THE ASTROPHYSICAL JOURNAL, 339:1073–1077, 1989 April 15

SPECKLE INTERFEROMETRY OF SN 1987A UP TO ONE YEAR AFTER EXPLOSION

P. R. WOOD,[1] P. E. J. NULSEN,[1] P. R. GILLINGHAM,[2] M. S. BESSELL,[1] M. A. DOPITA,[1]
AND C. MCCOWAGE[2]
Received 1988 May 24; accepted 1988 September 21

ABSTRACT

Speckle interferometric observations of SN 1987A have been obtained at Hα with the Anglo-Australian telescope on 1987 December 12–13 and 1988 February 10, days 292–293 and 352, respectively, after the explosion of the supernova. Uniform disk angular diameters of 23.1 ± 1.6 and 23.9 ± 0.9 mas, respectively, were obtained near line center on these two dates, corresponding to mean expansion velocities since explosion of 3300 and 2900 km s^{-1}. A diameter measurement at the wavelength of the [S II] doublet $\lambda\lambda$6716, 6731, which lies on the red wing of the Hα line at a redshift of 10,000 km s^{-1}, yields the larger diameter of 30.6 mas. No point source brighter than ~3.6 mag fainter than the supernova at Hα was found within a 0.″35 radius of SN 1987A on 1987 December 12–13; on 1988 February 10 the corresponding limits were ~4.8 mag fainter than the supernova within a 0.″43 radius. We discuss the early reports of the detection of a "mystery spot" near SN 1987A.

Subject headings: interferometry — stars: binaries — stars: individual (SN 1987A) — stars: supernovae

I. INTRODUCTION

Spectra obtained following the explosion of SN 1987A on 1987 February 23 show that the initial ejecta were thrown out with velocities of ~18,000 km s^{-1} (e.g., Dopita 1988 and references therein). Material passing through the photosphere at later times has been expanding at slower velocities and, at the time of the observations reported here, the expansion velocity obtained from the blueshifted Hα absorption was ~4500 km s^{-1}. At an expansion velocity of 4500 km s^{-1}, matter from the supernova will have expanded to an angular diameter of ~0.″04 after 1 yr. Since the Rayleigh limit of resolution of a 4 m telescope at Hα is 0.″04, speckle interferometry with high signal-to-noise ratio should provide a good indication of the supernova diameter at this time. Our first aim in making these observations was to try to obtain an angular diameter for SN 1987A. Another purpose of the current set of observations was to see if there was a bright point source near SN 1987A. Observers who made early speckle interferometric observations of SN 1987A (Nisenson *et al.* 1987; Meikle, Matcher, and Morgan 1987) claim to have seen such a bright point source (the "mystery spot") about 0.″06 from the supernova.

II. OBSERVATIONS AND DATA REDUCTION

The speckle observations reported here were made at the coudé focus of the Anglo-Australian Telescope (AAT) on 1987 December 12 and 13 and 1988 February 10. A microscope objective was used to enlarge the image scale at the coudé focus onto the detector and a narrow bandpass filter selected the wavelength of observation. Atmospheric dispersion was corrected with a pair of nondeviating dispersive elements constructed in the Mount Stromlo Observatory optical shop; a microprocessor system constructed at the Anglo-Australian Observatory (AAO) was used to control the atmospheric disperion corrector. The detector was an Image Photon Counting System (IPCS) as developed by Boksenberg (1978). It was run in an "event-tagging" mode (an enhancement built at the AAO) in which the addresses of all pixels with signals above a set threshold in each frame are recorded on magnetic tape. The event centering normally employed with the IPCS was not used because it can count two nearby photon events as just one. To provide for exposure times of less than one IPCS frame time (about 16 ms with the format used here) and to avoid confusion due to persistence of bright events from one frame to the next, a synchronized rotating shutter was introduced into the optical path at the coudé focus so that light was incident on the detector only for some fraction of each alternate IPCS frame. The scale of the detector pixels on the sky was determined as follows: first, an accurately calibrated grid was placed at the telescope focus and its size measured on the detector was used to determine the projected pixel size at the telescope focus; then the accurately known scale (arcsec mm^{-1}) of the telescope at the coudé focus was used to calculate the projected pixel size on the sky.

