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MEASUREMENTS OF THE DIAMETER OF THE LARGE MAGELLANIC CLOUD SUPERNOVA SN 1987A

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ABSTRACT

We present direct measurements of the angular diameter of SN 1987A in the Large Magellanic Cloud (LMC) made from high–angular resolution observations at the CTIO 4 m telescope in five observing runs from 1987 April to 1988 April. Diameters were determined to milliarcsecond precision from integrated power spectra, using speckle interferometric data. The accuracy of the technique was evaluated by laboratory experiments and measurements of the diameters of several stars of known angular size. The SN 1987A diameters measured near the center of the Hα line show clear evolution during this period. The rate at which the supernova size changed at this wavelength corresponds to 2850 km s^{-1} mean velocity of expansion. Diameter measurements obtained in several spectral lines and in the continuum indicate stratification of the expanding envelope of the supernova. Our continuum data yield diameters substantially larger than those calculated from photometric measurements and a blackbody fit to the observed spectra.

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

I. INTRODUCTION

High–angular resolution observations of SN 1987A provide valuable data that will contribute to the understanding of this extraordinary astrophysical event. Using speckle interferometric techniques, it is possible to overcome the resolution limits imposed by atmospheric turbulence and observe, in some detail, the morphology of the supernova (SN) and its environment. A wide variety of other observational techniques such as spectroscopy, photometry, and polarimetry are providing an extensive data base that, combined with the high–angular resolution measurements, will result in a detailed understanding of the mechanisms and dynamics of supernovae, thereby testing the validity of theoretical models.

Speckle observations at CTIO in 1987 March and April (Nisenson *et al.* 1987) have already revealed the presence of a second bright source 60 milliarcseconds (mas) from the SN and within a factor of 12 of its brightness. Observations at the AAT in 1987 April (Meikle, Matcher, and Morgan 1987), also using speckle techniques, produced supporting evidence for the second source. Furthermore, analysis of data acquired in five observing runs between 1987 April and 1988 April have provided measurements of the apparent diameter of the SN at several wavelengths. Diameter measurements were made by fitting the integrated power spectra obtained from the speckle process to the power spectrum of a uniform disk or a limb-darkened disk. Accurate fitting allows diameter estimates at scales well below the "diffraction limit" of the telescope, to a precision of a few milliarcseconds. Figure 1 illustrates the principle by which diameters well under the diffraction limit of the imaging system (λ/D, where λ is the wavelength and D is the telescope diameter) can be measured, showing the power spectra for stars with diameters 0.5, 1, and 2 times the diffraction limit. A star having an angular diameter smaller than the diffraction limit has a partial drop in power at the highest frequencies measured. Accurate measurement of this drop allows an estimation of the stellar diameter and this accuracy is only limited by the signal-to-noise ratio in the data. A recent demonstration of this principle has been given by Davis and Tango (1986). Using a two-element interferometer with an 11 m baseline which has a resolution limit of 10 mas (at 550 nm), they were able to measure the diameter of Sirius (5.5 mas) to a precision of 0.08 mas. Similar results have been obtained using the I2T interferometer at CERGA (Koechlin and Rabbia 1985). While measurements of equivalent precision have not previously been demonstrated using speckle techniques, the validity of our results is supported by laboratory simulations and measurements of stars whose diameters have been determined by other methods.

II. OBSERVATIONS AND PROCESSING

We report results from five observing runs using the Cerro Tololo Inter-American Observatory (CTIO) 4 m telescope. A summary of the observations is given in Table 1. Data were recorded using the PAPA two-dimensional photon counting detector (Papaliolios, Nisenson, and Ebstein 1986) and a front-end optics package. The optics package includes magnifying optics to match the telescope and detector pixel scales, atmospheric dispersion–correcting prisms, a set of narrow-band interference filters, and various neutral density filters. The camera records the x-y position and time of arrival of each photon event as it is detected, allowing construction of short-exposure speckle frames during the computer processing operations. A major advantage of this approach is that the optimum exposure time (as determined by the atmospheric correlation time) that maximizes the signal-to-noise ratio in the reconstruction may be determined during the data processing.

