X-RAY, OPTICAL AND UV OBSERVATIONS OF THE YOUNG SUPERNOVA REMNANT IN THE IRREGULAR GALAXY NGC 4449

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Abstract: A powerful young supernova remnant (SNR) similar to Cas A has recently been discovered in the irregular galaxy NGC 4449. We have obtained X-ray, optical and ultraviolet data which allow us to investigate possible models for this object and estimate its age. Several lines of argument indicate a massive star of order 25 $M_\odot$ as the precursor to this remnant. If the x-ray emission is attributed to a reverse shock in the ejecta, the remnant should be $\sim$ 120 years old.

In the past few years, several new SNRs with characteristics similar to Cas A have been detected. The study of such objects is important because it provides an opportunity to investigate not only the evolution of young SNRs, but the relation of these objects to nucleosynthesis and the distribution of heavy elements in the interstellar medium (ISM). Here we present data on one such object and discuss a self-consistent model that accounts for all of the observations presently available.

The SNR in the irregular galaxy NGC 4449 was first detected at radio wavelengths by Seaquist and Bignell (1978), who found a strong, unresolved non-thermal source about 1' north of the nucleus of the galaxy. At the presumed distance of NGC 4449 (5 Mpc; Sandage and Tammann 1975), the source is 25 times more luminous at 2.7 GHz than Cas A. Subsequent radio observations with the VLA (Seaquist, private communication) have only been able to place an upper limit on the diameter of the object of < 0"2, which corresponds to a linear diameter < 5 pc. The radio source is coincident with an emission region whose optical spectrum shows a composite of narrow emission lines belonging to a normal H II region and broad lines (full width $\sim$ 7000 km s^{-1}) which belong to the SNR (Balick and Heckman 1978, Kirshner and Blair 1980). However, broad components were initially detected only at the positions of [O I] λλ6300,6364, [O II] λλ7320,7330 and [O III] λλ4363,4959,5007.

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We have extended this early work by obtaining an additional high quality optical spectrum as well as observations with the HEAO-B (Einstein X-ray Observatory) and International Ultraviolet Explorer (IUE) satellites. The optical spectrum was obtained with the 2.1m telescope at Kitt Peak National Observatory and shows additional broad lines which belong to the SNR, including [O II] λ3727, [Ne III] λλ3869,3968 and [S II] λ4070.

Although only a handful of lines belonging to the SNR are evident, we can still estimate the physical conditions in the optically emitting gas. The ratio of [O II] λ3727/λ7325 can be used to infer a density of roughly log $N_e \approx 5.5$, assuming the lines are formed in a region with T $\approx$ 15,000 K. The ratio of [O III] λ4363/λ4959+λ5007 indicates T $\approx$ 50,000 K in the O^{++} region; however, the density is high enough that the nebular lines should be partially de-excited and T $\approx$ 40,000 K is probably more realistic. The assumption of pressure equilibrium between the O°, O^{+} and O^{++} zones allows the mass of oxygen in the currently cooling gas to be estimated using the method of Peimbert (1971); we find M(O) $\approx$ 0.01 $M_{\odot}$, which is about a factor of 50 higher than for Cas A.

Comparison of these observations to shock model calculations is difficult because of the distinctly non-solar abundances in this SNR. Itoh (1981) has calculated some shock models for a gas of pure oxygen composition and finds that a shock velocity of at least 140 km s^{-1} is needed to produce strong [O III] emission; however, none of these models incorporates a density as high as is indicated for this SNR.

Crude estimates of the abundances of neon and sulfur relative to oxygen can be made using the observed ratios of [Ne III]/[O III] and [S II]/[O II]. These estimates can be compared to the final abundances from the stellar evolution models of Weaver and Woosley (1980) for 15 $M_{\odot}$ and 25 $M_{\odot}$ stars, which include the effects of explosive nucleosynthesis. The relative Ne and S abundances are both consistent with a precursor star of $\gtrsim$ 25 $M_{\odot}$, a conclusion which is supported (at least indirectly) by the presence of massive stars in the H II region itself.

The IUE spectrum represents 17.7 hours of integration on the SNR. A very weak feature with Δv $\approx$ 7000 km s^{-1} appears at λ1660. If this is the O III] λ1664 line from the SNR, it is within a factor of two of the strength one would expect using Itoh's (1981) high density model "C" (assuming A_V = 0.7, which is determined from the narrow Hα and Hβ lines belonging to the H II region). We have been unable to entirely exclude the possibility that this is a weak camera feature, although two other "blank" long exposures have been checked and no comparable feature seems to be present. Even if this feature represents an upper limit to the O III] λ1664 strength, the absence of the (normally much stronger) C IV λ1550 and C III] λ1909 lines argues for a depleted abundance of carbon relative to oxygen. This is at least qualitatively in agreement with the 25 $M_{\odot}$ model discussed earlier.

