Supernova Remnants Associated with Molecular Clouds in the Large Magellanic Cloud

Kenneth R. Banas\(^1\), John P. Hughes\(^1,3\), L. Bronfman\(^4\), and L.-Å. Nyman\(^5,6\)

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ABSTRACT

We used the Swedish-ESO Submillimeter Telescope (SEST) to search for CO emission associated with three supernova remnants (SNRs) in the Large Magellanic Cloud: N49, N132D, and N23. Observations were carried out in the \( J=2\rightarrow1 \) rotational transition of CO (230.5 GHz) where the half power beamwidth of the SEST is 23\('' \). Molecular clouds were discovered near N49 and N132D; no CO emission was discovered in the region we mapped near N23. The N49 cloud has a peak line temperature of 0.75 K, spatial scale of \( \sim 7 \) pc and virial mass of \( \sim 3 \times 10^4 \) M\(_\odot\). The N132D cloud is brighter with a peak temperature of 5 K; it is also larger \( \sim 22 \) pc and considerably more massive \( \sim 2 \times 10^5 \) M\(_\odot\). The velocities derived for the clouds near N49 and N132D, +286.0 and +264.0 km s\(^{-1}\), agree well with the previously known velocities of the associated SNRs: +286 km s\(^{-1}\) and +268 km s\(^{-1}\), respectively. ROSAT X-ray images show that the ambient density into which the remnants are expanding appears to be significantly increased in the direction of the clouds. Taken together these observations indicate a physical association between the remnants and their...
respective, presumably natal, molecular clouds. The association of N49 and N132D with dense regions of molecular material means that both were likely products of short-lived progenitors that exploded as core-collapse supernovae.

1. Introduction

Stellar evolutionary models predict massive stars will die in supernova explosions near where they were born. It follows that supernova remnants (SNRs) associated with the molecular clouds from which their progenitors were born must have arisen from massive star, core-collapse supernovae. It is further believed that blast waves from supernova acting on dense atomic and molecular gas can initiate star formation as one part in a clearly cyclic process. Therefore the identification and study of SNRs/molecular clouds associations is important to our understanding of the structure and dynamics of the interstellar medium (ISM), the ratio of thermonuclear to core-collapse supernova, the life cycle of stars, the destruction of molecular clouds, and so on.

The Large Magellanic Cloud (LMC) is well suited to the identification and study of SNR and molecular cloud associations. The Cloud is nearby, relatively unobscured, and has been extensively observed at nearly all wavebands. A sizeable number (>30) of supernova remnants have been identified in the LMC from X-ray, optical, and radio measurements (Mathewson et al. 1983, 1984, 1985). Cohen et al. (1988) systematically surveyed the LMC for CO line emission and found a general correspondence between the CO emission and such Population I objects as SNRs and H II regions. However, because of the limited spatial resolution of the survey (12′), a detailed association between individual objects and molecular clouds was not possible. Guided by the results of this survey, we selected three probable SNR/molecular cloud associations for study at considerably higher angular resolution using the Swedish-ESO Submillimeter Telescope (SEST) at La Silla, Chile. The angular resolution of the SEST at 230 GHz, ~20″, corresponds to a linear size of 4.85 pc for a distance to the LMC of 50 kpc, which we adopt throughout.

The remnants we selected, in addition to being positionally coincident with CO emission from the LMC survey, were required to show evidence for enhanced X-ray and optical emission along part of the rim, which might be indicative of a density gradient in the ambient medium. The best candidates were the SNRs 0525−66.1, 0525−69.6, and 0506−68.0 (Mathewson et al. 1983), which we will refer to henceforth using their Henize (1956) catalog names: N49, N132D, and N23, respectively.

N49 shows the highest optical surface brightness of all LMC SNRs. Its X-ray (and
optical) morphology shows a sharp increase in emission along the southeast edge of the remnant (Vancura et al. 1992a). It appears to be embedded within one of the brighter and more massive CO clouds in the LMC (among clouds, that is, that are not in the 30 Doradus region). N132D is the brightest soft X-ray emitting SNR in the LMC (Mathewson et al. 1983) and optically it displays high velocity oxygen-rich material. Consequently it is one of the most frequently studied of LMC remnants. Toward the south, N132D has a nearly circular, very bright limb, which is about three-quarters complete, while the remaining quarter of the remnant appears as a “blow-out” toward the northeast. Hughes (1987) interpreted this structure as a result of the ionizing radiation and stellar wind of the progenitor acting on a medium with a strong gradient in ambient ISM density. The LMC CO survey showed N132D sitting on the northern edge of a relatively modest cloud. N23 has the weakest X-ray emission of the three chosen SNRs. Its morphology is similar to that of N49 and N132D in that it shows an increase in emission along one limb, in this case the eastern one. The remnant sits on the southern boundary of a modest CO cloud.

In the following, we describe our SEST observations, data reduction, and error analysis (§2); give the results on the molecular clouds found near N49 and N132D (§3); discuss these results in the context of what else is known about these remnants (§4); estimate the masses of the newly discovered molecular cloud (§5); and in §6 we summarize. A preliminary report on a subset of the SEST data was given in Hughes, Bronfman, & Nyman (1991).

