SN 1987A'S CIRCUMSTELLAR ENVELOPE. II. KINEMATICS OF THE THREE RINGS AND THE DIFFUSE NEBULA

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ABSTRACT

We present several different measurements of the velocities of structures within the circumstellar envelope of SN 1987A, including the inner, equatorial ring (ER), the outer rings (ORs), and the diffuse nebulosity at radii $\lesssim 5$ pc, based on CTIO $4 \text{m}$ and Hubble Space Telescope (HST) data. A comparison of STIS and WFPC2 [N II] $\lambda 6583$ loci for the rings show that the ER is expanding in radius at $10.5 \pm 0.3 \text{ km s}^{-1}$ (with the northern OR expanding along the line of sight at $\sim 26 \text{ km s}^{-1}$, and for the southern OR, $\sim 23 \text{ km s}^{-1}$). The best fit to CTIO 4 m echelle spectra of the [N II] $\lambda 6583$ line show the ORs expanding at $\sim 23 \text{ km s}^{-1}$ along the line of sight. Accounting for inclination, the best fit to all data for the expansion in radius of both ORs is $26 \text{ km s}^{-1}$. The ratio of the ER to the OR velocity is nearly equal to the ratio of the ER to the OR radius, so the rings are roughly homologous, all having been created $\sim 20,000 \text{ yr}$ before the supernova (SN) explosion. This makes the previously reported, large compositional differences between the ER and ORs difficult to understand. Additionally, a grid of long-slit 4 m echelle spectra centered on the SN shows two velocity components over a region roughly coextensive with the outer circumstellar envelope extending $\sim 5 \text{ pc}$ ($20'$) from the SN. One component is blueshifted $\sim 10 \text{ km s}^{-1}$ relative to the systemic velocity of the SN, while the other is redshifted by a similar amount. These features may represent a bipolar flow expanding from the SN, in which the ORs are propelled $10-15 \text{ km s}^{-1}$ faster than that of the surrounding envelope into which they propagate. The kinetic timescale for the entire nebula is $\gtrsim 350,000 \text{ yr}$ (and probably more, since material may be accumulating in an outer contact discontinuity). The kinematics of these different structures constrain possible models for the evolution of the progenitor and its formation of a mass-loss nebula.

Subject headings: circumstellar matter — stars: mass loss — supernovae: individual (SN 1987A)

1. INTRODUCTION

SN 1987A provides a uniquely detailed case for the study of the late evolution of massive stars with many surprising features. It is one of the very few supernovae (SNe) in which the progenitor was studied before the explosion. The internal composition of the progenitor structure and that of the ejecta have been the subject of intense scrutiny. The SN environment is dominated by a mass-loss nebula (or “circumstellar envelope” [CSE]) with many different features capable of betraying various phases and events during the life of the progenitor. The CSE can in turn be probed through its response to the ionizing flash from the SN explosion, followed by light echoes in the optical, followed by the collision with the CSE of the ejecta from the explosion.

We are studying the spatial structure of this nebula, as well as its velocity structure seen in narrow emission lines, in order to construct as complete as possible a history of the mass-loss phases of the star. With both the velocity structure and the full three-dimensional spatial structure that light echoes reveal, one can interpret observations in terms of the kinematic ages and therefore the evolutionary phases involved in mass loss. We are presenting these observations in a series of works detailing the spatial structure of the inner CSE (Crotts, Kunkel, & Heathcote 1995), its velocity structure (this paper), and the spatial structure of the outer CSE (in preparation).

While the velocity and distance from the SN of a feature yield a timescale characteristic of how long ago that material was ejected from the surface of the progenitor, these timescales can also be inferred more indirectly from compositional variations within the CSE: structures arising at different times result from different layers of the star, and hence should have different compositions. Detecting this level of differentiation across the CSE requires the spatial resolution of Hubble Space Telescope/Faint Object Spectrograph (HST/FOS) spectra to compare the rings (Panagia et al. 1996), indicating much less nitrogen in the outer rings than the inner ring, suggesting that the outer rings were ejected some $10^4 \text{ yr}$ earlier than the inner rings, whose kinematic age is $\sim 2 \times 10^4 \text{ yr}$ (Crotts & Heathcote 1991). Here we shall test this compositional age measure against the kinematic age of the outer ring, and attempt to explain possible discrepancies.

