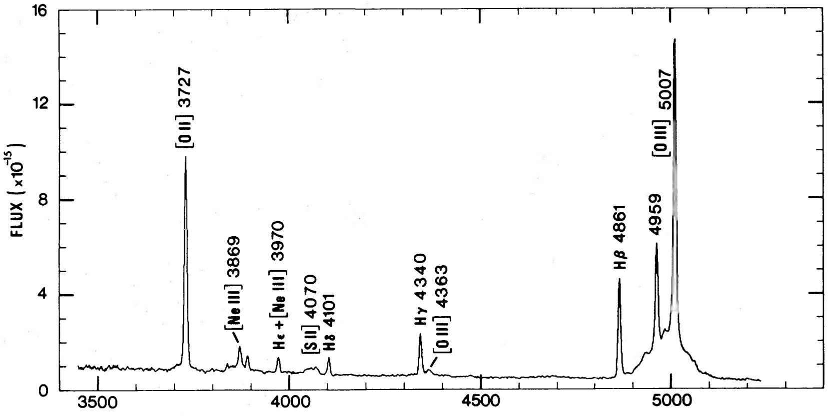

FIG. 1*a*

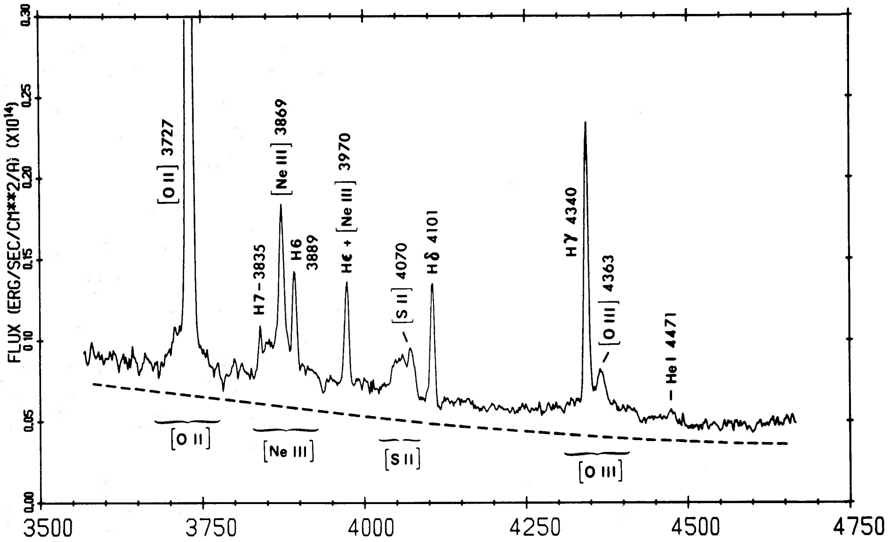

FIG. 1*b*

FIG. 1.—(*a*) KPNO 2.1 m spectrum of the emission region SB 187 in NGC 4449. The broad component of [O III] λλ4959, 5007 is clearly visible, but the other broad features are not obvious on this scale. The narrow lines belong to the H II region which surrounds the SNR. (*b*) Enlarged portion of Fig. 1*a* showing weak broad components of [O II], [Ne III], [S II], and [O III] λ4363. Narrow lines are identified above, and broad components are indicated below. The dashed line is drawn adjacent to the local continuum for reference purposes. The abscissa in each case is in Å, while the ordinate is scaled in flux units.

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TABLE 1A

LINE STRENGTHS IN THE H II REGION COMPONENT OF SB 187

Ion	λ	$F(\lambda)$	$I(\lambda)$[a]
[O II]	3727	224	273
H7	3835	3.3	3.9
[Ne III]	3869	20.0	23.6
H6	3889	12.1	14.3
Hϵ + [Ne III]	3967	16.0	18.7
[S II]	4070	$\lesssim 2.0$	$\lesssim 2.3$
Hδ	4101	16.7	19.0
Hγ	4340	37.6	41.4
[O III]	4363	$\lesssim 4.7$	$\lesssim 5.2$
He I	4471	$\lesssim 2.0$	$\lesssim 2.1$
Hβ	4861	100[b]	100[c]
[O III]	4959	107	105
[O III]	5007	362	355
He I	5876	14.8	12.9
[O I] + [S III]	6300, 6312	10.3	8.2
[O I]	6363	<4	<3
[N II]	6548	10.2	7.9
Hα	6563	360	286
[N II]	6584	30.5	23.2
He I	6678	3.7	2.8
[S II]	6717	37.8	28.6
[S II]	6731	25.3	19.2
[Ar III]	7136	3.6	2.6
[O II]	7325	20.5	14.6