2. Observations and Analysis Techniques

2.1. Observations

High resolution imaging of three candidate SNR/molecular cloud associations was undertaken with the SEST on La Silla, Chile, on June 18-21, 1989 and again on October 16-19, 1990. The CO $J = 2 \rightarrow 1$ (at 230.5 GHz) observations were done with a linearly polarized Schottky receiver giving a typical system temperature above the atmosphere of 800–1600 K, depending on elevation and weather conditions. At this frequency the beamwidth of the telescope is 23″ (FWHM), considerably better than the 12′ resolution of Cohen et al. (1988), thereby allowing us to resolve finer structure within the molecular clouds near the SNRs. The main beam efficiency of the telescope, $\eta_{mb}$, was 0.54 during the 1989 observations, and due to an improvement in the surface accuracy in 1990, the beam efficiency during the October 1990 observations was about 0.70. We quote results in terms of the antenna temperature corrected for beam efficiency, $T_{mb} = T_{\Lambda}/\eta$. Spectra were taken with an acousto-optical spectrometer with a bandwidth of 86 MHz, a channel separation of 43 kHz, and a resolution of 80 kHz, which at the observed frequency corresponds to a
velocity resolution of 0.1 km s$^{-1}$. Calibration was done with a standard chopper wheel method, and the intensities are expected to have a precision better than $\sim 10\%$.

The line emission was mapped on grids spaced uniformly by 20" starting at the center of each remnant. The extents of the mapped regions were chosen as appropriate to encompass the regions of bright CO emission discovered near the SNRs. For most of the observations the telescope was operated in frequency-switched mode with a throw of 21 MHz (corresponding to a velocity shift of about 27 km s$^{-1}$), although a subset of positions were observed in position-switched mode as a consistency check and to search for broad velocity wings to the CO emission. We chose the appropriate cloud velocity at which to observe from the data reported by Cohen et al. (1988). The total integration time at each grid position was usually 1800 s, although some shorter exposures were taken near N132D and N23. The system temperature outside the atmosphere was between 800 K and 1000 K during the two days N49 was observed, 1000 K and 1100 K for the two days N23 was observed, and varied from 1000 K to 1600 K for N132D.

2.2. Reduction

The spectrum at each scan position consists of 2000 channels which oversample the velocity resolution of the receiver by about a factor of 2. The frequency-switched data were reduced in the following manner. The spectrum was copied, shifted in velocity by the 21 MHz throw, inverted to correct for the amplitude inversion between the two phases, and then averaged with the original spectrum. The baselines of the frequency-switched data include temporal variations in the sky and instrument, and the folding procedure removes most of these effects. Only the central 45 km s$^{-1}$ is used during the rest of the reduction.

The continuum fitting task in IRAF, noao.onedspec.continuum, was used to fit baselines. Of the several fit parameters available, our analysis showed that the most important were (1) the type of function to fit to the data, (2) its order (generally low to avoid fitting noise), (3) the number of discrepant points to reject, and (4) the velocity range of the data over which to fit.

Several combinations of parameters produced final spectra with very similar quality baseline fits. Nevertheless we were concerned that the baseline fits could introduce a bias in the derived value of the velocity integrated CO brightness temperature, $W_{CO} = \Delta v \sum T_i$, where the summation is over the line profile, $T_i$ is the observed temperature in channel $i$, and $\Delta v$ is the velocity width of each channel (which is a constant for our SEST data). The set of parameters that we ultimately used for baseline subtraction were those that gave a
zero mean value for $W_{\text{CO}}$ in spectra which appeared to have no signal. These line-free scans were at the outer regions of each cloud, where, if there was any signal present, it was too weak to be distinguished from the noise. Since the baselines of all the lines were similar, we are confident that the functions that behaved well in the line region of scans with no signal were also well-behaved in scans with prominent CO line emission.

Line centroids and widths were computed directly from the individual spectra weighting by the observed brightness temperature in each spectral channel. All velocities are given in the local standard of rest (LSR) frame. The $W_{\text{CO}}$ velocity integration range was kept the same for all scans of each target. This interval was determined by examining the location and width of the line in the summed ensemble spectrum of the cloud. Although there is some velocity gradient within the clouds, there was not enough to prevent an identical procedure from being followed for all the scans of a single cloud.

The position-switched scans did not need to be folded, but the same baseline fitting procedures and error analyses were used. Lower order polynomial fits were used because the baselines were flatter. These data were used as a check on the frequency-switched scans and to search for broad velocity components in the detected clouds.

### 2.3. Error Analysis

The primary source of error in $W_{\text{CO}}$ is the baseline fitting procedure. We estimated the error in our fits by comparing the values of $W_{\text{CO}}$ obtained with two different fitting functions: a polynomial of the $n$-th order versus one of order $n+1$. The $W_{\text{CO}}$ values derived from these two fits were correlated and fitted by least squares to a linear relation. The root-mean-square (RMS) deviation of the various points from the linear least squares fit provided the error estimate, $\delta_{\text{BL}}$, from baseline fitting for a single spectrum.

To quantify the noise in the observations, the antenna temperatures in velocity channels free of emission were examined. When these values were plotted the histogram was Gaussian. We then sorted these values and extracted the temperature values corresponding to the 15.87 and 84.13 percentiles in the list. Half the difference between these values was taken to be the one $\sigma$ noise estimate per channel. This error, $\delta_T$, was propagated through the derived quantities, $W_{\text{CO}}$, line centroids, and widths.

