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OBSERVATIONS OF THE NEBULOSITIES NEAR SN 1987A[1]

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ABSTRACT

Direct images of SN 1987A taken during periods of good seeing at La Silla Observatory are combined with spectra to map the velocity and spatial structure of the dust and gas that surround SN 1987A. The data from 1989 December show that the supernova is embedded in a filamentary nebula of mixed gas and dust that is morphologically and kinematically similar to planetary nebulae. The narrowness of the filaments, their shape, their radial velocities, and the lack of detectable expansion in the plane of the sky imply that we are viewing a physical structure, not just the SN 1987A light curve seen reflected from a continuous sheet of background material. This inner, highly structured nebula is immersed in an outer, larger nebula which may be due to reflected light from Sk $-69°202$, the progenitor of SN 1987A. Alternatively, if it is due to reflected light from SN 1987A, it must lie in front of the supernova.

Subject headings: nebulae: general — stars: supernovae

I. INTRODUCTION

Early theoretical studies of the interaction between model supernovae and the circumstellar medium (see Chevalier 1987) for an early discussion of SN 1987A and other references) showed that the gas and dust surrounding the SN would be conspicuous when SN 1987A faded. The first evidence of circumstellar gas near the supernova (SN) was the detection, starting on about day 80, of narrow nebular lines in *IUE* spectra (Wamsteker *et al.* 1987; Fransson *et al.* 1989). Narrow optical lines were first seen in late 1987 on about day 300 (Wampler and Richichi 1989) and later by Wood and Faulkner (1989). The UV and optical lines gave early information about the density, size, shell thickness, and evolving temperature of the brightest parts of this circumstellar nebula (Fransson *et al.* 1989). As the initial ionization levels were very high, the emission-line nebula must have been produced by the outburst of SN 1987A.

Later, slitless spectra and direct images began to reveal increasingly finer nebular structures (Wampler, Richichi, and Baade 1989; D'Odorico and Baade 1989; Crotts, Kunkel, and McCarthy 1989; and Sparks, Paresce, and Macchetto 1989). Inspired by the light echoes seen at larger angular distances (complete references are provided by Sparks, Paresce, and Macchetto 1989) and the analysis given by Fransson *et al.* (1989) of the nebula in the immediate vicinity of the SN, there have been attempts (Crotts, Kunkel, and McCarthy 1989) to interpret the inner SN 1987A structures as light echoes from dusty sheets. Crotts, Kunkel, and McCarthy (1989) have noted the discrepancy between their model and "any configuration expected of the blue giant mass-loss nebula, blue giant wind/red giant wind interaction region, red giant wind, or red giant/ISM deceleration shock." The new observations presented in this *Letter* clearly demonstrate the existence of such configurations which should form an integral part of any models acceptable in the future.

[1] Based on observations made at the European Southern Observatory, La Silla, Chile.

II. DATA ACQUISITION AND REDUCTION

Table 1 gives an observing log for our observations with the European Southern Observatory's 3.5 m New Technology Telescope and the new Focal Reducer Spectrograph and Camera, EFOSC2 (Eckert, Hofstadt, and Melnick 1989). Our images, sampled at 0".152 per CCD pixel, have measured FWHM of 0".45. Examples are shown in Figure 1 (Plate L4). The background-subtracted images were "sharpened" using a deconvolution procedure described by Lucy and Baade (1989) and a point-spread function obtained from field stars. The Lucy and Baade algorithm, like other similar ones, has the drawback that it introduces artificial local minima (rings) in extended structures about one FWHM from point sources. The strength of the artificial rings was reduced by removing the SN image, together with the images of the SN's two companion stars before deconvolving the frame. The results are shown in Figure 1 together with the original and star-subtracted images.

On 1989 December 26 UT, EFOSC2 was also used under similar conditions (image width 0".5, spatial sampling 0".152 per pixel) to obtain also a low-resolution (2 Å per pixel, slit width 1".0) long-slit grism spectrum covering the range 3300–5400 Å.

