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DISCOVERY OF AN INNER LIGHT-ECHO RING AROUND SN 1987A

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ABSTRACT

CCD imagery obtained on 1989 January 24 reveals a third, inner light-echo ring around SN 1987A, in addition to the two previously known outer rings. Its mean radius is 8".2, corresponding to a projected radius of 2.1 pc from the supernova; for an optical maximum in 1987 May, the light scattering occurs off interstellar dust located only 4.4 pc in front of SN 1987A. The width of the ring is 3".0, so that the scattering material is distributed between radii 3.1 and 5.7 pc from the supernova. The ring is brightest on the eastern side, where the average surface brightnesses in *B*, *V*, and *R* are 23.3 ± 0.4, 22.1 ± 0.2, and 21.4 ± 0.3 mag arcsec^{-2}, respectively. These values imply an average column density of 2.2×10^{18} cm^{-2} and a local density of 1.7 cm^{-3}. The surface brightness in the western side is about 0.5 mag arcsec^{-2} fainter, indicating that the scattering material is not uniformly distributed around the supernova.

Following Chevalier and Emmering, we may attribute the inner light echo to a shell of red-supergiant wind material that has been decelerated by its interaction with the surrounding medium. Paresce and Burrows failed to detect the inner ring in the *B* band in 1987 December, and Burrows found only a stringent upper limit to the *R* surface brightness in 1988 September. These earlier null results imply that there is a cavity in the dust along the line of sight toward Earth, such that the shell material outside the cavity became illuminated only at the end of 1988. The cavity might have arisen if the ambient interstellar medium had an appreciable density gradient, such that SN 1987A is located just inside the near edge of an interstellar cloud. This situation would have allowed the dense wind from the red supergiant progenitor to penetrate to larger radii in the direction toward Earth.

Subject headings: interstellar: matter — nebulae: reflection — stars: circumstellar shells — stars: individual (SN 1987A) — stars: supernovae

I. INTRODUCTION

The outburst of a bright nova or supernova (SN) is expected to be followed by the phenomenon of a "light echo," produced as light emitted near the peak of the outburst illuminates nearby interstellar dust (Couderc 1939; Zwicky 1940; van den Bergh 1965). The appearance of a light echo around the brightest SN of modern times, SN 1987A, was predicted by Schaefer (1987) and Chevalier (1987).

When light echoes were actually detected around SN 1987A (Crotts 1988*a*, *b*), they appeared as two rings whose angular radii, in 1988 March, were 32" and 51". The geometry indicates that these two features do not arise near the SN, but from clouds or sheets of interstellar dust hundreds of parsecs in front of it (Crotts 1988*b*; Chevalier and Emmering 1988; Gouiffes *et al.* 1988; Suntzeff *et al.* 1988).

Under the assumption of a uniform interstellar medium (ISM) surrounding SN 1987A, the brightest portions of the light echo should arise from material quite close to the SN and should initially appear as a centrally condensed nebula (Schaefer 1987). In practice, this inner echo would be rather difficult to detect during early times after the outburst, because of the brightness of the SN itself. At later stages, the surface brightness in the central region of the echo should decline more rapidly than at larger radii, leading to an annular appearance.

In order to search for an echo from material physically associated with SN 1987A, Paresce and Burrows (1989; see also Paresce 1989) carried out coronagraphic observations of a 23" × 36" region centered on the SN, in 1987 December. No echo features were detected to *B* and *R* surface brightnesses of ~22.5 mag arcsec^{-2} and ~20.2 mag arcsec^{-2}, respectively. The failure to detect an echo was attributed to a failure of the assumption of a uniform ISM, specifically to existence of a cavity in the dust surrounding the SN, produced by a wind from the progenitor star, Sk −69°202, long before the outburst.

In this *Letter*, we report the first detection of an inner light echo around SN 1987A, on the basis of observations made some 23 months after the outburst.

