SUPERNOVA REMNANTS IN THE MAGELLANIC CLOUDS. IX. MULTIWAVELENGTH ANALYSIS OF THE PHYSICAL STRUCTURE OF N49

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ABSTRACT

We present a multiwavelength analysis of the supernova remnant N49 in the Large Magellanic Cloud. Using high-resolution Hubble Space Telescope WFPC2 images of Hα, [S ii], and [O iii] emission, we study the morphology of the remnant and calculate the rms electron densities in different regions. We detect an offset of [O iii] and Hα emission peaks of about 0.5″ and discuss possible scenarios that could give rise to such high values. The kinematics of the remnant is analyzed by matching individual kinematic features in the echelle spectra obtained at the Cerro Tololo Inter-American Observatory with the morphological features revealed in the WFPC2 images. We detect a narrow Hα emission component and identify it as diffuse preshock recombination radiation, and discrete broad emission features that correspond to the shocked gas in filaments. The overall expansion of the remnant is about 250 km s⁻¹. The dense clouds are shocked up to line-of-sight velocities of 250 km s⁻¹, and the less dense gas up to 300 km s⁻¹. A few cloudlets have even higher radial velocities, reaching up to 350 km s⁻¹. We confirm the presence of the cavity in the remnant and identify the center of explosion. Using archival Chandra and XMM-Newton data, we observe the same trends in surface brightness distribution for the optical and X-ray images. We carry out a spectral analysis of three regions that represent the most significant optical features.

Key words: ISM: individual (N49) — Magellanic Clouds — supernova remnants — X-rays: individual (SGR 0526-66)

Online material: color figures

1. INTRODUCTION

N49 is the most optically bright supernova remnant (SNR) in the Large Magellanic Cloud (LMC). In contrast to a classic shell-type SNR, N49 exhibits largely asymmetric morphology at optical wavelengths. The increased brightness of this SNR in the southeast and its unique filamentary structure at optical wavelengths has long set N49 apart from other well-understood SNRs. Inhomogeneities in the optical morphology and kinematics of N49 have been observed in the past (Shull 1983; Chu & Kennicutt 1988; Vancura et al. 1992b). However, the fine structure resolved from these kinematic observations was difficult to reconcile with the optical images taken from the ground. Recent mapping of molecular clouds in the region suggests that this SNR is expanding into a denser region toward the southeast, which has caused the asymmetric brightness enhancements in the shell (Banas et al. 1997).

The presence of such a filamentary structure suggests that dense material surrounded the progenitor star at the time of its supernova. In the case of a massive progenitor star, its strong stellar wind would have cleared most material from the environment during its lifetime. Considering the evidence for a relatively dense environment surrounding N49, a B-type star, which would lack a strong stellar wind, is the most likely candidate for the N49 progenitor (Shull 1983).

This SNR also appears notably bright at the X-ray (Williams et al. 1999; Park et al. 2003) and radio (Dickel et al. 1995) wavelengths, in which the complete spherical shell of the remnant is clearly visible. While the overall structure appears symmetric at X-ray wavelengths, the brightness peaks in the southeastern region as in the optical. In the Chandra observations, most of the optically bright filamentary structures have only diffuse X-ray counterparts. These observations also revealed a hard X-ray knot extending beyond the main shell in the southwest of N49, which has been suggested to be a fragment of the explosion accelerated beyond the shock boundary.

An additional point of interest is the existence of a known soft gamma-ray repeater, SGR 0526-66, within the boundary of N49. Recent Chandra images have resolved a point source, suggested to be the X-ray counterpart to this SGR (Kulkarni et al. 2003). No optical or radio counterparts of this SGR have been detected (Dickel et al. 1995; Smith et al. 1998; Fender et al. 1998), and the SGR does not seem to have a strong influence on the overall optical morphology of the remnant.

In order to understand the kinematics of the remnant and the distribution of X-ray emission in terms of the detailed physical structure of the N49 SNR, we have obtained high-resolution Hubble Space Telescope (HST) images in the Hα, [O iii], and [S ii] emission lines, which reveal N49’s bright filamentary structures with high precision. We have supplemented existing high-dispersion spectroscopy (Chu & Kennicutt 1988) with additional deep spectra for N49 to investigate the full extent of the velocity distribution. In this paper we analyze the above observations in conjunction with archival Chandra and XMM-Newton observations for a comprehensive multiwavelength study of the physical structure of N49. Section 2 describes the included observations, § 3 analyzes the HST emission-line images and the implications of the surface brightness and the line ratios, § 4 analyzes the nebular kinematics and correlates the kinematic and morphological features, § 5 compares the X-ray and optical morphologies and discusses the relative distribution of hot and cool gas, and a summary is given in § 6.