Details of the observations and observational setup are given in Table 1. On December 12 and 13, the seeing was poor (FWHM of the seeing disk ~2.″5–4″) while on February 10 it was good (FWHM ~0.″8). With each filter, an observation was made of SN 1987A and, immediately afterward, of a point source of similar brightness and zenith distance in a nearby part of the sky.

The data reduction process which we describe briefly here is similar to that used by Wood, Bessell, and Dopita (1986). In order to get diffraction-limited information from the speckle data, the digital autocorrelation of each frame was computed and the autocorrelations of all frames were added to give the cumulative autocorrelation. As is well known (e.g., Labeyrie 1978), the resultant autocorrelation has both a diffraction-limited component and a broad seeing disk–related pedestal which needs to be removed. The seeing disk component can be mostly removed by subtracting the cross-correlation function obtained by cross-correlating each frame with a frame taken ~0.5 s previously (Worden *et al.* 1977). However, because of translation of the image over a time scale of ~0.5 s, the cross-correlations tend to be slightly more spread out than the auto-correlations. Hence, the cross-correlations were multiplied by a function of the form $\alpha(1 - \beta r)$, where r is the radius from the

[1] Mount Stromlo and Siding Spring Observatories, Institute of Advanced Study, Australian National University.
[2] Anglo-Australian Observatory, Coonabarabran, N.S.W.

TABLE 1

SPECKLE OBSERVATIONS OF SN 1987A

Object	Integration Time (s)	Shutter Time (ms)	Pixel Size	Filter $\lambda/\Delta\lambda$	ϕ_{UD} (mas)	ϕ_{LDD} (mas)	ΔM (mag)
			1987 December 12 and 13				
SN 1987A	900	16	0″0046	6563/100	25.1	26.6	3.5
SN 1987A	500	16	0.0046	6563/100	23.0	24.5	3.4
ζ Vol	600	16	0.0046	6563/100	...	...	...
SN 1987A	1100	6	0.0046	6576/16	23.0	24.4	3.6
γ Vol	500	6	0.0046	6576/16	...	...	...
SN 1987A	500	16	0.0046	6596/15	21.1	22.4	3.3
γ Vol	500	16	0.0046	6596/15	...	...	...
			1988 February 10				
SN 1987A	600	4	0.0057	6566/15	24.6	26.1	4.8
ζ Vol	600	4	0.0057	6566/15	...	...	...
SN 1987A	600	4	0.0057	6576/16	23.3	24.5	4.4
δ Vol	600	4	0.0057	6576/16	...	...	...
SN 1987A	600	4	0.0057	6596/15	22.9	24.4	3.9
ζ Vol	600	4	0.0057	6596/15	...	...	...
α Ori	600	4	0.0057	6596/15 + ND2	58.8	62.2	...
SN 1987A	600	15	0.0057	6729/55	31.1	32.9	4.2
ζ Vol	400	15	0.0057	6729/55	...	...	...
SN 1987A	600	6	0.00356	6566/15	24.8	26.3	3.7
ζ Vol	500	6	0.00356	6566/15	...	...	...

origin of the cross-correlation. Values of α and β were determined by least-squares fitting the modified cross-correlation to the seeing pedestal of the autocorrelation outside the region where there was any significant diffraction-limited component. Typically, $\alpha(1 - \beta r)$ changes by less than a few percent over the full range of r.

