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THE PENULTIMATE SUPERNOVA IN THE LARGE MAGELLANIC CLOUD: SNR 0540−69.3

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ABSTRACT

We present spectra of the supernova remnant (SNR) 0540−69.3 in the Large Magellanic Cloud that cover the wavelength interval 3500–9800 Å. An optical continuum is observed over this entire wavelength range from synchrotron emission near the 50 ms pulsar inside the remnant. The spectrum contains emission lines which are shifted by +370 km s^{-1} from the local LMC rest velocity. The line widths average 2735 ± 200 km s^{-1} (FWZI), which indicates an expansion age of 762 ± 50 yr. We detect lines of [O I], [O II], [O III], [S II]. [S III], [Ar III], [Ni II], [Fe II], [Fe III], Hα, and possibly [Fe V] and [Fe VII]. The Hα identification differs from the suggestion of Ca I] made by previous workers. The strong lines of oxygen and sulfur are similar to those seen in Cas A, the remnant of a massive star. Iron and nickel mixed into the oxygen-rich zone emulate properties inferred for SN 1987A, while a pulsar inside the SNR resembles the Crab Nebula. It is very likely that 0540−69.3 is the young SNR following core collapse of a massive star akin to the progenitor of SN 1987A. Since the explosion took place less than 1000 yr before 1987A, this object may be its most recent predecessor in the LMC.

Subject headings: galaxies: Magellanic Clouds — nebulae: individual (SNR 0540−69.3) — nebulae: supernova remnants

I. INTRODUCTION

A comprehensive survey of supernova remnants (SNR) is underway for the Large and Small Magellanic Clouds in which we are obtaining spectra of each remnant from 3500 Å to 9800 Å. We aim to study the origin and evolution of supernova remnants and the structure and composition of the interstellar gas in those galaxies. One of the most interesting objects in our survey is the LMC remnant 0540−69.3, which is young ($t < 1000$ yr), dominated by the heavy elements of a stellar interior, and which contains a rapidly spinning neutron star. This paper reports our spectra for this extraordinary object.

The SNR was investigated by Mathewson *et al.* (1980), in an optical study of radio and X-ray remnants in the LMC. Their interference filter images revealed an annulus of [O III] λ5007 emission about 8″ in diameter. They also detected a faint, smaller ring through a filter designed to pass [N II] λ6584 and saw nothing in a filter centered at Hβ. With additional evidence from a spectrum, they concluded that 0540−69.3 (which for brevity we call 0540) is an oxygen-rich remnant of the type characterized by Cas A (Kirshner and Chevalier 1977; Chevalier and Kirshner 1978, 1979). The other members of this class include N132D in the LMC (Lasker 1980), 1E 0102 in the SMC (Dopita and Tuohy 1984, hereafter DT), G292.2+1.8 (Goss *et al.* 1979) and Puppis A in our Galaxy (Winkler and Kirshner 1985), and the SNR in NGC 4449 (Kirshner and Blair 1980; Blair, Kirshner, and Winkler 1983). In general, chemical properties of the oxygen-rich remnants match expectations for the interiors of massive stars which have progressed beyond helium burning, but the details are of great interest to connect the stellar evolution of massive stars with the chemical evolution of galaxies. Since SN 1987A is also the result of core collapse in a massive star of this type, these SNRs foreshadow the evolution of SN 1987A.

A characteristic age for 0540 is 760 yr, as described in § IV*b*. We note that SN 1987A is located only 25′ away from 0540 (a projected distance of 400 pc) and that both are in the extended complex of young stars and emission surrounding 30 Doradus. As pointed out by Chu and Kennicutt (1988), 0540 is near the H II region DEM 269 (Davies, Elliott, and Meaburn 1976), and the OB association LH 104 (Lucke and Hodge 1970). So 0540 is not only of the same general class as SN 1987A, but belongs to the same generation of stars from the same neighborhood of the LMC.

SNR 0540 also shows a nonthermal X-ray spectrum (Clark *et al.* 1982). Seward, Harnden, and Helfand (1984) found that most of the X-ray emission comes from an unresolved source near the center of the nebula and that 23% of the X-ray emission is pulsed with a 50 ms period. Optical observations by Chanan, Helfand, and Reynolds (1984) using interference filters showed a continuum source inside the [O III] shell whose flux matched the extrapolation of the nonthermal source from the radio measurements (Milne, Caswell, and Haynes (1980) to the X-rays. Optical pulses from the 50 ms pulsar were measured by Middleditch, Pennypacker, and Burns (1987). Evidently, 0540 contains a pulsar, as modeled by Reynolds (1985*a*). The pulsar and the synchrotron source in 0540 bear a strong resemblance to the Crab Nebula (Reynolds 1985*b*), although their effect on

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the optical spectrum of the surrounding nebula may be smaller, as discussed in § IV*c*. While no pulsar has yet been seen in SN 1987A, the neutrino signal of the core collapse is consistent with the formation of a neutron star (Burrows and Lattimer 1987), and the future evolution of SN 1987A from supernova to supernebula may follow a path similar to that of 0540.

Optical spectroscopy can indicate the chemical composition of the debris and provide kinematic information. These can test the predictions of stellar evolution and supernova explosion models. Pioneering work by DT demonstrated that the remnant emits [O I], [O II], and [O III] as well as [S II] and possibly [Ar III]. In addition, they identified a feature at 6580 Å as Ca I]. As presented in § II, our optical spectra have wider wavelength coverage, improved sensitivity that allows new identifications, and in the vicinity of $\lambda 6580$, higher resolution. In § III, we discuss the velocities and identifications, including a key point on which we differ from Dopita and Tuohy: the presence of Hα. In § IV, we discuss the continuum, kinematics, ionizing source, composition, and origin of 0540.

II. OBSERVATIONS AND REDUCTIONS

Table 1 details the data obtained at the CTIO 4 m telescope using the R-C spectrograph with various grating and detector combinations, including the SIT Vidicon and the GEC CCD, in 1983 and 1984. The slit was centered for each observation at $\alpha = 05^h40^m34^s$, $\delta = -69°21'30''$ (1950) with position angle 77°. Typical slit width was 1.″5, so we observed only about a quarter of the remnant. The resulting line ratios represent an average over inhomogeneities on scales smaller than 2″. Interference filter images show structure on larger scales, and it is likely that structure on smaller scales is also present. A healthy skepticism toward the details of the interpretation is never misplaced, but the outlines are likely to be valid as the observations do measure an average of emission over the remnant.

The two-dimensional spectra were reduced at the University of Michigan using programs developed by Todd Boroson. We subtracted the average of several bias frames from the data and then divided by a flat field formed from an average of several dome flats taken at the beginning and end of each night. Geometric rectifications were essential for the Vidicon data, and were carried out using dome flats observed through a multihole decker to obtain each locus of constant position on the slit and comparison spectra to map each locus of constant wavelength.

The two-dimensional spectra were placed on a linear wavelength scale, sky-subtracted, and one-dimensional spectra were extracted across the remnant using standard procedures of NOAO's IRAF (Image Reduction and Analysis Facility) at the Center for Astrophysics. The spectra were corrected for atmospheric extinction using standard CTIO extinction tables and flux calibrations were obtained through observation of several standard stars each night. The reduced spectra are shown in Figure 1.

Sky subtraction was especially delicate since the SNR is embedded in an H II region which has strong, narrow emission lines that vary in strength along the slit. Figure 2 (Plate 8) shows a typical data frame, with a region near the SNR where the sky subtractions has been performed. The SNR lines are very broad, and quite symmetric. Where the surrounding H II region varies in brightness, the resulting sky subtraction in the SNR sometimes leaves easily recognizable defects: narrow glitches on the blue side of the broad line profiles. Figure 3 shows the technique used to repair these subtraction defects. To reconstruct each line profile in the bad regions, we duplicated the shape of the red side of the line. While this assumes the lines are intrinsically symmetric, that is correct for lines where H II region emission is not a problem. We used this technique only in the most egregious cases and never changed the flux measurements by more than 10%. Figure 1*f* shows the spectrum of the H II region as extracted from observation 5. The weak [N II] and [S II] lines, relative to Hα are very different from the spectra of the SNR, but similar to spectra of the 30 Doradus nebula as reported by Mathis, Chu, and Peterson (1985).

Most of the instrumental configurations of Table 1 had resolution much better than the line width, so the spectra could be smoothed without significantly altering the profiles of the emission lines. Line centers and fluxes were measured using the utilities in IRAF. Those values, along with measurements of the full width of the lines where they meet the continuum are given in Tables 2 and 3.