2. OBSERVATIONS

2.1. Optical Emission-Line Images

We imaged N49 using the HST Wide Field Planetary Camera 2 (WFPC2) with three filters: F656N (Hα), F673N ([S ii] λ6717,
TABLE 1

| Observation  | Date       | Line  | Filter | Exposure (s) |
|--------------|------------|-------|--------|--------------|
| 1            | 2000 Jul 13| H\(\alpha\) | F656N | 2 × 500      |
| 2            | 2000 Jul 14| [S II] \(\lambda 6716, 6731\) | F673N | 2 × 600      |
| 3            | 2000 Jul 14| [O III] \(\lambda 5007\) | F502N | 720 + 637 + 800 |

TABLE 2

| Observation  | Date       | Exposure (s) | Location | Position Angle (deg) |
|--------------|------------|--------------|----------|----------------------|
| E1986-1......| 1986 Nov 20| 300          | N49 pos. 1 | 90                   |
| E1986-2......| 1986 Nov 20| 300          | N49 pos. 2 | 90                   |
| E1986-3......| 1986 Nov 20| 300          | N49 pos. 3 | 90                   |
| E1986-4......| 1986 Nov 20| 300          | N49 pos. 4 | 90                   |
| E1986-5......| 1986 Nov 20| 300          | N49 pos. 5 | 90                   |
| E1995-1......| 1995 Jan 19| 2 × 600      | N49 IRS pos. | 42.5                  |
| E2000-1......| 2000 Dec 10| 600          | N49      | 90                   |
| E2000-2......| 2000 Dec 10| 300          | N49, 34° S of E2000-1 | 90 |
| E2000-3......| 2000 Dec 10| 300          | N49, 31° S of E2000-1 | 90 |

6731), and F502N ([O III] \(\lambda 5007\)). The dates and exposure times of these observations are presented in Table 1. The data were reduced using the STSDAS package within IRAF. The continuum was not subtracted, as the line emission was so dominant that the presence of continuum would not affect our conclusions. Cosmic-ray events were removed by combining multiple exposures, and the resulting files were bias-subtracted. Each image was divided by its exposure time to produce a count-rate map. These maps in turn were multiplied by a conversion factor, given by the \(\text{photflam}\) parameter in the image header, to produce flux-density maps. We used the \text{synphot} task to determine widths for each filter, and multiplied the flux-density maps by the corresponding filter widths to produce flux maps. The resulting files were then mosaicked together for the final images.

2.2. Optical Spectroscopy

We obtained high-dispersion spectra of N49 with the echelle spectrograph on the Blanco 4 m telescope at Cerro Tololo Inter-American Observatory (CTIO) in three observing runs. A journal of our observations is given in Table 2. We used the 79 line mm\(^{-1}\) echelle grating in the single-order, long-slit observing configuration, with a flat mirror replacing the cross disperser and a postslit echelle grating in the single-order, long-slit observing configuration, of our observations is given in Table 2. We used the 79 line mm\(^{-1}\) echelle grating in the single-order, long-slit observing configuration, with a flat mirror replacing the cross disperser and a postslit H\(\alpha\) filter (\(\lambda_c = 6563\) Å, \(\Delta \lambda = 75\) Å) inserted to isolate a single order.

Due to the vignetting limitations imposed by the optics, the useful spatial coverage is \(\sim 3^\prime\). The spectral coverage includes both the H\(\alpha\) line and the neighboring [N II] \(\lambda 6548, 6583\) lines. We used a slit width of 250 \(\mu\)m (1.64") for all observations. The spectral dispersion and wavelength were calibrated by a Th-Ar lamp exposure taken in the beginning of each night, and fine-tuned using the geocoronal H\(\alpha\) and telluric OH lines present in the echellegrams. The 1986 observing run used the Air Schmidt camera and a GEC 385 \(\times\) 586 CCD. The 22 \(\mu\)m pixel size corresponds to about 0.21 Å and 0.63" along the dispersion and spatial axes, respectively. The instrumental profile had a FWHM of 21 \(\pm\) 0.5 km s\(^{-1}\), as measured from the Th-Ar calibration and sky lines. The echelle spectra obtained in this observing run have been reported by Chu & Kennicutt (1988). The 1995 observing run used the red long-focus camera and a Tek 2048 \(\times\) 2048 CCD. The 24 \(\mu\)m pixel size corresponds to roughly 0.082 Å and 0.26" along the dispersion and spatial axes, respectively. The instrumental profile had a FWHM of 16.1 \(\pm\) 0.8 km s\(^{-1}\).

The observations made in 2000 were recorded using the red long-focus camera and the SIte 2K #6 2048 \(\times\) 2048 CCD. The 24 \(\mu\)m pixel size corresponds to roughly 0.082 Å and 0.26" along the dispersion and spatial axes, respectively. The instrumental profile had a FWHM of 13.5 \(\pm\) 0.5 km s\(^{-1}\).

2.3. X-Ray Images and Spectroscopy

X-ray observations of N49 were made with both the XMM-Newton and Chandra observatories. We retrieved the pipeline-processed XMM-Newton data from the Science Operations Centre (SOC). Observations were made simultaneously with multiple XMM-Newton instruments; in this paper we concentrate on the European Photon Imaging Camera (EPIC) MOS and pn detectors. The data were taken in 2001 April (observation ID 0113000201; 26.9 ks; PI: J. S. Kaastra) over multiple time intervals, using the thick filter for two EPIC MOS1 exposures and the medium filter for the remaining EPIC MOS and EPIC pn exposures. The initial reduction and analysis were carried out using the Science Analysis Software package provided by the SOC, with subsequent spectral analysis in XSPEC.

The data were filtered to remove high-background times or poor event grades and merged to produce a single data set for each instrument with effective exposure times of 14.3 ks for EPIC MOS1, 19.5 ks for EPIC MOS2, and 0.8 ks for EPIC pn. Images were then extracted from the filtered merged event files. Spectra were extracted separately from each exposure, to avoid introducing distortions due to the different filters used. Background regions immediately surrounding the SNR but free of point sources were used to produce background spectra, which were then scaled and subtracted from the source spectra. Spectra from different exposures were jointly fitted.