III. RESULTS

Examples of the seeing-subtracted autocorrelation functions are shown in Figure 1 (Plate 13). The main components of the autocorrelation function of a point source are a bright central spot surrounded by a dark band surrounded in turn by a light ring. These are the counterparts of similar features in the Airy pattern; the bright central peak results from the central peak of the Airy function, while the surrounding bright ring results from the first bright Airy ring. We note that because of the central obstruction of $\sim$40% of the mirror diameter on the AAT, the first Airy ring is quite prominent and has a peak intensity of 7% of the central maximum.

An azimuthal average of the autocorrelation of one of the point source observations is shown in Figure 2*a*. Because each photon may be recorded in a few adjacent pixels, the autocorrelation function out to a radius of 4 pixels from the origin is contaminated and should be ignored. The amplitude A_{ij} of the plotted autocorrelation at pixel (i, j) is proportional to $N_{ij}/(n_f n^2)$, where N_{ij} is the number of vectors obtained in the digital autocorrelation, n_f is the number of frames, and n is the number of photons per frame. With this normalization, and fixed seeing conditions, the amplitude of the speckle component of the autocorrelation should depend only on the image size of the source (e.g., Wood 1985); in particular, all point sources should exhibit the same amplitude.

An interesting feature of Figure 2*a* is that the dip corresponding to the first dark Airy ring is deeper than that which results from the autocorrelation of the Airy function appropriate for the AAT. This result is predicted by Korff (1973) who shows that, when the seeing correlation size r_0 is much smaller than the mirror diameter D (i.e., the size of the seeing disk is

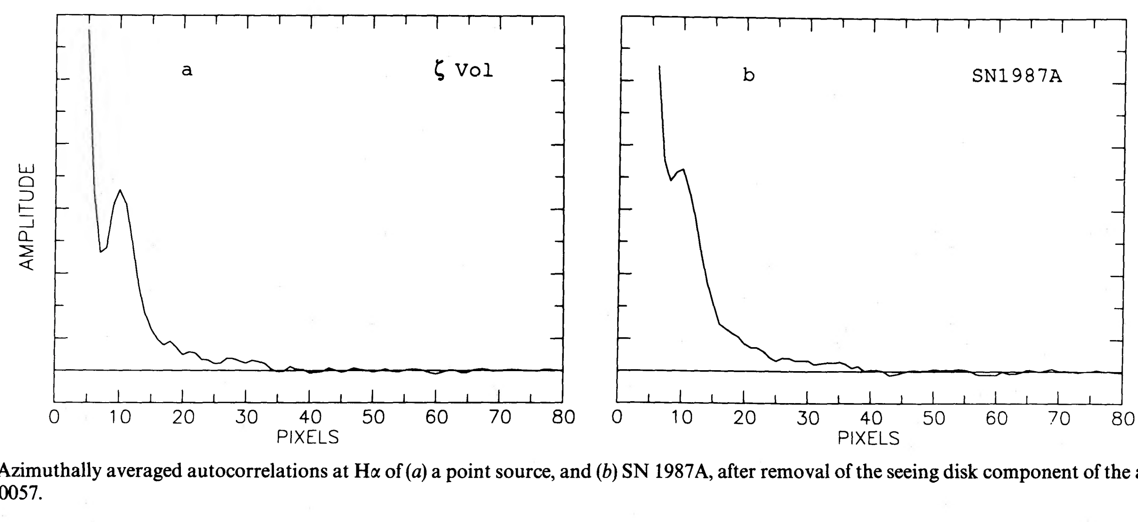

FIG. 2.—Azimuthally averaged autocorrelations at Hα of (*a*) a point source, and (*b*) SN 1987A, after removal of the seeing disk component of the autocorrelation. Pixel size is 0″0057.

