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Photographic imaging of light echoes from SN 1987A

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SUMMARY

The light echoes from SN 1987A have been photographed at the prime focus of the 3.9-m Anglo-Australian Telescope. The bright emission nebulosity and large number of faint stars in the field have been cancelled from the images by photographic subtraction. A more comprehensive view of the echoes results, revealing that the two previously known arcs are complete circles. Two new echo features are also revealed: an arc just interior to the inner ring over a small range of position angle, and a compact spot which appears to be part of a linear dust feature.

The geometry of the echo rings has been deduced from measuring-machine scans of the subtracted image. The inner ring is found to be concentric about the supernova, indicating that the illuminated cloud of dust, which lies ~ 130 pc in front of the supernova, is roughly normal to the line-of-sight. The outer ring is significantly eccentric about the supernova with its maximum displacement at PA = 29°, in the direction of the nearby OB association NGC 2044. This cloud is therefore inclined to the line-of-sight to the supernova. The possibility is discussed that both clouds are part of the N 157C supershell centred on NGC 2044.

1 INTRODUCTION

Supernova 1987A has provided a wealth of opportunities to observe a wide range of astrophysical processes. Among these has been its importance as a probe of the interstellar medium (ISM) in both the Large Magellanic Cloud (LMC) and in our Galaxy. One important manifestation of this was the appearance late in 1987 of light echoes. This phenomenon, which is the result of the supernova light pulse forward scattering off concentrations of dust as it expands out into the surrounding ISM, provides a rare chance to explore the *three-dimensional* structure of dust clouds in the LMC over the next several decades (Shaefer 1987; Chevalier & Emmering 1988).

Optical light echoes around SN 1987A were first reported by Crotts (1988a, b) whose coronographic CCD data taken in 1988 March revealed two thin arcs 32 and 51 arcsec to the north of the supernova. These features were promptly confirmed by Gouiffes *et al.* (1988) and Suntzeff *et al.* (1988); the expansion of the arcs proved them to be light echoes, and spectra confirmed that the reflected light left the supernova at the time of maximum (*c.* 1987 May 15). Adopting a distance of 50 kpc to the LMC, the common conclusion was that the light-scattering dust lay in two sheets located ~ 110 and ~ 330 pc in front of the supernova.

Here we report the first results of a programme to monitor the light echoes photographically using the 3.9-m Anglo-Australian Telescope (AAT). We have at our disposal high-quality plates of the field taken prior to the supernova; these offer the considerable advantage that we may photographically cancel the obscuring effects of nebulosity and faint stars in the region of the echoes. In the next section we describe this technique and the photographic material obtained. In Section 3 an analysis of the data is presented in which we show the outer light echo to be significantly eccentric about the supernova. The implications of this result are discussed in the last section.

2 OBSERVATIONS

2.1 Photographic material

The field of SN 1987A was photographed at the $f/3.3$ prime focus of the AAT using the triplet corrector on 1988 July 15. A single *V*-band plate was taken which had been hypersensitized using the standard AAO nitrogen-bake hydrogen-soak procedure. A similar plate had been taken three years before SN 1987A appeared. This plate was one of a *B*, *V*, *R*, set obtained of 30 Doradus to produce a composite colour picture of this exceedingly complex region of star formation with its associated dust clouds and emission nebulosity. Both plates were centred on 30 Doradus, but because the AAT has a well-corrected field of one degree at prime focus, they comfortably included the region of SN 1987A which lies 20 arcmin away. Details of both plates are given in Table 1 and a direct image made from the 1988 plate is shown in Plate 1(a).

Table 1. Photographic log.

Date	Plate #	Centre RA(1950)	Centre Dec(1950)	Emulsion	Filter	Exp(mins)	Seeing(arcsec)
5 Feb 1984	2312	05 38 30	-69 16 01	IIa-D	GG 495	25	1.5
15 July 1988	2582	05 38 31	-69 16 02	IIa-D	GG 495	30	2.0
6 Feb 1989	2590	05 38 00	-69 16 01	IIa-D	GG 495	30	2.0

To ensure complete subtraction of the image information common to both plates (see below), the two exposures involved should be closely matched in all respects. Unfortunately the 1988 July plate has substantially larger images than the earlier plate because of the unavoidably large zenith distances (approaching 60°) during the exposure. The resulting star images were ~0.5 arcsec larger than those on the 1984 plate. However, as described in the next section, this had surprisingly little effect on the visibility of the echoes in the subtracted image.