In combining the line measurements from several separate spectra, we have averaged the data where they overlap and have used observations in the overlap region to connect the flux scale from one spectrum to another, as indicated in Table 2. Short exposures were used to avoid saturation of the stronger lines in the Vidicon spectra. The agreement is generally very good, so that the resulting segments have line ratios that agree to about 10%. However, the lines redward of [S II] $\lambda 6724$ have been connected to [O III] $\lambda 5007$ through three such steps, and a cautious use of the line ratios is prudent.

The relative line fluxes for 0540 are tabulated in Table 3 on a scale where [O III] $\lambda 5007$ is taken as 100. We correct for two components of reddening: one from our Galaxy and another from dust in the LMC. We adopt a combined $E(B-V)$ of 0.19, attributing 0.07 to our Galaxy and 0.12 to the LMC in that direction (Isserstedt 1975; Koornneef and Code 1981; Nandy *et al.* 1981; Savage *et al.* 1983). This value agrees within the observational errors with the reddening derived from the [O II] and [S II] line strengths by the method of Dopita, Binette, and Schwartz (1982). While absolute fluxes are not our goal, the observed [O III] $\lambda 5007$ flux is roughly 3×10^{-4} ergs cm^{-2} s^{-1}, and the corresponding surface brightness is

TABLE 1

OBSERVATIONS OF SNR 0540−69.3

Number	UT Date	Detector	Wavelength (Å)	Resolution (FWHM, Å)	Time (s)
1	1983 Mar 15	Vidicon	3410–6995	12	4800
2	1984 Jan 31	GEC CCD	6150–8620	9	4800
3	1984 Feb 2	Vidicon	3430–6480	7	600
4	1984 Nov 28	GEC CCD	6860–10150	17	3600
5	1984 Nov 30	GEC CCD	6470–6900	2	1800

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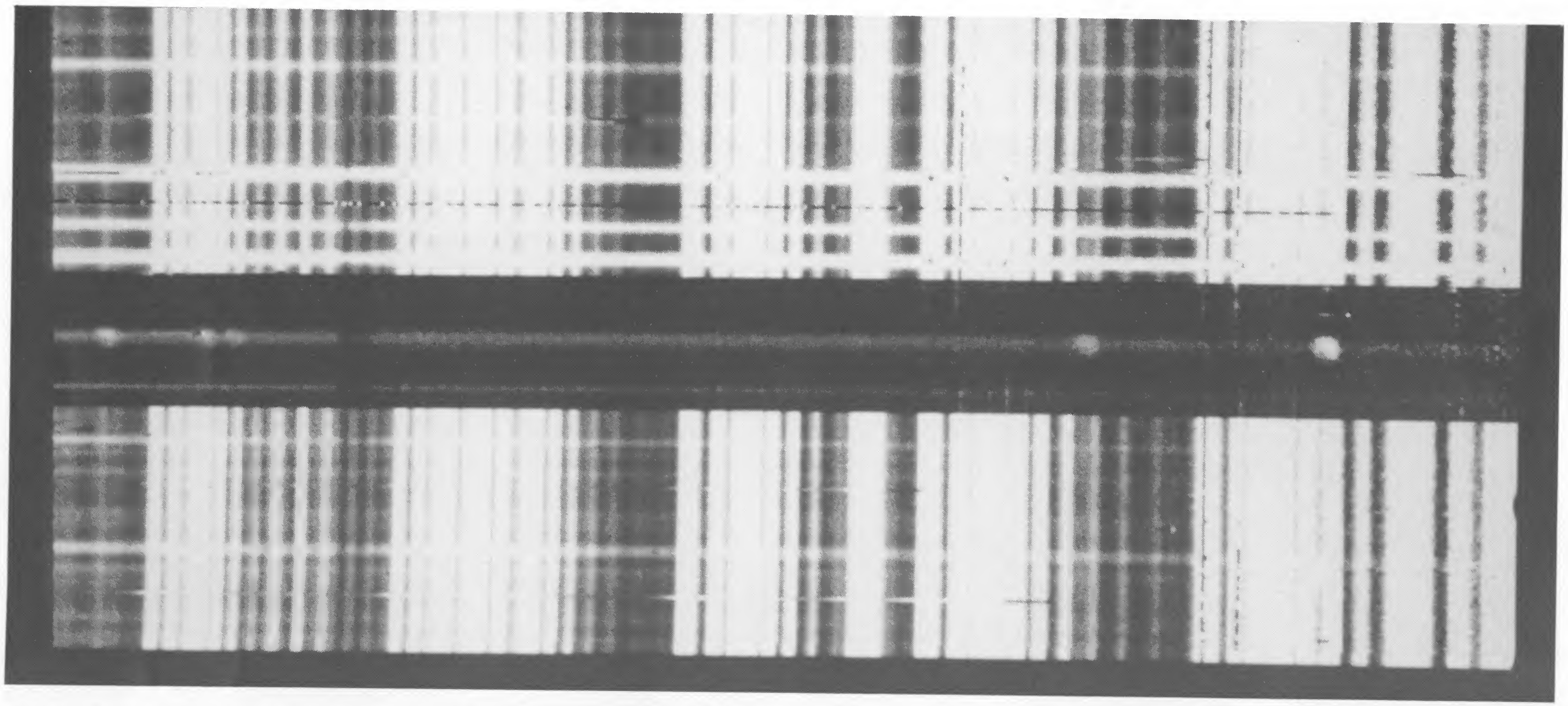

FIG. 2.—The two-dimensional data for SNR 0540−69.3. This frame, observation 4 of Table 1, covers the interval 6860–10150 Å. Numerous OH sky lines have been accurately subtracted in the vicinity of the SNR. Note the continuum that extends through the spectrum and the broad emission lines in the remnant compared to the unresolved night sky emission. The strong lines easily visible in this spectrum are (*left to right*) [Ar III] λ7135, [O II] λ7325, [Ni II] λ7379, [S III] λ9069, and [S III] λ9532. The line of [Fe II] at 8617 Å is easily seen in Fig. 1*d* but is difficult to pick out in this presentation

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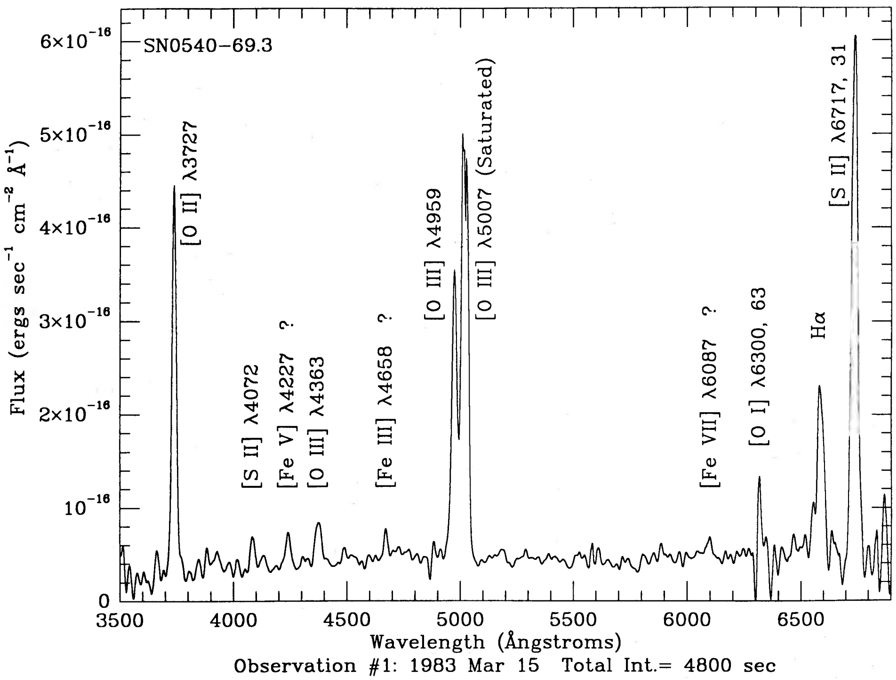