2. OBSERVATIONS

This is a difficult observational problem best attacked through the combination of ground-based and HST mea-
measurements. Over the entire central region, where they are expected to show the largest variation in velocity, the ORs are found within only ~0.3 of the ER, yet are many times fainter than the ER. This situation cries out for the high angular resolution of $HST$, but also requires high spectral resolution (preferably at least $R \approx 30,000$), which is available on $HST$ (Goddard High Resolution Spectrograph [GHRS] and Space Telescope Imaging System [STIS]/MAMA) only in the UV for transitions in which the ORs are too faint. Such high spectral resolution is readily available in the optical from the ground, but seeing limits its usefulness to the portions of the ORs separated from the ER by more than about $1\degree$. As we shall see, the $R \approx 5000$, STIS G750M setup for [N II] $\lambda 6583$ can detect velocity offsets of some ER and OR features if sufficient care is taken. Fortunately, for different segments of the ORs, one or the other observational alternative offers some way of measuring their velocity, and for some, these results can be intercompared.

To look at signals at different spatial scales and spectral resolutions, we used a total of four different kinds of data: from the ground (CTIO 4 m Echelle Spectrograph), single-slit spectra to study the ER and OR features 1"-2" from the ER and multislit spectra to study fainter features at larger radii, and on $HST$, STIS spectra of the ER and ORs compared to WFPC2 images, the latter used to fix the angular positions of different features in the STIS spectrograph slit relative to one another. To appreciate the relevance of each data set to the problem, it is helpful to see (Fig. 1) the placement of the STIS and CTIO echelle slits relative to the rings and adjacent stars. (“NOR” and “SOR” refer to the northern and southern ORs, respectively.)

### 2.1. $HST$ and STIS G750M Spectra and WFPC2 Images

The data used here, already described in Sonneborn et al. (1998) (their Fig. 6), were taken on UT 1997 April 26, day 3715 after core collapse. It was a 643 s STIS integration in the G750M mode ($6295-6867$ Å, resolution $= 1.02$ Å, or 46.5 km s$^{-1}$ at [N II] $\lambda 6583$). The 2" wide long-slit centered on the SN was oriented at P.A. = $87\degree$, nearly parallel to the ER’s projected major axis, and hence included the entire ER as well as much of the ORs, including the segments that might be expected to be seen expanding most rapidly from the SN along the line of sight.

Because of the wide spectrograph slit used, the position of a feature along the dispersion axis depends on both its velocity and its position perpendicular to the slit. Thus, in order to measure velocities within the rings, we must compare their dispersed images seen in the STIS spectra to their undispersed locus measured in WFPC2 images. For this purpose we have used an image through the narrowband F658N filter, which primarily admits flux in [N II] $\lambda 6583$ obtained on day 3478 (GO program 6437; Kirshner et al.) which had a total exposure time of 5400 s. The possible motion of the ring emission locus over this 237 day interval between the STIS and WFPC2 observations should be negligible, less than 0.1 pixel (cf. Plait et al. 1995).

### 2.2. CTIO 4 m Multiple-Order Echelle Spectra

These data were taken with the same setup used in Crotts & Heathcote (1991), using the f/8 Echelle Spectrograph on the CTIO 4 m, with the 31.6 line mm$^{-1}$ echelle grating and KPGL3 cross-disperser (527 lines mm$^{-1}$, blazed at 5500 Å in first order), which together deliver a resolving power

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**Fig. 1**—Schematic layout of the three rings, traced from the day 3478 WFPC2 F658N image, showing the inner, equatorial ring (ER), the southern outer ring (SOR), and the northern outer ring (NOR). Also shown are the positions of stars 2 and 3, and the SN (central dot). Overlying these are the locations of the three CTIO 4m Echelle Spectrograph slits (1'0 wide at P.A. 20°, 60°, and 130°), and the edges of the day 3715 STIS G750M slit (2'0 wide). The labels “a” through “d” rest immediately above the STIS samples referred to in the text and used to measure OR velocities. The scale in terms of arcseconds and light-years (for $D_{SN} = 50$ kpc) are shown.