The appearance of the light echoes in Plate 1(a) is similar to that reported previously, with two arcs located to the north of the supernova. The picture also shows well the competing effects of nebulosity in the field. In this respect it is noticeable that the arcs are most visible in the region of the brightest nebulosity. This was also noticed by Crotts (1988b) in Hα CCD images of the field, and led him to suggest that dust associated with this emission nebulosity to the north of the supernova was responsible for at least the outer echo. It can also be seen in Plate 1(a) that the inner echo extends, albeit at a very faint level, right around the supernova. The wisps of fainter nebulosity to the south, however, make it impossible to determine whether this is the case for the outer echo. The emission nebulosity appears even brighter on the 1984 blue and red plates; it is for this reason that we chose to image the echoes in *V*.

2.2 Photographic subtraction

A relatively simple and speedy photographic cancellation process was used to reveal the full extent of the light echoes. A high-contrast positive film contact copy of the 1988 July plate was made on Kodalith film developed in print-strength Kodak 'Dektol' developer for 2 min at 20°C. The exposure of the positive copy was adjusted so that the photographic density of the sky background was approximately equal to the density of the nebulosity above the sky background on the pre-supernova plates. After processing, the film positive was taped in contact and in register with the original negative pre-supernova plate. The final enlargement of this contact pair was made on Kodalith film developed in Dektol. This combination gave the high contrast necessary to compensate fully for most of the dynamic range of the moderate contrast Kodak IIa-D plate used in our exposures, and incorporated a degree of photographic amplification (Malin 1978) to emphasize the faint light echo.

The picture produced by this process is shown in Plate 1(b). Comparison with the pre-subtraction image of Plate 1(a) clearly shows the success of the experiment. The contaminating nebulosity has been almost completely removed, leaving only some residual grain noise from the dense photographic image of the nebulosity. Images of stars in the field fail to cancel fully because of the small difference in seeing between the two plates. Despite this shortcoming, the procedure has produced by far the best view of the echoes reported to date and *for the first time has shown both echoes to be complete circles.* It also reveals one and possibly two new features. The first is a curious diffuse circular echo spot just inside the outer ring to the west of the supernova suggesting reflection from a small blob of dust. There is also a hint of an arc just inward from the inner ring in the range PA = 180–270°. All these features are very faint and represent at most a 1–2 per cent enhancement in surface brightness above the subtracted background.

The appearance of the echoes as complete rings revealed that the outer echo was significantly eccentric about the supernova with its centre being offset in a north to north-easterly direction. This observation, and preliminary measurements of the ring radii made by hand off a ~1 arcmin mm^{-1} scale print, have already been reported (Allen, Couch & Malin 1988); we now present a more detailed analysis of the echoes and their geometry.

A later plate, taken in 1989 February, is also listed in Table 1. It is one of a *B, V, R* set that have been subjected to a similar photographic subtraction technique, and a preliminary report on their content was given by Couch & Malin (1989). A full quantitative analysis of these plates has not yet been undertaken, but in Section 4 we will make use of the features of the *V* plate to help interpret the July data. We note here that the diffuse circular spot repeats on the later plate, retaining its position relative to the two rings; this suggests a surprisingly elongated dust cloud.

3 ANALYSIS

To provide quantitative measurements of the light echo rings revealed in our subtraction process, a negative film copy of the difference image (enlarged by an arbitrary factor of 3.7 to 4.14 arcsec mm^{-1}) was digitized with the AAO PDS 1010A microdensitometer. A 3.4 × 3.4 arcmin area centred on the supernova was scanned using a 50 μm^2 aperture and a step size of 50 μm (0.2 arcsec). A program was written to bin the digitized data azimuthally and produced an averaged profile of the variation in film density with radius from the supernova. Some experimentation with the size of the azimuthal bins was necessary to reach the best compromise between signal-to-noise and sensitivity to variations in position angle. Our final choice was to bin over 45° segments.

The radial profiles derived in this manner are plotted in Fig. 1. Small, linear, radial gradients in the background have been removed from each profile in software. The inner 20 arcsec of each has not been plotted because of disruption to the profiles by the bright image of the supernova and its diffraction spikes (see Plate 1b).