High-resolution spectra were obtained on 1989 December 9 UT using the ESO 3.6 m telescope with the Cassegrain Echelle Spectrograph (CASPEC; D'Odorico *et al.* 1983) in its long-slit mode. The nebula was mapped with 10 adjacent settings of the slit, separated by 0".5 and aligned along an east-west axis. With a 0".5 wide slit the spectral resolving power was about $R \equiv \lambda/\Delta\lambda = 30{,}000$. Velocities in the nebula were measured using the [O III] λ5007 line (visual seeing estimate: ~1".2 FWHM) and the Hα and [N II] λ6584 lines (seeing: 1".4 FWHM).

III. RESULTS

Figure 1 shows that the nebulosities around SN 1987A are highly structured. The brightest feature is an oval nebulosity that is 0".1 off center to the west of SN 1987A. The long axis of this nebula is aligned east-west. The northern rim has somewhat less curvature than the southern one; the western edge is

TABLE 1

OBSERVING LOG FOR SN 1987A

Date (UT)	Exposure (minute)	Filter	λ_c (Å)	$\Delta\lambda$ (Å)
1989 Dec 18.........	5	Continuum	6649	75
	5	[N II]	6585	24
1989 Dec 26.........	3	[O III]	5008	56
	30	Spectrum	4370	2070

brighter than the eastern one, although it is farther from SN 1987A. The nebula is fainter in the center than at the rims as is clearly seen (Fig. 2) in an east-west cut through the center of the [O III] image.

Two much weaker arms protrude to the west end of the central oval and curve out, one to the south and one to the north, to apparently connect again to the eastern edge of the oval, thereby forming two roughly elliptical loops. The total flux in the outer loops in the [O III] image is one-half the flux of the inner oval. The major axes of the inner oval and the two outer loops appear to be about parallel, while the three minor axes are approximately collinear. A third filament extends from the eastern edge of the oval nebula toward the northeast. It is most clearly seen in the red exposures, and in the original data it can be traced for at least 4″ from SN 1987A. Because the light travel time since the supernova explosion was only 3″ in the plane of the sky when the exposures were made, the end of the filament must lie in front of SN 1987A if it is illuminated by the SN. There is no strong morphological evidence that either of SN 1987A's companion stars are physically associated with, or are interacting with, any part of the nebulosity surrounding the SN. While the faint outer arms pass close to the companion stars, they suffer no major distortion. Even on the best CCD

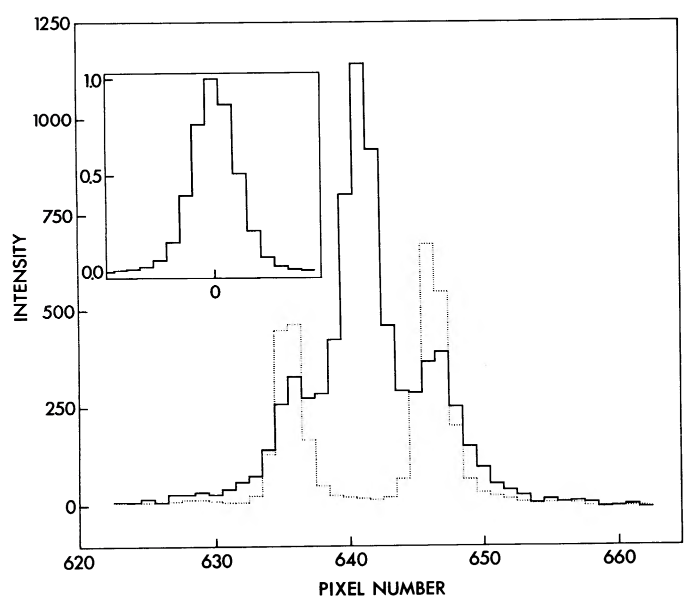

FIG. 2.—The flux (in arbitrary units) from the raw λ5008 image of SN 1987A as a function of position along an E-W line centered on the SN (*solid line*). The dotted line shows a similar cut through the image after processing to remove the stellar images and deconvolving the nebular image with a point-spread function obtained from field stars in the same frame. The point-spread function is shown in the upper left box. One pixel corresponds to 0″.152. East is to the left.

frames, the loops are over most of their length not significantly wider than the stellar images.