[a] Reddening correction assumes $A_v = 0.7$ mag.
[b] $F(\mathrm{H}\beta) = 2.91 \times 10^{-14}$ ergs cm^{-2} s^{-1}.
[c] $I(\mathrm{H}\beta) = 5.45 \times 10^{-14}$ ergs cm^{-2} s^{-1}.

TABLE 1B

LINE STRENGTHS IN THE NGC 4449 SNR

Ion	λ	$F(\lambda)$	$I(\lambda)$[a]
[O II]	3727	7.7	9.5
[Ne III]	3869, 3968	9.9	12
[S II]	4069, 4076	3.9	4.5
[O III]	4363	6.5	7.2
[Fe III]	4658	<3	<4
[O III]	4959, 5007	100[b]	100[c]
[O I]	6300, 6363	24	20
[N II]	6548, 6584	<3	<2
Hα	6563	<3	<2
[S II]	6717, 6731	<5	<4
[Ar III]	7136	<1	<1
[O II]	7320, 7330	54	38

[a] Reddening correction assumes $A_v = 0.7$ mag.
[b] $F([\mathrm{O\ III}]) = 2.02 \times 10^{-13}$ ergs cm^{-2} s^{-1}.
[c] $I([\mathrm{O\ III}]) = 3.79 \times 10^{-13}$ ergs cm^{-2} s^{-1}.

the SNR and H II region components of SB 187, as discussed in Paper I.

The absolute fluxes are known to within a factor of 2 and the relative strengths of lines stronger than Hγ are known to within 20%. For lines with both broad and narrow components, there is an additional uncertainty because the deblending of these features is somewhat subjective. It is also difficult to distinguish where the weak, broad features merge with the continuum. For these reasons, the relative fluxes of the weakest broad and narrow lines are only known to 50%.

III. HISTORICAL PLATE SEARCH

The age of the SNR is not known. De Bruyn, Goss, and van Woerden (1981) have examined several plates of NGC 4449 back to 1925 but have found no supernova or change in the appearance of SB 187. We have performed a more exhaustive plate search using the patrol plates of the Harvard College Observatory. We inspected about 125 plates from the RH series (1928 to 1954, limiting magnitude $m_v \approx 14$–15) and about 280 plates from the AC series (1898 to 1954, limiting magnitude $m_v \approx 12$) and found no indication of any supernovae in NGC 4449. With a distance modulus of 28.5, and $A_v \approx 1$, the apparent magnitude limit of $+12$ corresponds to $M_v \approx -17.5$. The absolute magnitude at maximum for Type I supernovae is -19 and for Type II is about -17. Hence, while a recent supernova might have been missed, there is no direct evidence that the SNR must be extremely young. Seaquist and Bignell (1978) have found that the radio luminosity of the NGC 4449 SNR is $\sim$25 times that of Cas A which led them to suggest that the NGC 4449 SNR is much younger. However, in the absence of a well-tested theory to predict the radio luminosity of young supernova remnants, there is no compelling reason to attribute the luminosity difference to age: The density of the surrounding medium may have an important effect.

IV. INTERPRETATION

As in Paper I, we interpret the spectra of Figure 1 as the result of a broad-lined SNR embedded in an H II region. The narrow line component of SB 187 appears to be a normal H II region for NGC 4449. Talent (1980) has investigated four H II regions in NGC 4449; SB 187 is closest (both spectrally and spatially) to his position NK. Comparison of the relative line intensities provides no evidence for peculiar abundances in the H II region component of SB 187, as might have been the case if an abnormally large number of supernovae had exploded in this region.