**Fig. 2**—Loci of the day 3715 STIS G750M data of the ER (squares) fitted to overlie the day 3478 WFPC2 F658N image (solid curve). This bilinear fit is compared to the anamorphic distortion of the STIS G750M setup to yield the velocity shear across the ER, which corresponds to radial expansion away from the SN of 10.5 ± 0.3 km s$^{-1}$. Note that the scales on the two axes are unequal, to account for the ring’s inclination.
$R \approx 40,000$ (corresponding to 7.5 km s$^{-1}$) with the 1′ slit used. We used the red, long-focus camera and red collimator, covering 5530–7050 Å. We concentrate primarily on the narrow emission line at [N II] $\lambda 6583$. For the slit decker used, each order is 19′ wide.

Data such as these were taken on numerous occasions between 1989 and 1997, and we chose the best of these, in terms of good seeing and signal-to-noise ratio (S/N) of the OR features. Those chosen were from UT 1996 December 1 (day 3569 after core collapse, shortly before the HST STIS observation), and have seeing of about 0.8 FWHM.

2.3. CTIO 4 m Single-Order Long-Slit Echelle Spectra

These data are described in Xu & Crotts (1999). They employed the 791 mm$^{-1}$ echelle grating on the CTIO 4 m Echelle Spectrograph, along with an order separation filter that selected H$\alpha$ and [N II] lines, projected through a set of five slits separated by 12′/5 perpendicular to their length. The free velocity range of 120 km s$^{-1}$ between successive slits was sufficient to prevent overlap of detectable LMC emission components. The data considered here were part of a 6′ × 6′ raster of north-south slits roughly centered on the SN (with one actually passing through the SN), with additional single, long slits oriented east-west in preliminary exposures to check that there were no observable components lying beyond the 120 km s$^{-1}$ no-overlap range. These spectra have a velocity resolution of 10 km s$^{-1}$. Exposures were obtained for 1 hour in each position, and up to five velocity components were disentangled from each spectrum, analyzed at each point on a grid with 13′ sampling north-south and 12′ east-west. These data were taken several years before the others, on days 2160–2162.

3. RESULTS

These four data sets are combined to map the velocity field of SN 1987A’s CSE. The ground-based data provide good measurements of the velocities of the ORs north and south of the SN, which are missed by STIS, but because of limited spatial resolution, they are less useful for the portions of the ORs closer to the ER, which STIS covers well. The emission from the portion of the sky containing the outer CSE, however, has too low an emission measure for HST to study easily, but is seen more easily by a telescope with a faster f-ratio. We consider each of these measurements in turn.

3.1. Comparison of OR Loci from WFPC2 and STIS

The G75OM STIS spectra in Figure 6 of Sonneborn et al. (1998) show excellent images of the ER and a portion of the NOR and SOR in [N II] $\lambda 6548$, 6583 and H$\alpha$ (as well as several other transitions) taken on day 3715, which can be compared to nearly contemporaneous images from WFPC2. The [N II] $\lambda 6583$ line has by far the greatest S/N (with the H$\alpha$ signal being smeared by thermal broadening). The difference between the positions of features in the dispersed STIS data compared to the direct WFPC2 image allows us to measure the relative velocities between different parts of the CSE. Unfortunately, the region of the NOR seen within the ER is largely obscured by the SN ejecta and in part by the blueshifted smear of the “hot spot” (Sonneborn et al. 1998; Michael et al. 1998) on the ER overlapping the NOR. Nonetheless, the entire ER and a large portion of the northern SOR and southern NOR can be compared between the STIS and WFPC2 data in this way.

Figure 2 shows the results of the best bilinear fit of the G75OM STIS locus of the ER to the position of ER from the day 3478 WFPC2 exposure with the F658N filter. The loci in each image are defined as the set of points of maximum brightness defined along radial crosscuts through the SN. (Note that the scale in one dimension is expanded to make the ER appear roughly circular.) This shows a close correspondence between the two loci with the STIS points following the WFPC2 track, matching most features in great detail, to within an rms difference of 0.12 STIS pixels. The anamorphic magnification of this STIS mode at this wavelength (Bowers et al. 1998) is 0.92786 (compressed in the dispersion direction). In comparison, the STIS-to-WFPC2 fit requires a 0.91058 compression along the dispersion, corresponding to a difference in velocity of 0.56 ± 0.02 STIS pixels, or 0.31 ± 0.01 Å between the northern and southern sides of the ER, in the sense that the southern side is redshifted. This implies a velocity shear of 14.3 km s$^{-1}$ across the slit, which corresponds (since the slit is well aligned with the ER) to a radial expansion velocity, i.e., outward from the SN, of 10.5 ± 0.3 km s$^{-1}$. This is a new, independent measurement of the ER expansion velocity, but it is in good agreement with some previous values (10.3 km s$^{-1}$; Crotts & Heathcote 1991; Cumming 1994) and is not far from others (11 km s$^{-1}$, Panagia et al. 1996; 8 km s$^{-1}$, Meaburn et al. 1995).

