Resolving SNR 0540−6944 from LMC X-1 with Chandra

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ABSTRACT

We examine the supernova remnant (SNR) 0540−697 in the Large Magellanic Cloud (LMC) using data from the *Chandra* ACIS. The X-ray emission from this SNR had previously been hidden in the bright emission of nearby X-ray binary LMC X-1; however, new observations with *Chandra* can finally reveal the SNR's structure and spectrum. We find the SNR to be a thick-shelled structure about 19 pc in diameter, with a brightened northeast region. Spectral results suggest a temperature of 0.31 keV and an X-ray luminosity (0.3-3.0 keV) of 8.4 $\times 10^{33}$ erg s^{-1}. We estimate an age of 12,000-20,000 yr for this SNR, but note that this estimate does not take into account the possibility of cavity expansion or other environmental effects.

Subject headings: galaxies: individual (LMC) – ISM: supernova remnants – X-rays: ISM

1. Introduction

Recent observations of the Large Magellanic Cloud (LMC) have opened up a new era in near-extragalactic studies of supernova remnants (SNRs). Thanks to advances in instrumentation over the last decade, we have been able to observe this large and varied sample of remnants without the difficulties in distance determination and obscuration for Galactic remnants, or those in resolution and sensitivity for ones in more distant galaxies. This has allowed us both to examine individual remnants in detail (e.g., Williams et al. 1997, 1999a; Chu et al. 1997, 2000) and as a group (e.g., Williams et al. 1999b; Williams 1999) to explore their interactions with the surrounding interstellar medium (ISM).

The completeness of the LMC sample, however, is a vexing question. Many SNRs lack one or more of the traditional SNR signatures (high [S II]/Hα ratios, nonthermal radio emission, and X-ray emission) and must be identified through other means (e.g., Chu 1997). New LMC SNRs continue to be found (e.g., Smith et al. 1994; Chu et al. 1993, 1995, 1999). Each discovery not only adds to the list of known SNRs, but provides additional insight into how to detect other such SNRs. This has profound implications for both the completeness of the LMC sample and the assemblage of samples from other galaxies, and thus for our understanding of the contribution from SNRs to the energetics and dynamics of the ISM.

One of these discoveries, SNR 0540−6944, may prove particularly informative in this regard. The SNR, discovered by Chu et al. (1997), is difficult to observe in optical and radio due to emission from the surrounding H II region N159; the X-ray emission was similarly obscured by that from the nearby X-ray binary LMC X-1. The SNR's expansion was serendipitously uncovered in optical echelle observations, and its SNR nature confirmed by using soft-band (0.1-1.0 keV) *ROSAT* PSPC images to separate the SNR's thermal emission from the much harder emission of LMC X-1. However, the SNR remained spatially and spectrally confused with LMC X-1 at the resolution of the *ROSAT* observations.

The unprecedented combination of spatial and spectral resolution and sensitivity from the Chandra (formerly AXAF) X-ray Observatory and its instruments allows us, for the first time, to get a picture of SNR 0540−6944 distinct from that of LMC X-1. Using these data, we are able to present images and spectra from the object itself. The results confirm the SNR identification of Chu et al. 1997; provide spatial and spectral data on the SNR itself; and illustrate the information that may be gleaned by separating objects whose close proximity confuses their emission. It provides a striking demonstration of the many new areas of investigation made possible by *Chandra* 's power, even in a brief observation.