In our error analysis we propagate the temperature noise per channel, $\delta_T$, through to the quantities derived above. In the case of $W_{\text{CO}}$, the baseline fitting error ($\delta_{\text{BL}}$) is included by direct summation (not root-sum-square) with the noise error $\delta_{W_{\text{CO}}} = \sqrt{N\Delta v \delta_T + \delta_{\text{BL}}}$, where $N$ is the number of velocity channels over which all summations were done.
3. Analysis and Results

3.1. N49

The CO emission of the cloud near the N49 mapped by SEST is rather weak and various different parameters were used in an effort to get the best baselines. The function that provided the best fits was a third-order Legendre polynomial which rejected no points and fit the regions from +263 to +280 km s\(^{-1}\) and again from +292 to +306 km s\(^{-1}\). These regions were chosen so as not to include the line or the effects present from the folding procedure. \(W_{\text{CO}}\) was calculated for the velocity region of +281 to +291 km s\(^{-1}\), as were the line center and width. A summary of the fit parameters and error analysis is given in Table 1.

To derive values for \(W_{\text{CO}}\), velocity, and line width for the ensemble cloud, we produced a composite spectrum by averaging the baseline-subtracted scans with individual \(W_{\text{CO}}\) values that were greater than 3\(\delta W_{\text{CO}}\) in order to include actual signal and avoid unnecessary noise. We plot this in Figure 1a. As described above, the optimum baseline fit was chosen for how well it subtracted the baseline in the line region. However, there remains a small residual baseline outside the line region due to the observational conditions. Table 2 lists the information derived from the averaged spectrum, showing the number of scan positions averaged, the velocity-integrated CO brightness temperature, the velocity centroid, and the root-mean-square velocity width of the line.

The mean \(W_{\text{CO}}\) of the “zero” scans was 0.09±0.32 K km s\(^{-1}\). This error is comparable to the \(\delta W_{\text{CO}}\) derived independently using the techniques outlined above. Figure 2 shows the individual spectra in their correct relative positions on the sky.

Two position-switched spectra were taken at the location of the peak CO emission. The derived \(W_{\text{CO}}\) values, line centroids, and widths were consistent with those from the frequency-switched data. No evidence for a broader component to the line was apparent.

3.2. N132D

The same reduction technique was used for N132D. The function that gave the best baseline fit to the N132D data was a fifth-order Legendre polynomial with no rejection, and fit over the regions from +243 to +256 km s\(^{-1}\) and +272 to +286 km s\(^{-1}\). \(W_{\text{CO}}\) and velocity information were calculated in the region from +257 to +271 km s\(^{-1}\). The velocity window for the line emission was wider here than for N49 because of a significant velocity gradient (~5 km s\(^{-1}\)) across the N132D cloud. The mean \(W_{\text{CO}}\) of the “zero” scans was
The error analysis for N132D was broken down into two parts, which are listed separately in Table 1. Upon examination of the data, it became obvious that there was much greater noise in the scans taken on October 17 and 19, 1990, which was likely the result of poorer weather conditions. The noise and fit statistics for these days were considered separately from the rest of the data. The total error in $W_{\text{CO}}$ (as the sum of the baseline and noise errors) was used in determining which scans were to be averaged to the total cloud spectra. Therefore, by considering the data in two separate sets, only true signal was added because the noisier data had a higher $3\delta_{W_{\text{CO}}}$ threshold.

Once again, to derive values of $W_{\text{CO}}$, velocity, and line width for the whole cloud, baseline-subtracted spectra with signal greater than $3\delta_{W_{\text{CO}}}$ were averaged. Table 2 lists information derived from this spectrum and the spectrum itself is shown in Figure 1b. Figure 3 plots the individual spectra throughout the cloud.

We took some position-switched data at five positions located near the southern X-ray emitting rim of N132D in order to search for a broad component to the line which might indicate interaction between the cloud and N132D. These data were reduced as described above, but with linear baselines. The same velocity ranges as for the frequency-switched data were used for the baseline fits and to calculate the line values. The mean difference in $W_{\text{CO}}$ when compared with the frequency-switched scans at the same positions was $0.6 \text{ K km s}^{-1}$, within $\delta_{W_{\text{CO}}}$. Because the baselines are flatter than the frequency-switched data, it was possible to search for broad velocity components to the main line, as well as other weaker lines over the entire velocity region from $+225$ to $+335 \text{ km s}^{-1}$. We began by summing all the position-switched scans to form a high signal-to-noise spectrum. This spectrum was fitted initially with a single Gaussian to quantify the main peak. To check for a broad CO emission line, we then added a broad Gaussian (with a fixed FWHM of $35 \text{ km s}^{-1}$) centered on the line region to the main line. The reduction in $\chi^2$ when this broad line was included was not statistically significant. There were also weak lines at $+243$ and $+285 \text{ km s}^{-1}$ that also turned out not to be statistically significant. In conclusion, our data provide no evidence for either a broad component to the main line nor for additional lines beyond that seen in the frequency-switched data.

### 3.3. N23

The frequency-switched scans taken near N23 were reduced with fifth-order Legendre polynomials with no rejection of discrepant points. The baseline was fit from $+243$ to $+274$
km s$^{-1}$ and from +286 to +306 km s$^{-1}$. The position-switched data were reduced with a second order Legendre polynomial baseline subtraction and fit from +225 to +274 km s$^{-1}$ and from +286 to +335 km s$^{-1}$. Figure 4 shows the spectra taken around the remnant in their positions on the sky.