Data were recorded at many different wavelengths and under a variety of atmospheric conditions. The general approach was to record a relatively short data set (5 or 10 minutes) on the SN, preceded and followed by a 5 minute set on a comparison star. In all cases, the comparison stars were chosen to be single stars close in angular position to the SN and to have expected angular sizes as small as possible (less than 1 mas). The comparison stars were also chosen to be as bright as possible, yielding maximum signal-to-noise ratio in

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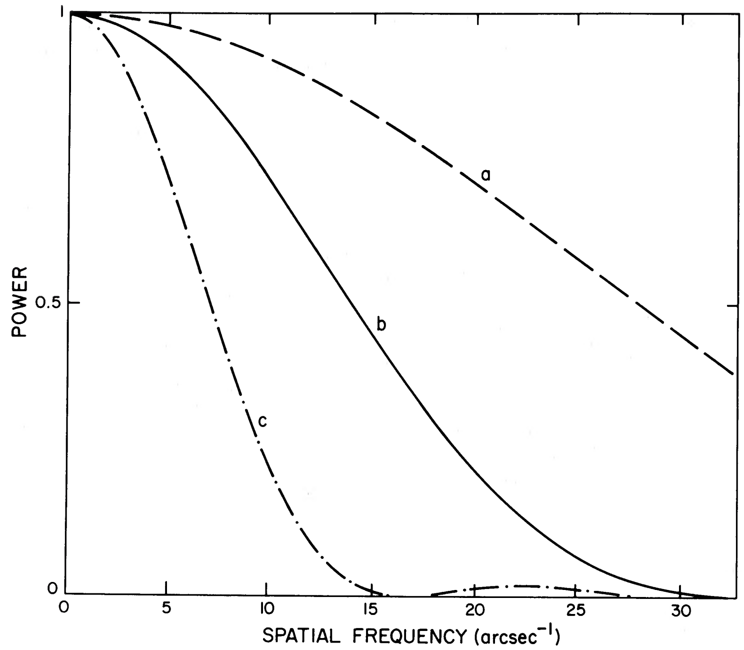

FIG. 1.—Ideal power spectra for stars with diameters (*a*) 0.5, (*b*) 1, and (*c*) 2 times the telescope diffraction limit. The right-hand axis corresponds to the 4 m diffraction limit at 6000 Å (33 arcsec^{-1}).

the time alloted for their observation, since they are used in a deconvolution calculation during the data processing. The diameter of the detector field for all data sets was 1".95 with 256 × 256 sampling, giving a 7.5 mas pixel size. The SN and its comparison star were never higher than an altitude of 55°, and were as low as 20° for some of our observations, so they all required a large and accurate correction for atmospheric dispersion. Precise correction was performed using the pairs of computer-controlled Risley prisms in our optical front end.

TABLE 1

SUMMARY OF SPECKLE OBSERVATIONS

Date	Days after Explosion	Central Wavelength (nm)	Bandpass (FWHM) (nm)
1987 Apr 2	38	450.2	10.0
		532.9	8.0
		656.5	10.7
1987 May 30–Jun 2	95–98	450.0	10.0
		532.9	8.0
		656.5	10.7
		775.0	10.0
1987 Nov 15–18	265–268	532.9	8.0
		640.0	10.0
		656.5	10.7
		658.5	10.0
		700.0	10.0
		850.0	25.0
1988 Feb 29–Mar 3	370–373	442.0	32.8
		533.0	8.0
		640.0	10.0
		656.5	10.7
		700.0	10.0
		850.0	25.0
1988 Apr 8–10	409–411	533.0	8.0
		656.5	10.7
		850.0	25.0

Since the comparison star's dispersion will be almost identical to that of the SN, any residual error due to dispersion will be corrected in the deconvolution during the data processing. The fit was only performed out to frequencies where both the reference and object power spectra were nonzero. The seeing was generally 2"–3" except in 1988 February, March, and April when seeing approached 1".

The first step in data processing is to calculate a flat field that corrects for the nonuniformities present in the photocathode sensitivity and the camera optics. The photons are grouped into speckle frames and each frame is flat-fielded before being Fourier transformed. The procedure for flat-fielding the data (Ebstein 1987) is to first generate a flat-field "mask" using a combination of "white-field" data (in which the camera is looking at the dome or an internal uniform source) and a filtered version of the long-exposure image of the object being flat-fielded. Use of the object data, itself, allows for any dynamic changes in the flat field and reduces the requirement of recording "white-field" data to about once per night. The synthesized flat field is then applied to each frame, after the photon addresses have been binned into individual frames. One ends up with frames in which each photon is given a fractional height proportional to the flat-field amplitude at that position.

The optimum frame time is determined by integrating the comparison star power spectra for several different frame times, calculating the variance and signal-to-noise ratio in the high-frequency region of the power spectrum and choosing the exposure time which maximizes the signal-to-noise ratio. Typical frame times were found to be about 10 ms, though they varied between 5 and 15 ms.