FIG. 1*a*

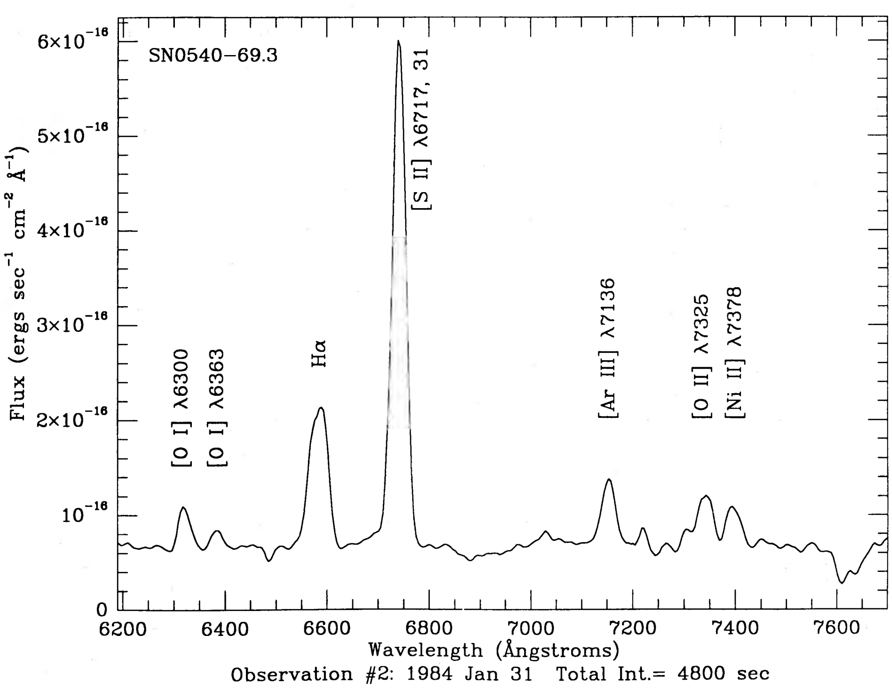

FIG. 1*b*

FIG. 1.—Spectra of SNR 0540−69.3. Note that the synchrotron continuum is visible in each spectrum. The flux is smaller than the flux from the remnant because the spectrograph slit is smaller than the remnant. (*a*) Observation 1; (*b*) observation 2; (*c*) observation 3; (*d*) observation 4; (*e*) observation 5.

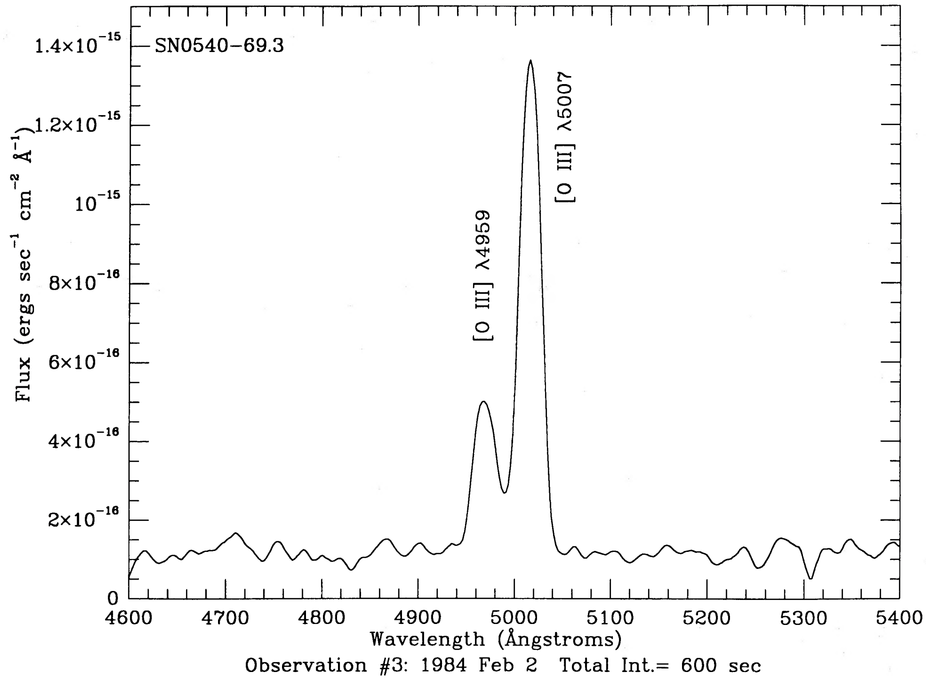

FIG. 1*c*

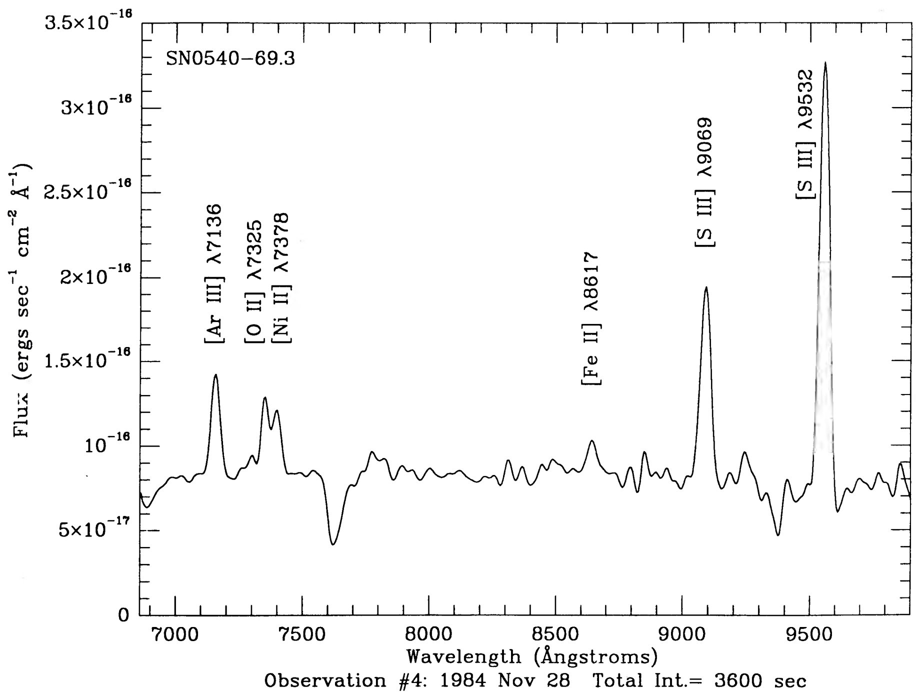

FIG. 1*d*

3×10^{-15} ergs cm^{-2} s^{-1} arcsec^{-2}. The uncertainty in the line ratios is as low as 10% when they are derived from a single spectrum, but uncertainties of 20% are more typical, with difficulties in calibration, sky subtraction, and photon statistics contributing to the error.

III. KINEMATICS AND LINE IDENTIFICATIONS

a) Velocities: Traces of a Runaway Star?

The observed wavelengths for strong unblended lines in Table 2 allow a reliable measurement of the systemic velocity of 0540. Using [O II] λ3727, [O III] λλ4959, 5007, [Ar III] λ7135, [Ni II] λ7378, [Fe II] λ8617, and [S II] λλ9069, 9432 we obtain $\langle v \rangle = +582 \pm 30$ km s^{-1}. This is startlingly different from the velocity of $+215 \pm 30$ km s^{-1} obtained for the adjacent H II region shown in Figure 1*f*. Wavelengths measured for night sky lines are accurate, and the H II region velocity agrees tolerably well with the systemic velocity of the LMC of +270 km s^{-1} (Sandage and Tammann 1981), and somewhat better with the H I observed at this location (Rohlfs *et al.* 1984) which has components at heliocentric velocities 262 and 280 km s^{-1}.