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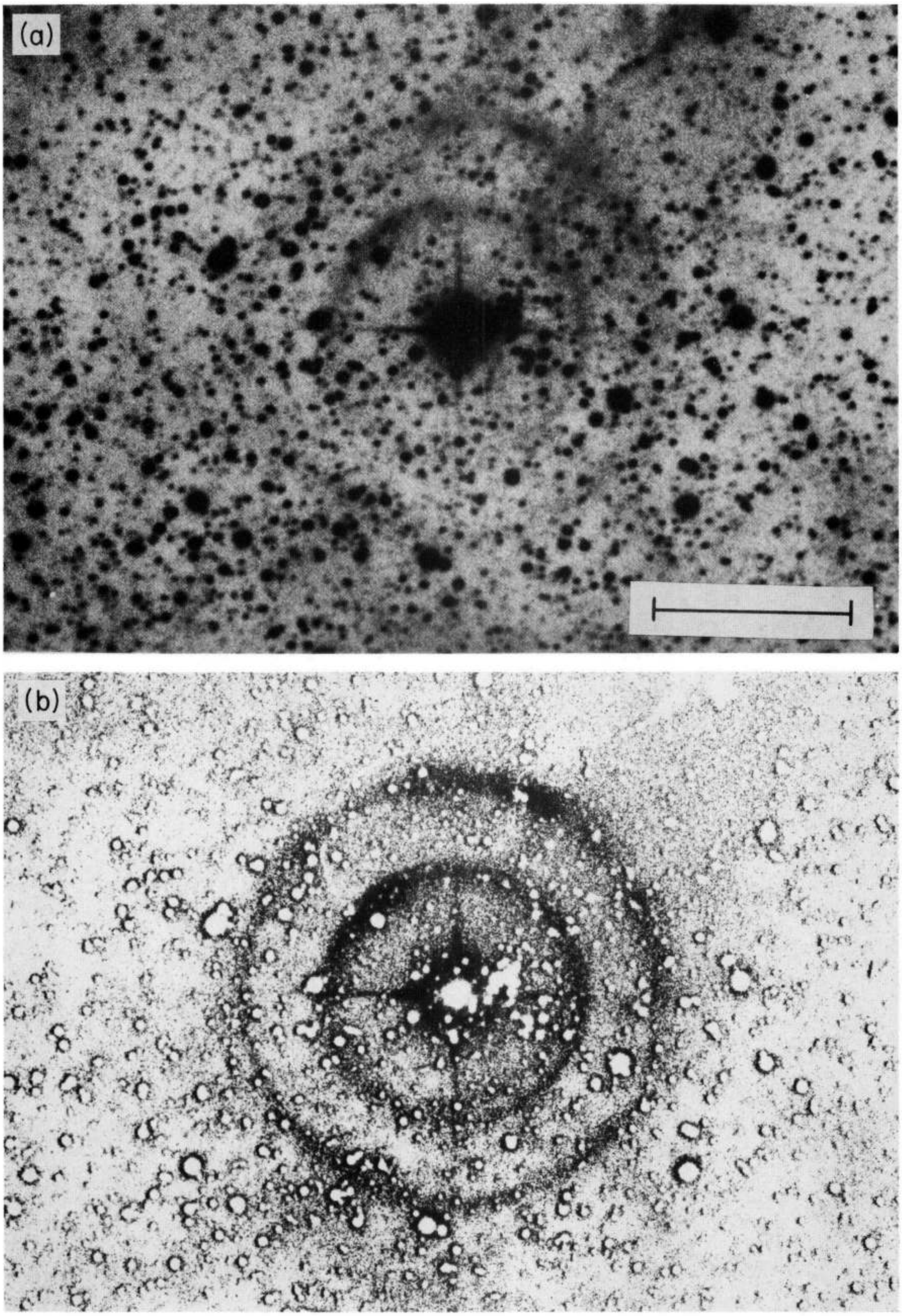

Plate 1. (a) A direct photographic image of the SN 1987A field and the light echoes as seen on the V plate taken on 1988 July 15. North is at the top and east to the left. The scale bar at the bottom right is 1 arcmin long. (b) The subtracted image of the supernova field.