Figure 3a shows the position of the STIS and WFPC2 OR signals after alignment of the ER signals as in Figure 2. The residual offset of the SOR and especially the NOR is a clear sign of the velocity difference between the ORs and the ER centroid. Intercalibrating the data in this way eliminates any possible sources of systematic error due to uncertainties in the standard STIS and WFPC2 plate scales, at the cost of only slightly increasing the random error due to the uncertainty of aligning the two ER signals. The useful sample of the ORs excludes those portions where they approach the ER, and also where they run nearly parallel to the dispersion axis. Additionally, the SOR signal is corrupted over a large extent by the continuum from star 3. The uncontaminated samples are shown in Figure 3a, and with the SOR signal magnified in Figure 3b. This remaining sample permits one useful measurement along the SOR at a point 1′:36 east of the SN (labeled “a” in Fig. 1), and three measurements of comparable accuracy along the NOR, 1′:04, 1′:40 and 1′:68 west (points “b” through “d” in Fig. 1). These yield velocity values of 21.5 km s$^{-1}$ (blueshifted) and 22.3, 24.6, and 21.1 km s$^{-1}$ (redshifted), respectively, relative to the 289 km s$^{-1}$ heliocentric redshift of SN 1987A, with 1σ errors of about 2 km s$^{-1}$, except for the last point, with an error of about 3 km s$^{-1}$.

3.2. Ring Velocities from [N II] $\lambda 6583$ Echelle Spectra

As discussed by Crotts & Heathcote (1991), the velocity field of the ER, best traced by [N II] $\lambda 6583$, has a centroid at 289 km s$^{-1}$, with little velocity shear across the ER at P.A. = 60°, almost parallel to the ER major axis, but with strong velocity shears on either side, at P.A. = 20° and 130°. There are additional, fainter emission patches at larger radius or velocity offsets from the centroid. Occasionally such faint sources correspond to transient spots (Crotts, Kunkel, & McCarthy 1989; Hanuschik 1990; Crotts & Heathcote 1991; Cumming & Meikle 1993; Cumming

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Fig. 3.—(a) Position of the STIS and WFPC2 OR signals in relation to the ER loci once the ER signals are aligned as in Fig. 2. The offset of the SOR and especially the NOR even at the dispersion position corresponding to the ER centroid (dashed line) is a clear sign of the velocity offset of the ORs vs. the ER centroid. The NOR can be split into three roughly equal segments, 1°04, 1°40, and 1°68 west of the ER centroid, with velocity offsets between the two data sets corresponding to 22.3, 24.6, and 21.1 km s$^{-1}$ (redshifted). (b) Same data as in (a), but with the SOR signal magnified. A single measurement of SOR velocity is possible, at a point 1°36 east of the SN, yielding 21.5 km s$^{-1}$ (blueshifted).

1994), but at the time of these observations no such spots were revealed in optical imaging. These fainter, outrigger sources observed here are almost certainly due to the ORs.

Figure 4 shows the portion of the echelle order centered on the [N II] $\lambda$6583 line, showing the broad emission lines from the SN and stellar continua extending horizontally, and the LMC interstellar [N II] emission extending vertically. The bright patch in the center is emission from the CSE. The underlying ISM is fitted linearly in the spatial dimension, interpolated across the CSE, and subtracted off.