II. DISCOVERY AND OBSERVATIONS OF THE INNER LIGHT ECHO

Direct CCD images of SN 1987 were obtained on 1989 January 24, with the 0.9 m reflector at Cerro Tololo Inter-American Observatory (CTIO). An RCA CCD with pixels projecting to 0".5 on the sky was employed, along with filters closely approximating the Johnson *B*, *V*, and *R* bandpasses. The exposure times (120, 110, and 60 s in *B*, *V*, and *R*, respectively) were adjusted so that the SN itself (which was then at $V \simeq 11.7$) would not be overexposed. Four exposures were obtained through each of the three filters, and the FWHM of stellar seeing profiles in the images was ~1".4.

Examination of the frames at the telescope revealed the previously known outer light-echo rings and in addition showed a new, third echo lying quite close to the SN. A photographic

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representation of our data is given in Figure 1 (Plate L1), which shows that SN 1987A is surrounded by a diffuse halo, extending out to a radius of $\sim 9''$. Since similar well-exposed but unsaturated images of other stars obtained with the same instrumentation did not show such halos, it was rather certain that the new feature was real. In order to confirm its reality, however, we examined frames taken 3 weeks earlier with the same telescope but with a Texas Instruments CCD; these frames had been obtained by K. Meech and were kindly provided in La Serena by N. Suntzeff and M. Hamuy. These images showed the same feature, and we therefore published an *IAU Circular* announcing the discovery (Bond *et al.* 1989). The appearance of this *Letter*, however, has been delayed in the refereeing process.

Additional confirmatory observations were subsequently announced by Couch and Malin (1989) and Crotts and Kunkel (1989); the latter investigators found that the inner echo had been detectable as early as 1988 October. However, as described above, the feature was below detectability in 1987 December (Paresce and Burrows 1989; Paresce 1989), and it was also not detected in 1988 September (Burrows 1989).

A detailed analysis of our images reveals the properties of the inner light echo discussed in the following paragraphs.

The halo appears annular and is centered on the SN. Figure 2 presents radial profiles (*filled circles*[5]) in the V band for four different position-angle (PA) ranges around SN 1987A. For each profile, the median, rather than the mean, was calculated in order to minimize the effects of embedded field stars.[6] Since the light echo is superposed on the wings of the image of SN 1987A itself, we also show, in each panel of Figure 2, a scaled profile (*continuous line*) for an isolated bright star from a frame taken on the same night. We chose a comparison star whose core was saturated, in order to increase the signal-to-noise ratio in the wings, and we verified that the profile provides a good fit to the wings of isolated stars in the SN 1987A frames.

The upper left-hand panel in Figure 2 shows the full profile of SN 1987A (i.e., for the PA range 0°–360°). Here the light echo appears as excess surface brightness between radii of approximately 7″ and 9″, but the profile is badly contaminated by the close companions of SN 1987A (stars 2 and 3 in the notation of Walborn *et al.* 1987), and by a clump of field stars WNW of the SN. Inspection of Figure 1 shows that the field star contamination is lowest, and the echo surface brightness highest, on the eastern side of the SN. We therefore calculated profiles for the eastern half only (PA range 0°–180°; upper right-hand panel of Fig. 2), and for the NE and SE quadrants (PA ranges 0°–90° and 90°–180°; lower left-hand and lower right-hand panels of Fig. 2). In these three profiles, there is considerably less field star contamination,[7] and the echo is more clearly defined. The inner echo appears as a ring, with observed inner and outer radii (measured for the PA range 0°–180°) of about 6″.5 and 9″.8, respectively, with an estimated accuracy of better than ±0″.5.