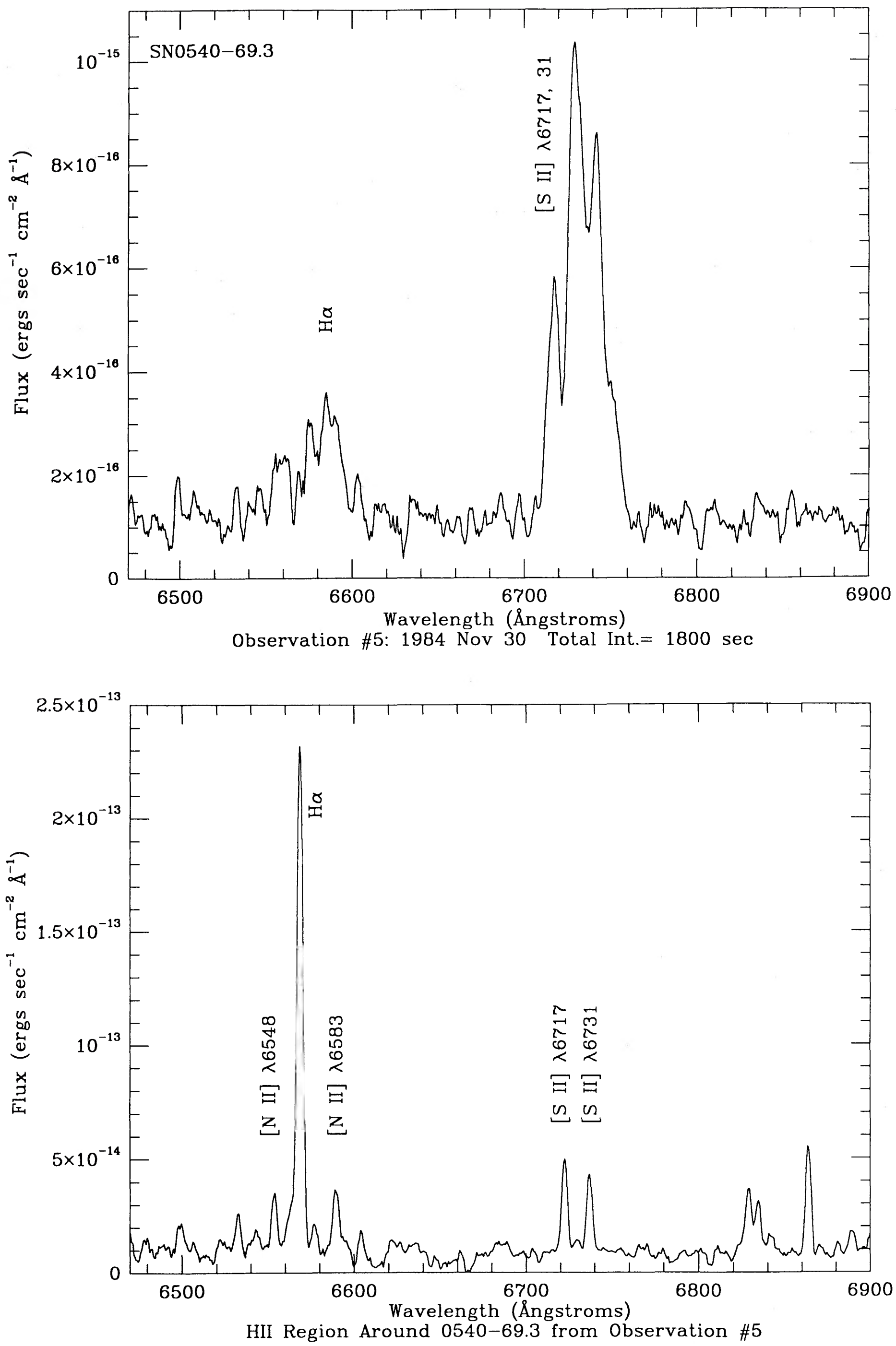

FIG. 1*e*

Molecular cloud velocities in the LMC fit a simple kinematic model that predicts 260 km s^{-1} at the SNR location (Dame and Thaddeus 1988). The SNR wavelengths we find agree with those measured by DT, so we are confident that the +370 km s^{-1} difference between the centroid of the SNR emission and the local gas is real. A similar offset between the surrounding H II region and the velocity center of the expanding debris is seen in NGC 4449, where the oxygen-rich material has a velocity difference of about 500 km s^{-1} (Balick and Heckman 1978).

There are at least two possible origins for this large velocity. It may reflect the motion of the star that exploded through the local interstellar gas. This requires a special history for the progenitor since random velocities for gas and young stars, and even the velocity of escape for the LMC, are much smaller than 370 km s^{-1}. A star might acquire this extraordinary velocity if it were formerly a member of a close, massive binary disrupted by a previous supernova explosion, as suggested in a more general context by Zwicky (1957). In that case, we might look for some sign of the other, originally more massive partner, although its demise might have occurred

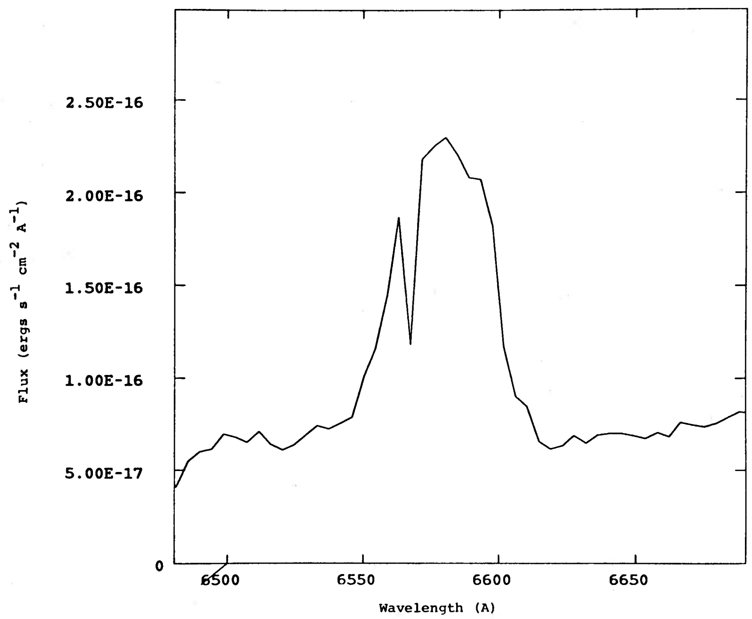

FIG. 3*a*

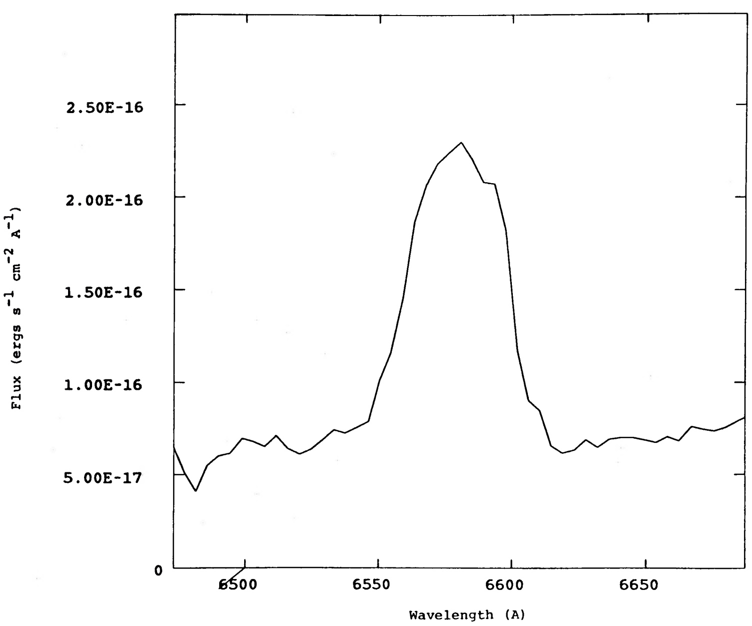

FIG. 3*b*

FIG. 3.—SNR 0540−69.3 Hα profiles (*a*) with sky subtraction defect from surrounding H II region and (*b*) as repaired

10^5 yr ago. Binary explanations have been advanced to account for the high space motion of the Crab (Gott, Gunn, and Ostriker 1970) and for the evolution of the progenitor of Kepler's SNR (Bandiera 1987) where the space velocity is inferred to be 340 km s^{-1}. Whatever their origin, high space velocities ($v_{rms} = 210$ km s^{-1}) are a general feature of the pulsar population in our Galaxy (Lyne, Anderson, and Salter 1982). Cordes (1986) has shown a correlation between the value of $P\dot{P}$ for Galactic pulsars and the space velocities. Using the value of $P\dot{P} = 25 \times 10^{-15}$ s from Seward, Harnden, and Helfand (1984), this relation predicts a space velocity of about 140 km s^{-1}. Since the origin of these pulsar velocities is not well understood, there is no simple way to predict the space motion of the debris, but velocities of order 100 km s^{-1} are not unbelievable.

The maximum distance the progenitor of 0540 could travel at 370 km s^{-1} in the 10^7 yr lifetime of a massive star is 3.5 kpc, comparable to the size of the LMC. The fact that the progenitor of 0540 exploded in the star-forming neighborhood means that it cannot have been traveling for more than about 10^6 yr. An origin in the nearest OB association (LH 104) would imply a travel time near 10^5 yr.

