

HIGH-RESOLUTION CORONAGRAPHY OF THE CIRCUMSTELLAR ENVIRONMENT OF SN 1987A¹

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ABSTRACT

The STScI coronagraph on the ESO 2.2 m telescope was used with broad-band *B* and *R* filters to image a region $23'' \times 36''$ in size centered on SN 1987A with $0''.8$ resolution ~ 300 days after eruption for evidence of a light echo from circumstellar dust. All the identifiable sources of radiation in these bands in this region correspond to objects observed before the eruption including star 2 of the Sk $-69^\circ 202$ complex located at $2''.8$, 320° p.a. of magnitude $B = 15.1 \pm 0.2$ and $R = 15.6 \pm 0.3$. The data allow a stringent upper limit of 22.5 mag arcsec⁻² to be set on the *B*-band brightness of an echo-like, largely azimuthally symmetric feature located anywhere between $4''$ from the SN out to the edge of the observed field. This limit implies an upper bound of 10^{18} hydrogen atoms cm⁻³ to the column density of any circumstellar shell of gas of average galactic properties located on the ellipsoid of equal delay points between ~ 2 and 20 pc from the SN. An echo from a uniformly distributed gas of this type around the SN of this limiting brightness would be obtained only if the average hydrogen density is between 2.5×10^{-3} and 10^{-2} cm⁻³, indicating that SN 1987A may be located in a cavity of very low gas density.

Subject headings: interstellar: matter — stars: circumstellar shells — stars: supernovae

I. INTRODUCTION

Detection of a light echo around a bright nearby supernova can be quite useful in unraveling the three-dimensional structure of the interstellar or circumstellar medium in its immediate surroundings at the time of eruption. This structure, in turn, may reveal interesting facets of the preeruptive history and evolution of the supernova progenitor. The SN 1987A event clearly represents a major opportunity to study this phenomenon in unprecedented detail since the physical characteristics of the direct emission from this object have been studied promptly and comprehensively. Echoes from sheets of interstellar gas located at distances of several hundred parsecs from the SN 1987A have been recently detected and interpreted (Crotts 1988; Gouffes *et al.* 1988; Suntzeff *et al.* 1988; Chevalier and Emmering 1988). The material revealed this way, however, is too far from the SN to carry any significant information about the past evolution of the progenitor.

It is quite likely, on the other hand, that the circumstellar environment out to ~ 20 – 30 pc from the star has been substantially affected by the progenitor evolution (McCray and Wei 1988; Chevalier 1987). Several complete shells of material of hydrogen column density $\geq 10^{19}$ – 10^{20} cm⁻² or fragments thereof are expected to occupy this inner region due to the various mass-loss episodes the star has undergone as it evolved from a giant O-type main-sequence star to a red and a blue supergiant through the pulsational instability strip. Consequently, it is extremely important to explore the region within a radius of $\sim 10''$ from the star over as long a time baseline as possible to attempt to detect an echo from the material therein. Such dense shells or clumps of gas or even a uniform distribution of interstellar material around the SN are expected to yield echoes of surface brightness of at least 18–19 mag

arcsec⁻² in the *B* band in this region. Our previous experience with the STScI coronagraph at the ESO 2.2 m telescope at La Silla indicates that such fluxes at these distances from a bright star can be easily detected in moderate exposure times. For these reasons, a search for a light echo from circumstellar matter around SN 1987A was begun. This *Letter* describes the results of this investigation obtained 300 days after eruption.

II. OBSERVATIONS AND DATA REDUCTION

The data presented here were obtained on 1987 December 21, at the 2.2 m MPI Cassegrain telescope at the ESO, La Silla, Chile. The optical configuration of the observational setup at La Silla is described in Paresce and Burrows (1987*a*, *b*) and Paresce, Burrows, and Horne (1988). Briefly, light from the central source is focused onto a blackened photo-etched mask located in the telescope focal plane. This occulting mask is shaped in the form of a long thin wedge which can be moved longitudinally by a micrometer in order to vary its projected width in the sky from $1''$ to $10''$ depending on seeing conditions and source brightness. Following the mask, an achromatic doublet reimages the telescope focal plane with a magnification of 5 onto the detector so that the effective focal ratio of the system becomes $f/40$.