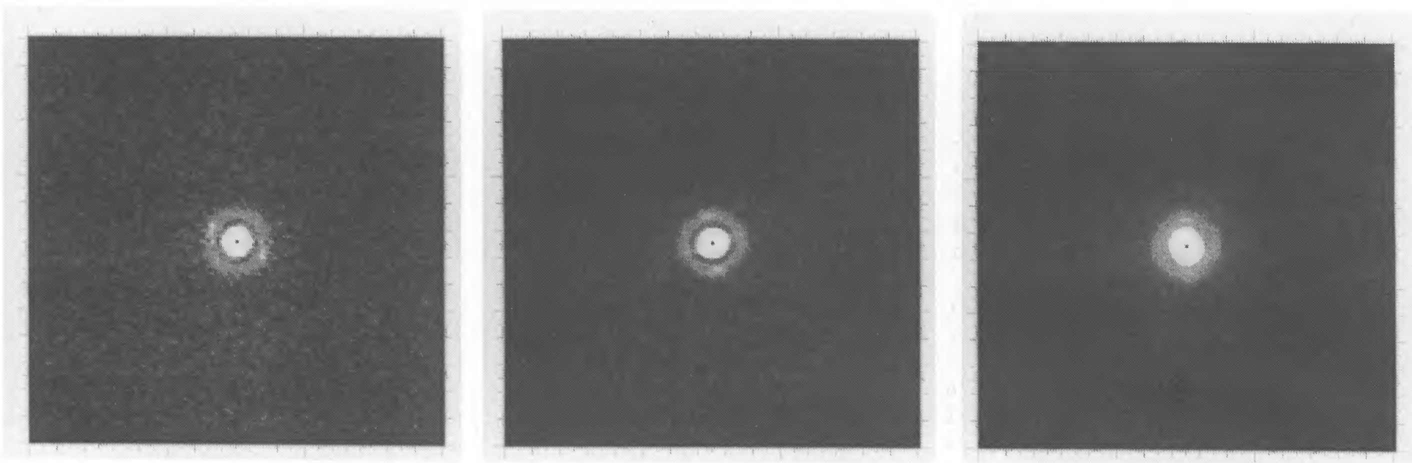

FIG. 1.—Some examples of autocorrelations from which the seeing disk component has been removed. Pixel size is 0".0057, and the whole autocorrelation field is 0.86 arcsec^2. (*left*) The autocorrelation of a point source observed at Hα on 1988 February 10. The horizontal and vertical directions correspond to the *x* and *y* scan directions, respectively, of the IPCS. The row of data along the *x* scan direction of the IPCS is contaminated by instrumental noise. The two brightest spots on the Airy ring are aligned along the north-south axis. (*middle*) The average autocorrelation of three point sources observed at Hα on 1988 February 10. The autocorrelation of each point source was rotated so that north was up before the three autocorrelations were added. (*right*) The average autocorrelation of three Hα observations of SN 1987A taken on 1988 February 10. North is up; east to the left.

WOOD *et al.* (*see* **339**, 1074)

much larger than the size of the central peak of Airy pattern), the shape of the autocorrelation will approach that of the Airy *intensity profile*. In very good seeing conditions ($r_0 \gtrsim D$), the autocorrelation profile will be similar to the *autocorrelation of the Airy intensity profile*.

In Figure 2*b* we show the azimuthally averaged autocorrelation of the observation of SN 1987A taken immediately before the observation of the point source shown in Figure 2*a*. It is immediately obvious that the dark ring in the autocorrelation of the SN 1987A data is not as deep as in the point source. This result implies that the supernova is resolved; Figure 2*b* is the result of the convolution of the autocorrelation of the true image of SN 1987A with the point source autocorrelation in Figure 2*a*. Each pair of point source, SN 1987A observations that we obtained shows this smearing of the point source autocorrelation by the supernova.