Chandra observations used the Advanced CCD Imaging Spectrometer (ACIS), primarily the S3 back-illuminated chip. Data sets were sequence 500107, observation 1041 (34.3 ks; PI: G. P. Garnire) and sequence 500134, observation 2515 (7.0 ks; PI: S. R. Kulkarni). Data were reprocessed following procedures recommended by the Chandra X-Ray Center: we removed afterglow corrections, generated new bad pixel files, and applied corrections for charge-transfer inefficiency and time-dependent gain for an instrument temperature of 120 K. The two data sets were filtered for high-background times and poor event grades, resulting in total “good time” intervals of 33.9 and 6.9 ks.

Spectral results were extracted from the new event files. Background regions were taken from source-free areas surrounding the SNR, and the spectra of these background regions were scaled and subtracted from the source spectra. Individual spectra for regions of interest, selected by comparison of optical and X-ray images, and the corresponding primary and auxiliary response files were extracted with the CIAO \text{acispspec} script and analyzed in XSPEC. Spectra were rebinned by spectral energy to achieve a signal-to-noise ratio of 4 in each bin.

3. ANALYSIS OF THE HST EMISSION-LINE IMAGES

3.1. H\(\alpha\) Surface Brightnesses and Electron Densities

The HST H\(\alpha\) image (Fig. 1a) displays a complex network of filaments, with the brightest emission located toward the southeast.
In Figure 1b we have marked the morphological features of the remnant, which will henceforward be referred to as features i–vi. The most prominent feature is the southeast ridge (feature i), a ridge of bright filaments in the southeast quadrant, tracing a line from east to south of the SNR. From the southeast ridge, straight bright filaments extend toward the northwest over lengths of 15″–30″ (feature ii). A network of bright filaments is present in the southwestern part of the remnant (feature iii), where the filaments are shorter than those in the southeast ridge. Beyond this network toward the outer edge of the remnant, there exist a number of fainter filaments (feature iv). Faint filaments are also seen in the northern and northeastern parts of the SNR (feature v). No bright filaments exist in the western part of the remnant.

The bright filaments are enveloped by a diffuse Hα emission component. This diffuse emission extends beyond the radio/X-ray (Williams et al. 1999; Park et al. 2003; Dickel et al. 1995) boundary along the circumference from the north through the east to the south. On the west side of the remnant, only faint patches of Hα emission exist (feature vi). While the outermost emission patches follow the X-ray/radio boundary, they do not appear to be embedded in a diffuse emission component, which is either absent or below the detection limit.
Due to its presence beyond the shock boundary, we identify the diffuse H\(\alpha\) emission as the recombination radiation of hydrogen ionized by the UV precursor in the preshock region. The H\(\alpha\) surface brightness (SB) of a 10\(^4\) K ionized gas can be expressed as

\[
SB = 1.9 \times 10^{-18} n_e^2 L_{pc} \text{ ergs s}^{-1} \text{ cm}^{-2} \text{ arcsec}^{-2},
\]

where \(n_e\) is the electron density in \(\text{cm}^{-3}\) and \(L_{pc}\) is the emitting path length in parsecs. Using the flux-calibrated \(HST\) H\(\alpha\) image\(^2\) and reasonable estimates of the emitting path lengths, we may determine the gas densities. For a filament, we adopt its length as an upper limit and its width as a lower limit for the emitting path length. For a diffuse emission region, we adopt its average diameter as the emitting path length.

In the brightest filaments, such as the southeast ridge, the long filaments extending to the northwest, and the bright short filaments in the southwest, SB is \(\sim (1 \pm 0.4) \times 10^{-13} \text{ ergs s}^{-1} \text{ cm}^{-2} \text{ arcsec}^{-2}\), with the peak emission reaching \(2 \times 10^{-13} \text{ ergs s}^{-1} \text{ cm}^{-2} \text{ arcsec}^{-2}\). The rms densities in these bright filaments are between 265 \(\pm 20\) and 515 \(\pm 20 \text{ cm}^{-3}\), adopting the length and width of the filaments as the emitting path lengths, respectively.

The filaments in the central and northeastern regions, as well as the brighter northern filaments, are slightly fainter than the southeast ridge, with an SB of \((3 \pm 1) \times 10^{-14} \text{ ergs s}^{-1} \text{ cm}^{-2} \text{ arcsec}^{-2}\). The rms electron densities in these filaments are between the limits of 115 \(\pm 20\) and 310 \(\pm 20 \text{ cm}^{-3}\). The SB of the fainter filaments in the remnant, such as the northernmost filaments, is \((0.9 \pm 2) \times 10^{-14} \text{ ergs s}^{-1} \text{ cm}^{-2} \text{ arcsec}^{-2}\). The rms densities here are between 70 \(\pm 20\) and 225 \(\pm 25 \text{ cm}^{-3}\).

The faint patches in the western quadrant have an SB of \((1 \pm 4) \times 10^{-15} \text{ ergs s}^{-1} \text{ cm}^{-2} \text{ arcsec}^{-2}\). Adopting their average diameters as the emitting path lengths, the rms densities in the patches are 90 \(\pm 10 \text{ cm}^{-3}\). The diffuse H\(\alpha\) emission that envelops the bright filaments has a similar SB but a larger emitting path length. Approximating the emitting path length by the radius of the remnant, we get rms densities of about 10 \(\pm 5 \text{ cm}^{-3}\).