A comparison with the images published by Crotts, Kunkel, and McCarthy (1989) suggests that, near star 2, the outer loops have not changed position by more than 0.25 arcsec between 1989 March and December. A detailed computer comparison of in-house images taken in 1989 March (D'Odorico and Baade 1989) and August (Gouiffes *et al.* 1989) with the December data reveals no significant change in position of the outer loops. Furthermore, the diameter of the inner, bright, oval nebula had been estimated to be 2″ in 1988 January (Wampler and Richichi 1989). Given the 1988 January measurement errors, about 1″, this is the same size as that estimated from the 1989 December NTT images.

Images of the filamentary structure taken in the light of nebular emission lines is indistinguishable from those taken in continuum bands (Fig. 1). However, the significance of this finding depends on the amount of contamination by continuum flux in the emission-line images. The search in direct images for structures due to narrow emission lines in the presence of a strong (quasi-)continuum source such as SN 1987A is a hazardous undertaking. While continuum sources are very weak compared to the late time [O III] images, they are still strong near Hα. We have convolved transmission curves of our filters with a low-resolution 1989 December spectrum of the SN. This shows that under the assumption of reflected light from the SN, the latter may account for up to 50% of the total flux if the ratio of continuum to narrow emission line flux is similar to that of the inner oval. The line contamination of the continuum band is less severe. The combined contribution of narrow Hα, [N II] $\lambda\lambda$6548, 6584 and [S II] $\lambda\lambda$6717, 6731 emission amounts to 5.5% of the flux in the λ6649 filter.

Figure 3 (Plate L5) displays a portion near the [O III] lines of a low-resolution spectrum taken with the slit aligned along stars 2 and 3. Because this is a low-resolution spectrum and because the velocities in the nebulosity are low (see below), the spatial structure of the nebula is not seriously masked by velocity gradients within the nebula. Since the atmospheric seeing was less than one-half of the effective slit width (0″.45 vs. 1″.0), the nebular structure near SN 1987A can be seen in the monochromatic slit image. Unlike point-spread function–subtracted direct images, the C shape of the emission lines from the central oval shows that inside this oval there is little narrow line emission.

Because for the given slit position the outer loops cross the slit very close to the positions of stars 1 and 2, we have carefully interpolated the three continua across the Hβ and [O III] emission lines and then subtracted the continuum fluxes. The result is also shown in Figure 3. It demonstrates unambiguously for the first time that the outer loops are a source of line emission. While we have insufficient data to accurately give the relative strengths of the continuum and line fluxes, the equivalent width of [O III] λ5007 in the observed portion of the outer loop is greater than 2 Å.

The results of the radial velocity measurements at representative positions are provided in the legend of Figure 4. The systemic velocity (296 km s^{-1}) of the combined outer loops agrees well with that of the central oval, whereas there is a difference (10 km s^{-1}) between the two loops. This suggests that the northern loop lies behind the central nebula, while the southern loop lies in front of it.

IV. DISCUSSION

Several observations strongly argue that the outer loops form a complete, physical structure as opposed to simply the intersection of the SN light cone with some continuous background dust distribution (Crotts, Kunkel, and McCarthy 1989; Crotts and Kunkel 1990): (1) the morphological appearance of the filaments; (2) their apparent connection to the central, oval nebula and the alignment of their symmetry axes with the ones of the oval; (3) the absence of the otherwise expected expansion, and (4) the probable foreground/background nature of the southern and the northern loop.

Further evidence can be added if, as Crotts *et al.* do, the assumption is made that the [O III] images are essentially uncontaminated by continuum flux.

1. If the extended filaments represented an excitation and recombination wave moving through a preexisting continuous sheet of material, the recombination time would have to be less than about 100 days in order for the filaments to appear so narrow.

2. There is no offset between the position of the filaments seen in reflected light and in the light of forbidden line emission that would correspond to the 80 day interval between the initial UV flash of the SN and its visible maximum.