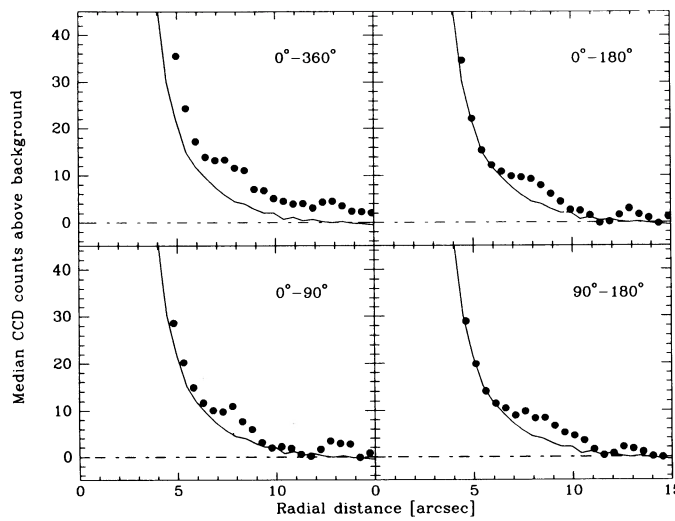

FIG. 2.—The filled circles show the azimuthally medianed radial profile of SN 1987A in the V band for the four indicated position-angle ranges (calculated for a stack of four V frames). The continuous lines show the observed profile for a well-exposed isolated field star, in order to illustrate the contribution from the wings of the supernova image. The presence of the new, inner light echo is shown by the excess surface brightness between radii of about 6″.5 and 9″.8. The full profile, shown in the upper left-hand panel, is badly contaminated by field stars, but the contamination is less for the eastern side of the image (*upper right-hand panel*), and for the NE and SE quadrants (*lower left-hand and lower right-hand panels*).

The mean radius of the inner echo is thus 8″.2, in very good agreement with that measured by Crotts and Kunkel (1989) in early 1989 January. Allowing for a seeing of 1″.4 in our images, the actual width of the ring is 3″.0, and the corrected inner and outer radii are 6″.7 and 9″.7, respectively. Such a width is substantially larger than the 0″.4 that would be expected as the effect of the width of the SN outburst alone (Chevalier and Emmering 1989). This is a clear indication that the scattering material is spread over an appreciable length along the line of sight.

As mentioned above, the inner halo's average surface brightness is highest along an arc on the eastern side of the SN. In this arc, for the PA range 0°–180° and radii 7″.0–9″.6, the average surface brightnesses (in mag arcsec^{-2}) are 23.3 ± 0.4 in B, 22.1 ± 0.2 in V, and 21.4 ± 0.3 in R. On the western half of the echo (PA = 180°–360°), the surface brightness is about 0.5 mag arcsec^{-2} fainter, but the field star contamination makes precise measurements difficult. The frames were calibrated using the known BVR magnitudes of the SN at the time of our observations ($B = 11.86$, $V = 11.68$, and $R = 11.14$, adopted from Whitelock *et al.* 1989) and of three nearby field stars with photometry by Walborn *et al.* (1987).

[5] The noise per pixel in the light echo is $N_{\rm pix} = [S + B + (RN)^2]^{1/2}$, where S and B are the contributions from the echo signal and from the background, respectively, and RN is the read-out noise of the CCD chip, all expressed in electrons (e^-). For the RCA chip, one CCD count corresponds to $8.3e^-$, and $RN = 46e^-$. The background signal B, determined to high accuracy from the entire frame, is 96 CCD counts, or $797e^-$ (due mainly to scattered moonlight), and for a typical filled circle in the upper right-hand panel of Fig. 2 at $r \simeq 8''$ from the SN, S is ~ 10 counts or $83e^-$. Hence $N_{\rm pix} \simeq 55e^- = 6.6$ CCD counts. Since the number of pixels contributing to a point at $r \simeq 8''$ is $\sim 16\pi$, and since Fig. 2 is based on the average of four frames, a typical error bar for the filled circles in Fig. 2 is $6.6/(4 \times 16\pi)^{1/2} = 0.5$ counts, or about the radius of the plotted circle. (Since we approximated the mean signal S by calculating the median, this is only a roughly correct estimate of the size of the error bars.)

[6] As an additional check on the reality of the inner light echo, we further suppressed field stars by calculating the profiles for the 30th percentile values (as opposed to the 50th percentile values of the usual median), and found that the light echo is still clearly present. For our light echo to be solely an artefact of field stars, the stars would have to contribute to more than 50% of all the pixels between radii of about 7″ and 10″ and to do so in both the northeast and southeast quadrants.

[7] The NE profile inside $\sim 6''$ in the lower left-hand panel of Fig. 2 is slightly contaminated by a faint, previously unreported star some 4″ northeast of SN 1987A. However, the effect of the previously known star 3 on the SE profile in the lower right-hand panel beyond 5″ is negligible.