A more mundane origin for the velocity of the SNR emission would be a mildly asymmetric explosion which happens to have ejected more of the optically bright material in a direction away from us. A net shift in the line center of 350 km s^{-1} when

TABLE 2

WAVELENGTHS OF EMISSION LINES IN SNR 0540−69.3

Line (1)	Rest (Å) (2)	Predicted Rest ($v = 582$) (3)	Measured (Å) (4)	Velocity (km s^{-1}) (5)	Width (km s^{-1}) (6)	Sources (Observation Number) (7)
[O II]	3727.5	...	3736.6	732 ± 80	3130 ± 150	1
[S II]	4072.5	4073.2	4081.1	...	3010 ± 100	1
[Fe V]	4226.8	4229.3	4237.5	...	3120 ± 100	1
[O III]	4363.2	4361.8	4370.3	...	3090 ± 100	1
[Fe III]	4658.1	4660.0	4669.0	...	...	1
[O III]	4958.9	...	4967.4	515 ± 100	3020 ± 150	1, 3
	5006.8	...	5014.5	461 ± 120	2995 ± 150	3
[Fe VII]	6085.5	6084.2	6096.0	...	...	1
[O I]	6300.2	6304.3	6316.5	...	2700 ± 150	2
	6363.9	6367.8	6379.8	...	2600 ± 150	2
Hα	6562.8	6566.3	6579.0	...	3110 ± 200	1, 2, 5
[S II]	6722.9	6723.0	6736.0	...	2810 ± 100	1, 2, 5
[Ar III]	7135.8	...	7150.8	630 ± 100	2730 ± 100	2, 4
[O II]	7325.4	7324.8	7339.0	...	2800 ± 400	2, 4
[Ni II]	7379.6	...	7392.6	530 ± 100	2560 ± 150	2, 4
[Fe II]	8617.0	...	8637.1	700 ± 100	2545 ± 100	4
[S III]	9069.4	...	9084.2	490 ± 100	2640 ± 100	4
	9532.1	...	9551.2	600 ± 100	2265 ± 100	4

the expansion velocity is close to 1400 km s^{-1} requires substantial asymmetry but does not seem too extreme, although retaining the symmetry of the line profile requires a special geometry for the expansion. A more complete view of the kinematics for the SNR could come from an imaging Fabry-Perot or equivalent instrument as carried out by Tuohy and Dopita (1983) for the young oxygen-rich remnant in the SMC, 1E 0102−7219, where large asymmetries are observed. Due to the small diameter of 0540, this is worth doing only under conditions of good seeing, with an instrument that preserves good spatial resolution.

TABLE 3

LINE RATIOS FOR 0540, CASSIOPEIA A, AND THE CRAB NEBULA

Line	Wavelength (Å)	0540−69.3 Observed *F*	Corrected[a] *I*	Cas A[b] *I*	Crab[c] *I*
[O II]	3727	32	39	30	110
[Ne III]	3869	<1.5	<1.5	<0.5	13
[S II]	4072	3	3	13	12
[Fe V]	4227	4	5	<0.4	3
[O III]	4363	6	7	4	2
[Fe III]	4658	2:	2:	<0.3	3
Hβ	4861	<1.5	<1.5	<0.16	15
[O III]	5007	100	100	100	100
[Fe VII]	6086	2:	2:	<0.1	1
[O I]	6300	6	5	7	18
Hα	6563	32	27	<0.04	56
[N II]	6584	<2	<2	<0.03	41
[S II]	6723	81	67	12	185
[Ar III]	7135	10	8	3	15
[Ca II]	7291	<2	<2	2:	2:
[O II]	7325	7	6	11	11
[Ni II]	7378	6	5	...	17
[Fe II]	8617	3	2	...	4
[S III]	9069	22	16	4	20
	9532	48	34	8	35

[a] $E(B-V) = 0.19$.

[b] Filament 1, Chevalier and Kirshner 1979.

[c] FK 10, Fesen and Kirshner 1982; Henry, MacAlpine, and Kirshner 1984.

b) Hα *or* Ca I]? *The* 6580 Å *Question*

Regardless of its cause, we use the observed velocity shift of +582 km s^{-1} to help identify lines in Table 2. For each line which was not used to measure the velocity shift, we calculate the rest wavelength that corresponds to the measured wavelength (col. [3] of Table 2). The feature whose observed wavelength is 6579.0 Å corresponds to a rest wavelength of 6566.3 Å at +582 km s^{-1}. We attribute this line to Hα. DT measured a similar wavelength of 6580.0 Å but attributed this line to Ca I], with rest wavelength 6572.8 Å, and in the original work on 0540, Mathewson *et al.* (1980) identified it as [N II] λ6584. The identification clearly deserves some discussion, both because our identification differs from previous work and because of the intrinsic importance of hydrogen in the chemical picture for an evolved star.

The identification by Mathewson *et al.* is due only to imaging through an interference filter of width 16 Å centered for [N II] λ6584 emission (presumably redshifted to 6589 Å for the LMC). They remarked that the emission observed this way formed a smaller disk of emission, concentric with the [O III] emission. Inspection of Figure 3 indicates that the redshifted emission of Hα would contribute to the light seen through this filter. This emission could form a small disk, since only the receding cap of the remnant would be imaged. The unacceptably poor match of the 6566 Å rest wavelength for the line in question to a 6584 Å rest wavelength and the absence of the [N II] λ6548 line in the spectra leave no question that [N II] is not the correct identification.

DT suggested Ca I] λ6573 as the identity of this line. They had three reasons for preferring this unusual attribution over Hα, despite the fact that this line had never been reported in nebular spectra, at least according to the catalog of astrophysical emission lines compiled by Meinel, Aveni, and Stockton (1968). First, DT argued that the overall pattern of abundances included material from deep inside a massive star, but not surface material. Hence they expected to see oxygen, sulfur, calcium, and argon as are seen in Cas A (Chevalier and Kirshner 1979), but no hydrogen in the fast-moving debris. Second, they observed no Hβ, and concluded that the ratio

Hα/Hβ would have to exceed 40. Since such high decrements are not observed elsewhere, they concluded that the Hα identification is untenable. Third, they argued that the smaller disk of the Ca I] line as seen by Mathewson *et al.* through their [N II] filter reflected a real concentration of the ^{40}Ca nuclei toward the interior of the remnant, which might be expected closer to the center than ^{16}O during nuclear cooking in the core.

Although the arguments of Dopita and Tuohy are interesting and form a coherent picture, we believe they are not conclusive, based on our spectra and theirs, and on new observations of other remnants. Before responding to each of the arguments for the Ca I] identification brought forward by DT, we note the simplest argument: as shown in Table 2 the predicted rest wavelength is within 3.5 Å for Hα, but differs by 6.8 Å for Ca I], which would make it by far the poorest fit of any line in the entire spectrum. If we examine the list of proposed identifications, the mean difference between predicted and observed wavelengths is 1.2 Å. Hα is the best fitting choice for our data, and also in the data of DT, where identifying the line as Hα would have given only half the velocity discrepancy that resulted from calling the line Ca I] λ6573.

First, we consider whether high-velocity Hα is out of the question for a young SNR from a massive star. New evidence from Cas A and from SN 1987A shows that it is not. In the case of Cas A, recent work by Fesen, Becker, and Blair (1987) and by Fesen, Becker, and Goodrich (1988) demonstrates that some hydrogen-bearing material has a velocity of 8600 km s^{-1}, comparable to the velocity of the oxygen and sulfur knots. For SN 1987A, the spectra at age 1 yr and beyond show infrared hydrogen lines with the same 3000 km s^{-1} width as observed for lines of iron group elements (Rank *et al.* 1988; Whitelock *et al.* 1988). Presumably this reflects mixing some hydrogen with the debris from deep in the explosion. At any rate, these recent observations suggest that it is not impossible to have 1500 km s^{-1} hydrogen in a young SNR.

Second, the Balmer decrement appears to be reported incorrectly by DT. In their Table 2, they cite the observed line strength for Ca I] (or Hα) as 17.4 in units where [O III] is 100, and in the text give an upper limit of 1.6 for Hβ. This corresponds to an observed decrement of at least 11, not 40 as they say in the text. Taking reddening into account in the amount of $E(B-V) = 0.19$, the intrinsic Balmer decrement exceeds 8, which does not seem a devastating objection to possible Hα.

