OPTICAL OBSERVATIONS OF FOUR BALMER-DOMINATED SUPERNOVA REMNANTS IN THE LARGE MAGELLANIC CLOUD

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We report the optical identification of four Balmer-dominated supernova remnants (SNRs) in the Large Magellanic Cloud. Both the Balmer-dominated spectra and the presence of a broad Hα component in one remnant can be understood in terms of a very high velocity non-radiative shock encountering gas which is partially neutral, as proposed originally by Chevalier and Raymond to account for the similar spectra of the galactic remnants, Tycho and SN1006. From a consideration of the optical and X-ray luminosities of the SNR with broad Hα emission, we infer that the fraction of neutral gas in the medium is $\lesssim$ 30%. Radio observations of the LMC remnants show that their surface brightnesses are anomalously low; this could be intrinsic to the supernova themselves, or a result of their environment. Finally, we argue that the four SNRs all resulted from Type I supernovae, in which case they are the first such remnants to be identified outside the Galaxy.

1. INTRODUCTION

A recent X-ray survey of the Large Magellanic Cloud (LMC) by Long, Helfand and Grabelsky (1981) has resulted in the detection of ∿10 new X-ray emitting supernova remnants (SNRs). As part of a program to identify the optical counterparts of these new SNRs (Mathewson et al. 1982,1983), we have isolated a group of four remnants which have optical spectra that are completely dominated by the Balmer lines of hydrogen. The four SNRs are thus very similar to the two galactic remnants, Tycho and SN1006, which have been detected only in the Balmer lines and which are believed to have resulted from Type I supernovae. In this paper we discuss the optical, X-ray and radio properties of the new LMC remnants. A more detailed account of this work can be found in Tuohy et al. (1982).

2. OPTICAL OBSERVATIONS

2.1 Results

The optical identifications were made using the Anglo-Australian

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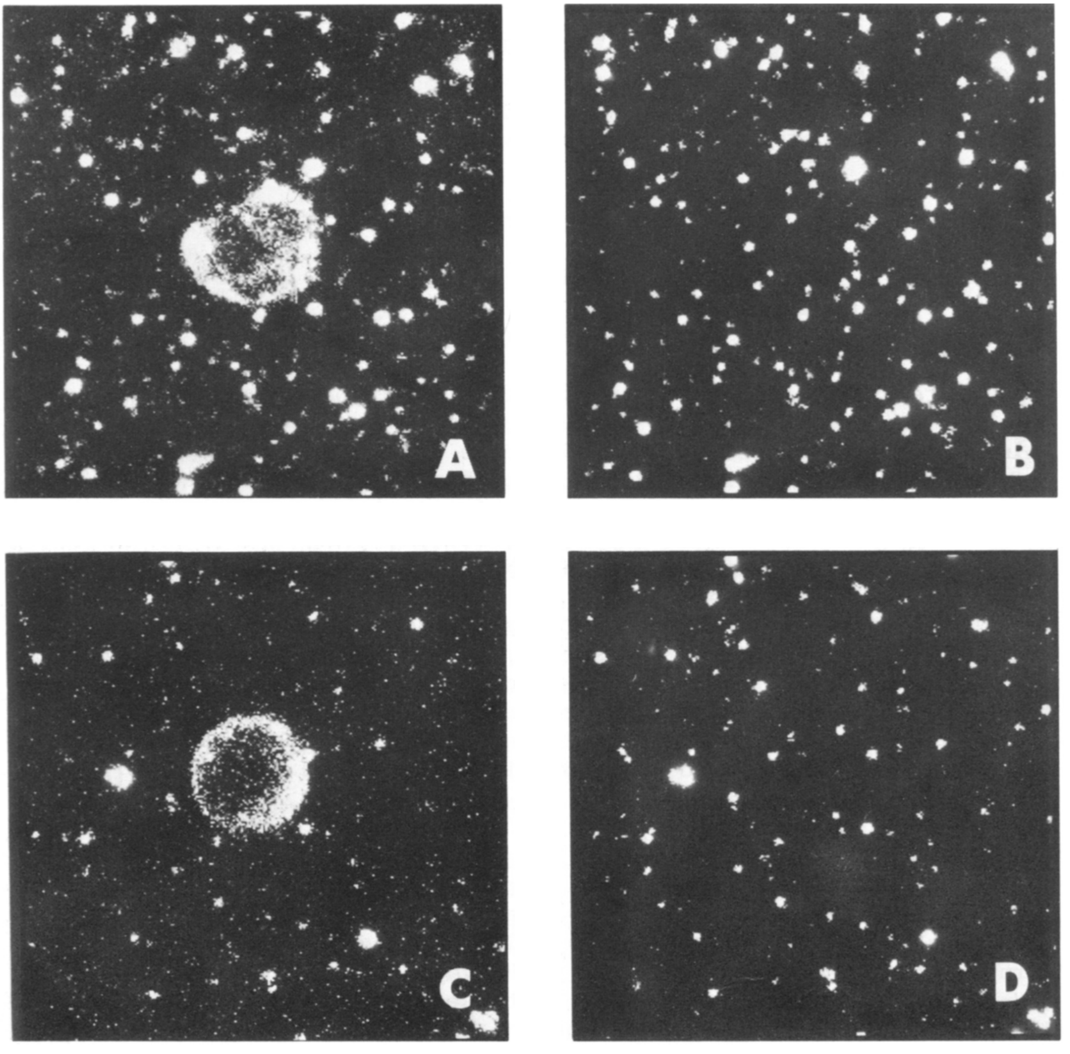