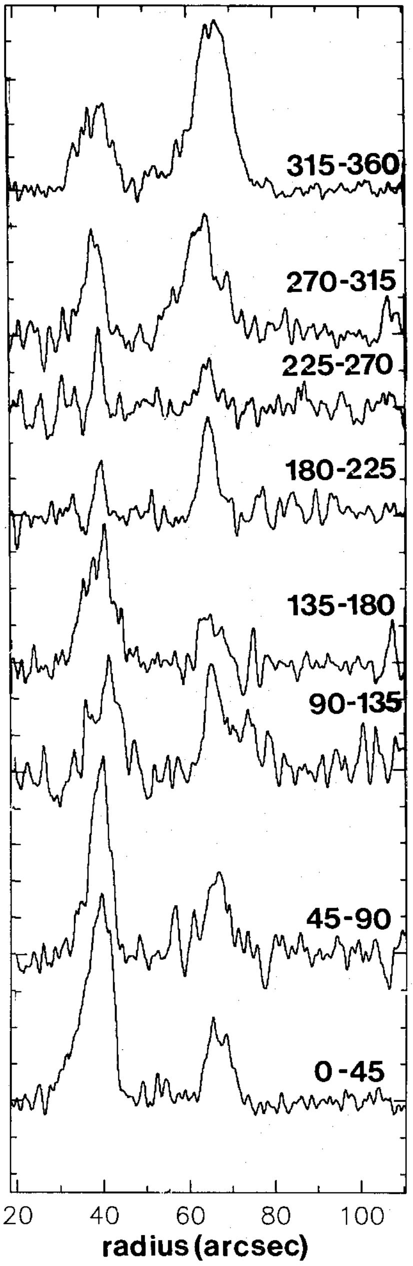

Figure 1. Radial profiles derived by digitizing the subtracted image and binning over 45° segments. *Ordinate:* averaged photographic density, *abscissa:* radius from the supernova. Indicated at the right end of each profile is the position angle range.

The broad peaks attributable to the echo rings are present in all eight azimuthal segments. The profiles show clearly the variations in brightness around the two rings. We have made no attempt to measure these, however, since although the photometric information recorded on the original plates is qualitatively preserved in the subtraction process, the wide variations in density superimposed on the rings by the nebulosity preclude quantitative photometry.

We use Fig. 1 to measure the azimuthal variations in radius and width of the echo rings. The inner ring has no noticeable variation in radius, whereas the eccentricity of the outer ring manifests itself as a weak sinusoid. The extremes in radius of the outer echo are at PA 180–225° and 315–45°. There are also significant differences in the width of the echoes at different position angles, which must be due to differences in the depth of the reflecting cloud over the area illuminated. Intriguingly, these differences appear to be coupled, in the sense that the two rings are both at their thinnest over the same PA range (180–270°).

In Table 2 we list exact measures of the radii and width of each echo determined from the radial profiles. For these we used the centroid and full width half maximum (FWHM), respectively, of the echo peaks. In determining the centroid the major uncertainty lay in setting the radial bounds of the peak in Fig. 1; we estimate a resultant uncertainty of ± 0.5 arcsec in our quoted radii. The value of the FWHM may be affected by local photographic saturation where the light echo is superimposed on bright nebulosity. At such points the echo would be flat-topped in the difference image. However, nowhere is this the case. Nor do our measurements exceed the widths reported by others (Gouiffes *et al.* 1988; Suntzeff *et al.* 1988) by more than one arcsec.

Table 2. Echo radii and thicknesses (all values are in arcsec).

	Inner Ring		Outer Ring	
Position Angle	radius	FWHM	radius	FWHM
0-45°	39.2	8	66.6	7
45-90°	39.5	6	66.0	8
90-135°	40.5	6	65.1	6
135-180°	39.7	7	64.8	7
180-225°	39.3	3	64.1	4
225-270°	39.5	3	64.6	4
270-315°	38.9	5	64.6	8
315-360°	39.9	9	66.2	9

The measured radii and widths are plotted as a function of position angle in Fig. 2. The data confirm that the inner ring had a constant radius to the limits of our measurement accuracy of 39.6 ± 0.2 arcsec. Hence the dust responsible for this feature lies 128 ± 2 pc in front of the supernova, in good agreement with the value of 123 pc derived by Crotts (1988b) from a photograph taken four months earlier. The ring expanded over this period at a rate of 0.057 arcsec d^{-1} or ~ 1.7 arcsec $month^{-1}$. The centroid of the cloud at the position sampled by the echo defines a plane that is inclined less than 7° to the plane of the sky.

The eccentricity of the outer echo is quite clearly seen in Fig. 2. Its radius ranges systematically with azimuth in a manner consistent with an off-centred ring. The application of a general ellipse-fitting routine indicates an optimal fit to a circle centred 0.4 arcsec east and 1.0 arcsec north of the supernova and with a radius of 65.3 ± 0.1 arcsec. Hence the outer ring arises from a sheet which is inclined with respect to the plane of the sky.★ The angle of inclination is given by

$$\tan \alpha = \delta r / ct_e \qquad \text{(Couderc 1939)},$$

★The intersection of a plane sheet with the ellipsoid of constant light travel time from the supernova is itself an ellipse which, when projected on to the sky, is offset from the supernova along its *minor* axis. However, for the parameters involved here its eccentricity is so close to zero that the echo appears circular.