Unlike the prosaic H II region in which it resides, the SNR in NGC 4449 provides an opportunity to investigate the evolution of a young SNR and study its relation to nucleosynthesis and the distribution of heavy elements in the interstellar medium. The new X-ray and improved optical data allow us to quantify the picture presented in Paper I and to determine a consistent set of parameters for the SNR and the surrounding H II region. In the following discussion we reevaluate some of the optically determined parameters from Paper I, describe the overall structure of the remnant and its environs, and compare it to other oxygen-rich SNRs and to model calculations.

a) Conditions in the Optically Emitting Regions

The results in Table 1 permit a refinement of many of the parameters derived in Paper I, based on the same general picture of high-density knots that are shock-heated. The ratio [O III] λ4363/$\lambda\lambda$5007, 4959 and the formulation of Kaler *et al.* (1976) show that the electron

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temperature where oxygen is doubly ionized is 50,000 K (+16,000 K, −12,500 K assuming a 20% error in λ4363). This high temperature, like that found by Chevalier and Kirshner (1979) for Cas A, suggests that shock heating, rather than photoionization, is at work.

Our new measurements of the broad [O II] λ3727 line allow a determination of the electron density from the ratio λ3727/λ7325, following the arguments of Paper I. Provided that these lines are formed in a region where the electron temperature is between 10,000 K and 20,000 K, as we expect for collisional ionization, the electron density is in the range $5.4 < \log n_e < 5.7$. Similarly, the ratio of [S II] (λ4069 + 4076)/(λ6717 + 6731) gives a consistent result of $\log n_e > 4.3$. These densities are remarkably high for any SNR. The densities in Cas A found from the same lines by Searle (1971) indicate an electron density of about 3×10^4 cm^{-3}. Since the same ions are expected at the same electron temperature, this indicates a substantially higher pressure in the NGC 4449 SNR than in Cas A. The high density can also produce collisional deexcitation of λ4959 and λ5007 of [O III]. For a density of 10^5 cm^{-3}, the effect is a 20% decrease in the strength of these lines relative to λ4363, and implies that a temperature estimate nearer 40,000 K is more appropriate.

Shock models show rough pressure equilibrium in the cooling zone behind the shock and provide a guide to the electron temperature for each stage of ionization. A consistent set of conditions which matches the observations is: $n_e \sim 4.5 \times 10^5$ cm^{-3}, $T \sim 10{,}000$ K in the O^0 zone; $n_e \sim 3 \times 10^5$ cm^{-3}, $T \sim 15{,}000$ in the O$^+$ zone; and $n_e \sim 1.1 \times 10^5$ cm^{-3}, $T \sim 40{,}000$ in the O^{++} zone. Using these revised parameters and the method described in Paper I, the total mass of oxygen presently emitting in postshock regions is $1 \times 10^{-2}\ M_\odot$. This estimate is lower than the estimate of Paper I by a factor of about 7, but is still 50 times higher than the value derived for Cas A by a similar method (Peimbert 1971).

b) The X-Ray Emitting Plasma

An overall picture of the remnant and its surroundings can now be constructed by combining the optical results with those from the X-ray observations. We have found (Paper III) that the NGC 4449 SNR is extremely luminous in X-rays: $L_x \approx 10^{39}$ ergs s^{-1}, which makes it over 100 times more luminous than Cas A, and at least 10 times more luminous than N132D in the Large Magellanic Cloud—heretofore the brightest known SNR at X-ray wavelengths. A comparison with the latter two remnants, both of which show high velocities and oxygen enrichment in their optical filaments, will guide us in developing a model for the NGC 4449 SNR. This argument by analogy is necessary because the size of the NGC 4449 remnant has not been measured and because the X-ray data contain no spectral information.

There are two types of shocks which are likely to result in heating and X-ray production in a young SNR: the blast wave propagating outward through the interstellar medium, and the reverse shock (McKee 1974; Gull 1973, 1975) heating supernova ejecta. Both phenomena may be present in NGC 4449, as they are in Cas A, but it is most probable that the reverse-shock emission is the dominant source of X-rays in the 0.2–0.4 keV band, as is also the case in Cas A (Fabian *et al.* 1980). We will now show that an X-ray spectrum dominated by emission from a reverse shock leads to a consistent picture for NGC 4449, but that a spectrum resulting from a blast wave does not.