2. Observations

LMC X-1 was observed as a calibration source by *Chandra* in late 1999 and early 2000. For our spectral and soft-band imaging studies, we used the Advanced CCD Imaging Spectrometer (ACIS) on-axis observation (sequence number 490002, 6.5 ksec) to avoid additional problems with off-axis distortions. Additionally, the target was focused on chip S3, a back-illuminated chip, which allowed for slightly greater spectral sensitivity, while avoiding the problems with radiation damage to which the front-illuminated chips were subject (Orbital Calibration reports, ASC, 1999). Only about 3 ksec of data are available for analysis; other datasets available for this object were off-axis, contained processing errors, or both. The ACIS (using a back-illuminated chip) has an angular resolution of $1''$, an energy resolution of 100 eV at 1.0 keV ($E/\Delta E = 9$), an energy range of 0.2-10 keV, and an effective area of 600 cm^{-2} at 1.0 keV (*Chandra* Observatory Guide, ASC, 1997). Data reduction and analysis were performed using the CIAO (Chandra X-ray Center software) and FTOOLS, XSPEC, and XIMAGE data-processing routines (Arnaud 1996).

3. Analysis

While SNR 0540−6944 can be spatially separated from LMC X-1 using the ACIS-S, the flux from the SNR is very low, and close to the background level. As a result, both spatial and spectral analysis are difficult. In addition, due to frame transfer effects, a "spike" of emission from LMC X-1 intersects the circle of emission from the SNR. These factors complicate attempts to isolate the the SNR itself from its much brighter neighbor.

3.1. Morphological Analysis

A first look at the image of this region on the *Chandra* ACIS-S is disappointing. Even using the S3 back-illuminated chip, more sensitive to low-energy emission, the SNR's presence is barely detectable next to that of LMC X-1. However, the emission from SNR 0540−6944 is likely to fall largely in the energy band between 0.1 and 3 keV, as is expected for a thermal plasma. We therefore make exposure-corrected images in the soft (0.3-3.0 keV) and hard (3.0-9.0 keV) bands and compare them. (Fig. 1a-b; note that we have used a low-energy cutoff of 0.3 keV to reduce contributions from the soft X-ray background. No counts are expected from the LMC below this cutoff due to the intervening column density.) We do indeed see emission at the position of SNR 0540−6944 in the soft image; but it is still overwhelmed by that from LMC X-1.

In order to eliminate some of the contamination by LMC X-1, we subtract the hard map from the soft map, thus removing emission from areas where hard X-rays dominate. In order to bring up the contrast in the resulting map, we divide by a total map. What remains is a "softness ratio" map in the form (soft - hard) / (soft + hard). This can be used to discern the structure of the soft emission, presumably that from the SNR (Fig. 1c-d). What is thus revealed is a roughly circular structure centered at J2000.0 coordinates $05^h40^m05^s$, -69°44′07″. The circle has a rough diameter of ∼1′.25, or 19 pc at the distance to the LMC (50 kpc). The emission is distributed over the remnant, suggesting a thick-shelled structure. The remnant is considerably brighter in a small (∼9″ radius) region to the northeast.

For the purpose of optical comparison we obtained archival *Hubble Space Telescope* images in the Hα and [O III] emission lines (Fig. 1e-f; PEP ID 6535; Hα: four 300 sec exposures; [O III]: four 230 sec exposures). These images show a roughly circular, highly filamentary structure amidst the emission from the rest of the N159 region. This structure corresponds very well to the position and extent of X-ray emission revealed by the ACIS ratio image, suggesting that the optical emission comes from the cooling shell of the SNR.

3.2. Spectral Analysis

In order to separate the SNR emission from that of LMC X-1, it becomes useful to consider the emission of the X-ray binary itself. In this we are aided by the availability of data from the *ASCA* SIS (ad43004000, 12.5 ksec). *ASCA* is insensitive at energies below 0.7 keV, so the contribution from the SNR to the data is expected to be minimal. We can, therefore, take the *ASCA* data as representative of LMC X-1 alone.

We therefore approached the problem using four separate spectra. Two were from *ASCA* observations using the SIS0 and SIS1 instruments; the region covered includes both LMC X-1 and SNR 0540−6944. A third spectrum was extracted from *Chandra* ACIS-S data, similarly covering a region including both LMC X-1 and SNR 0540−6944. A fourth spectrum, also extracted from *Chandra* ACIS-S data, covered SNR 0540−6944 only.