The ensemble average power spectrum is calculated for both the SN and its comparison star. Division of the SN power spectrum by the comparison star power spectrum corrects for the effects of the atmospheric and the telescope transfer functions. Diameter measurements were made by first azimuthally averaging the power spectra to enhance the signal-to-noise ratio before division. A visibility function (the power spectrum of a limb-darkened or a uniform disk), in the form of the Hankel transform of the stellar profile was least-square–fittted to the ratioed power spectra with two free parameters, the width, a, and the amplitude, m. The diameter in image space was calculated from the width parameter, a. In the fitting procedure, the data were weighted by the autocorrelation of a circle. This corresponds to the fall off in signal-to-noise ratio with increasing spatial frequency of an ideal telescope with no atmosphere. Errors were estimated by calculating the standard deviations of the data from the fits. When the supernova power spectrum was divided by the corresponding comparison star power spectrum, the signal-to-noise ratio at the higher frequencies in both object and comparison star power spectra was low, so fitting was restricted to the low and intermediate frequency range. In addition, fluctuations in seeing between recording of the object and the comparison star make correction at the lowest few frequencies inaccurate. Despite these restrictions, this approach appears to give reproducible results, and application of this technique to stars with known diameter gives accurate results.

III. LABORATORY SIMULATIONS

To check this technique, the same modeling and fitting was applied to data generated in laboratory simulations with disks of known diameter. The speckle camera system (including the PAPA detector) was set up to accept light from an optical system which simulates a telescope and a randomly varying atmosphere. The laboratory optics were scaled so that a 100 μm pinhole placed 85 cm from the telescope aperture was just resolved at 656 nm. The diameter of the optical system pupil was adjusted so that the moving piece of ground glass used to simulate atmospheric turbulence produced speckle images with the equivalent of 1″–2″ seeing. The light level and spectral passbands were set to match the SN observation levels. Speckle data were recorded for three pinholes of diameters 12 ± 2, 50 ± 5, and 100 ± 5 μm; the 12 μm pinhole was used as the comparison source after correction for its finite size by division of the appropriate Airy function. The power spectra and the best-fit Airy functions for the 50 and 100 μm data are shown in Figure 2. The diameters calculated from the best fits to the data were 55 ± 3 and 100 ± 3 μm. The accuracy of these results strongly supports the validity and precision of this technique for measuring diameters smaller than the diffraction limit of the imaging optical system.

IV. RESULTS

In an important test of the performance of our technique, we measured the diameter of a solar-type star, α Cen A. The data were recorded using the CTIO 4 m telescope on 1987 June 1 at 533.0 nm and 1988 February 29 at 450.0 nm. From both observing runs we obtained 9 ± 2 mas for the angular diameter, assuming a uniform disk. Figure 3 shows the data from 1988 February and the corresponding best fit. When the effect of limb darkening is taken in account (Allen 1973, p. 120) the measured diameter of α Cen A increases by approximately 10%. Our diameter measurement for α Cen A is very close to the diameter of 8.6 ± 0.2 mas obtained photometrically by Blackwell and Shallis (1977). The diameter of the red supergiant α Sco at 533.0 and 656.5 nm was also measured. Figure 3 shows the data recorded in 1988 April (at 533.0 nm) using the CTIO 4 m telescope and the corresponding best fit. At the two wavelengths of observation we obtained 35 ± 1 mas for the diameter of α Sco, assuming uniform disk. When limb darkening is included, assuming a linear limb-darkening law, a dia-