Our derived rms densities are significantly lower than the densities of 1000–1800 \(\text{cm}^{-3}\) calculated using the \([\text{S}\ ii]\) doublet ratio reported by Vancura et al. (1992a). This difference can be explained by the different weightings placed on density by these two methods. The flux of an emission line is proportional to \(\int n_e^2 dl\); thus, an overdense region along a line of sight will dominate the emission and dictate the electron density determined from the \([\text{S}\ ii]\) doublet ratio. On the other hand, the rms density is derived from the emissivity averaged over the entire emitting path length, and therefore is always lower than the peak value determined from the \([\text{S}\ ii]\) doublet. In general, the density determined from the \([\text{S}\ ii]\) doublet is representative of the densest regions, while the rms density better represents the density over the entire emission path length. The rms densities are particularly useful for a region whose density is \(< 100 \text{ cm}^{-3}\), the low-density limit of the \([\text{S}\ ii]\) doublet, such as the faint emission regions.

### 3.2. \([\text{S}\ ii]\) Emission and \([\text{S}\ ii]/\text{H}\alpha\) Ratios

Overall, the morphology of N49 in the \([\text{S}\ ii]\) line (Fig. 1c) resembles that in the H\(\alpha\) line. For example, the bright southeast ridge, the straight bright filaments extending to the northwest, the fainter filaments in the north and west, and the faint emission patches in the west are all observed in the \([\text{S}\ ii]\) image. The most notable morphological difference between the \([\text{S}\ ii]\) and H\(\alpha\) images is the lack of a diffuse \([\text{S}\ ii]\) emission component enveloping the bright filaments.

As the morphologies of N49 in the H\(\alpha\) and \([\text{S}\ ii]\) lines are similar, the ratio map (Fig. 1d) is fairly uniform, with a mean value of 0.75 \(\pm 0.05\). However, there are variations in this ratio, giving an overall range of 0.4–1.4. These variations result from different shock conditions. The highest ratios are found in the bright filaments extending northward from the southeast ridge, where the ratios reach values of 1–1.4. The lowest ratios can be seen in the outermost limb of the remnant, where the ratios are below 0.4, which may be due to the lack of a diffuse \([\text{S}\ ii]\) component. In addition, we find low ratios in the southeast ridge, where the H\(\alpha\) filaments are the brightest.

### 3.3. \([\text{O}\ iii]\) Emission and \([\text{O}\ iii]/\text{H}\alpha\) Ratios

The \([\text{O}\ iii]\) emission (Fig. 1e) is filamentary and peaks in the southeast just like the H\(\alpha\) and \([\text{S}\ ii]\) lines, but the filamentary structures differ in details. The \([\text{O}\ iii]\) emission associated with bright H\(\alpha\) and \([\text{S}\ ii]\) filaments is usually concentrated in faint thin filaments and shows an offset toward the leading edge of the shock fronts. The most extreme difference is exhibited in the bright H\(\alpha\) filament extending from the northern tip of the southeast ridge toward the northwest, where the \([\text{O}\ iii]\) emission is absent.

These and other morphological differences are best demonstrated by the \([\text{O}\ iii]/\text{H}\alpha\) ratio map (Fig. 1f). The ratios generally increase from the inner to the outer part of the remnant, spanning a wide range from nearly 0 to about 2.5. The ratios in the inner portions of the remnant range from 0 to about 0.5, with a few regions reaching ratios of 0.7. The ratio map in the inner portions of the remnant shows a filamentary structure that is not as sharp as the direct images. The brighter and fainter “filaments” on the ratio map have values of 0.4–0.7 and 0.05–0.15, respectively. Generally, the filaments bright in H\(\alpha\) have very low \([\text{O}\ iii]/\text{H}\alpha\) ratios. This can be seen in the southeast ridge, where the brightest H\(\alpha\) filaments are faint on the ratio map. Ratios above 0.5 are found primarily in the outer portions of the remnant. The most prominent feature of the ratio map is the increase in the ratios toward the outermost edge of the remnant, where they reach values between 0.8 and 1.5. A few small patches in the north, northeast, and southwest reach values of up to 2.5 on their outer edge.

The enhanced \([\text{O}\ iii]/\text{H}\alpha\) ratios at the edges of the remnant are due to at least as much due to a diminishment in the H\(\alpha\) emission as to an increase in \([\text{O}\ iii]\) emission. This morphology demonstrates an offset of \([\text{O}\ iii]\) emission toward the outer edge of the remnant, seen also in the composite image of H\(\alpha\), \([\text{S}\ ii]\), and \([\text{O}\ iii]\) emission (Fig. 4, right). We evaluate the offset by comparing the peaks of the brightness profiles across the filaments in \([\text{O}\ iii]\) and H\(\alpha\). Sample SB profiles demonstrating this offset are shown in Figure 2. We find the offsets to range from 0 up to ~0.5", or 0.125 pc (for a distance of 50 kpc; Feast 1990).