The count rate from the NGC 4449 SNR in the *Einstein* HRI is 2.5×10^{-3} counts s^{-1}, which corresponds to an energy flux of about 2×10^{-13} ergs cm^{-2} s^{-1} (0.2–0.4 keV); the exact flux for a given count rate depends on the source spectrum. For the absorption column density N_H we use our value of 0.7 mag for the visual absorption and the relation $N_\mathrm{H} \approx 7.1 \times 10^{21} E_{B-V} \approx 2.1 \times 10^{21} A_V$ cm^{-2} (Gorenstein 1975; Ryter, Cesarsky, and Audouze 1975) to obtain $N_\mathrm{H} \approx 1.5 \times 10^{21}$ cm^{-2}. The temperature is not known, but the *Einstein* SSS measured temperatures 5–8 × 10^6 K for all the young SNR observed by that instrument (Szymkowiak 1980). In particular, the effective temperature in the 0.8–4.5 keV band for Cas A is 7.3×10^6 K (Becker *et al.* 1979) and for N132D is 6.6×10^6 K (Clark *et al.* 1982). In Cas A the component at 7×10^6 K, which is evidently due to the reverse shock (Fabian *et al.* 1980), accounts for most of the X-ray luminosity. There is in addition radiation at higher temperature(s), presumably due to the blast wave, which dominates the X-ray spectrum above 5 keV but which accounts for little of the integrated X-ray luminosity (Pravdo and Smith 1979 and references therein). We shall here assume a temperature $T_x = 10^{6.8} \approx 6 \times 10^6$ K for the X-ray plasma in the NGC 4449 SNR. For a distance of 5 Mpc and $N_\mathrm{H} = 1.5 \times 10^{21}$ cm^{-2}, the indicated luminosity $L_x = 8 \times 10^{38}$ ergs s^{-1}.

We can obtain the electron density n_x of the X-ray emitting material by assuming approximate pressure equilibrium between the X-ray plasma and the optical knots, i.e., $n_x T_x \approx n_o T_o$. The optical data indicate $n_o T_o \approx 4.5 \times 10^9$ cm^{-3} K, and using T_x from above we have $n_x \approx 700$ cm^{-3}. We note that in Cas A this pressure equilibrium holds to within a factor of 2: The optical knots have $n_o T_o \approx 3 \times 10^8$ cm^{-3} K, and the X-ray pressures used by Fabian *et al.* (1980) are $n_x T_x \sim 7 \times 10^8$ cm^{-3} K.

For a thermal X-ray plasma, the emissivity is

$$\epsilon = n_e n_\mathrm{H} P(\Delta E, T) = n_e^2 P'(\Delta E, T)\,, \tag{1}$$

where the emission function $P'(\Delta E, T) \equiv (n_e/n_\mathrm{H}) P(\Delta E, T)$ depends on the electron temperature and plasma composition. We have calculated the emissivities using a revised version of the code of Raymond, Cox, and Smith (1976) for two models: model A, a plasma with cosmic abundances of Allen (1973), and model B, a plasma made up of undiluted ejecta from the 25 $M_\odot$ supernova model of Weaver and Woosley (1980). The latter has heavy ($Z > 8$) element abundances that are enhanced relative to hydrogen by a mean factor of 26. Since the real plasma is probably a mixture of supernova ejecta and swept-up interstellar material, these two models represent limits for the NGC 4449 SNR. For model A, the emission function $P'(T = 10^{6.8}\ \mathrm{K}) \approx 3 \times 10^{-23}$ ergs cm^{-3} s^{-1}, while for model B, it is about 20 times higher. This is because the X-ray emissivity is due primarily to heavy elements, so the increased metallicity of the ejecta-dominated model leads to a much higher emissivity per electron. Long, Dopita, and Tuohy (1982) have pointed out the importance of this effect in young SNRs. They further found that while the overall heavy element enhancement is very important, reasonable changes in relative abundances of the $Z > 2$ elements have little effect on the integrated emissivity. A defect of this type of argument is that it ignores the nonionization equilibrium effects discussed by Shull (1982). For Tycho's remnant, these time-dependent effects affect the mass responsible for the X-ray luminosity by a factor of 2. Here, we have so many other uncertainties that we neglect this effect.