Fig. 4.—Portion of the echelle order centered on the [N II] $\lambda$6583 line, showing the broad emission lines from the SN and stellar continua extending horizontally, and the LMC interstellar emission in [N II] extending vertically. The bright patch in the center is emission from the CSE. These data are for P.A. = 20°, with north at the top. Wavelength (vacuum, heliocentric) is shown along the abscissa (modified slightly by structure in the CSE perpendicular to the slit). These data have 8 km s$^{-1}$ velocity resolution.
The spectral continuum and broad emission is fitted quadratically, and likewise interpolated and subtracted. This subtraction produces the residual distribution of flux shown in the contour plot of the echellogram in Figure 5a (with a vertical scale of 0.26 and horizontal scale of 3.50 km s\(^{-1}\) pixel\(^{-1}\), at [N II] \(\lambda6583\)). There are notable protrusions from the nearly elliptical flux contours, particularly to the south at roughly the centroid velocity and to the north slightly to the red of centroid. Furthermore, the flux contours at low levels become more rectangular, as if flux might be appearing at the corners.

3.2.1. Inner Ring Fit

We know the flux distribution in [N II] \(\lambda6583\) of both the ER and ORs from the HST images, and have good constraints on the global velocity structure of the ER. Further-
more, comparing the width of the ER feature in the [N II] and Hα echellograms, we see a significant difference most likely due to thermal broadening. Accounting for the different atomic masses producing the lines, we find the temperature of the gas at day 3569 to be $T = 5000$ K (to within roughly 20%). (This compares to other temperature measurements at late times: $T \approx 17,000$ K on day 1278, from [O II] and [N II] recombination [Wang 1991, Sonneborn et al. 1997]; 55,000 K on day ~300 from [O III] [Wampler & Richichi 1989]. The lower temperature we measure on day 3569 may be due to the cooling of the gas, or due to Hα and [N II] emission arising from different gas. Recombination model calculations predict $T \approx 5000$ K throughout the ER by day 2000 [Lundqvist & Fransson 1996].) We can also measure the spatial and spectral line-spread functions of the spectrograph from the width of the stellar continuum and night sky lines in the echellogram. Given these parameters, we can model the image of the CSE.
produced by the spectrograph on the detector and construct the synthetic echellogram shown in Figure 5b. At high flux levels, it appears very similar to the actual data, but at low flux levels differs by the absence of the extensions mentioned above.

The width of the spatial and spectral line-spread functions, temperature, and placement of the slit are allowed to vary over a grid of values spanning approximately ±10% in each of these parameters, in order to produce a family of model echellograms, and the minimum χ² (in terms of the square root of counts per pixel), within the region covered by nonzero flux from the model. The resulting best fit model is shown in Figure 5b, and the difference between the data and the fit is shown in Figure 5c. This corresponds to a best fit of 9.5 km s⁻¹ in radial expansion velocity of the ring away from the SN, with a probable error of about 5–10% (which is difficult to estimate given systematic errors in other parameters). Note that the number of contours in the residual features is several times fewer than in the original, Figure 5a, and that the contour levels are 5 times finer in Figure 5c, so that the extreme residual features are only about 7% of the original peak flux, and cover regions on the scale of single pixels; thus, residual features within the region of the model are at most about 1% of the total. This compares to expected Poisson errors from photon counting statistics at the 0.3% level, so a much better fit would be difficult to achieve.

3.2.2. Outer Ring Signals

Outside the region modeled in § 3.2.1, several significant residuals appear: to the north and south at roughly the centroid position along the slit. These four residuals are centered at (−21.7 km s⁻¹, 0.39 north), (+2.8 km s⁻¹, 2°18' south), (+4.2 km s⁻¹, 1°98' north), and (+20.3 km s⁻¹, 0°05' south), and have flux amounting to 2.8%, 2.8%, 2.0%, and 1.1%, of the total, respectively. Note that these radii along P.A. = 20° correspond closely to those measured from the WFPC2 image for the northern SOR, southern SOR, northern NOR, and southern NOR, respectively: 0°71 north, 2°08 south, 1°96 north, and 0°08 south, with the first and fourth measurements being somewhat uncertain due to confusion with the ER and SN, respectively. These positions agree between the echelle and HST data sets to within about 0.2 rms, less than an echelle pixel (0.26').