On small scales we would expect an offset between the \([\text{O}\ iii]\) and H\(\alpha\) filaments because the emissivity and ionic concentration of a given line depend on the temperature and thus the distance from the shock front. In a plain, steady-shock model, the hydrogen recombination emission peaks roughly where the \([\text{O}\ iii]\) and \([\text{O}\ ii]\) emission diminishes and the \([\text{O}\ i]\) emission rises (Cox 1972). This timescale needed for a postshock region to evolve from \([\text{O}\ iii]/\text{bright}\) to \([\text{O}\ iii]/\text{faint}\) is ~2000 yr/h\(_0\), where h\(_0\) is the preshock density in units of H atoms \(\text{cm}^{-3}\) (Raymond et al. 1980). Therefore, we expect the postshock \([\text{O}\ iii]\) emission peak and the H\(\alpha\) emission peak to exhibit a displacement of \(v(2000 \text{ yr/h}_0)\), where \(v\) is the velocity of the postshock gas with respect to the shock front. In the case of an adiabatic (Sedov) shock, the postshock

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\(^2\) The WFPC2 H\(\alpha\) filter (F656N) also transmits the \([\text{N}\ ii]\) \(\lambda 6548\) line, which is \(\sim8\%\) as bright as the H\(\alpha\) line in N49 (Vancura et al. 1992a). This \([\text{N}\ ii]\) contamination has been corrected for.
gas expands downstream with one-fourth of the shock velocity; thus, the shocked gas in the clouds is observed to move with $v_s = (3/4)v_v$, where $v_v$ is the shock speed.

For a dense cloud with $n_0 = 1000$ cm$^{-3}$ (the lower limit for the filament density calculated by Vancura et al. [1992a]), with an observed expansion velocity $v_v = 250$ km s$^{-1}$, the displacement between [O\textsc{iii}] and H$\alpha$ will be $1.7 \times 10^{-4}$ pc, or 0.0007", which cannot be resolved by the HST. For a shock with the same velocity driven into the diffuse regions of N49, where the density $n_0$ is about 10 cm$^{-3}$, the offset between [O\textsc{iii}] and H$\alpha$ can be raised to 0.017 pc, or 0.07". This value still cannot be resolved by the HST.

There are several other scenarios that would produce an offset between the [O\textsc{iii}] and H$\alpha$ emission, each involving a departure from a steady-flow shock model. Using observations from the MagIC camera at the Clay Telescope, Rakowski et al. (2007) compared the locations of the [O\textsc{iii}] and H$\alpha$ peaks, finding separations of up to 0.62". Our HST observations, which do not suffer from seeing distortions, show peak separations of up to 0.5".

Rakowski et al. (2007) attributed these offsets to thermal instabilities dampened by a magnetic field, following the models of Innes (1992), who associates the offsets with the presence of secondary shocks. These models have predicted maximum offsets of $3 \times 10^{-7}$ cm, which for the distance of the LMC yields roughly 0.4" (Rakowski et al. 2007). However, the physical conditions for the models ($v_v = 175$ km s$^{-1}$, $n_0 = 1$ cm$^{-3}$, and $B_0 = 3 \mu$G) are different from the ones in the LMC. As Rakowski et al. (2007) point out, the abundances of the LMC will increase the cooling time by a factor of 3, which would tend to increase the offset by this factor. Our derived preshock density is 10 cm$^{-3}$, which is 10 times higher than the value used for the models, so the net result of these two effects is a decrease in the offset by a factor of 10/3, giving an offset of roughly 0.15". Rakowski et al. (2007) argued that the fast shocks seen in N49 made this the most probable scenario. However, without a substantial amount of magnetic support, the derived values are still smaller than the maximum observed offsets.

An alternate scenario was presented by Raymond et al. (1980, 1983) for such offsets in the Cygnus Loop. In this scenario, the offsets arise due to incomplete recombination zones behind a shock front driven into an inhomogeneous environment. For a SNR in a cloudy medium, the slow shocks driven into dense clouds produce the [O\textsc{iii}] and H$\alpha$ emission, while the fast shocks propagating into the less dense intercloud medium produce X-ray emission. The H$\alpha$ and [O\textsc{iii}] lines are both emitted from shocked dense clouds, but their "turn-on" times are different by ~2000 yr/n_0. As the fast shocks advance through the intercloud medium and encounter clouds, [O\textsc{iii}] emission is produced almost immediately in the freshly shocked clouds, and the H$\alpha$ emission is produced by clouds that were shocked ~2000 yr/n_0 earlier. The displacement between the [O\textsc{iii}] and H$\alpha$ peaks is thus $\sim(v_s - v_v)(2000$ yr)/$n_0$, where $v_s$ is the velocity of a fast shock through the intercloud medium and $v_v$ is the velocity of a slow shock through a dense cloud (Fesen et al. 1982).

The velocity of the fast shock in the intercloud medium can be estimated from the temperature of the postshock, X-ray-emitting gas, using

$$kT = \frac{3}{16} \mu m_H v_v^2,$$

where $m_H$ is the mass of the hydrogen atom and $\mu$ is the mean molecular weight. For a fully ionized gas with He : H = 1 : 10, $\mu$ is 0.6. Adopting the higher temperature component $kT = 1.0$ keV (Park et al. 2003), we get $v_s = 920$ km s$^{-1}$. The highest velocities seen in the dense shocked clouds, obtained from the echelle spectra (see § 4), are about 250 km s$^{-1}$. The postshock gas in the clouds was accelerated to 0.75$v_v$. The preshock density is 10 cm$^{-3}$. Therefore, the expected displacement between the [O\textsc{iii}] and H$\alpha$ peaks is 0.12 pc, or 0.5". This offset is in excellent agreement with the observation.

4. ANALYSIS OF FILAMENT VELOCITY STRUCTURE WITH ECHELLE SPECTRA

To determine the exact slit positions of the echelle observations, we match the SB profiles along the slit to those extracted from the HSTH$\alpha$ image. The high angular resolution of the HST images allows us for the first time to see one-to-one correspondence between the kinematical and morphological features of N49 (Fig. 3).