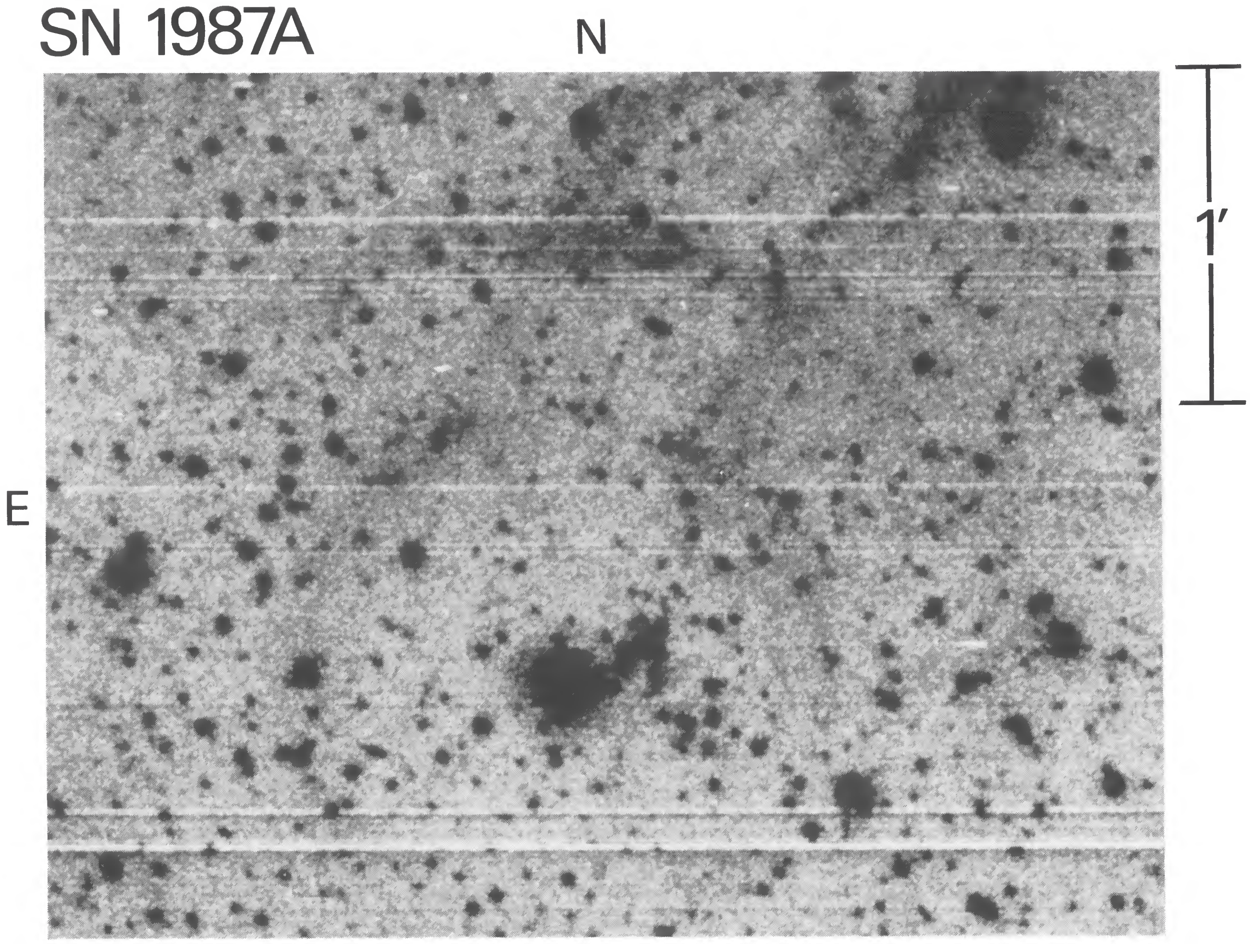

FIG. 1.—Photographic reproduction showing the field of SN 1987A on 1989 January 24. This image was constructed by stacking four *R*-band CCD exposures, obtained with the CTIO 0.9 m reflector. The previously known arclike light-echo structures are present, at angular radii of 49″ and 79″. In addition, the innermost ring, whose discovery is reported here, is visible as a diffuse feature of mean radius 8″.2, brightest on the northeastern side of the supernova, but encircling SN 1987A completely.