Fig. 1 Hα and [OIII] images of source 26 (A,B) and source 14 (C,D). The scale of each image is 2.1x2.1 arcminutes. North is at the top and East to the left.

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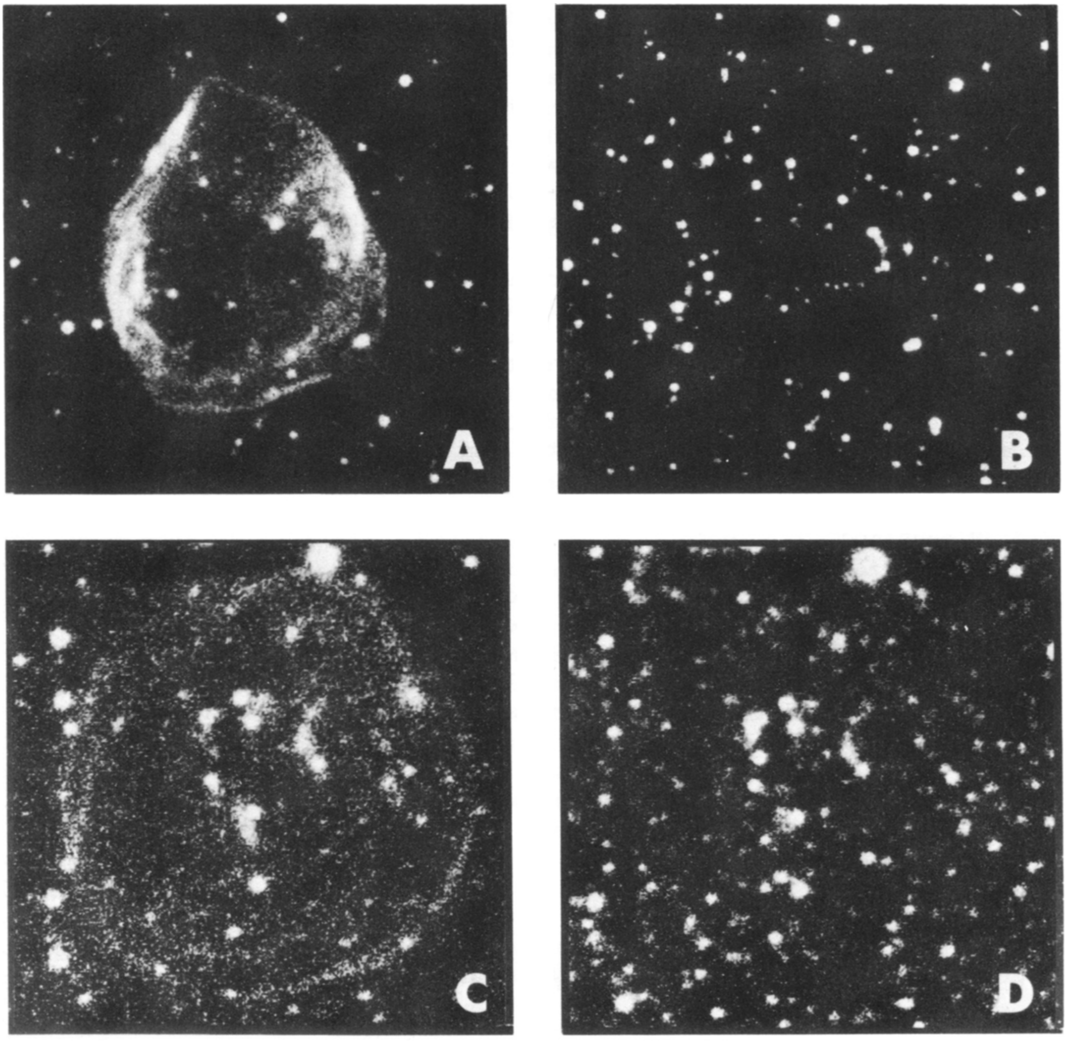

Fig. 2 Hα and [OIII] images of source 10 (A,B) and source 89 (C,D). The scale and orientation are the same as in Fig. 1.