An apodizing mask especially designed to reduce diffracted stellar light from the 2.2 m telescope pupil is located in the exit pupil and is rigidly attached to the lens mount to ensure that it remains there as the coronagraph is focused. The mask obscures $\sim 30\%$ of the exit pupil close to the images of the entrance pupil edges. After this mask, the light passes through optical filters in a rotating commandable two-wheel assembly mounted just in front of the detector which is a 512×320 30 μm square pixel RCA backside-illuminated CCD. In this particular configuration, each pixel corresponds to 5×10^{-3} arcsec² in the sky with a total rectangular field of view of $23'' \times 36''$.

Two standard broad-bandpass *B* and *R* filters were used in this study. The complete optical system was calibrated absolu-

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tely using the standard calibration source Feige 25 (Stone 1977) observed through both filters. The resultant overall sensitivity of the system amounted to ~ 92 and 201 detected counts per second for a flat 1 mJy source (10^{-26} ergs cm^{-2} Hz^{-1}) with the *B* and *R* filters, respectively. The wavelength dependence of the response of these two filters closely resembles that of the standard Johnson *B* and *R* response and is shown in Figure 1 of Paresce and Burrows (1987b).

SN 1987A is first placed on the unocculted area of the field with the *B* or *R* and a neutral density (ND) filter in the beam and the resultant images are used to focus the telescope secondary. During our observations, the FWHM of the seeing disk amounted to $\sim 0''.8$. The total count rate from SN 1987A amounted to 5.6×10^3 and 6.7×10^4 counts s^{-1} in the *B* and *R* bands, respectively, with an ND filter of optical density 2.0. These values correspond to $B = 7.2$ and $R = 5.0$ which, assuming $V - R = 1.2$ (Hamuy and Phillips 1988), corresponds to $V = 6.2$ in quite reasonable accord with independent simultaneous photometry (Beresford 1987).

Using the telescope TV autoguiding system, SN 1987A is placed behind the occulting wedge in a series of short acquisition exposures. With a series of increasingly smaller offsets, the source is centered behind the occulting wedge. This is accomplished by making the spillover light distribution above and below the wedge obtained with progressively less ND attenuation as symmetrical as possible. Finally, any ND filter remaining is removed and the long exposure in the specified bandpass begun. We estimate the centering accuracy thus obtained to be of the order of a few tenths of an arcsecond. The telescope pointing stability is also of order $\pm 0''.1$.

Several exposures of this type were obtained on the night of 1987 December 20–21 through the filters described above. The raw images were processed in a standard way to prepare them for scientific analysis. The effects of CCD bias level and the variations in response across the detector area are removed by subtracting a bias level derived from an overscan region and by dividing by a flat field taken through the appropriate filters a few hours after the observations. Cosmic rays are removed by identifying those pixels that differ from their neighbors by 3σ more than the average statistical noise, as a function of intensity. They are replaced by bilinear interpolation where possible, or masked out entirely. This interpolation is permissible as our plate scale is such that about 10 pixels cover the seeing disk diameter. All bad pixels are masked out and do not contribute to the subsequent analysis. This includes bad flat-field pixels defined as having an apparent QE more than a factor of 2 different from the average, bad columns, uncorrected cosmic-ray events, pixels within the geometric image of the occulting wedge, and overclocked pixels.