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The profiles shown in Figure 2 also hint at a second feature $\sim 13''$ from the SN. There is no obvious counterpart to this feature in Figure 1, other than a number of moderately bright field stars at about this radius, which should have been suppressed by use of the median. Continued monitoring of the light echo, and deeper imagery, will be required to confirm the reality of this faint feature.

We also measured the mean radii and surface brightnesses (over annuli within $\pm 2''$ of the mean radii) of the two outer rings in regions as free as possible of obvious nebulosities and of field stars. The following results were obtained: Ring 2: over the PA range 170°–315°, radius $= 49'' \pm 2''$ and surface brightnesses = 22.4, 22.0, and 21.4 mag arcsec^{-2} in *B*, *V*, and *R*, respectively; Ring 3: over the PA range 0°–20°, radius $= 79'' \pm 2''$ and surface brightnesses = 22.7, 22.1, and 21.4 mag arcsec^{-2} in *B*, *V*, and *R*, respectively.

III. DISCUSSION

a) Physical Association with SN 1987A

The geometry of light echoes is well known (Couderc 1939; Schaefer 1987 and references therein). An echo that is observed at an impact parameter $b = D\theta$, where D is the distance to, and θ is the angular radius from, the SN, arises from dust located a linear distance $r = ct[1 + (b/ct)^2]/2$ from the SN. In the latter equation, t is the time elapsed since maximum light, as seen by the observer.

For a Large Magellanic Cloud (LMC) distance of $D = 52$ kpc, the observed mean radius of the inner echo in 1989 January, $\theta = 8''.2$, corresponds to a projected radius of $b = 2.1$ pc. The optical maximum of SN 1987A covered an interval of ~ 60 days centered around 1987 May 20 (Panagia 1987). Therefore, $t \simeq 615$ days, and the mean echo radius corresponds to dust located at an average distance of only $r = 4.4$ pc from the SN (at an angle of 28° from the line of sight, as seen from the SN). Unlike the previously detected outer echoes, therefore, the inner echo arises from material that is *spatially associated* with SN 1987A.

It should be noted that the feature discussed here is distinct from the much smaller ($\theta \lesssim 1''$) ultraviolet line-emitting region detected with the *IUE* satellite by Fransson *et al.* (1989).

The annular appearance of our echo suggests that the supernova lies inside a hollow shell, of inner radius ~ 3.1 pc (corresponding to the inner angular radius of $6''.7$). Moreover, the scattering material must have a fairly sharp outer edge at $r \simeq 5.7$ pc, corresponding to the outer radius of $9''.7$.

Using standard model calculations (e.g., Schaefer 1987; Chevalier and Emmering 1988), and adopting for the dust scattering function a g-factor of 0.7 (using 0.6 or 0.8 would halve or double the optical depth estimate), we find that an average V surface brightness of 22.1 mag arcsec^{-2} implies the existence of a layer with an extinction optical depth of 0.0003 in the V band, and a geometric thickness of about $60/(1 - \cos 28°)$ lt-days, or $\sim 1.3 \times 10^{18}$ cm.

Our interpretation of the inner ring as a light echo is confirmed by polarization observations by Sparks, Paresce, and Macchetto (1989). On 1989 February 10 they measured a linear polarization of about 15% in a ring between radii of about $7''$–$10''$. Such a value of the polarization is consistent with scattering by small dust grains at an angle of 25°–30°.

In the LMC, the ratio of the V extinction to the hydrogen column density has been found to vary between 1×10^{-22} and 5×10^{-22} mag cm^{-2}, with the former being more appropriate for the 30 Doradus nebula (Fitzpatrick 1986). Therefore, an optical depth of 0.0003 translates into a gas column density of $\sim 2.2 \times 10^{18}$ atoms cm^{-2}, with an uncertainty of $\pm 20\%$, over a length of 1.3×10^{18} cm, and, therefore, a local density of 1.7 cm^{-3}.

b) A Punctured Shell?