Results from the two models are summarized in Table 2. We have assumed that the X-rays stem from a plasma with uniform electron density n_e confined to a thin spherical shell of radius R and thickness $R/12$ (filling factor $f = 0.25$). This geometry is undoubtedly oversimplified, but imaging data show that most SNR X-ray sources, including Cas A and N132D, have a limb-brightened shell morphology. The X-ray luminosity is given by

$$L_x = \tfrac{4}{3}\pi R^3 f n_e^2 P'(\Delta E, T)\,. \qquad (2)$$

We take $n_e = n_x$, the estimate from pressure equilibrium and in convenient units equation (2) gives for the radius

$$R = 1.48\ \mathrm{pc}\left(\frac{L_x}{10^{39}\ \mathrm{ergs\ s^{-1}}}\right)^{1/3}\left(\frac{n_e}{1000\ \mathrm{cm^{-3}}}\right)^{-2/3} \times \left(\frac{f}{0.25}\right)^{-1/3}\left(\frac{P'(\Delta E, T)}{10^{-23}\ \mathrm{ergs\ cm^{-3}\ s^{-1}}}\right)^{1/3}. \qquad (3)$$

This radius corresponds to angular diameters of 0".10 and 0".04 for models A and B, respectively. These are somewhat below the present upper limit of 0".2 derived from VLA observations by Seaquist and Bignell (1981), but are within the potential resolving power of the VLA or VLBI techniques.

A blast wave as the dominant source of the observed X-ray emission from NGC 4449 would require a shell much larger than the upper limit on the radio size of the remnant. The width of the broad optical lines implies an expansion velocity of $u = 3500$ km s^{-1}. Interstellar gas crossing a shock of this velocity will be adiabatically heated to a temperature $T_x \approx 14u^2 \approx 1.7 \times 10^8$ K. (Plasma at about this temperature has been reported in Cas A, which has similar optical velocities, by Pravdo and Smith 1979.) If the X-rays in NGC 4449 come from a blast-wave shell at $T_x \gtrsim 10^8$ K, then pressure equilibrium requires $n_x \lesssim 45$ cm^{-3}, and a higher luminosity $L_x \gtrsim 1.7 \times 10^{39}$ would be required to give the observed HRI count rate. By equation (3) the radius would be greater than 14 pc, and the angular diameter would be larger than 1", far in excess of radio upper limit.

Returning to our models A and B for emission at lower temperature from a reverse shock, we can express the mass of X-ray emitting material by

$$M_x = 26\, M_\odot\left(\frac{n_e}{1000\ \mathrm{cm^{-3}}}\right)\left(\frac{f}{0.25}\right)R^3\ (\mathrm{pc})\,. \qquad (4)$$

The mass range 2–34 $M_\odot$ allowed by models A and B is certainly plausible, bracketing the estimate of 15–20 $M_\odot$ for Cas A obtained by Fabian *et al.* (1980). The 34 $M_\odot$ value from model A is probably too large to be entirely of supernova origin; much of the mass must be swept-up ISM, consistent with the assumption of cosmic abundances in that model. The 2 $M_\odot$ from model B could easily have come from the supernova of a massive star, consistent with the assumption of enhanced heavy-element abundances. Note that the values obtained from equation (4) represent only the mass now emitting X-rays. The total mass, including material not yet heated by the reverse shock, may well be larger.

For model B we can establish a rough lower limit on the ISM density n_0 in the vicinity of the SNR by noting that in order for the reverse shock to have become well enough established to produce X-ray emission, the ejecta must have run into something. According to

TABLE 2

NGC 4449 SNR MODELS

Model Parameter	ISM-Dominated Reverse Shock (Model A)	Ejecta-Dominated Reverse Shock (Model B)	Blast Wave
T_x(assumed) (K)	6×10^6	6×10^6	$\gtrsim 10^8$
L_x(0.2–4 keV) (ergs s^{-1})	0.8×10^{39}	0.8×10^{39}	1.7×10^{39}
Electron density (cm^{-3})	700	700	$\lesssim 45$
Radius (pc)	1.2	0.4	14
X-ray emitting mass ($M_\odot$)	34	2	3000
Swept-up mass ($M_\odot$)	30	0.2	3000
Ambient ISM density (cm^{-3})	150	25	11
Age (yr)	140	120	1600