From previous studies of LMC X-1 (e.g., Schlegel et al. 1994) we know that the spectrum of this X-ray binary is well represented by the combination of disk-blackbody and power-law models. Previous studies (e.g., Schmidtke, Ponder, & Cowley 1999) suggest that there are no significant long-term variations in the spectrum of LMC X-1, allowing us to meaningfully compare datasets taken at different times. We expect the SNR contribution to be reasonably well modeled by a thermal plasma model (Raymond & Smith 1977). Our combined model for the region, then, has four components: one for photoelectric absorption (based on Morrision & McCammon 1983), applied to a combined Raymond-Smith, disk-blackbody and power-law model. Abundances for the Raymond-Smith model were set to 0.3 solar, as appropriate to the ISM of the LMC (Russel & Dopita 1992).

This model was simultaneously fit to our four spectra. The model parameters were linked, with the exceptions of the normalizations, which were allowed to fit independently to the four spectra. For the *ASCA* spectra, the Raymond-Smith normalizations were set to zero, as little thermal contribution was expected. Likewise, the normalizations for the disk-blackbody and power-law components were set to zero for the *Chandra* spectrum of 0540−6944 alone, as the contributions from LMC X-1 were expected to be minimal.

The best-fit parameters are given below, with the 90% confidence ranges given in parentheses. The best fit for the X-ray absorption of the region, $N_H = 7.2(6.9 - 7.5) \times 10^{21}$ cm^{-2}, is similar to that found by Schlegel et al. (1994) and Schmidtke et al. (1999) for LMC X-1; it is also somewhat atypically high for the LMC. The best-fit parameters for LMC X-1 are a blackbody temperature of kT$_{bb}$ =0.82 (0.81-0.83) and a power-law index of Γ=2.3 (2.2-2.4), again consistent with the results from Schlegel et al. (1994) and Schmidtke et al. (1999). The thermal plasma component yields a best-fit temperature of kT$_{rs}$=0.31 (0.18-0.43), reasonable for an older SNR (Fig. 2). Based on these spectral results, we computed a flux from the SNR in the 0.3-3 keV range of 2.8 $\times 10^{-14}$ erg cm^{-2} s^{-1}, and a luminosity in the same range of 8.4 $\times 10^{33}$ erg s^{-1}. When we look at the data for SNR 0540−6944 and LMC X-1 combined, we find a flux in the 0.3-3 keV range of 1.9 $\times 10^{-12}$ erg cm^{-2} s^{-1} and a luminosity of 5.7 $\times 10^{35}$ erg s^{-1}. Thus, within the energy range specified, the SNR contributes about 1.5% of the X-ray flux from this region.

4. Discussion

Morphologically, the SNR is without a sharply defined shell in X-rays. The large and distributed X-ray structure, interior to much of the optical emission, implies an older, Sedov-stage SNR. This picture is strengthened by the relatively low temperature and low luminosity of the X-ray emission. The velocity of $\sim$180 km s^{-1} found by Chu et al. (1997) indicates a slow expansion consistent with this picture. If this velocity is representative of the actual expansion velocity of the remnant, and the SNR is undergoing Sedov-like expansion, we would expect the shock velocity to be $v_{shock} = 4/3 v_{exp} = 240$ km s^{-1}.

This shock velocity, in turn, would imply a temperature of $kT = 3/16 \mu v_{shock}^2$, where μ is the mean molecular weight (assumed $1.1 m_H$). For the shock velocity given above, this gives approximately 0.12 keV. The temperature derived from X-ray spectral fits is somewhat higher; the X-ray temperature would imply $v_{exp} = 280$ (220-340) km s^{-1}. Similar discrepancies have been noted for other LMC remnants (Williams 1999). One possible explanation for this discrepancy is that the highest-velocity material may be too faint to show up clearly in the echelle spectrum. Another possibility is that the expansion velocity is indeed accurately reflected by the echelle spectroscopy and that this slow shock speed is insufficient to produce X-ray emission at the shock front. In this latter case, the remnant may have entered the shell-forming phase, as evidenced by the pronounced Hα shell. The observed X-rays in such a case are likely to be "fossil" radiation produced by the cooling of gas shocked to high temperatures earlier in the remnant's expansion.