In order to estimate a size for the supernova, it is necessary to convolve the point source autocorrelation with the autocorrelation of some model for the true image of SN 1987A. Two models were used, a uniform disk and the limb-darkened disk of a gray atmosphere (e.g., Mihalas 1978). Before the autocorrelation can be done, the central structure of the autocorrelation of the point source out to a radius of 4 pixels has to be determined (the instrumental photon spike dominates the observed autocorrelation here). We have replaced this region by a mixture of the Airy function appropriate for the AAT and its autocorrelation, where this mixture is fitted to pixels of radius ≥ 5 pixels from the origin. The proportion of Airy function and autocorrelation of Airy function was varied to get the best fit to the observed point source autocorrelation; our final results are quite insensitive to the relative proportion of the two functions. Having obtained a complete point source autocorrelation function, this function was then convolved with the autocorrelation of a model for SN 1987A, and a least-squares fit of the resultant function was made to the two-dimensional autocorrelation of SN 1987A in the interval from ~ 5 to ~ 15 pixels from the origin (where the photon spike does not contaminate the data but the autocorrelation is still of reasonable amplitude). The angular diameters obtained from these fits are given in Table 1 for both uniform disks ($\phi_{\rm UD}$) and limb-darkened disks ($\phi_{\rm LDD}$). As a test of our method, we observed Betelgeuse and obtained a uniform disk angular diameter of 58.8 mas, well within the range of values measured by other authors (Wilkerson and Worden 1977).

All the angular diameter determinations made above assumed axial symmetry in SN 1987A as we were not able to find any convincing evidence for asymmetries. We note that our data is not very sensitive to asymmetries as the central few pixels of the autocorrelation (which are most sensitive to asymmetries in the object being measured) are dominated by the detector generated "photon spike." Although there were asymmetries present at the same level in the autocorrelations of both SN 1987A and the point sources, we suspect that these asymmetries were due to the motion of speckles during our exposures in a preferred direction set by the winds above the telescope.

Finally, we have made estimates of the maximum brightness possible for a point source object associated with the supernova if it is to remain undetected in our two-dimensional autocorrelations. There are certainly no point sources that are apparent to the eye in the autocorrelations. In order to quantify this statement, we note that the intensity of the first Airy ring is 7% of the intensity of (2.9 mag fainter than) the intensity at the center of the Airy disk on the AAT; this provides us with a reference intensity with which to compare possible point sources in the autocorrelations of SN 1987A. The autocorrelations of SN 1987A were smoothed with a Gaussian smoothing function of size comparable to the size of an autocorrelated Airy disk. Then the peak with maximum height above the local background was obtained in the interval from twice the radius of the first bright Airy ring (0".11) to a radius of 0".35 (1987 December) or 0".43 (1988 February). The height of this peak relative to the height of the first Airy ring gives the maximum possible brightness of any point source associated with the supernova, or equivalently, the minimum magnitude difference ΔM between any point source near SN 1987A and SN 1987A itself. Values of ΔM obtained in this way are given in Table 1. Clearly, any point source associated with the supernova at the time of these observations was much fainter than the supernova itself.

The reason we have excluded the region inside 0".11 (which is the region where the "mystery spot" was seen) from this analysis is that diffraction and, even more importantly, refraction effects adjacent to the north-south and east-west spider vanes holding the secondary mirror can give rise to bumps on the first bright Airy ring ("Mickey's Ears"—Foy 1987). This effect is demonstrated in Figure 1, where bright spots corresponding to north-south and east-west are clearly visible on the first Airy ring.

IV. DISCUSSION

For the three filters near the center of the Hα emission line (the filters with redshifts of 0, 500, and 1500 km s^{-1}), the uniform disk angular diameters on 1987 December 12–13 and 1988 February 10 are 23.1 ± 1.6 and 23.9 ± 0.9 mas, respectively, where the errors are standard deviations computed from the multiple diameter estimates. These two values are essentially identical, indicating that there was little change in the Hα diameter of the supernova between the two observations. The angular diameters are also significantly larger than the Hα angular diameter of 9 ± 4 mas reported by Karovska *et al.* (1987) on 1987 June 1. However, the angular diameters given by Karovska *et al.* (1987) at three wavelengths other than Hα on 1987 June 1 are very similar to the values measured here at Hα about 6 months later.