Although the scan pattern around N23 may appear haphazard, there is an explanation for the apparently odd placement. The position-switched scans (Figure 4), which were carried out first, were arranged in a pattern similar to those for N132D and N49 – centered on the remnant and extending toward the edge where the X-ray emission appears strongest. When no CO emission was found there and, since the observing time was running short, the mapping strategy was changed in an attempt merely to locate the CO emission, which according to the Cohen et al. (1988) map, should have extended generally toward the northwest. Two areas were mapped: a 9′.3 long north-south strip of scans and a 2′ square pattern to the northeast. These spectra were integrated for only 120 s and were taken in frequency-switched mode. None of these scans show significant CO emission, as indicated in Table 3.

### 3.4. X-ray Images

For comparison with our maps of CO emission, we obtained high resolution X-ray images from the ROSAT and Einstein archives. N49 was observed by the ROSAT high resolution imager (RHRI) for a total live-time corrected exposure of 41972.4 s in several intervals from March 1992 to March 1993 (ROR numbers 400066 and 500172). N132D was observed by the RHRI in February 1991 for 26830.8 s (ROR number 500002). Since the RHRI observations of N23 are not yet publicly available, we used the Einstein HRI data instead. The EHRI observed N23 in May 1980 for 15433.3 s.

All images were deconvolved with a small number of iterations of the Lucy-Richardson algorithm using the implementation in IRAF. The resulting X-ray maps are shown in Figures 5, 6, and 7 for N49, N132D, and N23, with the SEST scan positions and contours of $W_{\text{CO}}$ emission overlaid. Our X-ray maps of N49 and N132D agree well with those published by Mathewson et al. (1983); however our N23 map shows much less structure than the previously published one, although the overall appearance is similar, since our effective smoothing of the X-ray image is greater than the 2″ Gaussian sigma used before.
4. Discussion

4.1. N49

The peak X-ray and optical emission from N49 lies along the eastern limb and coincides extremely well with the position of the mapped CO emission (Fig. 5). In addition to the agreement in projected position, the agreement in velocity, or line-of-sight position, is also quite good. N49 shows a narrow emission line in its optical spectrum that arises from the photoionization of unshocked gas at rest with respect to the local environment and preceding the supernova blast wave (Shull 1983, Vancura et al. 1992a). The LSR velocity of this material is \( +286 \pm 1 \) km s\(^{-1}\) which is in excellent agreement with our integrated cloud velocity of \( +286.0 \pm 0.1 \) km s\(^{-1}\).

The prevailing picture of the N49 environment is one of relatively high density with a gradient in the ambient density increasing from NW to SE. Vancura et al. (1992a) estimate the mean preshock density of the intercloud medium surrounding N49 to be \( 0.9 \) cm\(^{-3}\) based on the observed X-ray emission. They find that the optical emission must arise from much denser regions with a range of preshock densities covering 20 to 940 cm\(^{-3}\). The lack of spectral variations with brightness can be well explained in terms of sheets of optical emission formed as the supernova blast wave encounters a large dense cloud of gas. The molecular cloud that we have discovered provides a natural explanation for this general picture.

N49 lies at the northern edge of a complex infrared emitting region. The closest cataloged IRAS source (from the Leiden–IRAS Magellanic Clouds Infrared Source Catalogues, Schwering & Israel 1990), LI-LMC 1022, lies just north of the CO cloud at a position of 05:25:59.5, \(-66:07:03\) (B1950). Graham et al. (1987) have argued that collisionally-heated dust in the SNR could be the explanation for the IRAS source. We consider it unlikely that this is the entire explanation, since the flux of LI-LMC 1022 (19.5 Jy at 60 \( \mu \)m) corresponds to a luminosity about an order of magnitude larger than the far infrared luminosity of similar sized Galactic remnants where comparative morphology and other considerations make it clear that we are observing heated dust in the SNR (Saken, Fesen, & Shull 1992). In addition, the four times higher gas-to-dust ratio of the LMC (Koornneef 1984) would suggest lower comparative IR fluxes.

It is more likely that the molecular cloud is the origin of the IR emission. Israel et al. (1993) detect CO emission from a large fraction (87%) of a sample of LMC IRAS sources over a wide range of infrared luminosity. Far infrared emission can arise from the heating of dust in a molecular cloud by embedded stars, the general interstellar radiation field, stellar radiation from nearby star clusters, or other sources. Caldwell & Kutner (1996) have
studied a number of molecular clouds in the LMC using the ratio of far infrared luminosity $L_{\text{FIR}}$ to the cloud virial mass $M_V$ as a measure of star formation activity, assuming that the infrared luminosity arises from embedded young stars. For LI-LMC 1022 we estimate $L_{\text{FIR}} \sim 13 \times 10^4 L_\odot$, while the cloud mass is $M_V \sim 3 \times 10^4 M_\odot$ (see below). The derived ratio $\sim 4 L_\odot/M_\odot$ is well within the range of other LMC clouds studied by Caldwell & Kutner.