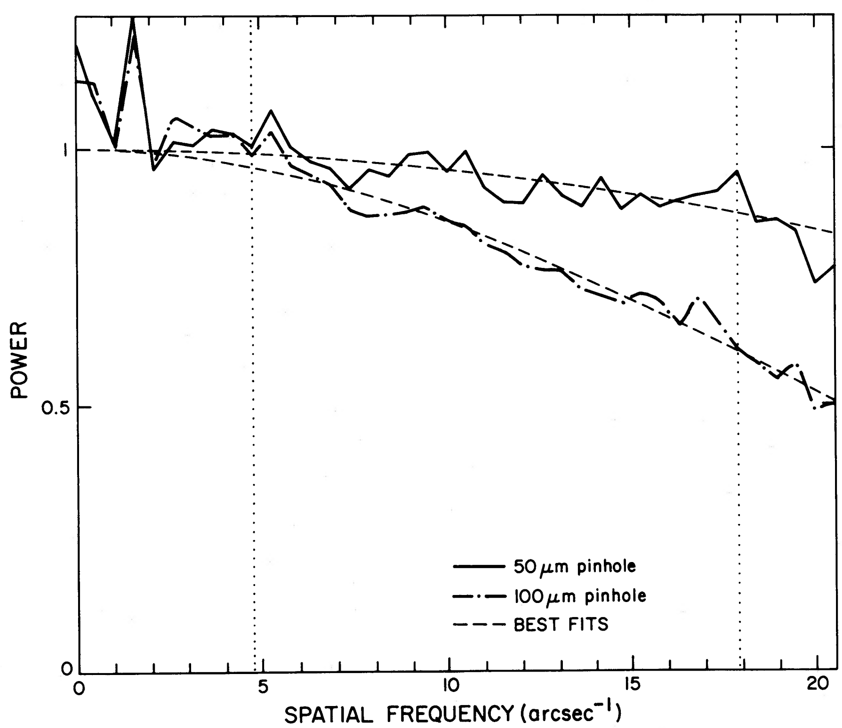

FIG. 2.—Laboratory simulation power spectra and best-fit Airy disks for the 50 and 100 μm pinholes. Vertical dotted lines show the range of fitted region. The diffraction limit of the optical system at 6563 Å was 30 arcsec^{-1}.

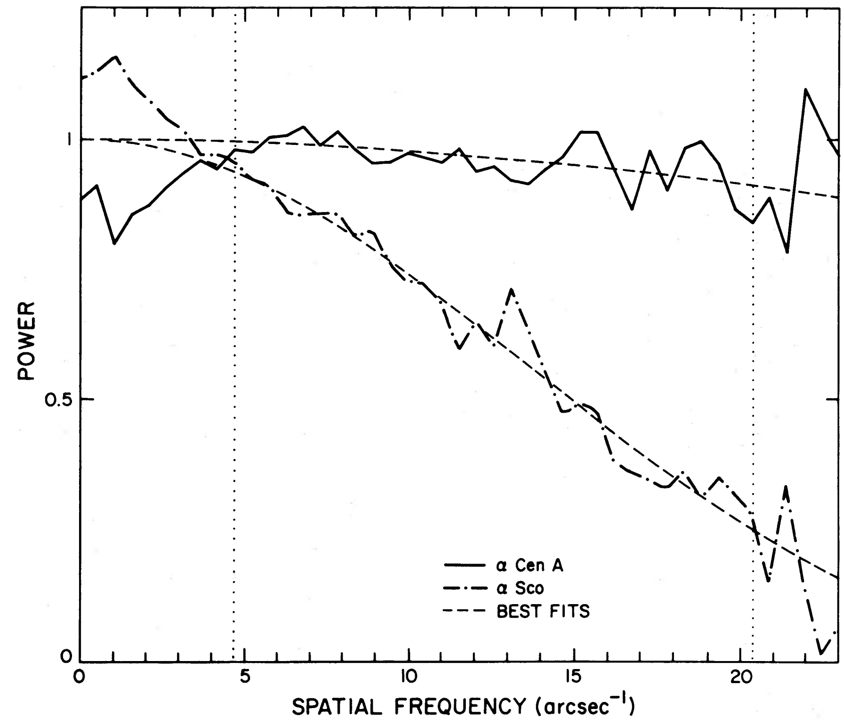

FIG. 3.—Power spectra for α Cen A and α Sco, stars with known diameters. The best fits to the data (corresponding to a uniform disk of 9 mas for α Cen A and 35 mas for α Sco) are also plotted. Vertical dotted lines show the range of fitted region.

meter of 39 ± 1 mas was obtained. These measurements are very close to the diameter of 36 ± 3 mas, obtained by Blackwell and Shallis (1977). Also, they are in good agreement with the measurements from several observers using different techniques (summarized by White 1980).

Table 2 shows the summary of the results of diameter measurements of SN 1987A (assuming a uniform disk) made from data recorded at the five different epochs corresponding to the 38th, 95th–98th, 265th–268th, 370th–373d, and 409th–411th day after the explosion. While the data are not of sufficient quality to allow us to calculate the profile of the SN, the effect of limb darkening (or brightening) on the measured diameters can be estimated. Calculations show that extreme limb darkening (or brightening) will change the diameter measurement by no more than 15%.

From the March–April observations (at wavelengths of 450.0, 533.0, and 656.5 nm), the SN was found to be resolved at 450.0 nm (12 mas) and at 533.0 nm (11 mas), while at 656.5 nm it was essentially unresolved (≤ 5 mas). The error bars for April measurements were relatively large (± 4 mas) and reflect the relatively low signal-to-noise ratio in the power spectra due to poor seeing.