From our angular diameters and the time since explosion, a mean expansion velocity for the Hα material can be derived. Adopting a distance to the LMC of 50 kpc, these velocities are 3300 km s^{-1} in 1987 December and 2900 km s^{-1} in 1988 February, about $\frac{2}{3}$ the expansion velocity obtained from the Hα absorption dip in the spectrum of SN 1987A at the time of the speckle observations.

From photometry of the supernova (Catchpole *et al.* 1988) a photospheric angular diameter can be derived by using the definition $F_{\rm tot} = 4\phi^2\sigma T^4$, where $F_{\rm tot}$ is the total flux per unit area received at Earth, obtained by integrating under the observed flux spectrum; ϕ is the photospheric angular diameter; and T is the temperature obtained by fitting a blackbody to the observed spectrum. The radii obtained by Catchpole *et al.* (1988) up to early 1987 November were extrapolated to the dates of our speckle observations to give photospheric angular diameters of 0.85 and 0.58 mas on 1987 December 12–13 and 1988, February 10, respectively. These values are much smaller than the observed Hα angular diameters. Of course, the diameter at Hα is expected to be larger than the blackbody diameter as the flux in the Hα emission line at the time of observation was ~ 15 times the flux at nearby parts of the continuum. However, this accounts for only about a factor 4 in diameter [since, for a given blackbody temperature, $\phi \propto (F_\lambda)^{1/2}$], whereas the ratio of our speckle-derived diameter to the blackbody diameter is about 30. Thus the photons originating from the remote ejecta must either be scattered or produced by a highly non–LTE process.

We now examine the plausibility of the suggestion that electron scattering determines the size of optical surface of SN 1987A. In order to obtain the optical depth of the envelope, we adopt the hydrodynamical model of Shigeyama, Nomoto, and Hashimoto (1988), which has an envelope mass of 6.7 $M_\odot$ and an explosion energy of 10^{51} ergs. We assume the envelope material expands ballistically so that the radius r of a given mass element is $r(M_r) = v(M_r)t$, where t is the time since explosion and v is the expansion velocity of the mass element. The density ρ in the expanding ejecta is obtained from

$$\rho = \frac{1}{4\pi r^2}\frac{dM_r}{dr} = \frac{1}{4\pi r^2}\frac{dM_r}{dv}\frac{dv}{dr}\,.$$

From the ballistic assumption $dr/dv = t$, while Figure 5 of Shigeyama, Nomoto, and Hashimoto (1988) shows that throughout most of the envelope, dv/dM_r is very nearly constant at 2.5×10^{-26} cm s^{-1} g^{-1}. We assume that the envelope material has a hydrogen mass fraction X and that a fraction f of the hydrogen atoms is ionized. Then the electron scattering opacity $\kappa_e = 0.4fX$ (cm^2 g^{-1}), and the electron scattering optical depth into the envelope is $\tau_e = \int \kappa_e \rho\, dr = 0.4fX \int \rho\, dr$. The apparent size of the envelope of ejecta is defined by the position where $\tau_e \approx 1$. At 300 days after the explosion of SN 1987A, assuming $X = 0.5$, we find the angular diameter D at $\tau_e = 1$ in the model of Shigeyama, Nomoto, and Hashimoto (1988) is given by $D(\text{mas}) \approx 66f/[t/300) + 1.8f(300/t)]$, where t is in days. Given our measured angular diameter of 23 mas at $t \sim 300$ days, we require an ionization fraction $f \sim 0.94$, i.e., the outer ejecta need to be almost fully ionized if electron scattering is to supply the opacity necessary to produce the size observed for SN 1987A.