The remnant N49 is itself a strong source of optical, UV, and X-radiation of which $\text{Ly}\alpha$ and the O vi $\lambda 1035$ doublet are the principal sources of flux. Our estimate of N49’s intrinsic $\text{Ly}\alpha$ luminosity, $2.1 \times 10^{38}$ ergs s$^{-1}$, is based on a two-photon continuum flux of $2.3 \times 10^{-10}$ ergs cm$^{-2}$ s$^{-1}$ (Vancura et al. 1992a) and a value of 3 for the ratio of $\text{Ly}\alpha$ to two-photon continuum, as expected from models of planar shocks over a broad range in velocity (Hartigan, Raymond, & Hartmann 1987). We estimate the O vi $\lambda 1035$ luminosity by scaling C iv $\lambda 1550$ ($2.8 \times 10^{37}$ ergs s$^{-1}$) by a factor 4 (Vancura et al. 1992b). Together with the X-ray luminosity of $1.9 \times 10^{37}$ ergs s$^{-1}$, this yields a total luminosity of hard photons of $3.4 \times 10^{38}$ ergs s$^{-1}$. If the molecular cloud intercepts half of these photons and all that luminosity is subsequently re-radiated in the infrared band, then we would expect $L_{\text{FIR}} \sim 4 \times 10^4 L_\odot$, which is potentially a sizeable fraction, about one-third, of that actually seen.

Since there are no other obvious signs of active star formation (cataloged OB associations or H ii regions) in the vicinity of N49, heating by the interstellar radiation field may be negligible and an embedded source origin for the remainder of the far IR emission may need to be considered. However, since this region of the LMC is rather complex and the angular resolution of IRAS is modest ($\sim 1'$), a definitive explanation for the origin of this emission awaits a more comprehensive study of the N49 environment using higher angular resolution IR data.

4.2. N132D

Figure 6 shows the spatial relationship between N132D and the bright CO cloud discovered near it. To complete the association between them, we turn to the photoionization precursor in the quiescent gas upstream of the expanding supernova blast wave that N132D (like N49) displays. Morse, Winkler, & Kirshner (1995) studied this component to the optical emission and found it to display apparently normal LMC abundances and to be spectrally unresolved at a resolution of 30 km s$^{-1}$. Its LSR velocity of $+268 \pm 7$ km s$^{-1}$ is in excellent agreement with our velocity of $+264.0 \pm 0.1$ km s$^{-1}$ for the cloud. As with N49, this agreement of velocities along with the proximity in projected position implies a definite physical association.
Based on a study of its X-ray morphology, Hughes (1987) proposed that N132D was expanding into a region with a density gradient increasing from northeast to southwest. To explain the X-ray emission, mean preshock densities of $2 \text{–} 3 \, \text{cm}^{-3}$ were required in the southern (denser) region. Recently Morse et al. (1996) studied the optical photoionization precursor in this area in more detail and derived a preshock density of roughly $3 \, \text{cm}^{-3}$ from the surface brightness of $[\text{O III}] \lambda 5007$. The presence of a dense molecular cloud toward the south of the remnant provides a general framework for understanding these results. N132D’s incomplete morphology (i.e., the lack of emission or “break-out” to the northeast), the fact that the pre-shock ambient density is considerably lower than the densities usually associated with the cores of molecular clouds, and the spatial separation between the bright CO core and the remnant itself, strongly suggest that N132D lies near the northern boundary of its associated molecular cloud. Numerical hydrodynamic simulations of the explosion of a SN near the edge of a molecular cloud (Tenorio-Tagle, Bodenheimer, & Yorke 1985) do bear some similarity to the observed features of N132D. Given the wealth of specific information known about N132D, further numerical work in this area could yield important information on the structure of molecular clouds and their interface with the general ISM.

Morse et al. (1995) first pointed out an apparent association between the CO emission (as published by Hughes et al. 1991) and an H II region about 2′ south of N132D. Figure 8 shows an optical Hα image of both the SNR and H II region overlaid with contours of CO emission from our current analysis. The position and shape of the H II region agree remarkably well with the cloud core. There is also an IRAS source nearby at 5:25:32.3, −69:43:28 (B1950) (LI-LMC 1008, Schwering & Israel 1990) with a flux at 60 μm of 24.8 Jy. The inferred far infrared luminosity $L_{\text{FIR}} \sim 16 \times 10^4 \, L_\odot$ compared to the virial mass of the cloud (see below) $M_V \sim 2 \times 10^5 \, M_\odot$ yields a ratio $\sim 1 \, L_\odot/M_\odot$ which is consistent with other LMC clouds (Caldwell & Kutner 1996) and indicates a substantial amount of heating of the cloud. Like N49, N132D has a substantial UV and X-ray flux. Integrating N132D’s effective ionizing spectrum (Morse et al. 1996), we estimate the remnant’s intrinsic luminosity (including Lyα and harder photons) to be $1.8 \times 10^{38} \, \text{ergs s}^{-1}$. Again assuming that half these photons are absorbed and re-radiated by the molecular cloud gives us an estimate of the far infrared luminosity of $\sim 2 \times 10^4 \, L_\odot$, which is evidently only about 10% of the observed $L_{\text{FIR}}$. Another source of cloud heating is the ionizing flux from the same star (or set of stars) that is exciting the H II region.