4.1. Discrete Features

The echellograms in Figure 3 show discrete broad emission features, as well as a narrow component extending continuously along the slit. The narrow component, detected by Chu & Kennicutt (1988) and Vancura et al. (1992a), shows SB enhancements within the boundary of the SNR, indicating physical association; we therefore adopt its heliocentric velocity ($v_{\text{hel}}$) of 315 km s$^{-1}$ as the SNR’s systemic velocity. Due to our extended slit coverage, we are able to pin down the location of this enhanced narrow component in the SNR. The SB variation of this narrow component is similar to that of the diffuse H$\alpha$ emission, brighter in the east and fainter in the west. We therefore associate this narrow component with the faint diffuse H$\alpha$ component identified morphologically in § 3.1. The narrow velocity width and the preshock location of this narrow component are consistent with its
origin as recombination radiation of hydrogen ionized by the UV precursor of the SNR shocks.

We also observe broad emission features which indicate a bulk expansion of about 250 km s\(^{-1}\). Some of the broad emission features have a “head-tail” structure; the bright emission at the head has a smaller radial velocity offset (\(\Delta r\)) from the systemic velocity, and the fainter emission in the tail stretches to larger \(\Delta r\). Among the discrete broad emission features, the brighter ones have smaller \(\Delta r\), ranging from 0 to 160 km s\(^{-1}\) at the “head” and up to about 250 km s\(^{-1}\) at the “tail.” They can be well matched to individual bright filaments.

The structure of these emission features can be explained by the interaction between the shock and the encountered dense gas. The shock gets dampened more by the dense gas in the filaments than in the lower density cloudlets. Therefore, the postshock gas in the inner part of the dense bright regions is propelled to velocities significantly lower than the original shock velocity, thus producing smaller velocity spreads. The presence of gas at systemic velocity suggests that the gas in these regions retarded the shock sufficiently to prevent its propagation throughout the whole filament, leaving the innermost gas unshocked. Because it emits H\(\alpha\) recombination radiation, it must have been ionized by the UV precursor. The fainter “tail” emission comes from the outer layers of these dense filaments, which encountered the undampened shock and have been accelerated to higher velocities.

The less dense gas, which can be identified on echelle spectra as a fainter emission component, can be accelerated by the shock to very high velocities. The lower density gas is unable to significantly slow down the shock, and the postshock gas is consequently accelerated to higher speeds. We observe velocity spreads of up to 300 km s\(^{-1}\), which is consistent with Sankrit et al. (2004). Some of these cloudlets have no systemic velocity components, which implies that all of the gas is shocked.

A few cloudlets have velocity spreads that exceed 300 km s\(^{-1}\). One example is a faint emission knot seen at the edge of the remnant in observation E2000-1, which has been marked in Figure 3 as feature a. The clump has a radial velocity spread of 350 km s\(^{-1}\). Due to its location at the edge of the remnant, it likely has a significant tangential velocity component, and thus, the actual velocity of the blob is even higher. Assuming the two components to be comparable, the actual velocity of some of the gas in this blob could be up to \(\sim 500\) km s\(^{-1}\).

4.2. Overall Kinematic Structure

The observed distinct broad emission features have implications for the physical structure of the SNR. The echelle spectra do not suggest the presence of an expanding shell, which would demonstrate itself as a simple bow-shaped line image. The absence of this expanding shell signature in the echelle spectra implies that the observed filaments are not projection effects of an expanding sheet of gas, but actual long ribbon-like structures, which indicates clumpiness in the surrounding gas prior to the explosion.

We have taken echelle spectra in the southern part of the remnant (E2000-2 and E2000-3) to see whether the arclike filament in the south is Balmer-line-dominated. We can, however, observe an \([\text{N}\ ii]\ \lambda 6584\) line in the spectra, and thus conclude that the arc is not Balmer-line-dominated.

In observations E1986-2 and E2000-1, we observe very few broad component features at systemic velocity around the center of explosion determined from X-ray and radio data. In the blue-shifted part of the echelle spectra, we see no broad features at all in E1986-2, and only few faint ones in E2000-1. In the redshifted part we observe a number of broad features in both spectra, but only one of these in E2000-1 has the lower end of its velocity spread at the systemic velocity. The rest of the broad features are seen at higher velocities. Such spectra suggest the presence of a central cavity; its position matches the X-ray and radio observations. The asymmetry of the emission in this central region implies uneven density distribution of matter prior to the explosion, with higher density at the far side of the remnant.

The comparison of the echelle spectra with optical morphology of the SNR allows us to see three-dimensional geometry of the remnant. Using the echelle spectra, we are able to discern whether individual filaments are on the approaching or the receding side of the remnant. Assigning blue and red colors to the blue- and redshifted filaments, respectively, we have constructed a three-dimensional (3D) image of N49 (Fig. 4, left). For the most part, we see the near and the far side of the remnant superimposed, but we observe a number of prominent red and blue filaments. The most prominent redshifted filaments are the straight, long filaments extending from the southeast ridge northward. The majority of the outer filaments are blueshifted, for example, a filament extending westward from the southeast ridge.

5. COMPARISON OF X-RAY AND OPTICAL MORPHOLOGY

To better trace the relationship of the warm ionized gas in the optically emitting filaments with the hot shocked gas, we compared the \(HST\) images with data from \(XMM-Newton\) and \(Chandra\). All
of the X-ray images show a bright, pointlike X-ray source to the north corresponding to the location of the soft gamma-ray repeater SGR 0525-66, as noted by Rothschild et al. (1994). This bright source appears between optically bright features, in a relatively void optical region, and it is not associated with any optical source.