The results of this processing are shown in Figure 1 where the image shown corresponds to a 10 minute exposure with the *B* filter. The measured position of the center of the SN 1987A seeing disk is marked by a cross. The occulting wedge is $1''.90$ wide at this location. North is up, east to the left, and the intensity scale is linear from 0 to 100 counts normalized to a 30 minute exposure. The left half of the image corresponds to the eastern half of the direct image obtained with the coronagraph with the prominent SN 1987A seeing-broadened image. The right half of the image corresponds to the western half of the direct image after subtraction of the stellar seeing profile as described in the next section. The vertical stripe near the right edge is due to a bad CCD column. The azimuthally averaged radial profile of the *B* image in magnitude arcsec^{-2} shown in

Figure 1 is plotted in Figure 2 (*dashed line*) as a function of angular distance from the center of the SN position. Assuming SN 1987A is at 52.5 kpc, $1''$ in these images corresponds to a linear scale of ~ 0.83 lt-yr at the source. The echoes recently detected from interstellar gas in front of the SN lie well outside our field of view at the time of observation and are not expected to contribute to the data in Figure 1.

III. ANALYSIS AND DISCUSSION

It is clear from the image shown in Figure 1 and its average radial profile presented in Figure 2 that a substantial part of the observed signal, especially in the central $10''$ or so from the SN position, is due to light originating at the SN and subsequently scattered from that direction by the effects of the atmosphere and the telescope. An accurate measurement of radiation from possible sources in the field, therefore, relies heavily on an accurate subtraction of this locally scattered component. Two methods can be used to perform this task. The first and most straightforward, in principle, is to use an accurately registered and normalized image of a nearby control star taken in as close to identical observing conditions and time as possible. Several stars observed during the same night were used for this purpose but, in all cases, the results were not completely satisfactory in this particular application for the following reasons. First, the absolute photometry of the available control stars was too uncertain to allow an accurate independent normalization. Second, seeing fluctuations between observations seemed to mimic possible real structure and, third, the precise contribution of the sky background in the outer regions of the image was unknown. Thus, although a subtraction of the control star images yielded very low residual counts, the possibility remained that the echo would have the same profile as the atmospheric and telescope scattering function, and therefore would be removed or a spurious signal added if the wrong normalization for the control star was chosen or if the seeing changed during the control exposure.

Because of these uncertainties in generating a precise measurement or upper bound on possible echos, we discarded this method in favor of a second which makes use of a more complete understanding of the origin of the scattered light observed. The theoretical seeing profile is well understood through atmospheric turbulence theory and the associated effects of turbulence on the structure function of the wavefront. The expectation of the point-spread function (which is equal to its time average in a long exposure) can be derived by multiplying the telescope diffraction OTF by the atmospheric MTF and performing a Fourier transform.

We approximated the telescope OTF with the appropriate function for a circularly symmetric aperture with a central obscuration, and zero wavefront errors. The atmospheric MTF depends only on the Fried parameter, which is roughly the size of a telescope aperture that would give a diffraction limited image of the same size as the seeing disk. Thus, the theoretical profile depends on only one parameter. That parameter, in turn, is completely fixed by the FWHM of the seeing profile which is determined from background stars in the images. Therefore, use of the theoretical profile normalized from the photometry of the supernova, gives a parameter-free prediction of the observed wings of the seeing profile. By subtracting this prediction from the observations, one can assess whether or not any significant extra signal remains at any point of the image.