In May–June we measured the SN diameter at four wavelengths: 450.0, 533.0, 656.5, and 775.0 nm. The smallest diameter was measured at 656.5 nm (8 ± 1 mas). The diameters measured at 450.0, 533.0, and 775.0 nm were 23 ± 4, 18 ± 2, and 15 ± 1 mas, respectively.

In 1987 November diameter measurements were obtained at six different wavelengths: 530.0, 640.0, 656.6, 658.5, 700.0, and 850.0 nm. The diameters ranged from 15 mas at 640.0 nm to 20 mas at 533.0 nm. The signal-to-noise ratios in these data were higher than in the data from the two previous observing runs. This resulted in an improvement of the measurement accuracy (making it ± 1–2 mas.)

We observed a substantial asymmetry in the data recorded in 1988 February–March and 1988 April at several wavelengths (Karovska *et al.* 1988). The images were elongated 30%–40% along an axis tilted 20°–30° from the north. Images of comparison stars and α Cen A did not show this asymmetry. These results will be more extensively described in a separate paper.

In Table 2, we present our estimates of an "effective" diameter for the SN in 1988 February–March and 1988 April obtained by fitting the azimuthally averaged power spectra to visibility functions computed for different stellar disks with uniform brightness distribution.

Figures 4–6 show examples of the data and fitted curves. In Figure 4, we show the supernova in Hα from the 1987 April run, an unresolved comparison star, and the fitted curves. The fit is a horizontal straight line for both of them, which is the expected result for an unresolved star. In Figure 5, we plot the

TABLE 2

ANGULAR DIAMETER MEASUREMENTS OF SN 1987A[a]

λ (nm)	DAYS AFTER EXPLOSION: 38	95–98	265–268	370–373	409–411
442.0	...	...	...	25 ± 2	...
450.0	12 ± 5	23 ± 4	...	...	...
532.9	11 ± 4	18 ± 2	20 ± 2	20 ± 1	26 ± 2
640.0	...	...	15 ± 1	17 ± 1	...
656.5	≤ 5	8 ± 1	18 ± 1	21 ± 1	27 ± 1
658.5	...	...	17 ± 1	...	...
700.0	...	...	17 ± 1	17 ± 1	...
775.0	...	15 ± 1	...	...	...
850.0	...	...	16 ± 1	18 ± 2	24 ± 2

[a] Angular diameters are given in milliarcseconds. Errors correspond to 1 σ.

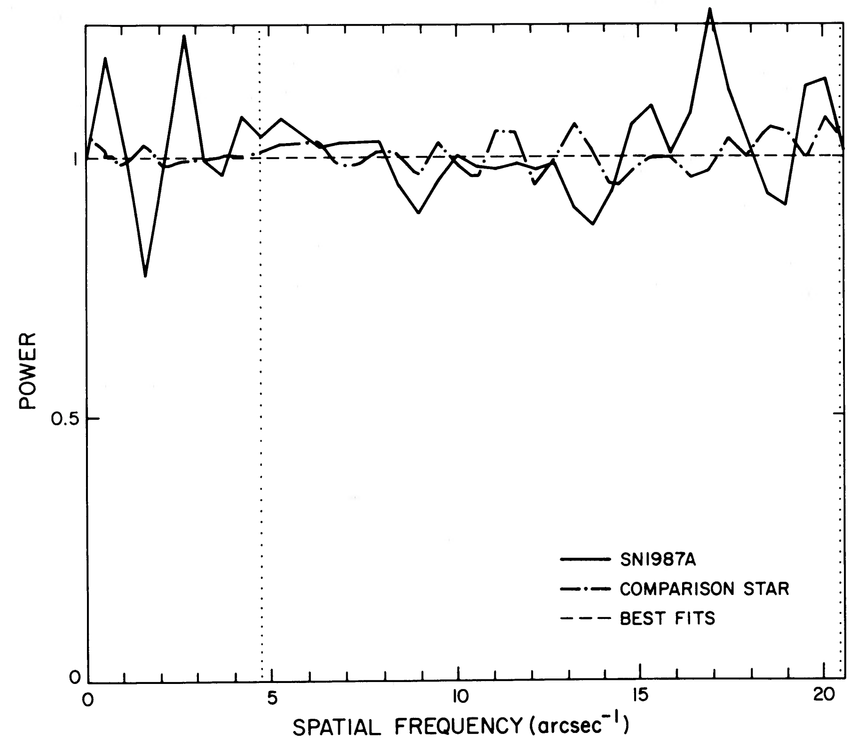

FIG. 4.—Power spectra and best fits for SN 1987A (1987 April) and an unresolved comparison star recorded in Hα. Vertical dotted lines show range of fitted region.

