KINEMATICS OF SUPERNOVA REMNANTS IN THE GALAXY AND LMC

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The optical emission lines of six SNRs have been observed at very high angular and kinematic resolutions. Kinematic ion temperatures were derived, and evidence was found in shocked regions for Maxwellian microturbulence on scales $\lesssim 0.01$ pc, and for non-Maxwellian macroturbulence on scales > 0.1 pc. The widths of shocked regions in the Cygnus Loop and the existence of three types of spectral feature in the LMC remnants are discussed in terms of SNR evolution in cloudy interstellar media.

1. OBSERVATIONS AND RESULTS

The Cygnus Loop, IC 443, Puppis A, Vela X, N49, and N63A were observed with 4-m echelle spectrographs at Kitt Peak and Cerro Tololo with resolutions of 2" and 2.7 km s^{-1}. Widths, intensities, and radial velocities of bright spectral features (about 5" in size) visible in Hα, Hβ, and the doublets of [O III], [N II], and [S II] were measured. Thermal and non-thermal components of the Gaussians were determined from the differing widths of the H I and heavy-ion Gaussians. This report presents only portions of the results. Complete accounts may be found in P. Shull et al. (1982) and three in-press (1983) Astrophys.J. articles by P. Shull.

Bright knots in the smallest visible filaments of the galactic SNRs were observed. Mean values and standard deviations (not errors) of the line half-widths at half-maximum, v, corrected for the instrumental function, for knots in the eastern Cygnus Loop, are: $\langle v \rangle = 21 \pm 5$, 14 ± 5, and 18 ± 10 km s^{-1}, respectively, in H I, [N II], and [O III]. In the western part, the dispersions are 28 ± 4, 25 ± 8, and 29 ± 11 km s^{-1}.

The velocity dispersions for H I are larger than for [N II], as one would expect if thermal equilibrium prevailed. However, the [O III] dispersions are larger than the dispersions of H I and [N II]. On high-resolution spectra and photographs, the patterns of [O III] emission usually differ from the patterns of the other emission lines, indicating that the [O III] emission arises in physically distinct volumes. The mean ion temperatures and their standard deviations (not errors) for the

J. Danziger and P. Gorenstein (eds.), Supernova Remnants and their X-Ray Emission, 295–298.

galactic SNRs are in Table 1. The [O III] temperatures were derived by assuming that the narrowest observed lines are purely thermal in origin.

TABLE 1. Mean Ion Temperatures of the Galactic SNRs

SNR	Region	<T([O III])>	(1000 K)	<T([N II])>
Cygnus	E (SE2,3)	...		13 ± 4
	W	...		16 ± 9
	All 5 Regions	40-50		16 ± 9
IC 443	NE (A)	...		15 ± 9
	Both Regions	30		15 ± 9
Vela	SW (A)	...		27 ± 9
	SW (B)	...		22 ± 7
Puppis	NW (C)	...		19 ??

There is no apparent correlation between the nonthermal velocity dispersions, u, within knots (microturbulence) and the standard deviations of the radial velocities of the knots (macroturbulence). Both types of turbulence are characterized by speeds of 10-30 km s^{-1}.

In LMC N49 and N63A, spectral features named spikes, narrow bands, and broad bands may be distinguished on the basis of v and projected expansion velocity (see Table 2). The bands expand relative to the spikes, which are low-v, slit-length features with heliocentric radial velocities typical of neighboring LMC H II regions. Kinematic ages for N49 and N63A, based on maximum observed expansion velocities, are 16 000 and 10 000 years, respectively.

TABLE 2. Properties of Spikes and Bands in N49

Feature Type	v (km s^{-1}, HWHM)	v_{exp} (km s^{-1})	Surface Brightness
Spike	5-15	0	...
Narrow Band	30-60	100-140	Low
Broad Band	80-130	20-70	High

The mean values and standard deviations of v (corrected for instrumental broadening) and of T in the eastern part of N49 are shown in Table 3. For the spikes in N49 and N63A, the mean [O III], [N II], and H I velocity dispersions become progressively larger. For the bands of these remnants, however, the velocity dispersions of the heavier ion species can exceed those of the lighter species. Therefore, the ion temperatures derived for the bands will be useless (notice their large standard deviations).