Telescope (AAT) with the Image Photon Counting System (IPCS). Figures 1 and 2 show Hα and [OIII] λ5007 images of the four SNRs, namely 0505-67.9, 0509-67.5, 0519-69.0 and 0548-70.4. For convenience, we will refer to the objects as Sources 10, 14, 26 and 89, as in the X-ray catalog of Long, Helfand and Grabelsky. Sources 14 and 26 are only visible at Hα, and have similar angular sizes (25 and 28 arcsecs). Sources 10 and 89 are considerably larger (83 x 67 arcsec and 103 arcsec diameter), and although predominantly visible at Hα, they show faint wisps of [OIII] nebulosity in the inner NW and central regions respectively. The X-ray images of the SNRs show limb-brightened shells in each case, with diameters comparable to the optical dimensions (Mathewson et al. 1982).

Low resolution spectra of sources 14 and 26 have been obtained with the AAT, and are shown in Figure 3. The spectra are similar, except that a broad emission component is clearly visible beneath the Hα line in source 26. Comparison of the Hα profile with the spectrograph response to a night-sky line confirms that the broad component is intrinsic to the SNR. By fitting a double Gaussian to the Hα profile, we obtain a velocity width of 2800±300 km s^{-1}, and a ratio of the broad to narrow emission components in the range 0.4 to 0.8.

2.2 Discussion

The four LMC remnants are the clearest examples of Balmer-dominated SNRs yet identified, and the first of their class to be detected outside the Galaxy. The Balmer-dominated spectra can be understood in the context of the model developed by Chevalier and Raymond and Chevalier, Kirshner and Raymond (1980; hereafter CKR) to

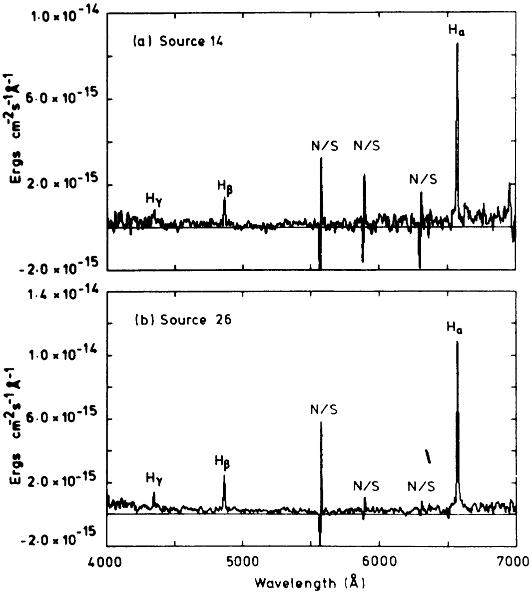

Fig. 3 Low resolution AAT spectra obtained for Source 14(a) and Source 26(b). Balmer lines and imperfectly subtracted night-sky features are indicated. The blue continua may represent 2-photon emission (in this case, the slight red excess above ∿6400 Å can be attributed to a grating leak.

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explain the spectra of Tycho and SN1006. The strong Balmer emission results from the interaction of a high velocity non-radiative shock with gas that is partially neutral; the neutral hydrogen atoms have a probability of being excited several times before being ionised, and owing to the high electron temperatures behind the shock, the usual forbidden line emission typical of most SNRs is suppressed. The CKR model also accounts for the broad Balmer component which has been observed previously in Tycho (CKR), and now in source 26; this component results from charge exchange between high velocity protons and neutral hydrogen atoms. A further interesting feature of the spectra of sources 14 and 26 is the possible presence of a faint blue continuum, which may be due to hydrogen 2-photon emission.

The ratio of the broad to narrow Hα components determined above is a function of the shock velocity (v_s) in the CKR model; for source 26, we find that a value of $v_s \sim 2900 \pm 400$ km s^{-1} is consistent with both our ratio determination and our velocity width measurement. This shock velocity leads to a Sedov age of ∿500 years.

An estimate of the density of the *neutral* component of the shocked gas can be made for source 26, based on our measured shock velocity and the Hα surface brightness. We obtain a value of $n_H \sim 0.06$ cm^{-3}. This density estimate is considerably lower than the *total* density of the gas, $n_X \sim 4.7$ cm^{-3}, calculated from the X-ray luminosity ($L_X = 1.1 \times 10^{37}$ erg s^{-1}) assuming ionisation equilibrium and cosmic abundances. If both density estimates are correct, the gas must be mostly ionised (> 95%). We note that even if the gas was fully ionised by a UV flash at the time of the explosion, there has been time for the gas to partially recombine within the ∿500 year lifetime of the remnant.