One possible source of ionization in the outer ejecta is the flux of X-rays detected by the *Ginga* satellite (Itoh *et al.* 1987). Under the assumption that there was a flux of X-ray photons through the envelope of SN 1987A with an energy spectrum similar to that given by Itoh *et al.* (1987), but limited to the range 1–10^3 keV, the ionization equilibrium in the envelope of the model of Shigeyama, Nomoto, and Hashimoto (1988) was computed. At the observed speckle radius we find that the equilibrium ionization fraction should be only $\sim 10^{-4}$. The X-ray flux was therefore far below the value required to produce significant ionization necessary in the envelope. We have also computed the flux of Hα photons resulting from the recombination of hydrogen atoms ionized by the X-rays; this Hα flux is only $\sim 10^{-5}$ times the observed Hα flux.

The above calculations show that, unless there is some unidentified excitation mechanism in the outer layers of SN 1987A, electron scattering cannot provide the opacity necessary to produce an envelope of the observed size. Furthermore, the Hα photons in the spectrum cannot originate in the ejecta at, or outside, the radius obtained from the present speckle observations; they are presumably produced deeper in the envelope and are scattered out to the observed radii. The only scattering mechanism that we can suggest is multiple scattering of Hα photons by neutral H atoms, provided that an adequate $n = 2$ population can be maintained by Lyα scattering. In fact, a large Lyα population is quite plausible as the number of ionizations and excitations to the $n = 2$ level produced by X-ray photons is large (the total number of excitations and ionizations per X-ray photon is roughly the X-ray photon energy/Lyα photon energy). However, this explanation cannot account for the 1987 June results of Karovska *et al.* (1987), where a smaller angular diameter was found at Hα (9 ± 4 mas) than at other wavelengths ($\sim$20 ± 4 mas at 4500, 5335, and 7750 Å).

One of the observations reported here was obtained at a wavelength away from the Hα emission line peak. That observation, at the wavelength of the [S II] doublet $\lambda\lambda$6717, 6731, falls on the far red wing of the Hα emission line at a redshift of $\sim$10,000 km s^{-1}. The diameter obtained from this observation (31.1 mas) is significantly greater than the diameter obtained nearer Hα line center.

One possible explanation for the larger angular diameter at $\lambda \sim 6729$ Å results from considering the scattering of Hα line photons emanating from deep within the envelope (the spectrum of SN 1987A at the time of the speckle observations indicates that Hα line photons provided about one-half the flux in the region under consideration). At a redshift of 10,000 km s^{-1}, many of the photons we see in the spectrum will be scattered from the faster (10,000 km s^{-1}) ejecta on the limb of the supernova image; this material will have moved further from SN 1987A than the slower ejecta seen with the filters nearer Hα line center and will thus yield a larger diameter.

A second possible explanation for the larger diameter in the [S II] filter is that we are indeed seeing emission from S II atoms. In objects such as planetary nebulae, such emission tends to occur outside the region of Hα emission so we might expect to determine a larger diameter in the [S II] filter than near Hα line center. However, there is no evidence in the spectrum of SN 1987A for a separate emission component arising from [S II]; it therefore does not appear that this explanation for the larger diameter at $\lambda \sim 6729$ Å is valid.

Our final comments relate to the reported detection of a point source "mystery spot" near SN 1987A by Nisenson *et al.* (1987) and Meikle, Matcher, and Morgan (1987). First, we note that our autocorrelations of SN 1987A do show spots close to the position of the "mystery spot" (Fig. 1); however, so does the point source. As explained above, these bright spots in the autocorrelations are caused by diffraction/refraction effects around the vanes of the spider holding the secondary mirror.