The negative result of Paresce and Burrows (1989) may provide further constraints on the geometric distribution of the scattering material. Their data were obtained in 1987 December, at a time $t \simeq 215$ days after optical maximum, when SN 1987A was at $V = 6.2$. At that time, material located in a spherical shell with radii between 3.1 and 5.7 pc would have produced an echo with angular radii between $4''.1$ and $5''.7$. The average surface brightness in the B band should have been 1.7 mag arcsec^{-2} brighter than we observed in 1989 January, i.e., 21.6 mag arcsec^{-2}.

Nevertheless, at $\theta \simeq 5''$, Paresce and Burrows (1989) found an upper limit to the B surface brightness of ~ 22.5 mag arcsec^{-2}, more than a factor of 2 below what we would have expected if our dust shell had a uniform density and had been illuminated at that time. This discrepancy suggests that the density distribution of the scattering material is not uniform, being considerably lower in our direction. In other words, it indicates that there is a cavity in the dust shell, located along the line of sight from SN 1987A to Earth, such that there was no detectable illumination in 1987 December. From their upper limit on the surface brightness, Paresce and Burrows estimated an upper limit to the total (dust plus gas) density of about 5×10^{-2} cm^{-3} for possible diffuse material up to a distance of 10 pc from SN 1987A. This is about 35 times lower than the density in our echo ring and implies that the surrounding space in front of the SN is actually rather empty, possibly due to the effect of a stellar wind from the progenitor star when it was on or near the main sequence.

Moreover, R-band observations made by Burrows (1989) on 1988 September 8 show no apparent light echo in the angular range $5''$–$10''$ to a limit of ~ 22 mag arcsec^{-2}. Our dust shell, observed in 1989 January, would have had a mean radius of $7''.3$, a width of $2''$, and an average R surface brightness of 21.1 mag arcsec^{-2} at the time of Burrows's observation. Again, the earlier nondetection confirms the lack of appreciable amounts of matter up to about $7''$ from SN 1987A.

Still further evidence for a cavity is that Crotts and Kunkel (1989) found that the inner echo had become detectable by 1988 October and had brightened significantly by 1988 December.

Chevalier and Emmering (1989) have recently suggested that our inner light echo corresponds to the decelerated outer edge of the stellar wind from the SN progenitor when it was in the red-supergiant phase. They have shown that the required density for the scattering material could be achieved with reasonable choices of the relevant parameters (the supergiant's mass-loss rate and wind velocity, and the pressure of the ambient ISM). However, the observational picture that is emerging is more complicated. Provided that the observational upper limits stated above are realistic, the data indicate that there are substantial amounts of matter at distances greater than 3.1 pc from the SN, but that, in the region *in front of* the SN in our direction, the density is much lower, by almost two orders of magnitude.

Such a "punctured shell" could have resulted from an anisotropy in the distribution of the ISM around the supernova progenitor; a lower density in our direction would have offered less resistance to the expansion of the red supergiant wind and, therefore, the shell would have a lower density near the line of sight. Such a geometry might have resulted if SN 1987A were located just within the near edge of a large cloud (within which the progenitor was formed some 10–15 × 10^6 yr ago), with the bulk of the cloud lying *behind* the SN as seen from Earth. This suggested configuration is similar to that of the Orion A/M42 nebula; this is the H II region ionized by the Trapezium stars, which happen to lie on the side of a massive cloud nearest the direction to Earth.

c) Recent and Future Developments

In the future, the light echo will progressively illuminate material to the side of, and finally behind, SN 1987A (Chevalier and Emmering 1989; Felten and Dwek 1989). Continuing observations are thus very important because of the possibility of detailed mapping of a red-supergiant wind.

Observations that we obtained on 1989 September 24, after the original version of this *Letter* was submitted for publication, dramatically illustrate the importance of continued monitoring. The inner light echo is now considerably fainter than in 1989 January, providing additional evidence that we are indeed dealing with a transient light-echo phenomenon. This development, confirmed also by Wampler *et al.* (1990) and Crotts and Kunkel (1990) on the basis of observations made in 1989 December, will be the subject of a forthcoming paper by us.

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