TABLE 1
NGC 4449 SNR Models

Model Parameter	ISM-Dominated Reverse Shock (Model A)	Ejecta-Dominated Reverse Shock (Model B)	Blast Wave
T_x (Assumed)	6×10^6 K	6×10^6 K	$\gtrsim 10^8$ K
L_x(0.2-4 keV)	0.8×10^{39} erg s^{-1}	0.8×10^{39} erg s^{-1}	1.7×10^{39} erg s^{-1}
Radius	1.2 pc	0.4 pc	14 pc
X-ray Emitting Mass	36 $M_\odot$	2 $M_\odot$	3000 $M_\odot$
Swept-up Mass	30 $M_\odot$	0.2 $M_\odot$	3000 $M_\odot$
Ambient ISM Density	150 cm^{-3}	25 cm^{-3}	11 cm^{-3}
Age	140 yr	120 yr	1600 yr

The X-ray data consist of a 32,000 sec HRI exposure that encompasses all of NGC 4449. Although low level emission from the galaxy is apparent in this image, three point sources are clearly visible, one of which corresponds precisely with the radio and optical positions of the SNR. Since no spectral information is available from the HRI detector, the interpretation of the X-ray data rest on the choice of a model for the X-ray emission.

There are two types of shocks which are likely to produce X-rays in young SNRs: a blast wave propagating outward through the ISM, or a reverse shock (cf. Gull 1975). Both phenomena may be present in the NGC 4449 SNR, but it is likely that the reverse shock emission is the dominant source of X-rays in the 0.2-4 keV HRI band, as is also the case in Cas A (Fabian et al. 1980). With this assumption, we estimate a temperature in the X-ray gas of $T_x = 6 \times 10^6$ K and derive L_x (0.2-4 keV) = 8×10^{38} ergs s^{-1}.

If the emission is dominated by a reverse shock, we can investigate two models which should bracket the real situation. In model A, we assume the material heated by the reverse shock is swept-up ISM material with cosmic abundances and in model B we assume a plasma made of undiluted ejecta from the supernova (for which we have assumed the abundances from the 25 $M_\odot$ model of Weaver and Woosley 1980). The emissivity is much higher ($\sim$ 20 x) in the ejecta-dominated model B, so much less material is needed to create the X-ray emission.

Table 1 summarizes the results from these two models as well as showing the predictions of the blast wave model mentioned earlier. We have assumed a simplified geometry whereby the X-rays occur in a uniform density plasma in a thin spherical shell of radius R and thickness R/12 (filling factor f = 0.25). The X-ray luminosity can then be expressed,

$$L_x = 4/3\ \pi R^3 f n_x^2 P'(\Delta E,T) \qquad (1)$$

where n_x is the electron density in the X-ray emitting gas and $P'(\Delta E,T)$ is the emission function, which depends on the electron temperature and plasma composition. The electron density n_x is obtained by assuming pressure equilibrium between the X-ray and optically emitting gas, i.e. $n_x T_x \approx n_o T_o$. From the optical data, $n_o T_o \approx 4.5 \times 10^9$, so using T_x from above, $n_x \approx 700$ cm^{-3}.

Equation (1) can be solved for the radius, R, with the results shown in Table 1. Both reverse shock models lead to predicted radii below the upper limit given by the VLA observations, but the radius from the blast wave model is too large. These predicted radii allow estimates of the mass of X-ray emitting gas, the swept-up mass (both $\propto R^3$) and the age of the remnant ($\propto R$) all shown in Table 1.

All things considered, something close to model B appears to be most plausible, as summarized below. The Hβ flux from the H II region implies that many massive stars must be present in the H II region to keep it photoionized. About 100-150 years ago, one of these stars exploded sending forth 10-30 $M_\odot$ of ejecta enriched by a factor of 5-50 in heavy elements. The surrounding H II region is dense enough that a reverse shock has now developed in the fast moving ejecta. Rapid cooling occurs behind this shock and knots condense to become optical filaments. The cooling time,

$$t_c = \frac{n_e k T_e}{n_e^2 P'(\Delta E,T)} \qquad (2)$$

is only about 60 years for model B, so substantial changes may be evident over a period of a few years.

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