Software was written to perform a least-squares fit to the

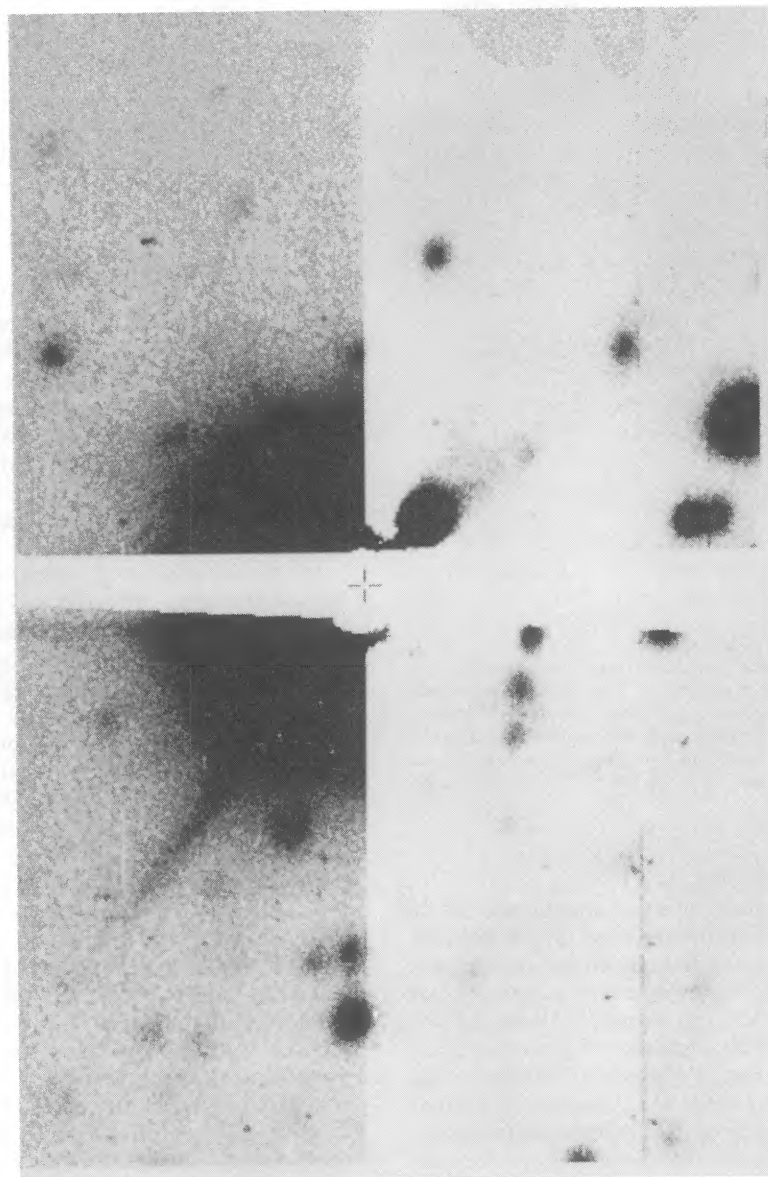


FIG. 1.—Composite image of a $23'' \times 36''$ region of the sky centered on SN 1987A whose location is marked with a cross. North is up, east is to the left with each pixel in the 512×330 pixel frame subtending an area of 5×10^{-3} arcsec². The opaque stripe running EW through the center of the image is due to the occulting wedge of the coronagraph whose projected width at the cross position is $1''.9$. The intensity scale is linear with all counts between 0 and 100 displayed. The left (eastern) half of the image represents the eastern half of the cleaned, bias-subtracted, flat-fielded image of the field, while the right (western) half represents the western half of the image obtained by subtracting from the former an azimuthally averaged stellar profile as described in the text.

bright star just to the north of the finger at the far west edge of the frame. The derived seeing with other fainter stars was found to be essentially the same. The fit function used was a Gaussian, with a variable background. The theoretical one-dimensional seeing profile was separately fitted by a Gaussian, with appropriate weights to give correct radial weighting. The same algorithm was used to define the seeing there. The Fried parameter was adjusted until the theoretical seeing agreed with the measured seeing. The theoretical and observed curves for the variation of the RMS with the size of the box within which the fit is made were almost identical showing that the precise box size chosen did not affect the results.

The seeing profile varies slowly with wavelength. We used wavelengths of 400 nm for the *B* bandpass and 600 nm for the *R* bandpass when computing the theoretical profiles. Although

these wavelengths are not exactly the effective wavelengths of the bandpass, the error introduced is small. The Fried parameter (at a fiducial wavelength of 500 nm) was found to be 16.5 cm for both bandpasses. This shows that the atmospheric conditions were virtually identical for the two exposures. The corresponding FWHM of the Gaussian fits are $0''.813$ for the *B* band image and $0''.879$ for the *R* band image.