Gull (1975), the onset of strong X-ray emission occurs around $M_s \gtrsim 0.05M_e$, where M_e is the mass of ejecta and $M_s = 4/3\pi R^3 n_0 m_p$ is the swept-up mass. The reverse-shock model has most of the X-ray emission coming from ejecta, but not all the ejecta need be emitting at present. Thus we require $M_e \gtrsim M_x$, and using equation (4) obtain $n_0 \gtrsim 0.012(f/0.25)n_e \approx 9\ \mathrm{cm}^{-3}$. Thus the ISM surrounding the NGC 4449 SNR must be relatively dense, which supports the idea that it is embedded in the SB 187 H II region. The above limit is consistent with the density estimate (Paper I) from the narrow optical lines: $n_0 \approx 25\ \mathrm{cm}^{-3}$. Taking the latter value, we obtain 0.2 $M_\odot$ for the swept-up mass in model B.

We can estimate the age of our model B SNR by assuming that it has been freely expanding at constant velocity 3500 km s^{-1}. This leads to an age $t = R/u =$ 120 yr. If the material has decelerated, the actual age would be younger. However, since the above arguments indicate that $M_s \ll M_e$, deceleration is probably not significant.

For model A we require that the interstellar density be high enough that most of the 34 $M_\odot$ of X-ray plasma be of interstellar origin, and obtain $n_0 \approx 150$ cm^{-3}. While this is an extremely high density, much larger than the 25 cm^{-3} for the surrounding H II region, it is not inconceivable that the SNR might be buried in a dense cloud. If so much material has been swept up, then the SNR must have decelerated substantially. For the age here we assume it has spent most of its life in the Sedov phase and obtain $t = 0.4R/u = 140$ yr. The higher average velocity compensates for the larger size to give a result almost identical to that from model B.

Of the models we have considered, something close to model B appears most plausible, as summarized in the following scenario. A massive star exploded, sending forth 10–30 $M_\odot$ of ejecta enriched by a factor of 5–50 in heavy elements. The surrounding ISM is relatively dense, $\sim 25\ \mathrm{cm}^{-3}$, so after 100–200 yr enough material has been swept up to develop a strong reverse shock in the fast-moving ejecta. Some 2 $M_\odot$ of material behind the reverse shock is now emitting X-rays. High-density and abundant heavy elements contribute to the extraordinarily high X-ray luminosity.

It is interesting to consider the cooling time for the X-ray plasma, $t_c = n_e k T_e/[n_e^2 P'(\Delta E, T)]$. For the heavy-element–dominated model B, $t_c \approx 60$ yr, shorter than the age of the remnant. As the reverse shock moves inward (in a Lagrangian sense) through the expanding ejecta, rapid cooling occurs and knots condense to become optical filaments. We might well expect to see significant changes in both the X-ray and the optical properties of the remnant over a period of a few years.

V. ELEMENTAL ABUNDANCES

In the past few years, several new SNRs with characteristics similar to Cas A have been detected. These include G292.0+1.8 in our Galaxy (Goss *et al.* 1980), N132D (Lasker 1978, 1980) and 0540−69.3 (Mathewson *et al.* 1980) in the Large Magellanic Cloud (LMC) and 1E 0102.2−7219 (Dopita, Tuohy, and Mathewson 1981) in the Small Magellanic Cloud (SMC). The quality of observational material is quite different for each of these objects: Cas A has been studied in detail and 1E 0102.2−7219 has just been discovered. Table 3 shows a compilation of relative line intensities for the objects with available spectra.