TABLE 3. Mean Velocity Dispersions and Ion Temperatures for N49 (East)

Feature Type	$\langle v \rangle$ (km s^{-1}, HWHM) H I	$\langle v \rangle$ (km s^{-1}, HWHM) [N II]	$\langle v \rangle$ (km s^{-1}, HWHM) [O III]	$\langle T \rangle$ (1000 K)
Spike	16 ± 5	12 ± 6	7 ± 1	16 ± 3
Narrow Band	53 ± 8	44 ± 9	47 ± 18	65 ± 69
Broad Band	88 ± 22	85 ± 15	109 ± 24	257 ± 336

2. INTERPRETATION

2.1. Cloud-Knot-Cell Hierarchy

The temperatures derived for the band features in N49 and N63A, too high for optically emitting regions, can be understood if the shocked medium consists of clouds (filaments about 1 pc in size), which contain knots (about 0.01 pc), which contain cells (unresolved). The knots' velocity distribution is non-Maxwellian, while that of the cells is Maxwellian. A knot and its cells are in thermal equilibrium.

With this model, the spectrograph slit (about 1" x 100") resolves the individual knots within clouds at 1 kpc (MWG SNRs); T and u can be derived because they are constant within a knot. At 50 kpc (LMC SNRs) the slit resolves only clouds; T and u cannot be derived because they vary from knot to knot within a cloud. Evidently, these variations become significant on length scales between 0.01 and 0.5 pc.

2.2. Knot Wandering

In high-resolution [OIII] and [S II] photographs of the eastern Cygnus Loop, the [O III] filaments are narrow (5"), and the knots are collinear; curiously, the [S II] filaments are broad (30"), and the knots are scattered. In contrast, the emission layer of a steady-state shock in the Cygnus Loop should be about 0".3 thick. However, the filament widths are comparable to the products of the knots' random velocities (10-30 km s^{-1}) with the emission lifetimes of postshock [O III] and [S II] gas, about 200 and 1000 years, respectively. Apparently, randomly wandering knots can broaden the filamentary structure of SNRs.

2.3 Cloud Accelerations and Velocity Dispersions

The overall symmetry in N49's spectra suggests that the SN produced one main blast wave. The acceleration of a cloud by a blast wave (Cox 1979) is proportional to (intercloud matrix density)/(cloud density). If the bands are produced by shocked clouds, the ratio of expansion speeds of the broad and narrow bands should give the relative densities of the clouds. Typical values of the narrow and broad bands' expansion speeds are 120 and 40 km s^{-1}, respectively, implying that broad bands are three times denser than narrow bands on the average. This is qualitatively confirmed by the greater surface brightness of the broad bands as compared to the narrow bands (Table 2). A 1000 km s^{-1} blast striking clouds having cloud/matrix preshock density ratios of 10 to 100 would accelerate them to 15-150 km s^{-1} (approximately what is observed).

The width of the band structure indicates that the blast produces shock wave ensembles as it propagates in the surrounding heterogeneous medium. The internal velocity dispersions, v, of clouds should be less than the velocities of the slow (optical) shocks within the clouds, postulated to be 70-120 km s^{-1}. Indeed, v is 30-130 km s^{-1}. If these shocks conserve kinetic energy, then v should be proportional to $d\rho\ \rho^{-3/2}$ where $d\rho$ is the internal clumpiness of a cloud. Since v for the narrow bands is about 2-3 times smaller than for the broad bands, and broad bands have densities three times higher than narrow bands, the narrow-band clouds should be 15 times less clumpy than the broad-band clouds.

2.4. The N49 and N63A Spikes

The spike of N49 probably results from an H II regions ionized by UV photons from the cloud shocks. It has the spectral and kinematic properties of nearby LMC H II regions, and exactly the same spatial extent as N49. Its brightness correlates with the SNR's band structure. J. Shull and McKee (1979) model a shock and its UV precursor flux for LMC-like abundances. The Stromgren layer and line intensities calculated from this model (corrected for the model's N overabundance) agree with observations although problems concerning the brightness of the spike remain.

For the same reasons as in N49, the N63A spike may be associated with an H II region. Actually, two superposed spikes are observed. The fainter, longer spike results from an extended region around the SNR. The shorter, brighter spike is produced by a round "blob" near the SNR's southwestern limb. One or both of these regions may be ionized by a star in the nearby cluster NGC 2030, although available data indicate that no star is hot enough ($T_{eff} \gtrsim 35000$ K) to produce the high [O III]/Hα ratio observed in the extended region. Possibly the extended region, and maybe also the blob, are fossil regions, ionized by the SN progenitor or the UV/X-ray burst accompanying the SN explosion. Results based on the model burst spectrum by Falk (1978), especially involving the relative decreases of the [O III]/Hα ratios in both regions, support this idea.

It is a pleasure to acknowledge discussions with R. Dufour and R. Parker, NSF grant AST 80-07450 and NASA Contract 09-15940 to Rice University, and observing time grants from Cerro Tololo and Kitt Peak.

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