Independent of DT, we have our own more stringent limit on the strength of Hβ. With an upper limit on Hβ of 1.5 in the units of Table 2, we find Hα/Hβ > 20. While this is a powerful constraint on hydrogen emission mechanisms, it is not necessarily a fatal objection to this identification. For example, Raymond (1988) has pointed out that the resonance excitation of O I could be important in creating Hα photons without creating Hβ. Since photons scattering in the resonance O I line at 1025 Å could excite the $n = 3$ level of hydrogen because of its coincidence with Lyman-β, a gas with a high oxygen abundance and low ionization could produce a large amount of Hα emission without producing Hβ. However, Raymond also points out that the observed limits on other O I lines, such as λ8446, are not consistent with this scheme. As a matter of method, it seems more plausible that the correct understanding of the Balmer decrement has eluded our grasp than that so unlikely a line as Ca I] is masquerading as Hα.

Third, the distribution of the "calcium" is not necessarily more concentrated toward the center of an oxygen-rich remnant. Since the measured velocity width of the putative Ca I] line is the same as the velocity width measured for the [O III] emission, we should expect the two elements to have about the same spatial extent. In the one case where the spatial resolution of chemical abundances can be observed, Cas A, the heavy nuclei of sulfur, argon, and calcium are seen at higher velocities and further from the center than the oxygen-rich gas (van den Bergh and Kamper 1983). However, this issue is better settled by observations through the appropriate filters than through polemics. We have obtained images of 0540 through a 60 Å Hα filter centered at the LMC Hα velocity. Preliminary analysis shows that the Hα image is in fact smaller than the [O III]. A thorough investigation of the spatial distribution of each element in 0540 is underway; it will be difficult because of the small angular size for this object and space-based observations may eventually be more helpful.

c) *Other Lines of Inquiry*

In Cas A, Chevalier and Kirshner (1979) found that the abundances of sulfur, calcium, and argon are correlated, as predicted by models for the interiors of massive stars. In 0540 we see strong sulfur lines, and the identification of [Ar III] λ7135 which was barely detected by DT seems secure. While the Ca I] suggestion by DT seems questionable, the possible identification of calcium is an important issue. Other lines of Ca I which might be present would be the resonance line at 4226 Å and two forbidden lines that connect to the ground state: a doublet at λλ4913, 4916 (Multiplet 1*F*), and λ4575 (multiplet 2*F*). We do see a weak feature at 4229.2 Å, but none at 4575 Å or 4913 Å. We prefer the identification of [Fe V] λ4227 for the 4229 Å feature in the absence of any other line of calcium. A more likely way to detect calcium than the neutral atom is the [Ca II] line at 7291 Å. This line is equal in strength to the [O II] λ7325 line in the Cas A knots which are dominated by sulfur, but more typically it is not strong enough to be seen in Cas A knots where [O II], [S II], and [Ar III] are all detected. While there is a hint of possible [Ca II] λ7291 on the blue edge of the [O II] line in Figure 1*b*, calcium could be present in the expected ratio to sulfur and argon without producing a detectable line. We conclude that there is no strong evidence for calcium in 0540.

The red [S II] lines at λλ6717, 6731 are density-sensitive, but blended. Still, an estimate of the density can be made from the observed centroid wavelength of the blended pair. In the low-density limit, the 6717 Å and 6731 Å lines have the centroid of their flux at 6723 Å, and in the high-density limit, the blended lines have a wavelength of 6727 Å. The measured wavelength, when corrected for a +582 km s^{-1} shift, is 6723.0 Å, consistent with the low-density limit. While the accuracy of this technique is not very high, it seems likely that $n_e < 2000$ cm^{-3} in the S^+ zone. We note that [S II] λλ4069, 4076 matches the observed feature with a rest wavelength of 4073.1 Å. The [S III] lines are very strong, and a good value for the sulfur abundance should, in principle, be available from these data, since S^+ and S^{++} are likely to be the abundant ions of sulfur, as explored in § IV*e*.

Another identification worth discussing is the [Ni II] line at 7378 Å. This line is seen in the Crab Nebula and in many other astrophysical settings (Henry and Fesen 1988). While there is reason to suspect that the atomic data are not entirely correct for deriving abundances from these lines, there is no reason to doubt the attribution to nickel. The width of this line is similar to the widths of all the other lines; this may indicate that the nickel is well mixed with oxygen and other lighter elements.

We have attributed several lines to iron emission: [Fe V] λ4227, [Fe II] λ4658, [Fe VII] λ6087, and [Fe II] λ8617, guided by the identifications in the Crab Nebula (Fesen, Kirshner, and Chevalier 1978; Fesen and Kirshner 1982). Of these, the [Fe III] and [Fe VII] are very weak lines at the threshold of detection, and the [Fe V] is just one possible identification for the feature at 4229 Å. The [Fe II] λ8617 identification seems secure: it is the strongest line from a strong multiplet and is seen both in the Crab Nebula (Henry, MacAlpine, and Kirshner 1984) and in Cas A (Kirshner 1988). The width of this line is well measured, and like the [Ni II] line, it is the same as that for the oxygen lines, indicating that the iron is also mixed with oxygen in the debris.

The curious incident of the dog in the night-time (Conan-Doyle 1892) demonstrates that lines which are absent can be as significant as lines which are present. A reasonable upper limit to lines of [Ne III] λλ3869, 3968 and to He II λ4686, He I λ5876, and He I λ6678 is 2 in the units of Table 2. We also do not see the recombination lines of O I 7774 Å and 8446 Å, [Ca II] λ7291, the 7751 Å line of [Ar III] or the [C I] lines at 9823, 9849 Å. In this part of the spectrum, sky subtraction is more difficult, but the differential reddening makes an upper limit of 2 units (the measured flux of [Fe II] λ8617) a plausible estimate. The absence of neon is an important clue to the perpetrator of the 0540 explosion, pursued in § IV*e*.

In Table 3, we have included spectra from Cas A and from the Crab. Some items are conspicuously different: for example, the Cas A filament has no hydrogen emission to an extremely low level. Other items of interest are the weak lines of [O II] λ3727 and [S II] λ6724, which are collisionally deexcited at the high densities encountered in the Cas A knots. The absence of [N II] from both 0540 and Cas A, but not from the Crab, is an important clue that the Crab is much closer to normal abundances, although the strong helium lines in the Crab (e.g., He I λ5876 = 8, in the units of Table 3) imply a distinct difference from solar values (Davidson and Fesen 1985). The relative weakness of [O III] λ4363 in the Crab is an indication, as described below, that photoionization is more important in the Crab than in 0540.

IV. DISCUSSION

a) Continuum

All the spectra show a nonzero continuum. This is most easily seen in the two-dimensional spectrum of Figure 3. This continuum was not noted by DT, but it is surely the synchrotron emission observed through interference filters by Chanan, Helfand, and Reynolds (1984). Our observations show that the continuum is less extended along the slit than the emission lines, appears featureless, and extends in wavelength from 3500 Å to 9800 Å. In addition, Blair *et al.* (1989) have detected the faint, diffuse continuum from the remnant in a 660 minute exposure with the SWP camera of the *IUE* satellite. The optical and UV results are consistent with the findings of Chanan, Helfand, and Reynolds who measured a 4″ diameter for the synchrotron source, which is expected to be devoid of spectral features, and emits from the X-rays to the radio.

b) Age and Sweeping

The widths of the lines have been determined by direct measurement and are listed at zero intensity in Table 2. A significant fact is that all the lines have essentially the same width, so that there is unlikely to be clear separation of chemically distinct regions on the basis of expansion velocity. In detail there may be chemically inhomogeneous structures as observed in Cas A or in Puppis A, but we do not have the spatial resolution to resolve them. Using the same unblended lines used to establish the velocity, we find a characteristic velocity width of 2735 ± 200 km s^{-1}, corresponding to an expansion at less than 1400 km s^{-1}. This is lower than some young SNRs, but comparable to the velocities seen in the Crab (Clark *et al.* 1983), N132D (Lasker 1980), or G292 (Braun *et al.* 1983). The characteristic age of the remnant t, at distance D with angular diameter d and velocity width v is

$$t = 762(D/55\ \text{kpc})(d/8'')(2735\ \text{km s}^{-1}/v)\ \text{yr}\ . \qquad (1)$$

This estimate has an uncertainty of about 100 yr, but the real uncertainty is whether the remnant has been accelerated by the pulsar, as in the model of Reynolds (1985*a*) who finds an age of 800–1100 yr, or decelerated by interaction with surrounding matter in which case the actual age is less than 760 yr. Either way, the age is consistent with the rate of supernova explosions in the LMC, inferred to be at least 1 per 1000 yr from X-ray observations (Hughes, Helfand, and Kahn 1984).