In Paper I, we compared the NGC 4449 SNR to one of Raymond's (1979) solar abundance shock models (model AA; $v_s = 60$ km s^{-1}) which roughly matched the relative oxygen line intensities. Recently, Itoh (1981) has calculated shock models for the special case of pure oxygen gas: three of these models are shown in Table 3. These models assume a much higher velocity of $v_s =$ 141.4 km s^{-1}, which Itoh finds necessary to produce

TABLE 3

COMPARISON OF O-RICH REMNANTS TO SHOCK MODELS

Ion	λ	Cas A Filament 1[a]	Cas A Oxygen Knot[a]	N132D Knot B[b]	N132D Knot R[b]	G292.0+1.8[c]	NGC 4449 SNR	Itoh Model C[d]	Itoh Model G[d]	Itoh Model B[d]
[O II]........	3727	23	42	261:	101	240	9.5	25.7	71	102
[Ne III]......	3869, 3968	<0.7	...	<3:	5.8	19.9	12	...	...	...
[S II]........	4069, 4076	9.7	<5	<6.4:	<2	...	4.6	...	...	...
[O III].......	4363	2.9	<4	3.2:	5.0	3.2	7.2	9.2	7.2	7.7
[O III].......	4959, 5007	100	100	100	100	100	100	100	100	100
[O I]........	6300, 6363	7.8	4.5	<3.5:	...	<45	20	82	10	0.2
Hα..........	6563	<0.03	<0.3	...	...	<4	<2	...	...	...
[N II]........	6548, 6584	<0.03	<0.3	...	...	<10	<2	...	...	...
[S II]........	6717, 6731	9.0	<0.3	...	...	<14	<4	...	...	...
[Ar III]......	7136	2.8	<0.3	...	3.3:	...	<1	...	...	...
[O II]........	7320, 7330	8.5	13	...	...	...	38	17	10	8.2

[a] Chevalier and Kirshner 1979.

[b] Lasker 1978; no correction for reddening has been applied.

[c] Goss *et al.* 1979; no correction for reddening has been applied.

[d] Itoh 1981; models of shocked pure oxygen gas showing effect of preshock density; Model C, $n_i = 1000\ \mathrm{cm}^{-3}$; Model G, $n_i = 30\ \mathrm{cm}^{-3}$; Model B, $n_i = 1\ \mathrm{cm}^{-3}$.

substantial [O III] emission. Model C uses a preshock density of $n_i = 10^3$ cm^{-3}, while model G uses $n_i = 30$ cm^{-3} and model B assumes $n_i = 1$ cm^{-3}. These models show the effect of collisional de-excitation on the [O II] λ3727 line, although the density assumed in model C is still not high enough to match the very weak [O II] λ3727 seen in the NGC 4449 SNR. Taken at face value, this indicates that the optical knots of Cas A and the NGC 4449 SNR are denser than those in G292.0+1.8 or N132D.

By varying model parameters, Itoh was able to match the observed spectra of the Cas A oxygen knot (Chevalier and Kirshner 1979) and N132D (no attempt was made to fit G292.0+1.8), but was unable to find a parameter set which matched the NGC 4449 SNR. This could have several explanations. The observations of the galactic and LMC objects refer to small knots within the overall structure of the remnant, whereas the entire NGC 4449 remnant is observed at once since it is unresolved. We are no doubt seeing the summed spectra of a large number of knots, which may have varying characteristics. Also, the detection of emission lines of [Ne III] and [S II] makes it clear that we are not dealing with a pure oxygen gas, so the pure oxygen model cannot be expected to reproduce the observations completely.

The detection of [Ne III] λλ3869, 3968 in the NGC 4449 SNR is significant because it has only been marginally detected in Cas A. Recent observations of Cas A (van den Bergh 1971; Searle 1971; Kirshner and Chevalier 1977; Chevalier and Kirshner 1979) have failed to detect [Ne III] λ3869, although spectra in unknown locations in Cas A by Minkowski (1957) do show it very weakly (see also the discussion in Chevalier and Kirshner 1979). The data of Table 2 show that the [Ne III]/[O III] ratio increases in going from Cas A to N132D to the NGC 4449 SNR to G292.0+1.8. Raymond's (1979) models show that over a large range of abundances and shock conditions, this ratio is roughly proportional to the relative abundances of these elements. Hence the progression in line ratios may indicate a progression in the relative Ne/O abundances as well. Table 4 shows the derived Ne/O abundances obtained using the formulation of Dopita, D'Odorico, and Benvenuti (1980).