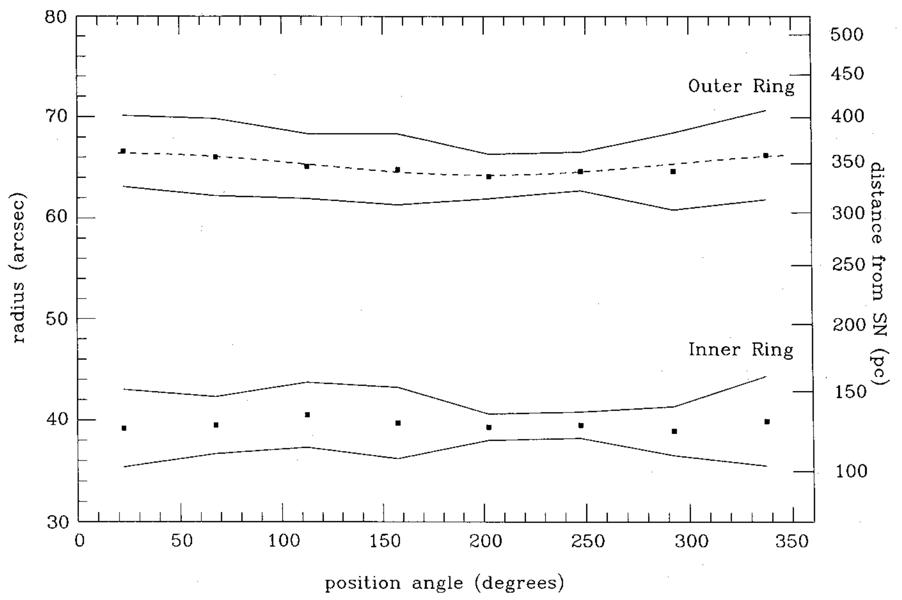

Figure 2. The variation in radius and width of the inner and outer echo rings with position angle. Radii are represented by the filled squares while the FWHM widths are indicated by the bracketing envelope. The optimum fit of an off-centred circle to the outer ring is shown by the *dashed* line.

where δr is the angular distance of the centre of the echo ring from the supernova, t_e is the interval between maximum light (1987 May 15; Chevalier & Emmering 1988) and the epoch of observation, and c is the speed of light. Our value $\delta r = 1.1 \pm 0.1$ arcsec at $t_e = 1.17$ yr implies $\alpha = 37.2 \pm 2.5°$. The point at which the cloud is closest to the Earth is at PA $29 \pm 4°$, the direction in which the ring's centre is offset from the supernova. The distance from the supernova to the point of reflection ranges between 362 pc at PA 29° and 338 pc at PA 209°.

We also see in Fig. 2 and Table 2 variations with PA in the width of each echo, from 3 to 9 arcsec for the inner ring and from 4 to 9 arcsec for the outer. The observed width is the combination of two smearing effects: the finite depth of the reflecting clouds and the breadth in time of the supernova light maximum. Taking a FWHM of 64 d for the V light curve, as measured from the data of Hamuy *et al.* (1988), the contribution of the latter effect to the FWHM of the rings is 3.0 arcsec for the inner ring and 4.8–5.4 arcsec for the outer.

Clearly the effect of cloud depth contributes to the apparent width of the echoes at most position angles. Only in the PA interval 180–270° can the observed thickness of the echoes be accounted for by the light curve effect alone. This is the case for *both* rings and it is curious that there should be such angular coherence in features that are due to clouds separated by more than ~200 pc with no evidence of material between. The excess width seen in both rings implies cloud depths of up to 70 pc along the line-of-sight, or about one third of the separation of the two clouds. This is greater than the diameter of the echoes, so that the description of the clouds as thin sheets is quite inappropriate over much of the area currently sampled. Once again we see angular coherence: both clouds have their greatest depths at PA 330–45°.