There is a velocity shear of about 5 km s$^{-1}$ across the cloud with the peak of the emission increasing from $\sim 263 \, \text{km s}^{-1}$ in the east to $\sim 268 \, \text{km s}^{-1}$ in the west (see Fig. 3). In addition to this velocity shear, there are asymmetric wings on the line profiles that extend to higher velocities in the eastern part of the cloud and to lower velocities in the
west. These results are qualitatively consistent with simple rotation of the cloud (Dubinski, Narayan, & Phillips 1995). However, we favor a somewhat different interpretation. We believe that there are (predominantly) two clouds at radial velocities of $\sim 263$ km s$^{-1}$ and $\sim 268$ km s$^{-1}$, with intrinsic velocity widths $\sigma \sim 1.8$ km s$^{-1}$, containing bright dense cores centered near the CO peaks in the east and west of our maps. These cores are each surrounded by lower density material covering larger regions of the sky. The emission we observe at any particular position in the map is a blend of these two components. For example, consider the set of spectra at declination $-69:42:22$ (corresponding to the fourth row of scan points south of position 0,0 in figure 3). At right ascension 5:25:27 (immediately below position 0,0) and 5:25:23 (one scan position to the west of 0,0) we see emission that is considerably broader and weaker than scans further to the east or west. In these positions, which lie between the brighter cores, we suggest that we are seeing nearly equal contributions from the lower density “halos” of the two separate clouds. Further to the east or west the spectra are dominated by a single component, but the weaker emission from the other cloud remains as an asymmetric wing on the line profile. In any event, our data reveal that this region is quite complex both morphologically and dynamically.

### 4.3. N23

In general N23 is not as well studied as the previous two remnants. Its X-ray morphology (Fig. 7) is similar to that of N49, showing a brightening toward the east. In this same direction the optical image (Mathewson et al. 1983) also shows a brightened limb and, in addition, there appears to be a cluster of bright stars beyond the supernova shock front. The nearest cataloged IRAS source is some 200″ south of N23. Two other IRAS sources lie 4′ and 5′ west and southwest.

As mentioned above, the remnant sits near the southern boundary of a modest CO cloud (# 9 from Cohen et al.). However as our results on N49 and N132D clearly show, these lower angular resolution data provide only a coarse guide to the existence of molecular gas on sub-arcminute spatial scales. We were unable to map a large region near N23 to a sensitive level (due to limited observation time) and so our null result on the association of a molecular cloud with this remnant must be considered tentative. We point out that our upper limit to CO emission over the region surveyed northeast of the remnant is consistent with the velocity-integrated CO emission from the cloud actually detected near N49. This region would be an interesting one to follow-up with additional SEST observations.
5. Cloud Masses

The mass of a spherical, self-gravitating molecular cloud of radius $R$ in virial equilibrium can be estimated as $M_V = 5 R \sigma^2 / G$, where $\sigma$ is the line width (RMS) of the ensemble cloud spectrum. We determine the effective radii of the clouds from our maps as $R = (A/\pi)^{1/2}$, where the cloud area $A$ is given by $A = N S L^2$. $N_S$ is the number of scans with significant signal averaged in the ensemble spectrum (see Table 1) and $L$ is the spacing between our scans (20″ or 4.85 pc at the LMC). The effective cloud radii are 7.2 pc (N49) and 22.9 pc (N132D). For the N49 cloud we derive a virial mass of $M_V = 3 \times 10^4 M_\odot$ and for the N132D cloud we find $M_V = 2 \times 10^5 M_\odot$.

It is also possible to estimate molecular cloud masses using the empirical relationship between velocity-integrated CO intensity and $H_2$ column density. A recent redetermination of the ratio between these quantities for the $J=1\rightarrow0$ transition of CO in the Galaxy yields a value $X_G = N_{H_2} / W_{CO(1-0)} = 1.56 \times 10^{20} \text{ cm}^{-2} \text{ K}^{-1} \text{ km}^{-1} \text{ s}$ (Hunter et al. 1996). For our data on clouds in the LMC, we must correct this factor for (1) the observational fact that LMC molecular clouds are intrinsically less luminous in CO than Galactic clouds of similar mass (due in part to the lower metallicity and the higher gas-to-dust ratio of the LMC), and (2) the intensity ratio between the $J=2\rightarrow1$ and the $J=1\rightarrow0$ transitions of CO. We use the scaling given by Cohen et al. (1988), $X_{LMC} = 6X_G$ to account for the first item. Sakamoto et al. (1995), based on a study of molecular clouds in the first quadrant of the Galaxy, find a value of 0.66 for the mean ratio $W_{CO(2-1)}/W_{CO(1-0)}$, with a variation from 0.5 to 0.8 as a function of Galactocentric distance. This value is in substantial agreement with other recent measures of this ratio, such as that of Chiar et al. (1994), who find a value of $0.85 \pm 0.63$ from a study of molecular clouds in the Scutum arm of the Galaxy. For clouds in the Chiar et al. study with $M_V < 5 \times 10^4 M_\odot$ based on the $J=2\rightarrow1$ transition, we find a ratio of $\sim0.5$, which should be the appropriate value to use for the N49 cloud. For clouds with $M_V$ in the range $(1.58 - 2.32) \times 10^5 M_\odot$ and therefore similar to the cloud near N132D, the ratio is slightly higher, $\sim0.8$. Combining these factors, we come up with a relationship of $N_{H_2} / W_{CO(2-1)} = 1.87(1.17) \times 10^{21} \text{ cm}^{-2} \text{ K}^{-1} \text{ km}^{-1} \text{ s}$ for the N49 (N132D) cloud. The masses we derive (including a correction for He assuming [He]/[H] = 0.085) are $M_{CO} = 9 \times 10^3 M_\odot$ (N49 cloud) and $M_{CO} = 3 \times 10^5 M_\odot$ (N132D cloud).