The X-ray image of N49 from XMM-Newton is presented in Figure 5 (left). The corresponding X-ray contours are overlaid on the Hα observation from HST in Figure 5 (right). The 2σ contour provides a nicely defined boundary to the expanding shell. In general, the comparison of XMM-Newton and optical images reveals a strong relationship between X-ray brightness and the regions of highest optical flux. The normalized X-ray fluxes for selected regions are listed in Table 3. As with the optical brightness, the X-ray flux declines toward the west, although the western side of the SNR is still detectable. To the southeast, the steeper X-ray contours indicate a substantial X-ray brightening corresponding to the bright southeast ridge in optical; this emission appears to be resolved without any obvious point source. Westward from this X-ray peak, the central cavity described in the velocity structure analysis (§ 4) appears somewhat brighter in X-rays than do regions to the west and north of the SNR.

A recent short Chandra exposure enables an X-ray/optical comparison at higher resolution. The X-ray image of N49 from Chandra is presented in Figure 6 (left). Again, the corresponding X-ray contours are overlaid on the Hα observation from HST in Figure 6 (right) for a multiwavelength comparison. As seen for the XMM-Newton observation, the overall X-ray surface brightness distribution is similar to that in Hα, in agreement with earlier Chandra ACIS observations by Park et al. (2003). In particular, the ACIS observations show X-ray features which roughly correspond to the brightest groups of optical filaments, such as the southeast ridge and the filaments that project from this region to the northwest and southwest. Similarly, the “patches” of optical emission on the western face of the remnant are accompanied by a
minor X-ray enhancement in that region. The X-ray emission also outlines the optical cavity region, with the emission decreasing toward the interior of the region. Brighter X-ray emission traces the boundary with a radius of curvature similar to that expected from both the optical and echelle data. On the eastern and southern sides of the remnant, the faint X-ray extent matches very well the SNR boundary seen in diffuse Hβ emission.

In addition to this morphological study, we examined the X-ray spectra using XMM-Newton data for three regions corresponding to significant optical features. These regions include one covering the southeast ridge of optical emission, one along the optically faint region in the northwest, and a third region corresponding to the cavity described in § 4. For each region, spectra were extracted for each of the three XMM-Newton instruments (MOS1, MOS2, and pn) and fit jointly with spectral models for a thermal plasma modified by a model of photoelectric absorption.

The primary plasma model used is a plane-parallel shock, nonequilibrium ionization model (vphstack in XSPEC). This model presumes a simple shock structure with a constant postshock electron temperature $kT$. Ionization timescales are modeled as a broad distribution described by the ionization age $\tau = n_e t$, where $n_e$ is the postshock electron number density and $t$ is the time since the plasma was shocked. This model provides a reasonable, if simplified, approximation to shocked plasma conditions for relatively high-temperature shocks in limited spatial regions of an SNR (Borkowski et al. 2001).

When describing broad spatial regions of an SNR, as we do here, one should keep in mind that the spectra arise from a range of temperatures and densities within that region. A single-temperature approximation is therefore of only limited utility in correctly describing the “characteristic” physical conditions. In many cases, it is necessary to use at least two linked models at different temperatures in order to better fit a spectrum which is in reality produced by a superposition of shocks in different conditions. However, particularly in smaller regions, too few counts are often present to constrain a large set of parameters, as for instance those created by adding extra temperature components. The model fits are therefore a compromise: we use as few parameters as possible to characterize a given data set, adding complexity as the number of counts increases sufficiently to require—and support—additional spectral components.

The best-fit spectral models for the SNR and for the selected spatial regions are given in Table 4. Listed in this table are the plasma model components used and the fitted values for absorption column density ($N_{\text{H}}$), postshock temperature ($kT$), abundances of significant elements as a fraction of solar values (O/O$_{\odot}$, etc.), and ionization age ($\tau$). Also listed are normalization values, proportional to the emission measure, for each of the XMM-Newton instruments (MOS1, etc.). Finally, for each model fit the statistical goodness-of-fit is given: reduced $\chi^2$ ($\chi^2_{\text{red}}$) and degrees of freedom (dof). Considering the associated errors and the lower spatial resolution of XMM-Newton, the results agree well with the fits to Chandra ACIS data made by Park et al. (2003).

The X-ray spectra reflect the morphological differences between the eastern and western sides of the SNR. To the west, a single-component plasma model can adequately describe the spectrum. Likewise, the cavity region requires only a single plasma component for a reasonable fit. To the southeast, on the other hand, the spectrum requires two plasma components for a reasonable fit ($\chi^2/\text{dof} = 1489/744$). Notably, a combination of plasma and power-law components provides a considerably poorer fit ($\chi^2/\text{dof} = 1122/743$). Notably, a combination of plasma and power-law components provides a considerably poorer fit ($\chi^2/\text{dof} = 1489/744$), allowing us to rule out, at the 90% confidence level, the possibility that the high-energy component of the spectrum is due to a nonthermal contribution.