The reported intensity of the "mystery spot" is almost identical to the intensity expected in the first Airy ring (the AAT and the CTIO 4 m telescopes have similar central obstructions), so we would expect that the first Airy ring should be visible in the autocorrelations of the SN 1987A speckle data. Yet the autocorrelations shown in Figure 1 of Meikle, Matcher, and Morgan (1987) and Figure 2 of Nisenson *et al.* (1987) do not show the first bright Airy ring (compare with our Figs. 1 or 2, noting that at the time the "mystery spot" was observed, SN 1987A was essentially a point source). The absence of the first Airy ring in the autocorrelation shown by Meikle, Matcher, and Morgan (1987), together with the fact that on the AAT diffraction produces spots on the first Airy ring very close to the position of the mystery spot, leads us to doubt the reality of their reported detection. However, the lack of an Airy ring in the autocorrelations shown by Nisenson *et al.* (1987) is probably explained by the fact that they have deconvolved their autocorrelations of SN 1987A using point source autocorrelations. For unresolved objects, the deconvolved autocorrelation is essentially the autocorrelation of their smoothing function. We believe the data of Nisenson *et al.* (1987) could be made much more convincing if they were to display their autocorrelations without smoothing or deconvolution. Then the autocorrelations should show (1) the Airy rings (which would confirm that diffraction-limited information is readily detected at the reported intensity and separation from SN 1987A of the mystery spot), (2) diffraction/refraction spots on the Airy rings at position angles of 45°/225° and 135°/315° (due to the spider vanes on the CTIO 4 m telescope), and (3) the mystery spot sitting on top of the Airy ring at a position angle of 194°/14° and with a peak height roughly twice that of the Airy ring itself. Given the difficulty of finding a theoretical explanation for the mystery spot, it is important that extra effort be made to confirm the authenticity of the observational detection.

We would like to thank the director of the AAT, Dr. Russell Cannon, for providing us with director's time on some of the nights during which these observations were obtained, and on some of the many earlier nights during which we were clouded out.

REFERENCES

Boksenberg, A. 1978, in *Proc. ESO Conference, Optical Telescopes of the Future*, ed. F. Pacini, W. Richter, and R. N. Wilson (Geneva: ESO), p. 497.
Catchpole, R. M., *et al.* 1988, *M.N.R.A.S.*, **231**, 75P.
Dopita, M. A. 1988, *Space Sci. Rev.*, in press.
Foy, R. 1987, in *Santa Cruz Summer Workshop Instrumentation for Ground-Based Optical Astronomy*, ed. L. B. Robinson (Berlin: Springer), in press.
Itoh, M., Kumagai, S., Shigeyama, T., Nomoto, K., and Nishimura, J. 1987, *Nature*, **330**, 233.
Karovska, M., Nisenson, P., Papaliolios, C., and Standley, C. 1987, *IAU Circ.*, No. 4450.
Korff, D. 1973, *J. Opt. Soc. America*, **63**, 971.
Labeyrie, A. 1978, *Ann. Rev. Astr. Ap.*, **16**, 77.
Meikle, W. P. S., Matcher, S. J., and Morgan, B. L. 1987, *Nature*, **329**, 608.
Mihalas, D. 1978, *Stellar Atmospheres* (San Francisco: W. H. Freeman), p. 71.
Nisenson, P., Papaliolios, C., Karovska, M., and Noyes, R. 1987, *Ap. J. (Letters)*, **320**, L15.
Shigeyama, T., Nomoto, K., and Hashimoto, M. 1988, *Astr. Ap.*, in press.
Wilkerson, M. S., and Worden, S. P. 1977, *A.J.*, **82**, 642.
Wood, P. R. 1985, *Proc. Astr. Soc. Australia*, **6**, 120.
Wood, P. R., Bessell, M. S., and Dopita, M. A. 1986, *Ap. J.*, **311**, 632.
Worden, S. P., Stein, M. K., Schmidt, G. D., and Angel, J. R. P. 1977, *Icarus*, **32**, 450.

M. S. Bessell, M. A. Dopita, P. E. J. Nulsen, and P. R. Wood: Mount Stromlo and Siding Spring Observatories, Private Bag, Woden P.O., A.C.T. 2606, Australia

P. R. Gillingham and C. McCowage: Anglo-Australian Observatory, Private Bag, Coonabarabran, N.S.W. 2857, Australia