The theoretical radial profile corresponding to this choice of Fried parameter for the *B* band image is plotted in Figure 2, where all the curves are normalized to give 8.2×10^8 total counts in a 30 minute exposure corresponding to the observed $B = 7.2$ in the *B* bandpass. Similar results were derived for the *R* image.

The observed azimuthally averaged radial profile is also plotted in Figure 2 (*dashed line*). Only pixels that were not

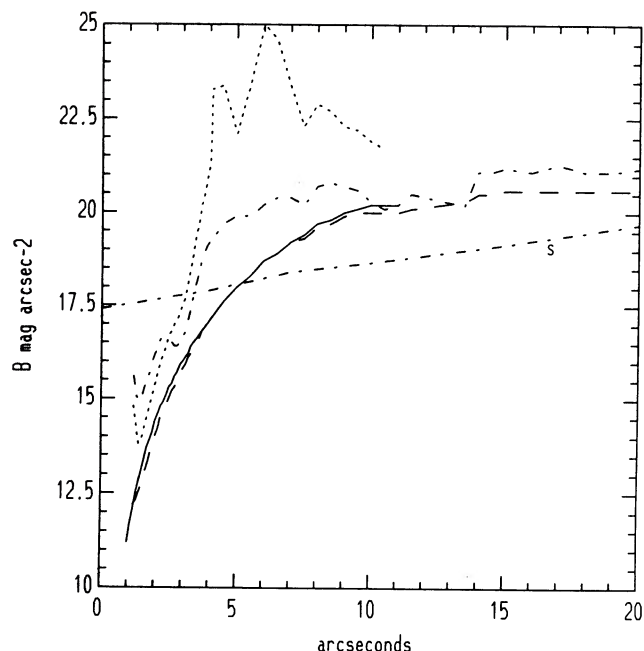


FIG. 2.—(solid curve) The theoretically predicted seeing profile corresponding to the 10 minute B band image in B mag arcsec $^{-2}$ vs. the angular distance from SN 1987A in arcseconds. (dashed curve) The azimuthally averaged observed profile. (dotted curve) The absolute value of the observed minus the predicted profile. (dot-dash curve) The RMS variation in the observations about the azimuthal average. (dot-dash curve marked S) The predicted echo brightness from Schaefer (1987).

masked for any reason are included in the averaging process. It is easily seen that the agreement between the theoretical and observed curves is excellent, even though no parameters are available to vary. The theoretical profile was not continued beyond 11" because of numerical instabilities in the transform routines used to compute it. At distances of about 10", the average radial profile flattens due to scattering from the mirror surfaces and/or to background light. The dotted curve plotted in Figure 2 is the absolute value of the difference between the observed and predicted intensities. In a sense, this provides the best estimate of the bound on surface brightness from largely azimuthally symmetric features like the ring echos observed at larger angles.

Finally, instrumental scattering also leads to radial artifacts that are evident in the data, particularly at the larger scattering angles. The sample standard deviation of the pixels contributing to the azimuthal average in each bin provides an estimate of the magnitude of these radial fluctuations. Clearly, if an echo were to have strong azimuthal dependence, like those artifacts, it would not be unambiguously detected if it had the same amplitude as them. Therefore the upper bound on the echo intensity independent of its morphology must be the RMS fluctuations about the mean radial profile. This curve is also plotted in Figure 2 (dot-dash line). The R band limits are not as stringent as those determined from the B band because the SN was considerably brighter in R and the exposure time of the R image used was only 30 s as opposed to 600 s for the B image.

The result obtained by subtracting an image having the average radial profile shown in Figure 2 is shown in the right-hand panel of Figure 1 which represents the western half of the processed image. The eastern half of the direct cleaned image

serves as a useful comparison. The brightest objects in the field are $B \approx 15$ while the faintest barely detectable above background are $B \approx 21$. Apart from some areas very close to the center of the profile and near a faint diffraction spike at 35° p.a., the subtraction process works remarkably well leaving a clean image down to $\sim 2''$ from the center of the supernova.