We can use the relative strength of the ER and ORs in the WFPC2 images to predict relatively how much light is entering the echelle spectrograph slit. From the STIS G750M data, we know that the OR flux in the vicinity of the ER (but beyond ~0.3 to avoid being overwhelmed by the ER) is 2.5–3.5 times stronger in the [N ii] λ6583 line than in Hz. Additionally, the throughput at the SN redshift in the WFPC2 F658N filter is 3.8 times greater at [N ii] λ6583 than at Hz, hence the OR signal in the WFPC2 F658N image is 92% due to [N ii]. This implies that even if the Hz flux were to vary by 100% of its strength relative to the [N ii] λ6583 flux at different points around the ORs, the OR [N ii] λ6583 flux can still be predicted to within 9%.

The flux values inferred from WFPC2 for the south SOR is 2.0% and for the north NOR is 1.8% of the ER signal within the slit, close to the values seen in the echellogram. The brightness of the north SOR and south NOR is difficult to determine in the WFPC2 image, again because of the contributions by the ER and SN. Given that most of the signal in the residual echelle features corresponds to the actual OR fluxes, it would appear that errors in the flux could only decelerate the signal by at most about 1 pixel in velocity, or about 4 km s⁻¹. We will take this as the probable error on the echelle OR measurements.

3.3. Kinematic Model of Ring Velocities

To interpret these OR velocity measurements, we compute a simple model for OR loci in a homologous velocity flow, without imposing any constraint that the OR and ER velocities should compare, and then require that the projected shape of each OR be consistent with its observed shape and location. For the purpose of computing homologous velocities, we make the approximation that all three rings are coaxial. For the NOR, which appears nearly elliptical, we adopt an inclination angle set by assuming that the ring is really circular and is only seen as an ellipse in projection. This inclination angle is 42°7 (Burrows et al. 1995) with an error that we infer to be about 1°. In contrast, the ER has an inclination measured variously as 43° ± 3° (Jakobsen et al. 1991), 45°3 (Burrows et al. 1995), or 44°0 ± 1°0 (Plait et al. 1995). The SOR is not truly elliptical, but the best-fit ellipse corresponds to an inclination of 31° (Burrows et al. 1995). For the SOR we adopt two alternative geometries: that it is inclined by 31° (model A), and that it is inclined by 45° (model B), parallel to the ER, but distorted from a circle. Perhaps neither alternative is correct, but these at least span a reasonable range of possibilities.

Under these assumptions, the NOR is expanding outward from the SN at 26.1 km s⁻¹, while the SOR expands at either 25.5 km s⁻¹ (model A), or 26.3 km s⁻¹ (model B, along the minor axis), according to a best fit to the observed velocities from STIS + WFPC2 and the CTIO 4 m Echelle. These fits are shown in Figures 6a, 6b, and 6c (for the NOR model and the SOR models A and B, respectively). All three fits are reasonable, with reduced χ² near unity. OR model B (31° inclination) fits slightly better than model A. The 1σ errors on all of these derived expansion velocities are about 2 km s⁻¹. (Note that the above results appear consistent with those quoted by Cumming & Lundqvist 1994.)

These velocities should be compared to the radial distance of the ORs from the SN in order to derive a kinematic timescale. For the sake of discussion, we adopt a semimajor-axis length of 1.7 for both ORs. (We measure a slightly smaller value than the semimajor axis lengths found by Burrows et al. 1995: 1.77 and 1.84.) For a distance to SN 1987A of 50 kpc, these models correspond to OR distances from the SN of 0.58 pc for the NOR, 0.52 pc for the SOR (model A), or 0.56 pc for the SOR (model B), along the minor axis. Compared to the corresponding expansion velocities, these correspond to kinematic timescales of 21,700, 19,900, and 20,800 yr, respectively, indicating the time in which the ORs would have coasted at their current velocities to their current positions. Similarly, the ER, with a semimajor axis of 0°86 (Plait et al. 1995) or 0.21 pc, would require 19,500 yr expanding at 10.5 km s⁻¹. Clearly, these kinematic ages are consistent within the errors (of ≈11%).