The variation in Ne/O may be due to different masses of the precursor stars for each of these objects. Weaver and Woosley (1980) have calculated the complete evolution of 15 $M_\odot$ and 25 $M_\odot$ stars including the effects of explosive nucleosynthesis and have derived the relative abundances that would be ejected to form the young remnant. They find that explosive processing is mostly responsible for heavier elements (e.g., silicon to iron), while elements between oxygen and magnesium are only slightly modified from their values before core collapse (cf. Weaver, Zimmerman, and Woosley 1978). In Table 3, the resulting Ne/O abundances from these models are shown for comparison to our derived abundances. The moderate enhancements in Ne/O (relative to the solar ratio) as seen in the NGC 4449 SNR and G292.0+1.8 are understandable in the context of these massive star models; the low values seen for Cas A and N132D are not. This may indicate that the precursors for the latter two objects were not in the mass range covered by these models or that for some reason the precursors exploded at some slightly different phase of evolution, or that we do not observe a well-mixed sample of the stellar interior. The evidence on inhomogeneities in Cas A (Chavalier and Kirshner 1979) is that the ejected debris do not resemble a well-mixed stellar material, but come from different layers of the stellar interior.

The ratio [S II] λ4070/[O II] λ7325 has been used to estimate the relative S/O abundance in a manner similar to that described above for Ne/O, with results shown in Table 4. As with neon, a precursor mass greater than 25 $M_\odot$ is indicated for the NGC 4449 SNR, while the enhanced ratio seen for Cas A is outside the range of the models.

Recently, John Raymond (1983, private communication) has obtained an ultraviolet spectrum of the NGC 4449 SNR with the *International Ultraviolet Explorer* satellite (see also Blair *et al.* 1982). While the overall spectrum is quite poor, a weak feature of width $\Delta v \approx 7000$ km s^{-1} appears to be present at λ1660 Å. If this feature is the O III] λ1664 line belonging to the SNR, it is within a factor of 2 of the strength predicted by Itoh's (1981) model C. Models with normal abundance sets show both C III] λ1909 and C IV λ1550 to be stronger than O III] λ1664; the apparent absence

TABLE 4

RELATIVE NEON AND SULFUR ABUNDANCES IN O-RICH REMNANTS

Ratio	Cas A Filament 1	N132D Knot R	NGC 4449 SNR	G292.0+1.8	15 $M_\odot$[a] Model	25 $M_\odot$[a] Model
$\frac{\mathrm{Ne/O}}{(\mathrm{Ne/O})_\odot}$[b]	<0.08	0.67	1.37	2.29	3.63	1.77
$\frac{\mathrm{S/O}}{(\mathrm{S/O})_\odot}$[c]	2.0	...	0.6	...	1.2	0.7

[a] Output from models by Weaver and Woosley 1980.

[b] Scaled relative to the $\odot$ ratio Ne/O = 0.126.

[c] Scaled relative to the $\odot$ ratio S/O = 0.024.

of the carbon lines in the *IUE* spectrum may indicate that carbon is depleted relative to oxygen. This is at least qualitatively in accord with the 25 $M_\odot$ model, which shows carbon depleted by a factor of roughly 2.

Of course, the connection between specific burning zones and the mass of the precursor star is not necessarily well defined, as pointed out by Johnston and Joss (1980). Some specific problems in this regard are treated by Johnston and Yahil (1983). Nevertheless, the classification of stellar burning by comparing Ne/O and S/O may be a useful way to measure the evolutionary state of a star at the precipice of supernova explosion.

VI. CONCLUSIONS

We have used optical and X-ray data to develop a self-consistent model for the young supernova remnant in NGC 4449. Because the X-ray data contain no spectral information, we have relied heavily on comparison with the galactic remnant Cas A. The model is not unique, as many of the parameters have been assumed rather than directly determined. Nonetheless, a massive precursor (of order 25 $M_\odot$) has been implicated from several lines of argument.

Weaver and Woosley (1980) have shown that even though such massive stars are rare, they are important contributors to the overall yield of heavy elements. For some time, Cas A was the only example of a young SNR with peculiar abundances, but it is important that we now begin investigating the class of oxygen-rich remnants *as a whole*. Comparison of all of the spectral data presently available on these objects to models such as those of Weaver and Woosley (1980) indicates that the relative abundance of neon to oxygen may be a useful parameter for estimating the mass of the precursor star.

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