According to earlier suggestions (Chevalier 1987; Fransson *et al.* 1989), this filamentary nebula was ejected during a previous red supergiant stage of the SN progenitor. A nice example of richly structured ejecta from a red giant is the reflection nebula IC 2220 around HR 3126 (a beautiful color photograph is reproduced in Allamandola and Tielens 1989). Even more pronounced is the similarity to some Galactic planetary nebulae (PNs), such as NGC 7009, that during their previous evolution to a hot blue star also have passed through a red supergiant stage and also possess outlying filaments. The structure of classical PNs have been hypothesized to have resulted from the collision between the fast low-density wind of the hot subdwarf nucleus and the earlier, slow high-density wind of the red supergiant (Balick 1987; Balick, Preston, and Icke 1987; see also Lucy and Perinotto 1987, Kahn and Breitschwerdt 1990, and Breitschwerdt and Kahn 1990). If applicable, such models would suggest the inner oval to actually be a ring due to the red supergiant wind and the outer loops to be polar blobs formed by the blue supergiant wind. As its linear diameter extends to 2 pc, this nebula around SN 1987A is larger than most classical PNs (Wood *et al.* 1987). Yet such a giant nebula is not implausible given the much larger mass-loss rates (at comparable velocities) of blue supergiants like Sk $-69°202$ relative to PNs central stars. Assuming 10^4 yr for the blue supergiant phase preceding the supernova explosion, the dimensions of this nebula are consistent with existing interaction models (Chevalier 1987).

The outer loops can also be well described as a corkscrew structure seen nearly end on. See Figure 4 and the deconvolved [N II] image shown in Figure 1. The preliminary velocities measured for the structure are in accord with this interpretation if SN 1987A is centrally placed in the loops and the expansion is radial. The possible corkscrew structure is best recognized in the deconvolved [N II] image shown in Figure 1 (*middle, right*).

Red continuum images show an additional, smooth diffuse nebula extending into the northern hemisphere 6″ from SN 1987A (Fig. 1). This nebula is not strong in [O III] light. Among the possible explanations for this observation are that the gas-to-dust ratio is much greater in the outer nebula than the ratio for in the inner nebula, or that the outer nebula lies outside the SN 1987A Strömgren sphere. A further possibility is that there is strong red fluorescence of the type seen by Witt

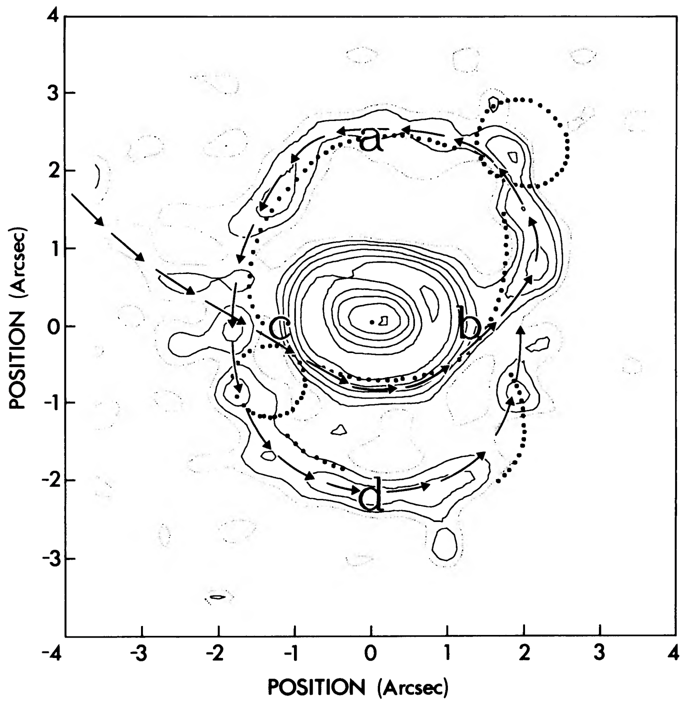

FIG. 4.—A contour map of the deconvolved $\lambda5008$ image together with the sketch (*dotted*) given by Crotts *et al.* (1989) of the positions of the outer filaments in 1989 March. The contours are logarithmic; the flux differs by two between levels. The two dotted circles give the positions of stars 2 and 3 and were used for scaling the figure. The heliocentric velocities at positions a, b, c, and d are 291, 291, 301, and 301 km s^{-1}, respectively. The arrows indicate the locus of a possible corkscrew structure of the outer filaments. They move from the foreground into the plane of the sky. North is up; east is to the left.

and Schild (1988) in Galactic reflection nebulae. Finally, we may be seeing the outer nebula in the reflected light of the progenitor star. If this is true, the nebula would not have to lie in front of the SN, and the lack of strong line emission would also be explained.