3.4. Spatial Extent of Long-Slit Velocity Components

The longslit survey by Xu & Croots (1999) of the 6' square area around SN 1987A was intended to observe structure on
scales considerably larger than the spatial sampling of 13", but nonetheless provides some information on the CSE of the SN. As seen in light echoes (Crotts & Kunkel 1991; Crotts 1999), there is an echo feature apparently centered on the SN extending some 5 pc toward Earth, corresponding to an angular scale of 20°. A search for features on this scale in the long-slit data set reveals two features (Fig. 7). One, centered near 279 km s⁻¹ (10 km s⁻¹ blueshift with respect to the SN) is found between 25" east and 13" west, and between 18° north and 4° south of the SN. A second feature at 301 km s⁻¹ (12 km s⁻¹ redshift) extends between 13" and 38" west, and 4" north and 15" south of the SN. These appear to form a possibly bipolar, or double-lobed, nebula, with the near side to the northeast, assuming material is being ejected. The axis of symmetry of this structure would lie along P.A. ≈ 50°. These features are not perfectly coherent in velocity, however. While the S/N detection level of individual segments of these features is low, there appear to be significant gradients in velocity, so that the differences from the SN velocity centroid can extend up to 15 km s⁻¹.

It is evident from Figure 7, however, that patches of roughly this spatial scale and velocity coherence exist in locations far away from the SN, such that there is a significant probability that one or both features are chance superpositions in projection against the SN. One possible method of investigating the association of these two features with the SN is to determine if their elemental abundances are more similar to the anomalous values found in the rings (e.g., Lundqvist & Fransson 1996; Sonneborn et al. 1998), or those typical in the LMC. We are currently pursuing this test of the origin of this gas.

4. DISCUSSION

Why do the kinematic and compositional timescales (Panagia et al. 1996) disagree? Of course, the simple kine-

Fig. 7.—Figure 7 shows a 70" × 40" array of long-slit echelle spectrograms from a field centered on SN 1987A (the bright spot in the center), in the [N II] λ6583 line. The data were collected five slits at a time as part of a larger (6' × 6') survey, and four such exposures are shown here, separated by bold black lines. The free velocity range between successive slits is 120 km s⁻¹, with 10 km s⁻¹ velocity resolution, and the slits are separated by 12.5 on the sky. North is up, east is to the left (from slit to slit), and higher velocities (between slits) are to the right, as indicated by the larger set of arrows. Two features, centered −10 km s⁻¹ and +12 km s⁻¹ with respect to the SN, are found between two slits east and one slit west, and between one to three slits west of the SN, respectively. The first feature is found between the vertical pairs of white arrows, and the second between pairs of black arrows. Note that other features of similar size are also seen in different locations in the field, casting some doubt on the association of the two features with the SN.
matic timescale $t_{\text{kin}} = r/v$ does not account for the acceleration of the red supergiant (RSG) wind by the lower density (and not directly observed) blue supergiant (BSG) wind, so that at a given radius the winds interface, i.e., the freshly shocked RSG material, is actually expanding faster than the RSG wind just exterior to the shock. Since this exterior wind has presumably coasted freely since leaving the progenitor, $t_{\text{kin}}$ for this material is close to the actual time $t_{\text{can}}$ since the material left the progenitor. However, this may not be so for the material actually observed. In comparing $t_{\text{kin}}$ for different parts of the CSE we wish to know whether the ratio of $t_{\text{kin}}/t_{\text{can}}$ is constant throughout. Recent models of interacting winds within a wind-compressed disk outflow (Collins et al. 1999) can lead to velocity fields over the winds' interface that produce a nearly constant $t_{\text{kin}}/t_{\text{can}}$ throughout (Collins et al. 1999, Fig. 2; A. Frank 1999, private communication), while simultaneously producing a shape for the CSE consistent with that observed. Other models (Blondin & Lundqvist 1993; Martin & Arnett 1995) have a more complicated velocity flow, in which $t_{\text{kin}}/t_{\text{can}}$ is nonuniform even on scales as small as $10^{17}$ cm. Thus while a constant $t_{\text{kin}}/t_{\text{can}}$ is consistent with the known morphology of the CSE, it is by no means assured.

In contrast, the compositional ratios computed by Panagia et al. (1996) are highly time-dependent, since the system is far from equilibrium while still recovering from the pulse of EUV photons emitted during the first hours of the SN explosion. While the elemental ratios can be recovered from a time-dependent analysis of line ratios, the particular line ratios arising from the same gas can vary by large amounts over the course of time (Lundqvist & Fransson 1996). The Panagia et al. study does not sufficiently explore these time-dependent effects. It is unclear that a compositional difference between the ER and the ORs can be disentangled from these effects given the single epoch of data and relatively simple models considered, as a unique solution to the elemental abundances requires knowledge of the temperature and ionization shortly after it was heated and ionized by the SN flash (P. Lundqvist 1999, private communication).