It is interesting to compare the various age estimates for 0540 and for the Crab. The Crab is known to have an age of 934 yr; the pulsar spin-down time, $t_s = P/2\dot{P}$, is 1240 yr; and the diameter divided by twice the expansion velocity is about 2.4 pc/3000 km s^{-1} or 810 yr. For 0540, we do not know the true age, $P/2\dot{P}$ is 1600 yr, and equation (1) gives the kinematic age as 762 yr. If we take 762 yr to be the real age, t, then since the pulsar braking index (Middleditch, Pennypacker, and Burns 1987) is known to be $n = 3.6$, we can calculate the initial period of the pulsar, P_i, in terms of the present period P_0:

$$P_0/P_i = \left[1 - \frac{(n-1)}{2}\frac{t}{ts}\right]^{1/(n-1)} . \qquad (2)$$

For a present period of 50 ms, the initial period would have been 35 ms. Recently, Manchester and Peterson (1989) have measured the braking index as $n = 2.0$, which would give an initial period of 38 ms.

For any reasonable history, 0540 is the youngest known remnant in the LMC (not yet counting SN 1987A among the remnants). The closest competitor is the remnant N132D, whose size and expansion velocity imply an age near 1300 yr. SNR 0540 is the supernova in the LMC previous to SN 1987A and might have been visible to austral observers near the year A.D. 1100.

Since the remnant has a radius of about 1 pc, the swept-up hydrogen mass of gas at mean density n_H will be

$$M = 0.1(r/1\ \text{pc})^3(n_H/1\ \text{cm}^{-3})\ M_\odot\ . \qquad (3)$$

The ejected mass is likely to be much larger than this, so swept-up interstellar matter should not dominate the dynamics. However, if circumstellar matter surrounds 0540, as it may for SN 1987A (Fransson *et al.* 1989), then the effects on the evolution of the remnant could be significant.

c) Ionization: Photo or Shock?

What is the source of excitation for the optical emission we observe for 0540? Is it shock heating, as suggested by Dopita and Tuohy, or does the synchrotron continuum play an essential role, as it does in the Crab? One way to assess the effects of the synchrotron emission is to compare the ratio of ionizing flux to density, the ionization parameter (see, for example, Henry and MacAlpine 1982), for Crab filaments and for those in 0540. A direct comparison matches the ultraviolet flux for the Crab, as derived from ultraviolet photometry by Wu (1981), with that seen for 0540. Wu found the normalized ultraviolet flux at 1550 Å is 2576 Jy. Although the *ANS* band includes the wavelength of the C IV emission line that is observed in filaments of the Crab (Davidson *et al.* 1982), the contribution of that line to the flux is probably small for the nebula as a whole. The *IUE* observation of 0540 by Blair *et al.* (1989) provides a flux of about 2×10^{-15} ergs cm^{-2} s^{-1} Å^{-1} at 1550 Å. No hint of C IV λ1550 emission is present. This corresponds to roughly 0.26 mJy, which can be compared with extrapolating the 4400 Å flux using the $\nu^{-0.8}$ power law out to 1550 Å to find 0.18 mJy. Taking the distance to the Crab as 2 kpc and to 0540 as 55 kpc, we find that if 0540 were at the Crab's distance, we would receive 270 Jy at 1550 Å. Since the two remnants are about equal in size, the ionizing flux as seen by a filament in the Crab is 10 times larger than for a filament in 0540. The denominator in the ionization parameter is the density. Fesen and Kirshner (1982) measured the electron density in 10 Crab filaments using [S II] and found a typical value of 1300 cm^{-3}. Our measurement of [S II] wavelength in 0540 corresponds to a density which is less than 2000 cm^{-3}, consistent with the same density in both remnants. In summary, the ionization parameter for 0540 filaments is 10 times smaller than in Crab filaments which could have a significant effect on the relative importance of photoionization and shock heating. It seems likely that DT have pursued the correct line of approach by modeling 0540 with shocks, as elaborated by Dopita (1987).

A more empirical way to assess the importance of shocks compared to photoionization is to examine the [O III] temperature. In general, shocks have collisional ionization, so the [O III] temperature reflects the requirement to ionize oxygen twice, and for shock-heated supernova remnants the temperature is generally in the range 20,000–50,000 K (Fesen, Blair, and Kirshner 1982, 1985). In the Crab Nebula, as in photoionized gas more generally, the ionization is set by the incident radiation and the temperature by the balance of heating and cooling. Temperatures of [O III] in the Crab Nebula are measured at 11,000–18,300 K (Fesen and Kirshner 1982). In our data for 0540, the temperature-sensitive ratio [O III] $\lambda\lambda$5007 + 4959/4363 is 22, while for the Crab it is typically 65. This corresponds to an [O III] temperature of 34,000 K for 0540, very much like the temperatures observed for [O III] in shock-heated nebulae.

Blair *et al.* (1989) present evidence that the SMC oxygen-rich remnant 1E 0101−7219 is photoionized by the strong soft X-ray emission from the remnant. However, the measured [O III] temperature of 1E 0102 is about 25,000 K, somewhat higher than expected in the photoionization case. Nonequilibrium effects or some contribution from shocks are not ruled out in 1E 0102.

Following DT, we can also use other 0540 line ratios to estimate temperatures. Our [O II] (7319 + 7330)/(3726 + 3729) ratio of 0.15 helps establish the temperature for [O II] as $T > 30{,}000$ K for $n_e < 2000$ cm^{-3}. Calibration errors connecting the spectra below 4000 Å with those beyond 7000 Å makes this measurement a weak one. A more trustworthy measurement is the [S II] ratio (4069 + 4076)/(6717 + 6731). We measure 0.04, which corresponds to a temperature below 10,000 K. This is consistent with the behavior usually observed in shock heated gas, where S^+ typically has a temperature near 10,000 K (Fesen, Blair, and Kirshner 1982).

From this discussion, we conclude that 0540's line emission is not as strongly affected by photoionization as is the Crab's. Photoionization models are probably not the right way to make progress in analyzing the spectrum of 0540, despite its resemblance to the Crab Nebula where this type of model has been useful (Davidson 1985; Henry and MacAlpine 1982; Pequignot and Dennefeld 1983). The approach of Dopita, Binette, and Tuohy (1984), using shock models, seems the most straightforward way to proceed, although models in which the composition is more closely tailored to the individual objects are desirable. Dopita (1987) and Blair *et al.* (1989) have recently considered the X-ray ionization that would precede the shock as a likely ionizing source for the oxygen-rich remnants. The electron temperature in these models is substantially lower than measured by us in the [O III] lines.

d) Hydrogen: A Question of Quantity

The hydrogen lines remain a vexing problem. We have not advanced a really satisfactory explanation for the large Balmer decrement, so it is difficult to infer the correct physical mechanism for producing the hydrogen lines, to say nothing of estimating O/H. While the resonance lines of oxygen may prove helpful in producing a large Balmer decrement, other mechanisms, including low-temperature collisional excitation or even excitation caused by the nonthermal particles that give rise to the synchrotron emission are not excluded. A crude limit on the ratio O^+/H^+ can be derived from the absence of visible O I λ7774 due to recombination. As computed by Winkler and Kirshner (1985) in the context of the Puppis A oxygen knots, an observed upper limit to λ7774 of 1/14 Hα corresponds to $O^+/H^+ < 1/30$. There is a great deal of room between this value and the local 30 Doradus value of 2×10^{-4} (Mathis, Chu, and Peterson 1985). Thus the gas in 0540 can easily be greatly enriched in oxygen without violating the observational constraints imposed by this picture for oxygen and hydrogen recombination. On the other hand, the basic picture presented here of oxygen-enriched ejecta hinges on a quantitative question: what is the O/H ratio? A comprehensive model for the ionization and excitation of the gas is urgently needed to answer this question accurately. It is likely that the correct initial conditions for such a model are neither as hydrogen-rich as the standard interstellar medium abundances nor as hydrogen-poor as the models of Dopita, Binette, and Tuohy (1984).

e) Neon, Oxygen, and Sulfur: Products of Massive Stars

The goal of studying young supernova remnants is to test the picture of nucleosynthesis through stellar evolution. Generally speaking, the high velocities, the paucity of hydrogen, and the strong lines of oxygen and oxygen-burning products in the debris of Cas A and the other remnants of this type present a strong case that we are observing the interior of a massive star that reached an advanced stage of evolution. To move beyond this platitude, we need to make finer distinctions among the abundance patterns of the remnants and the evolutionary histories of their progenitors. One significant clue is the absence of neon in 0540 and in most spectra of Cas A, while the [Ne III] $\lambda\lambda$3869, 3968 lines are easily detected in N132D, 1E 0102, G292, and the SNR in NGC 4449.

