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SPECKLE INTERFEROMETRY OF SN 1987A: FINAL MEASUREMENTS

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ABSTRACT

We present further speckle interferometric measurements of the angular diameter of SN 1987A up to 573 days after explosion of the supernova. These measurements cover the epoch of dust formation in the supernova. Most measurements were made in the emission line of Hα. Further observations will not be possible due to the faintness of SN 1987A. Our results indicate a linear increase in the angular diameter at Hα with time, corresponding to a velocity of 2825 km s^{-1}. We are not able to confirm or exclude the existence of asymmetry in the Hα image of the supernova.

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

I. INTRODUCTION

Speckle interferometric measurements of the angular diameter of SN 1987A in the Large Magellanic Cloud have been made by Wood *et al.* (1989) (hereafter Paper I) and Karovska *et al.* (1989) up to 410 days after the explosion of the supernova. The results of these studies show that the angular diameter at Hα increased approximately linearly with time at a rate corresponding to a velocity of expansion of ~2850 km s^{-1}. In this paper we present further speckle interferometric measurements of the angular diameter of SN 1987A up to 573 days after the explosion. This period of observation roughly covers the epoch of dust formation between 470 and 600 days after the explosion (Whitelock *et al.* 1989). The measurements were made with the Anglo-Australian Telescope using the instrumentation described in Paper I; the data reduction techniques are also described in that paper.

II. RESULTS AND DISCUSSION

The results of our measurements of the angular diameter of SN 1987A are given in Table 1. The angular diameter ϕ_{UD} given in the table in milliarcseconds (mas) is that obtained by fitting a uniform disk model to the autocorrelations of the speckle images, as described in Paper I. Figure 1 shows the angular diameter plotted against the time since the explosion of the supernova. The angular diameter has increased linearly with time throughout the period of observation, and the rate of increase shows no evidence of slowing. A linear fit to the data in Figure 1 corresponds to a velocity of expansion of the Hα emitting region of 2825 km s^{-1} if the distance to the LMC is assumed to be 50 kpc.

As noted by Wood *et al.* (1989) and Karovska *et al.* (1989), the angular diameter observed at Hα is much larger than any estimate of a "photospheric" angular diameter. Indeed, at these late times, we expect that the continuum photosphere will have disappeared almost entirely, leaving only a dense central core. For example, the atmospheric models for SN 1987A by Höflich (1988) predict that the hydrogen recombination region of the atmosphere expands to a maximum angular diameter of ~4.4 mas at ~90 days after the explosion and proceeds to shrink thereafter. Clearly, this model is inconsistent not only with the Hα results but also with the sizes measured at other wavelengths, these sizes being similar to the size measured at Hα (this paper; Karovska *et al.* 1989).

At the time of the present observations, SN 1987A is firmly into the supernebular phase, and the spectrum formation process at this epoch is very nonlinear. The γ-ray photons from radioactive decay first lose their energy due to Compton scattering and photoelectric absorption, generating highly energetic electrons. These are then slowed in the envelope by Coulomb scatterings, and by the ionization and excitation of ions in the envelope. Radiative de-excitations and recombination of ions produce a multitude of UV resonance lines. Because of the high line optical depths, these cannot escape from the nebula, but undergo multiple scattering and wavelength redistribution, until finally they appear as optical photons which can escape from the nebula (Xu and McCray 1989). Thus, in this phase, the apparent diameter of the source in the quasi-continuum above 4000 Å is determined by the surface for line scattering in the UV. This explains the size we observed at 4870 Å, a region of the spectrum dominated by Fe II emission lines at the time of observation. What about the Hα diameter?

Again referring to the work of Xu and McCray, we note that the radioactive energy can be used efficiently to ionize hydrogen provided the gas is metal-rich (in the present case due to mixing of heavy elements from the core into the hydrogen-rich envelope). In such a gas, much of the fast electron energy is deposited, through ionizations and excitations, in the heavy elements since these have many states and large cross sections. The $n = 2$ state of hydrogen is heavily populated as a result of Lyα trapping, and the UV photons produced by the metals are capable of ionizing hydrogen directly from the excited state. The Hα photons subsequently emitted during recombination will thus originate from the metal-rich region where the UV lines are produced and scattered.

Outside the metal-enhanced regions, the fractional ionization of hydrogen will fall very steeply. Furthermore, because the density is also falling steeply with radius, and because the envelope is optically thin, the outer zones will emit only very weakly. The Hα emitting region is therefore expected to show a sharp outer boundary which coincides in extent with the Fe II–emitting optical quasi-continuum.