However, the calculation of the total density from the X-ray luminosity is subject to considerable uncertainties associated with the assumptions of ionisation equilibrium and normal abundances. In particular, allowance for enrichment of the gas by metal-rich ejecta (Long, Dopita and Tuohy 1982) reduces the total density estimate to $n_X \sim 0.3$ cm^{-3}. This value is an order of magnitude less than the above estimate, and results in a considerably lower ionised fraction (∿ 70%) for the medium.

The X-ray observations and the estimate of the current shock velocity allow constraints to be placed on the supernova precursor for source 26 (Tuohy et al. 1982). We can set the following limits on the energy of the explosion (E_O), the core mass of the star (M_C), the envelope mass (M_{en}), and the total mass of the star (M_*) : $1.8 \times 10^{51} \lesssim E_O \lesssim 2.2 \times 10^{51}$ ergs, $1.0 \lesssim M_C \lesssim 1.4\ M_\odot$, $0.0 \lesssim M_{en} \lesssim 3.0\ M_\odot$ and $1.2 \lesssim M_* \lesssim 4.0\ M_\odot$.

3. RADIO EMISSION

The 408 MHz fluxes of the four LMC remnants, kindly provided by

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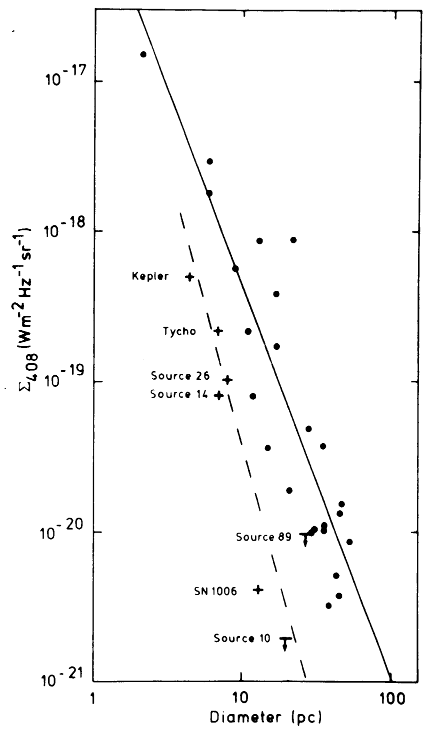

Fig. 4 The 408 MHz Σ - d distribution for SNRs in the LMC (solid dots) taken from Mathewson et al. (1982,1983). Data points for sources 10, 14, 26 and 89 (derived from Mills and Crawford 1981) and for the galactic SNRs Kepler, Tycho and SN1006 are superimposed.

Mills and Crawford (1981) from a more sensitive analysis of the Molonglo survey data (Clark, Little and Mills 1976), have been used in Figure 4 to plot the radio surface brightness versus mean optical diameters. The plot includes the 408 MHz surface brightnesses of the remaining SNRs in the LMC (Mathewson et al. 1982a,b), and also the corresponding points for the three galactic SNRs, SN1006, Tycho and Kepler, each believed to have resulted from a Type I explosion. The four LMC remnants lie systematically below the mean Σ-d line, with the difference for source 10 being more than a factor of 40. Interestingly, the three galactic SNRs also lie systematically below the line.

There are at least two possible interpretations of the anomalously weak radio emission from the Balmer-dominated SNRs. First, the low surface brightnesses may result from low interstellar densities in the environment of the SNRs (e.g., SN1006; Caswell and Lerche 1979). The second possibility is that the weak radio emission is intrinsic to the class of remnant; e.g., due to a reduced supply of relativistic particles, or inefficient magnetic field amplification.

4. THE EVIDENCE FOR TYPE I SUPERNOVAE

The similarity between the optical, X-ray and radio properties of the four LMC remnants and the galactic Type I remnants, argues that the

LMC SNRs were also produced by Type I supernovae. More quantitatively, the mass limits that we derive for source 26 (section II) rule out a Type II supernova for which substantially higher masses are expected. We conclude therefore that source 26, and by analogy, sources 10, 14 and 89 resulted from Type I explosions.

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DISCUSSION

MILLS: The results I have presented based on MOST observations show that the radio emission in two cases is normal. X89 is normal also if the identification is correct although there is some suggestion that the radio source may be extra-galactic. Only X10 is well below the normal. I also believe that the apparent differences in radio emission of galactic SNRs is a result of observational selection. All historical SNRs fall within the range of absolute luminosities we find for the Cloud SNRs, Type II as well as Type I.

TUOHY: The 408 MHz data supplied by you from the Molonglo Archival Data Bank shows that the two SNRs in question (sources 14 and 26) lie factors of 13 and 8 below the mean Σ-d line (note also that their diameters are accurately determined). We consider it significant that, without exception, the Balmer-dominated SNRs all have substantially lower surface brightnesses than the average.