The giant molecular cloud near N132D shows good agreement between its CO-derived mass and the virial mass. It also represents a significant fraction, roughly 30%, of the total CO mass of the cloud complex near N132D from the lower resolution Cohen et al. (1988) complete survey of the LMC (cloud # 22 in their Table 1). This complex has an estimated mass of $9.5 \times 10^5 M_\odot$ after including the revised $X_G$ factor from above. The smaller molecular cloud we found near N49 is far from being a major constituent of
the corresponding cloud (# 23) in the LMC survey, encompassing less than 0.5% of the total mass. In addition, the SEST cloud may not be in virial equilibrium based on the considerable difference between its CO mass and virial mass, the latter being over three times larger than the former. The use of this observation as evidence, albeit weak, for a direct interaction between the cloud and N49’s blast wave must be tempered by strong caveats about the large uncertainties in these mass estimates. A convincing case for interaction between these SNRs and their associated clouds will require new considerably deeper observations and the discovery of broad molecular emission lines (30–40 km s\(^{-1}\)) from the interaction region.

6. Summary

We used the SEST to map the vicinity of three LMC SNRs, N49, N132D, and N23, in the \(J = 2 \rightarrow 1\) transition of CO emission and found that:

(1) The SNRs N49 and N132D show spatial relationships with molecular clouds that coincide with increased X-ray and optical emission from the remnants. There is also good agreement between the mean velocity of the ensemble CO emission, \(+286.0 \pm 0.1 \text{ km s}^{-1}\) (N49) and \(+264.0 \pm 0.1 \text{ km s}^{-1}\) (N132D), and the optically determined velocities of the remnants, \(+286 \pm 1 \text{ km s}^{-1}\) (N49, Shull 1983) and \(+268 \pm 7 \text{ km s}^{-1}\) (N132D, Morse et al. 1995). The agreement of the SNR and cloud velocities along with the two-dimensional proximity indicate that the two systems are indeed physically associated.

(2) CO and virial equilibrium masses were derived for the two newly discovered molecular clouds. The different mass estimates agree quite well for the N132D cloud and indicate a mass of \(\sim 3 \times 10^5 M_\odot\) which is within the range expected for a giant molecular cloud. Our two mass estimates for the cloud near N49 are internally inconsistent, which may indicate that the cloud is not virialized. The CO mass for this cloud is \(9 \times 10^3 M_\odot\) while the virial mass is \(3 \times 10^4 M_\odot\). In neither case does the SEST cloud account for the entire emission observed at lower spatial resolution by Cohen et al. (1988) in their complete LMC CO survey. The N49 SEST cloud is indeed a negligible fraction (<0.5%), although the N132D SEST cloud corresponds to about 30% of the total cloud mass observed at lower resolution.

(3) We detected no CO emission from the vicinity of the SNR N23. Since the area mapped was limited, this null result should not be overinterpreted. The X-ray and optical morphology of N23 and its proximity to CO emission in the Cohen et al. (1988) survey continue to support the presence of dense molecular gas near N23 and further observations
with the SEST are warranted.

(4) The association of N49 and N132D with dense molecular clouds supports the picture in which their progenitors were short-lived, hence massive, stars that exploded as core collapse (i.e., Type II or Type Ib) supernovae. This is consistent with other known characteristics of the remnants, such as the presence of high-velocity, oxygen-rich stellar material in N132D, which is the traditional signature of a massive star progenitor. The work we present here has also made clear that the good angular resolution of the SEST provides the essential key for being able to make SNR/molecular cloud associations in the LMC. Discovery of CO emission in the near vicinities of other LMC SNRs with the SEST would allow us to determine the SN type of a larger fraction of the remnant sample in the Cloud and should be pursued.

The Swedish-ESO Submillimeter Telescope, SEST, is operated jointly by ESO and the Swedish National Facility for Radio Astronomy, Onsala Space Observatory at Chalmers University of Technology. This research has made use of data obtained through the High Energy Astrophysics Science Archive Research Center Online Service, provided by the NASA-Goddard Space Flight Center. We thank Jon Morse for providing the Hα image of N132D and the nearby H II region and we acknowledge very useful discussions with Mark Birkinshaw, Tom Dame, and John Raymond. We would also like to thank Kristin Kearns, Kim Dow, and everyone associated with the Smithsonian Astrophysical Observatory Summer Intern Program, which was funded through the National Science Foundation. L.B. acknowledges support by FONDECYT Grant 1950627, República de Chile. Additional financial support for this research was provided by NASA (ROSAT Grant NAG5-2156) and the Smithsonian Institution.