Without a real model for the emission from 0540, it is hard to make a quantitative estimate of the Ne/O abundance in the remnant, although comparison to models of Dopita, Binette, and Tuohy (1984) for which the [O III] temperature matches the observations predict Ne lines which are roughly 10 times stronger than our upper limits. Since the prediction of [Ne III]/

[O III] depends principally on the neon abundance, rather than density or temperature, we conclude that the neon abundance is low in 0540. In the Dopita, Binette, and Tuohy models, the adopted abundance set has Ne/O = 0.39 by number, so a rough guess might be that Ne/O < 0.05 in 0540. However, the difficulty experienced by Dopita, Binette, and Tuohy in accounting for the general features of the spectra of young, oxygen-rich remnants through shock models shows that a better theoretical framework for the emission is needed to make real progress on the abundances.

In the same spirit, the observations of [O II] λλ3726, 3729 can be compared to [S II] λλ6717, 6731 and those of [S III] λλ9069, 9532 to [O III] λλ4959, 5007. Since these pairs of lines are formed from analogous ions with the same atomic physics, only the collision strengths and the excitation potentials are involved in calculating the ratio of O^+/S^+ and of O^{++}/S^{++}, given the observed line ratio and the temperature. Using the observations from Table 3, collision strengths from Osterbrock (1974), and the temperatures for O^+ and O^{++} derived in § IV*c*, we find $O^+/S^+ = 2$, and $O^{++}/S^{++} = 4$. No one should confuse these estimates with a real calculation, but they are moderately insensitive to temperature, and a value of O/S of 3 ± 2 is useful. The value derived by Dopita (1987) is 16. Since the observed value (Mathis, Chu, and Peterson 1985) in the 30 Doradus gas is O/S = 40, the observations suggest enrichment of sulfur.

Models for massive stars (for example, Thielemann and Arnett 1985) have been summarized by Woosley (1986). In his compilation, stars with masses smaller than 10 $M_\odot$ on the main sequence eject very little heavy material ($Z > 6$), stars of 12 and 15 $M_\odot$ have moderately high Ne/O in the ejecta, stars of 20 $M_\odot$ have reduced Ne/O (about 0.03 by number), and stars at 25 $M_\odot$ are at the upper limit for neutron star formation. It is tempting, but risky, to identify the 0540 progenitor with a star toward the high-mass end of this sequence on the basis of the neon. Even if the precise mass is not known, there should be a qualitative difference between stars which have had extensive shell burning of neon and oxygen, and the lower mass stars which have not. Using the ratio of oxygen to sulfur, the observed value of 3 or so can be compared with values of 4–15 predicted for stars in the 15–20 solar mass range. These comparisons assume that all the sulfur and all the oxygen in the presupernova star are available for our analysis, and that the explosion does not alter the presupernova values. If this is correct, the progenitor of SNR 0540−69.3 might have been very similar to the 20 $M_\odot$ star Sanduleak −69°202 which became SN 1987A (Sonneborn, Altner, and Kirshner 1987). Of course, the ratio Ne/O in models for massive stars is sensitive not only to the mass of the star, but also to details of the assumed physics. As outlined by Woosley and Weaver (1988), the nucleosynthesis yield is sensitive to the notorious $^{12}C(\alpha, \gamma)^{16}O$ rate, overshooting, semiconvection, and details of Coulomb screening for nuclei. Quantitative Ne/O, C/O, S/O, Fe/O, and O/H ratios will help make it reasonable to compare the data with models and to constrain uncertain parameters of stellar evolution theory.

Even without good models, it is worth noting that the available evidence for oxygen-rich remnants suggests that there are two types: those like Cas A and 0540 which show little Ne, but strong S and Ar, and those like 1E 0102, N132D, G292, and the NGC 4449 SNR in which Ne is strong and the Si-group elements weak or absent. Perhaps Cas A and 0540 are objects which have gone past C-burning to an extensive shell phase of Ne/O burning so that we see oxygen and oxygen-burning products, while the others are the result of He-burning or C-burning, but not later stages. To have two of the six correspond to the high end of the mass range is poor statistics, but consistent with expectations. Even without coupling the nuclear burning to detailed stellar interiors, this may be a useful way to think about 0540. Stringent limits on C, Ne, and Mg lines from improved optical data could help improve the contrast in this picture.

f) 0540, SN 1987A, the Crab Nebula, and Cas A

Comparing abundances to calculations is appealing, but there are many pitfalls. A more modest approach to the problem of understanding 0540 is to compare it to the cases we know more thoroughly. As a way of summarizing the results of this investigation, we compare 0540 to SN 1987A, the Crab Nebula, and Cas A.

SNR 0540 comes from the same episode of star formation in the LMC as SN 1987A, and from a star of comparable mass: perhaps 15–20 $M_\odot$ as indicated by the heavy element abundances. It will be interesting to see whether comparable chemical abundances are observed for SN 1987A: [O I] lines are strong (Whitelock *et al.* 1988) and argon lines have been identified in the infrared spectrum (Rank *et al.* 1988); As the nascent remnant turns transparent, the full range of IR, optical, and UV spectroscopy will provide an analysis of the star's interior. Some details of SNR 0540 resemble interesting features of SN 1987A: fast-moving iron and nickel seen in 0540 may be related to the radioactive ^{56}Co source distribution inferred for SN 1987A from the early onset of X-ray and γ-ray emission (Woosley 1988). The presence of some hydrogen in the fast-moving gas of 0540 may be related to the fairly broad Hα lines observed at late times for SN 1987A and for other Type II supernovae (Uomoto and Kirshner 1985). One aspect of the SN 1987A observations which may be significant for the evolution of the young remnant is the presence of a circumstellar shell, presumably lost when Sk −60°202 was a red supergiant (Fransson *et al.* 1989). A similar shell for 0540 is worth considering. It might be related to the larger diameter (33″) which is observed in radio measurements (Mills *et al.* 1983) and could be visible in X-ray observations with high spatial resolution carried out with ROSAT or AXAF.

SNR 0540 also bears some resemblance to the Crab Nebula, but the optical spectra indicate some significant differences which are not emphasized in the analysis by Reynolds (1985*a*). For example, the progenitor of the Crab probably is not a 20 $M_\odot$ star, but is more likely to be a star of about 9 $M_\odot$ (Nomoto 1985). While the pulsar in 0540 is certainly similar to that in the Crab, the effect of the synchrotron nebula on the debris appears to be less important in the case of 0540. The Crab filaments have large helium abundances (Henry and MacAlpine 1982), but are otherwise quite tame compared to those in 0540.

SNR 0540 has chemical abundances in its fast-moving gas which are like those in Cas A, although the Cas A fast-moving knots are different in some significant ways. In Cas A, the inferred density is high enough so that collisional effects on [S II] and [O II] are important (Chevalier and Kirshner 1978). While fast-moving hydrogen has now been seen (Fesen, Becker, and Blair 1987; Fesen, Becker, and Goodrich 1988), it is not mixed with the oxygen-rich material. Inhomogeneities in the kinematics and composition of Cas A are the rule, not the exception (Chevalier and Kirshner 1979), so the simple analysis carried out here for 0540 may prove to have some essential flaws. Still, the similarity in observed heavy element abundances between Cas A and 0540 and the overall resemblance of this class of supernova remnants to models for massive stars is very encouraging. A proper understanding of the hydrogen emission in 0540 is needed to ensure that the classification of this object as oxygen-rich has an adequate quantitative foundation. An important kinematic difference is that Cas A velocities are much higher (5000 km s^{-1} is typical) compared to the 1400 km s^{-1} we see in 0540. Reynolds (1985*a*) attributes the velocity of 0540's inner debris to acceleration by the pulsar, a continuing energy source which Cas A apparently does not have. These differences should provide clues to the stellar structure and the explosion physics of the progenitors. The possibility of extensive mass loss for the hydrogen-rich layers, as suggested by SN 1987A, may make the history of the remnant quite intricate.

As the set of observations for remnants grows more detailed and the analytic tools are sharpened, the program of taking line strengths in young supernova remnants back through the composition of the debris to the structure of the progenitor star will become more convincing and may prove useful in refining models for stellar evolution and the chemical evolution of galaxies.

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