Using the Sedov equation and the velocity from Chu et al. (1997), and assuming constant external density, we find an age of ∼20,000 yr for this SNR. The velocity derived from the X-ray temperature would give an age of ∼12,000 yr. These must be regarded as only approximate figures. For instance, if the SNR is expanding in the wind-blown bubble formed by its progenitor - a quite plausible scenario, as the remnant is within an H II region - it may very well be considerably younger than these estimates. Given this estimate of age, we do not expect a causal connection between SNR 0540−6944 and LMC X-1. The projected distance between the center of the SNR and LMC X-1 is about $1\overset{\prime}{.}75$, or a minimum of 26 pc separation. To reach this distance within the estimated age of the SNR, the compact object would have had to travel at a constant speed of over 1200 km s^{-1}.

Our fits to the X-ray spectrum use a normalization constant directly related to the emissivity, $K = 10^{-14} \int n_e n_H dV/(4\pi D^2)$. Here D is the distance to the remnant, n_e and n_H the electron and particle densities (we assume $n_e = 1.1 n_H$), and V the remnant volume. This allows us to make estimates of the density, energy and pressure within the X-ray emitting gas of this remnant. Using the fitted value of $K = 5.66 \times 10^{-4}$ and assuming a volume filling factor for the gas of 10% (corresponding to a shell thickness of about 0.33 pc, 3% of the radius, a reasonable value for a middle-aged remnant), we calculated the gas density at about n=1.2 cm^{-3}. Using the formula $E_{th} = (3/2)NkT$, where N is the total particle number in the hot cavity, we find a thermal energy of about 10^{49} erg, suitable for a remnant in which much of the remaining energy is tied up in the kinetic energy of expansion. The thermal pressure of the hot gas, according to $P = nkT$, is about 6 $\times 10^{-10}$ dyne cm^{-2}. These figures should, of course, only be regarded as rough estimates, as there is perhaps an order of magnitude uncertainty in the actual volume occupied by the hot gas, as well as additional uncertainties in the fitted temperature and emissivity.

The reason for the brightening of X-rays in the northeast section of the remnant is unclear. A search for timed emission revealed no significant peaks in the power spectrum; however, given the short exposure and high background for this observation, further investigation is indicated. The X-ray brightening occurs near an optical "knot" of bright emission, and may indicate a region where the SNR shock is encountering denser material.

In summary, we find that Chandra data are sufficient to distinguish SNR 0540−6944 from the emission of the nearby X-ray binary LMC X-1. While these findings are preliminary, as there remain uncertainties in the spatial and spectral responses, they are still informative. Given that this SNR has a lower luminosity than most LMC SNRs (eg Williams 1999), the results point out the capacity of Chandra to distinguish faint objects in confused regions. As observations continue, we may uncover an entire population of low-luminosity, older SNRs, in the LMC and even in more distant galaxies. This has the potential to substantially increase our estimates of SNR rates, which to date have been largely based on the fraction of SNRs that are more readily detected. SNR 0540−6944 also suggests the possibility of finding previously undetected SNRs within the crowded environs of H II regions, where we would indeed expect a high population of Type II SNRs.

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Fig. 1.— Image of SNR in (a) ACIS soft map; (b) ACIS hard map; (c) ACIS ratio map; (d) ACIS ratio map scaled to HST field, with contours at 2, 4, 6, 8, 10, 12σ over background; (e) HST Hα with ACIS 2, 6, 10σ contours; and (f) HST [O III] with ACIS 2, 6, 10σ contours

Fig. 2.— Spectral fits to X-ray data from (top two) *ASCA* SIS for LMC X-1; (middle) *Chandra* ACIS for LMC X-1 and SNR; (bottom) *Chandra* ACIS for SNR