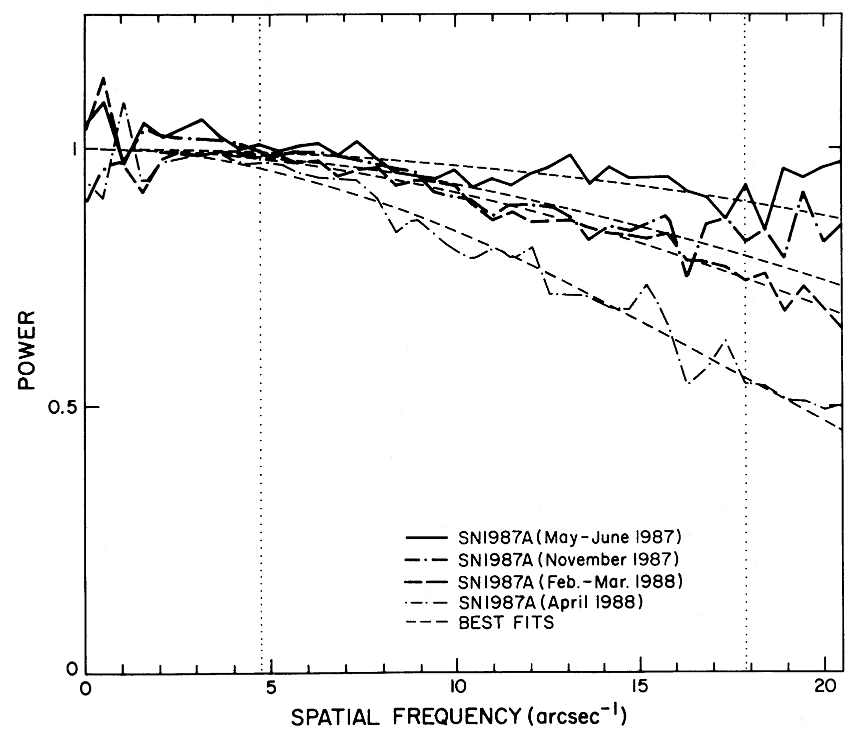

FIG. 5.—Power spectra and best fits for SN 1987A Hα data from 1987 May–June, 1987 November, 1988 February–March, and 1988 April observing runs. Vertical dotted lines show range of fitted region.

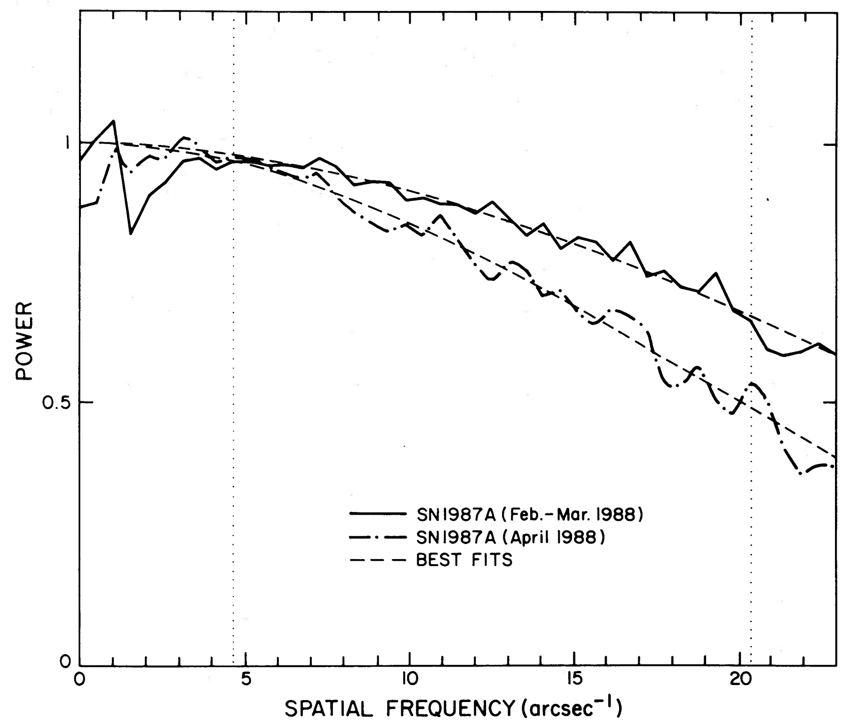

FIG. 6.—Power spectra for SN 1987A 533 nm data from 1988 February–March and April and corresponding best fits. Vertical lines show the range of fitted region.