If the extended two-lobed nebula apparently in Figure 7 is indeed associated with SN 1987A, its expansion velocity is $10$--$15$ km s$^{-1}$ slower than the OR velocities but roughly equal to the ER expansion velocity. If this nebula is associated with the SN, what is its three-dimensional configuration? This is difficult to know certainly, given the absence of light echoes from the outer regions of this double-lobed object. This absence might simply be due to insufficient light-travel time to cover the whole structure, which would probably require 30 yr or more. In two-dimensional projection, the correspondence of this structure to gas at smaller radii is not obvious. Its symmetry axis (P.A. $\approx 50^\circ$) is far from the axis of the ring system (P.A. $\approx 40^\circ$) or its equatorial plane. Since this nebula does extend significantly to the north and south of the SN, however, if it does surround the SN, it likely envelops the ORs, too. In this case, the ORs are expanding at $\sim 25$ km s$^{-1}$ into a medium expanding at only $10$--$15$ km s$^{-1}$, and are therefore being accelerated by the BSG wind into the slower RSG wind medium. It is not clear that the ER has been accelerated by a proportionally large fraction of its own velocity, implying that it might be younger than the ORs. This runs in the same sense as the inequality between ER and OR ages inferred by Panagia et al.

Regardless of the nature of the extended nebulosity, it is evident that the inner portions of the CSE are expanding at different velocities. This is different from at least the initial conditions assumed in all simulations of the SN's CSE, with the exception of Collins et al. (1999). Other simulations tend to produce an asymmetric boundary between the BSG and RSG winds with an isotropy in matter density, not velocity. It is interesting that both can be probed using not only narrow-line emission but also light echoes, which trace dust density. Furthermore, if the CSE terminates in a contact discontinuity against an interstellar bubble of constant pressure (Chevalier & Emmering 1989), the shape of this contact discontinuity is a measure of the momentum flux as a function of angle around the SN, since pressure must be matched along the discontinuity's surface. Thus in directions from the SN of higher outward ram pressure $p v^2$ at a given radius, the wind will be forced to a halt at a larger radius. This will be investigated in the third paper in this series.

Regardless of the shape of the CSE, its size scale combined with the outflow velocity, especially where gas is simply coasting and not being accelerated along a wind interface, provides an estimate of the minimum age of the CSE. It is only a lower limit because mass has accumulated in the contact discontinuity. A CSE radius of 5 pc and a velocity scale of $\sim 15$ km s$^{-1}$ implies a minimum CSE lifetime of $\sim 350,000$ yr. This compares to model predictions of the duration of the RS phase of SN 1987A of about 190,000 yr (Woosley, Pinto, & Enssman 1988) minus a terminal BSG phase beginning 10,000--20,000 yr before explosion (Woosley et al. 1988; Saio, Kato, & Nomoto 1988). While the terminal BSG phase lifetime is in agreement with observations, the RSG phase appears too short in the models. This would imply that the SN progenitor depleted its core helium supply earlier than expected.

Further work is needed to explain the production of these three rings. Lloyd, O'Brien, & Kahn (1995) interpret the rings in terms of interacting winds from the progenitor in the presence of a companion star. Also, Chevalier & Dwarakadas (1995) propose that the rings arose from the collision of the BSG and RSG winds, with the further action of ionization by the progenitor, but no complete interacting-wind model has yet to be formulated. Models (Meyer 1997; Soker 1999) that naturally explain the formation of a three-ring system fall in other important respects, either in not predicting (Meyer 1997) the cavity interior to the three rings, as evidenced by the rapid fall and only gradual rise of the radio signal from ejecta/CSE interaction (Turtle et al. 1987; Staveley-Smith 1993), or in failing to incorporate (Soker 1999) the diffuse nebulosity seen in the outer CSE (Crotts & Kunkel 1991; Crotts 1999) and between the rings (Crotts et al. 1995; see also Lundqvist & Fransson 1996). The eventual model, in order to be successful, must now account for the motions seen in the rings and beyond.

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