4 DISCUSSION

The enormous and morphologically complex H II filaments and shells found in the LMC by Meaburn (1980) suggest outflows centred on the star-forming regions at the eastern end of the LMC. These structures appear in a wide range of sizes; several are located in the 30 Dor region (e.g. Lortet & Testor 1984), and have radii ranging from 50 pc to 1 kpc. The most likely formation mechanism for these giant shells is mass-loss winds and repeated supernovae from OB associations which carve out a cavity of hot, low-density coronal gas in the ISM and sweep up surrounding dust and gas into dense peripheral shells (Chevalier 1977; McCray & Kafatos 1987). A cavity with a radius of at least 200 pc can be formed within 10^7 yr; subsequent supernova activity will cause the bubble to grow even larger. Absorption-line studies of the [Fe x] line in the direction of SN 1987A (Pettini *et al.* 1989) have provided evidence that the supernova lies behind or within such a supershell cavity. We might therefore expect the light echoes from SN 1987A to be reflected from material in the form of thin sheets.

Although the sheets on the line-of-sight to SN 1987A are not thin, the clumping of dust into discrete clouds is certainly consistent with the existence of cavities. A further clue is offered by the eccentricity of the outer light echo. In our first report (Allen, Couch & Malin 1988) we noted that its displacement in the general direction of 30 Dor was suggestive of the illuminated material being part of a shell centred on that region. Crotts (1988b) subsequently pointed out that the nebulosity to the north of the supernova (see Plate 1a) is part of the supershell nebula N 157C centred on the prominent nearby OB association NGC 2044 (catalogued as LH 90 by Lucke & Hodge 1970). On the basis of small (~1.5 arcsec) displacements in the general (northern) direction towards

NGC 2044, which he saw in both the inner and outer echoes, Crotts concluded that they probably arose from reflection off dust on the back and front sides, respectively, of the N 157C bubble.

Using our measurements of the complete rings we can examine this suggestion in more detail. The direction of displacement of the outer ring, PA $29 \pm 4°$, intersects the centre of the NGC 2044 complex, which is ~5.5 arcmin from SN 1987A. This provides strong support for at least the outer echo being reflected from what must be the front side of a shell centred on NGC 2044. On the assumption that the shell has a *spherical* geometry we use its inclination angle α, the projected NGC 2044–supernova distance and the supernova–sheet distance to calculate that the supernova must be 240 ± 10 pc *behind* the NGC 2044 complex and that the radius of the shell is 135 ± 8 pc. This figure is more accurate than Crotts' (1988b) value of 300 pc because we have fitted a complete ring. An interesting implication is that the rear side of the shell crosses our direct sight line 140 ± 20 pc in front of the supernova, very close to where the cloud responsible for the inner echo is located.

If the two echoes were part of the same thin, spherical sheet, we would expect the centre of the inner echo to be displaced from the supernova by the same angular distance as the outer echo but in the opposite direction. A displacement of this kind is certainly ruled out by our data; the largest amplitude sine curve that can be fitted to the inner ring is displaced towards PA ~110° by only 0.7 arcsec.

Despite this inconsistency, we are inclined to believe that the two rings are indeed portions of the same feature. The inner and outer rings have projected diameters of 19 and 31 pc at the point of reflection, considerably smaller than the depth of the clouds in some PAs. Therefore, the inclination of the cloud is a somewhat arbitrary concept, dictated by local variations of the density profile along the line-of-sight. The Hα pictures of the LMC published by Meaburn (1980) show supergiant shells to be extremely wrinkled and distorted, and to approximate to spheres only on the widest scale. It is possible that a wrinkle in the shell in the region where the inner echo ring is formed renders it normal to the line-of-sight. But it is also possible that the apparent inclination of the cloud responsible for the outer echo is simply a random irregularity in a shell which is not centred on NGC 2044 at all.

What encourages us to prefer the first of these possibilities is the similarity of echo structure at different position angles in the two shells, and the subsequent splitting of both shells over a similar range of PA seen in our 1989 February photograph (Couch & Malin 1989). Indeed, splitting of the inner shell over the PA range 180–250° is already suspected on our processed image (Plate 1b), although it is not revealed in the profile plots. Some part of the extra width of both echoes may result from unresolved splitting.

If indeed the two echoes are portions of a common shell or system of shells, then we should eventually see them merge at the shell peripheries, near PA 210°. For the case of the spherical shell addressed above, the limb lies 53 pc from the line-of-sight, and will be reached by the echo in ~20 yr.

The simplicity, sensitivity and large format afforded by our photographic approach makes us well poised to monitor the continual evolution of the light echoes. This we intend to do at regular intervals of 3–6 months.

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