Hα data from 1987 June, 1987 November, 1988 February–March, and 1988 April and their fits. The drop in high-frequency power between data sets corresponds to the increasing size in the SN diameter. In Figure 6, we show the 533 nm data and fits from 1988 February–March and 1988 April. The signal-to-noise ratio for these data was extremely good and allowed us to determine the SN diameter to an accuracy of better than 1 mas.

V. DISCUSSION

Our measurements of the SN diameter on April 2 (38 days after the explosion) and May–June (95–98 days after the explosion) show a substantial dependence on the wavelength of observation. At both epochs we obtained the smallest diameter at 656.5 nm and the largest at 450.0 and 533.0 nm. The 656.5 nm filter was located redward from the Hα absorption minimum and encompassed a large fraction of the P Cygni Hα emission feature (Phillips 1987). The 450.0 nm filter is in the absorption line corresponding to Ba II (Phillips 1987), while no prominent absorption or emission line could be distinguished in the 533 nm region. In May–June we observed the SN using an additional filter centered on the O I absorption feature at 775.0 nm. At this wavelength, the diameter is smaller than the one measured at 450.0 and 533.0 nm, but almost twice as large as the diameter measured at 656.5 nm.

The wavelength dependence of the measured diameters is probably due to the stratification of the expanding envelope of the SN. Evidence of stratification in the SN shell has already been found from spectral observations of the absorption minima of several spectral lines (Hα, Hβ, Hγ, Ca II, Na I) during the first month of expansion (Hanuschik and Dachs 1987*a*, *b*). However, the fact that the angular diameter measured in the O I absorption trough is twice that measured in the Hα emission line requires that hydrogen lie within the oxygen shell, a result that is not predicted by current SN atmosphere models.

It is interesting to note, however, that the speckle diameters measured at the 656.5 nm spectral bandpass in 1987 April and May–June are consistent with the estimates of the effective diameters of the line-forming regions at both epochs. Figure 7

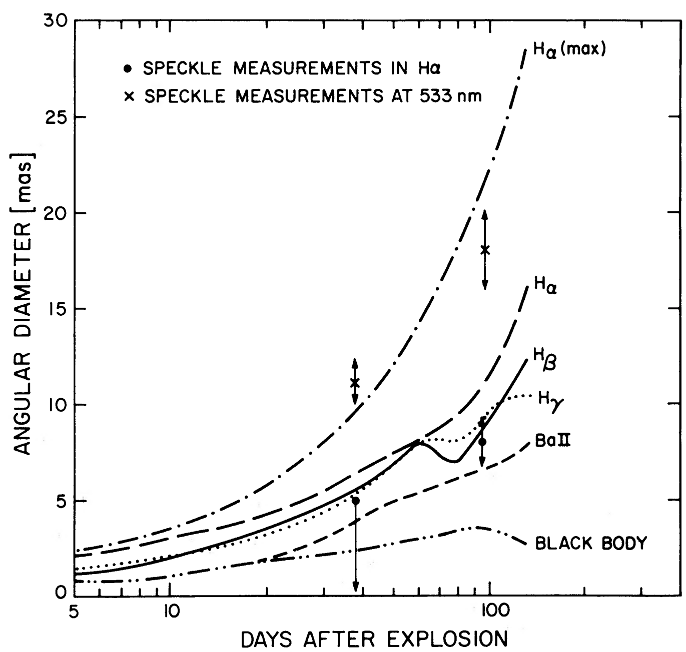

FIG. 7.—Diameters vs. time for SN 1987A calculated using velocities estimated from minima of a various spectral lines and the blackbody photometric diameter estimates for the first 130 days since explosion (Phillips *et al.* 1988). The two measurements in Hα and at 533 nm are also shown.

shows the estimates of the effective diameters of the line-forming regions which were obtained by integrating the radial velocities corresponding to the absorption minima of several spectral lines during the first 130 days after the explosion (Hanuschik and Dachs 1987*a*, *b*; Phillips *et al.* 1988). On the 38th day after the explosion, the estimated angular diameter of the Hα shell (i.e., the diameter of the region where Hα becomes optically thick) is 6 mas, and we measured an angular diameter ≤ 5 mas at 656.5 nm. The angular diameter corresponding to the Hβ and Hγ "shell" is around 5 mas. The estimated diameters derived from the radial velocity of the minimum of the Ba II absorption line is 3.8 mas. On the 98th day after the explosion we obtained an 8 mas diameter at 656.5 nm, which is in close agreement with the estimated effective diameter of 9 mas for the Hβ and Hγ "shells," and a 7 mas diameter for the Ba II.