REFERENCES

### Table 1. Error analysis of CO line emission

<table>
<thead>
<tr>
<th>Associated SNR</th>
<th>Baseline Fit Region (km s(^{-1}))</th>
<th>Line Region (km s(^{-1}))</th>
<th>(\delta_T) (K)</th>
<th>(\sqrt{N\Delta v\delta_T}) (K km s(^{-1}))</th>
<th>(\delta_{BL}) (K km s(^{-1}))</th>
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<tr>
<td>N49</td>
<td>263–280, 292–306</td>
<td>281–291</td>
<td>0.13</td>
<td>0.093</td>
<td>0.22</td>
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<tr>
<td>N132D (total)</td>
<td>243–256, 272–286</td>
<td>257–271</td>
<td>0.32</td>
<td>0.28</td>
<td>0.37</td>
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<tr>
<td>N132D (high noise)</td>
<td>243–256, 272–286</td>
<td>257–271</td>
<td>0.58</td>
<td>0.52</td>
<td>0.52</td>
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<tr>
<td>N132D (low noise)</td>
<td>243–256, 272–286</td>
<td>257–271</td>
<td>0.22</td>
<td>0.20</td>
<td>0.18</td>
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<tr>
<td>N23 (pos switched)</td>
<td>225–274, 286–335</td>
<td>275–285</td>
<td>0.23</td>
<td>0.17</td>
<td>0.30</td>
</tr>
<tr>
<td>N23 (freq switched)</td>
<td>243–274, 286–306</td>
<td>275–285</td>
<td>0.70</td>
<td>0.53</td>
<td>1.5</td>
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</table>

### Table 2. CO line emission for molecular clouds near N49 and N132D

<table>
<thead>
<tr>
<th>Associated SNR</th>
<th>Number of Averaged Spectra</th>
<th>(&lt;W_{\text{CO}})&gt; (K km s(^{-1}))</th>
<th>(v) (km s(^{-1}))</th>
<th>(\sigma) (km s(^{-1}))</th>
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<tr>
<td>N49</td>
<td>7</td>
<td>1.72±0.12</td>
<td>+286.0±0.1</td>
<td>2.0±0.1</td>
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<tr>
<td>N132D</td>
<td>70</td>
<td>9.95±0.08</td>
<td>+264.0±0.1</td>
<td>2.8±0.1</td>
</tr>
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</table>

### Table 3. CO line emission near N23 (Scan positions explained in text)

<table>
<thead>
<tr>
<th>Scan Position</th>
<th>Number of Averaged Scans</th>
<th>(&lt;W_{\text{CO}})&gt; (K km s(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>East of N23</td>
<td>9</td>
<td>0.01 ± 0.16</td>
</tr>
<tr>
<td>Square NE of N23</td>
<td>16</td>
<td>1.58 ± 0.52</td>
</tr>
<tr>
<td>Strip North of N23</td>
<td>15</td>
<td>0.25 ± 0.53</td>
</tr>
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</table>
Fig. 1.— Ensemble spectra of the molecular clouds near N49 and N132D. Only scans with signal stronger than $3\delta_{W_{CO}}$ are averaged in these spectra. The zero baseline level is shown. The values listed in Table 1 are calculated from these spectra.

Fig. 2.— Spectra of CO $J = 2\rightarrow1$ emission from the molecular cloud near N49. The spectra were observed on a grid spaced 20'' apart. The center of N49 is marked as position (0,0). The reference lines show the zero baseline level, the line center (+286.0 km s$^{-1}$) and FWHM (4.65 km s$^{-1}$) of the ensemble cloud spectra (shown in Figure 1). (North is to the top, east is to the left)

Fig. 3.— Spectra of CO $J = 2\rightarrow1$ emission from the molecular cloud near N132D. The spectra were observed on a grid spaced 20'' apart. The center of N132D is marked as position (0,0). The reference lines show the zero baseline level, the line center (+264.0 km s$^{-1}$) and FWHM (6.64 km s$^{-1}$) of the ensemble cloud spectra (shown in Figure 1). (North is at the left of the page and east is toward the bottom.)

Fig. 4.— Spectra of position-switched CO $J = 2\rightarrow1$ emission near N23. The center of the remnant is marked with (0,0). The spectra were observed on a grid spaced 20'' apart. Boxed comments show the locations of the southernmost positions of short, frequency-switched scans. (North is at top, east is to the left)

Fig. 5.— ROSAT X-ray image of N49 overlaid with velocity integrated CO emission contours. The X-ray contours are at 0.35, 0.87, 1.4, 1.9, 2.4, 3.0, and 3.5 counts s$^{-1}$ arcmin$^{-2}$. The CO contours are 1.0, 1.3, 1.7, 2.0, 2.3, and 2.7 K km s$^{-1}$. The grid pattern for the CO observations is shown. Coordinates are in epoch B1950.

Fig. 6.— ROSAT X-ray image of N132D overlaid with velocity integrated emission contours. The X-ray contours are at 0.54, 1.1, 1.6, 2.1, 2.7, 3.2, and 3.8 counts s$^{-1}$ arcmin$^{-2}$. The CO contours are 5.0, 8.3, 11.7, 15.0, 18.3, 21.7, 25.0, 28.3, and 31.7 K km s$^{-1}$. The grid pattern for the CO observations is shown. Coordinates are in epoch B1950.

Fig. 7.— Einstein X-ray image of N23. The X-ray contours are at 0.023, 0.070, 0.12, 0.16, 0.21, 0.26, and 0.30 counts s$^{-1}$ arcmin$^{-2}$. The grid pattern for the CO observations is shown. Coordinates are in epoch B1950. (Squares are 840 second position-switched scans and triangles are short 120 second frequency-switched scans.)

Fig. 8.— Narrow-band H$\alpha$ optical image of N132D and a nearby H II region from the Rutgers/CTIO imaging Fabry-Perot spectrometer (Morse et al. 1995) overlaid with contours of molecular emission. Note the strong spatial correlation between the molecular cloud and the H II region. North is at top, east is to the left.
Southwest corner of 2' by 2' map of pointings

Southernmost spectrum in 20'' by 9.3'' strip of pointings