Finally, SN 1987A lies at the apex of a dark bay seen in the background nebulosity of the LMC. This bay is best seen in the light of [N II] (Fig. 5 [Pl. L6]). There is very little reflected light south of SN 1987A. Where the arcminute-size light echo rings cross the bay, they disappear. If the bay is devoid of matter also outside the plane of the light echo, one possible scenario is that this bay was formed by the progenitor stellar wind blowing a cavity into the local interstellar medium (ISM). The one-sidedness of this structure could reflect the progenitor's proper motion with respect to the local ISM. If so, the opening angle of $\sim 45°$ of the dark triangle suggests that the velocity difference between the progenitor and the ISM in the plane of the sky and the terminal velocity of the red supergiant wind were approximately equal. If the wind-driven shock pushed the ambient interstellar medium back with a velocity of 10 km s^{-1}, the straight boundaries of the bay which extend over ~ 30 lt-yr would, then, imply that for at least $\sim 10^6$ yr, this wind has not undergone major variations.

V. CONCLUSIONS

The morphology we observed of the nebulosities around SN 1987A and their stability in the plane of the sky lead us to conclude that they are physical entities that closely resemble some classical PNs and may, therefore, have been formed by the mass-loss and evolution mechanisms of the SN progenitor. The empty bay south of SN 1987A may furthermore imply that the outer dimension of the progenitor interaction region with the ISM is as large as 10 pc. Such a large physical structure associated with the evolving SN must, of course, show the effects of the finite light travel time. Future high-quality data will be required to map the variability of the loops (as announced by Crotts and Kunkel 1989) and the spectra of the loops. These data are required before a proper distinction can be made among (1) a light echo from the SN, (2) illumination by the progenitor, or (3) local line emission excited by (i) the SN, (ii) the progenitor, or (iii) other stars.

If there is no nearby ($\leq 3''$) optical light echo from a background sheet, the nature of the brightening of an extended 10 μm source after day 450 (Roche *et al.* 1989) may have to be readdressed. Roche *et al.* attribute their observations to dust behind the SN, and Crotts, Kunkel, and McCarthy (1989) identify it with the outer loops which in the light echo model would have been small enough on day 450 to have had about the right size. As we find no convincing evidence for substantial expansion of the filamentary loops, the existence of the necessary background sheet is in doubt. Furthermore, the data of Wampler and Richichi (1989) showed that the *inner*, oval nebula was already present on day 330. A convolution of that nebula with a Gaussian of $1\farcs7$ FWHM (the beamwidth of the 10 μm data of Roche *et al.*) is adequately described in the east-west direction by a Gaussian of $2\farcs7$ FWHM, i.e., quite similar to the $2\farcs3$ measured by Roche *et al.* Our red continuum data (Fig. 1) indicates the presence of substantial amounts of dust in the inner nebula. In the red continuum, the nebular luminosity integrated over the inner nebula is 3.5 times that integrated over the outer loops. Accordingly, the inner nebula may be more effective in scattering SN 1987A light than are the outer filaments. Given the uncertainties in the low-resolution IR data, an identification with the inner oval is possible. A third alternative has been developed by Lucy *et al.* (1990) who argue that dust appeared in the expanding envelope of SN 1987A on about day 500.

Combining the theoretical result that the progenitor has passed through a red supergiant stage with our observations, one would expect that a very small percentage of the blue supergiants in the Magellanic Clouds show similar circumstellar structures. That percentage could provide a weak but independent observational constraint on the relative duration of evolutionary phases.

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