The diameters measured in the continuum bandpasses in 1987 April and 1987 May–June are substantially larger than those obtained from photometry and a simple blackbody fit to the observed spectrum (Catchpole *et al.* 1987; Danzinger *et al.* 1987; Whitelock *et al.* 1988). These estimates of the SN diameter are shown in Figure 7. Larger continuum diameters obtained using speckle interferometry may be a result of electron scattering in the SN envelope. Lucy (1987) computed the "last-scattering" diameters (scaled to the blackbody photospheric diameter) for the 38th and 98th day after explosion. These computations were performed for the appropriate bandpasses of the speckle observations. Calculated diameters are 2–4 times larger than the blackbody diameter estimates, but they are still 1.5–3 times smaller than the diameters obtained using speckle interferometry. This suggests that the phenomenon of electron scattering cannot entirely account for the larger size of the SN measured by speckle interferometry. These models assume a uniform distribution of material in spherically symmetric shells. Clumpiness or asymmetries in the distribution of the material may well produce very different results.

The observations in 1987 November, 1988 February–March, and 1988 April were obtained during the period when the SN was already in its "nebular" phase. The SN diameter measured at 656.5 nm showed clear temporal evolution when compared with our earlier measurements at the same wavelength. Figure 8 shows the evolution of the Hα diameter as measured by speckle interferometry during the first 411 days after the explosion. In addition to our measurements we show the speckle measurements near the center of the Hα line obtained by Wood *et al.* (1988) on 1987 December 12 and 13, and 1988 February 20 using the Anglo-Australian Observatory 4 m telescope. The uniform disk angular diameters estimated for these two epochs are, respectively, 23.1 ± 1.6 and 23.9 ± 0.9 mas. We performed a linear least-squares fit to these data assuming that the diameter at the moment of the explosion was zero. If the increase of the diameter reflects the expansion of the SN atmosphere, then the slope of the fitted straight line gives a mean velocity of expansion of approximately 2850 km s^{-1}. Our measurement from February–March seems to underestimate the diameter of the SN at that epoch. This measurement has been affected by the asymmetry in those data.

Diameter measurements from the last three observing runs still show some dependence on the wavelength of observation, though the differences between the diameters measured in Hα and in the other wavelengths are not as dramatic as they were in 1987 April and May–June. Diameter measurements in the 533 nm continuum from 1987 May–June and November and 1988 February are practically indistinguishable from one another. This is also true for the diameters measured at 640, 700, and 850 nm in 1987 November and 1988 February–March. If the 533 nm measurements correspond to the size of the SN photosphere then we conclude that they do not indicate any recession at these epochs.

At this point, it is difficult to find a simple interpretation for all our results. New, more detailed models for the SN are required. We plan to continue to monitor the changes in the SN diameter over a large spectral range and to follow the

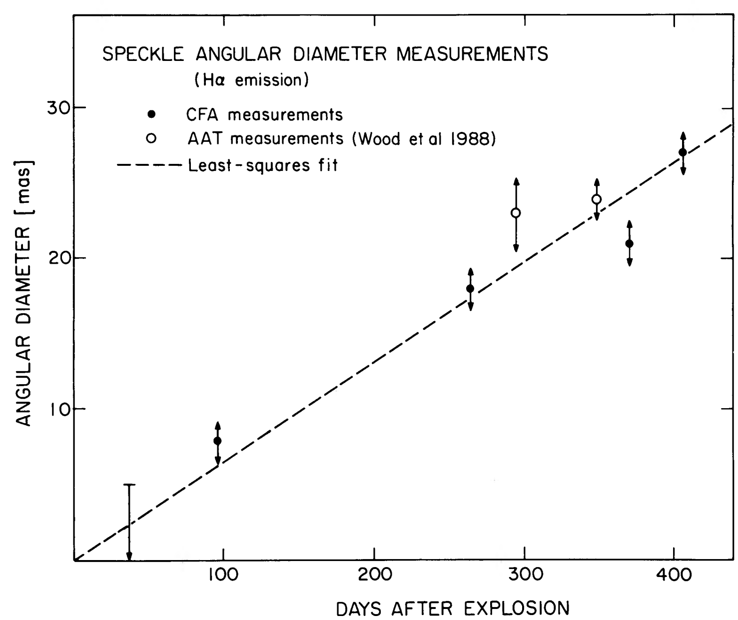

FIG. 8.—Evolution of the SN diameter during the first 411 days after the explosion as observed by speckle interferometry techniques with 3 σ errors and best-fit straight line giving a velocity of 2850 km s^{-1}.

evolution of the expanding shell. If the present slow decline in brightness of the SN continues, we can observe the SN for several years before the magnitude limit of the speckle process is reached.

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