The velocity of expansion of the Hα emitting region, as defined by our speckle observations (2825 km s^{-1}), is only somewhat larger than the minimum expansion velocity (2100

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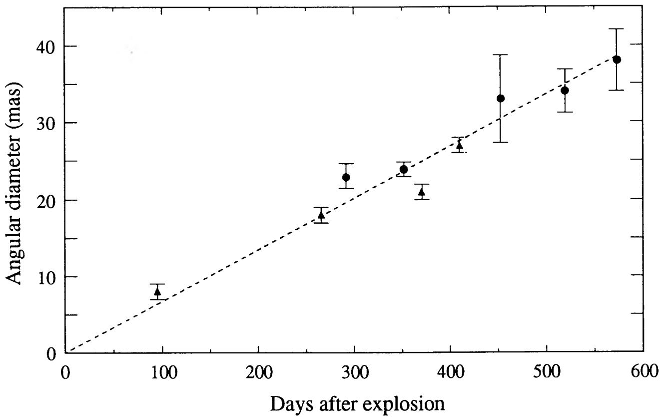

FIG. 1.—The angular diameter of SN 1987A at Hα plotted against the time after explosion. Circles are data from the present paper and Paper I, while the triangles are from Karovska *et al.* (1989). For our data, the 1 σ error bars were computed from the dispersion of the multiple angular diameter determinations obtained during each run except for the last where only one measurement was made; in this case the error bar (±4 mas) was derived from a χ^2 test for the goodness of fit of the observed autocorrelation to the uniform disk model. For the data of Karovska *et al.* the error bars are those given by those authors. The dashed line is a least-squares fit to the data.

km s^{-1}) determined from the H I Paschen-α absorption trough (McGregor 1988). The latter velocity is thought to represent the expansion velocity of the inner edge of the hydrogen envelope. Thus, if the Xu and McCray picture is correct, the zone between these velocities is the region in which the metal-rich core has penetrated into the hydrogen envelope, and vice versa. Thus our speckle data place important constraints on the degree of mixing in the ejecta.

These results should be compared with theoretical models (Shigeyama, Nomoto, and Hashimoto 1988; Nomoto, Shigeyama, and Kumagai 1989; Pinto and Woosley 1988) which give a good description of the optical light curve and which also describe the early escape of the hard X-rays and γ-rays from the fireball (Dotani *et al.* 1987; Sunyaev *et al.* 1987; Cook *et al.* 1988; Sandie *et al.* 1988). These models require hydrogen to be mixed down as far as $\sim 1\ M_\odot$ from the remnant neutron star (where the velocity is ~2100 km s^{-1}, in agreement with observation), but they also require metal-rich ejecta to be mixed up to within $\sim 1\ M_\odot$ of the stellar surface in order to explain the 16–28 keV light curve. Such a high degree of mixing, if uniform, appears to be excluded by our observations. However, it is likely that only a small amount of metal-rich material was in fact mixed to such high levels, this material being in the form of chemically inhomogeneous fingers. This appears to be confirmed by the form of the late light curve from 300 to 800 days (Whitelock *et al.* 1988; Catchpole *et al.* 1989; Whitelock *et al.* 1989) which demonstrates very clearly that much of the energy from the radioactive decay is still being trapped and converted, via atomic processes, to optical and near-IR emission and, via absorption on dust, to far-IR emission.

Finally, we note that we are unable to comment on possible asymmetry in the image of SN 1987A as reported by Karovska *et al.* (1988). Because of the instrumental "photon spike" produced by the IPCS detector, our measured autocorrelation function is contaminated in the region near the origin which is most sensitive to the speckle content of the observed images (Wood *et al.* 1989). As a result, our observations are less sensitive to asymmetries, and indeed to size information, than are the observations of Karovska *et al.*

TABLE 1

SPECKLE OBSERVATIONS OF SN 1987A

Date 1988	Days after Explosion	Seeing (″)	Exposure Time (s)	Shutter Time (ms)	Pixel Size (mas)	Filter $\lambda/\Delta\lambda$	ϕ_{UD} (mas)
May 21	454	1.5	600	11	6.2	6566/15	37
			600	11	6.2	6576/15	29
Jul 27	521	2.0	1000	4	5.7	6585/50	32
			600	7	5.7	6585/50	36
			1000	4	5.7	4870/180	30[b]
Sep 18	574	2.5	3600[a]	7	5.8	6585/50	38

[a] The sum of three exposures of 1500, 1500, and 600 s. Standards were observed between each observation of the supernova.

[b] A χ^2 estimate of the 1 σ error is 4 mas.

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