Park et al. (2003) interpret this two-component fit to emission from the southeastern SNR as follows: a low-temperature component arising from the forward shock moving slowly into dense clouds, and a high-temperature component originating from the reheating of postshocked material by shocks reflected from dense clumps. Based on our velocity analysis, however, we suggest a slight modification of this picture. Rather than having two distinct temperature regimes, we suggest that this region of the SNR is the location of a distribution of shock velocities. This picture is supported by the broad range of measured optical expansion velocities, as well as by the modeling of optical-line emission by

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TABLE 3

| Region       | Area (arcmin$^2$) | Avg. Flux (ergs cm$^{-2}$ s$^{-1}$) | Norm. Flux (ergs cm$^{-2}$ s$^{-1}$ arcmin$^2$) |
|--------------|------------------|-------------------------------|---------------------------------|
| SE limb      | 0.269            | $2.23 \times 10^{-11}$       | $8.3 \times 10^{-11}$          |
| NW limb      | 0.300            | $9.47 \times 10^{-12}$       | $3.2 \times 10^{-11}$          |
| Cavity       | 0.097            | $9.54 \times 10^{-12}$       | $9.8 \times 10^{-11}$          |

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Fig. 6.—Left, Smoothed contours of Chandra ACIS X-ray data; right, same contours overlaid on the optical Hβ image from HST. This image was processed with a 2 pixel Gaussian smoothing. Contours plotted on the image range from 2 to 100 $\sigma$ above the background in five evenly spaced linearly increasing contours. [See the electronic edition of the Journal for a color version of this figure.]
Vancura et al. (1992b). The two-temperature fit to the X-ray emission can therefore be regarded as an approximation to emission at a wide range of temperatures, generated by forward and reflected shocks at various speeds. These variations in local shock speed presumably arise from the encounter of the overall blast wave with material at different densities, as would be expected where the SNR is encountering the molecular cloud (Banas et al. 1997).

6. SUMMARY

We have conducted a multiwavelength study of SNR N49 using HST images in Hα, [O iii], and [S ii] emission lines and archival Chandra and XMM-Newton images, and have compared the morphological features to SNR kinematics using the high-dispersion echelle spectra obtained at CTIO.

All emission-line images reveal a highly filamentary morphology, with the most prominent features being the southeast ridge, long filaments extending northwest, and a network of filaments in the southeast. The optical emission from the western part of the remnant is significantly lower. We also detect a diffuse Hα emission component protruding beyond the shock boundary in all regions except for the west, where this emission is absent or undetected. We identify this diffuse component as the recombination radiation from the gas ionized by the UV precursor. Using Hα surface brightness, we have estimated the rms electron densities in different regions of the remnant.

Good correlation between [S ii] and Hα morphology is demonstrated in the uniformity of the ratio map, with a mean value of 0.75 ± 0.05 and an overall range of 0.4–1.4. [O iii] images and a wide range of values on the [O iii]/Hα ratio map manifest morphological differences between the [O iii] and Hα emission. The most prominent feature, an offset between [O iii] and Hα bright filaments, is demonstrated on the ratio map as an enhancement of the [O iii]/Hα ratio toward the outer edge of the image, where ratios reach between 0.8 and 1.5, with a few patches reaching up to 2.5. The highest offset observed was 5°. We propose that such an offset would arise in one of two scenarios: (1) The offset is due to thermal instabilities cushioned by magnetic fields and the associated secondary shocks. The fast shocks observed in N49 make this a likely scenario; however, a substantial amount of magnetic support is needed to account for the maximum observed values of the offsets. (2) The offsets arise due to shocks propagating into a clumpy medium. The fast shocks just encountering the cloud produce the [O iii] emission, while Hα comes from previously shocked clouds that have cooled sufficiently. The offset produced by this model matches the observations.

We have also carried out a detailed study of the remnant kinematics using high-dispersion echelle spectra at seven different slit positions throughout the SNR. The spectra reveal a clumpy velocity structure, with discrete broad emission features matching well the positions of filaments across the slit and with radial velocity spreads reaching up to 160 km s⁻¹. We also detect a number of fainter clumps with very high radial velocity spreads that reach 350 km s⁻¹, and estimate the actual velocity of these clumps to be up to 500 km s⁻¹. In addition, we detect a narrow component extending throughout the slit, and we associate it with the diffuse Hα component identified morphologically.

We do not observe a bow-shaped signature of an expanding shell in the spectra. This indicates a true filamentary characteristic of the remnant and implies a clumpy structure of the gas surrounding the star prior to the explosion.

We also confirm the presence of the cavity in the remnant which matches the X-ray and radio data, and observe the asymmetric expansion of the gas in this region, which we associate with irregular density distribution of the surrounding matter prior to the explosion. Matching discrete emission features to actual filaments allows us to identify the blue- and redshifted filaments. Through a detailed comparison between the echelle spectra and the optical images, we have constructed a rough 3D map of the remnant.

We have compared the archival Chandra and XMM-Newton images to the Hα morphology. The X-ray morphology of N49 correlates well with the general trends seen at optical wavelengths. Even though we do not observe filamentary structure in X-rays, the brightest emission in X-rays comes from the southeast, and the emission diminishes toward the west. The X-ray boundary matches the extent of optical filaments. Unlike in the optical, we observe the whole spherical envelope of the SNR in X-rays.

In addition to the images, we have carried out spectral analysis of the remnant. While the cavity region, as well as the western side of the remnant, can each be fit by a single plasma component, the eastern and southeast regions require a two-component plasma. We rule out nonthermal radiation with 90% confidence. We suggest that the two plasma components are approximations to a
range of temperatures generated by forward and reflected shocks at various speeds.

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