The prominent object in these images at a distance of $2''.8 \pm 0''.5$ and at $320^\circ \pm 2^\circ$ p.a. from the geometrical center of the SN light distribution is a star having $B = 15.1 \pm 0.2$ and $R = 15.6 \pm 0.3$ and is certainly to be identified with star 2 of the Sk $-69^\circ 202$ complex (Walborn *et al.* 1987). The small difference in position with the preeruption observations reported by these authors can, most likely, be ascribed to the uncertainty in locating the actual center of the supernova image which we can only infer from the isophotes beyond $1''$ or $2''$ from the SN itself. Star 3 at $1''.5$ and 115° p.a. is undetectable in our observing configuration as it would lie under the occulting wedge but is probably contributing to the excess spillover emission measurable in that direction near the diffraction spike in the SE quadrant.

We have compared our images to the preeruption CTIO 4 m prime-focus plates referred to in Walborn *et al.* (1987), especially those with comparable limiting magnitudes. All the features detectable on our images can be identified with objects on these plates and vice versa. No other unambiguously detectable source of radiation can be found in any of our B and R images. More specifically, excepting a thin strip of sky of $\approx 2''$ width running EW and centered on the SN due to the occulting wedge, we can exclude the presence of any new source in the field surveyed of surface brightness greater than the values specified by the curves plotted in Figure 2 for the B band. The corresponding R band limits are 18.8 mag arcsec $^{-2}$ for any type of source and 20.2 mag arcsec $^{-2}$ for an azimuthally symmetric feature.

These limits have interesting implications concerning the physical characteristics of the SN circumstellar medium located on the 300 day time delay ellipsoid corresponding to our observations (210 days if we count from the time of peak B brightness). This ellipsoid (Couderc 1939) would intercept circumstellar material located at ~ 1 –20 pc from the star for the angular distances between $2''$ and $10''$ appropriate to our observing configuration. With this short a delay, all the observable material lies in front of the SN in our line of sight. Schaefer (1987) recently computed the expected surface brightness in the B band of an echo from a uniformly distributed gas out to 300 pc as a function of the angular distance and delay assuming the gas has the same properties as the galactic intercloud medium. After correction for an overestimation of the total optical depth (B. E. Schaefer, private communication), the expected fluxes appropriate to our situation are also plotted in Figure 2 (dash-dot line marked S). These results should be compared to the derived upper limits for a mainly azimuthally symmetric feature that are ~ 5 mag fainter than expected. Thus, assuming the dust around SN 1987A is not too different from that found in other regions of the LMC, the observed intensity upper bound implies that the region in front of the SN out to 20–30 pc has an average atomic hydrogen density in the range 2.5×10^{-3} to 10^{-2} atoms cm $^{-3}$ depending on the precise gas-to-dust ratio chosen (Fitzpatrick 1986). These values are quite consistent with those expected within a hot wind-swept bubble (Weaver *et al.* 1977).

It is also straightforward to compute an upper bound to the gas density in a circumstellar shell located at the intercept with

the delay ellipsoid by making the same assumptions concerning the characteristics of the dust in the shell. Specifically, for this, we have assumed a peak luminosity of the SN in the B band of 5×10^{40} ergs s^{-1} , a dust asymmetry factor of 0.6, a scattering efficiency of 1, an effective grain cross section of 10^{-9} cm^2 , a total extinction A of 0.5, and a dust-to-gas particle number ratio of 4×10^{-13} grains per H atom ignoring the contribution due to molecular hydrogen. Because of the geometry of a thin dense shell illuminated by a pulse of radiation of relatively short duration, we can derive an upper limit to the hydrogen column density in the shell $N_H \leq 10^{18}$ cm^{-2} from the observed upper limit of ~ 22.5 B mag $arcsec^{-2}$ from $3''$ – $4''$ out to $\sim 15''$ from the SN as shown in Figure 2. Most known or expected circumstellar shells around stars such as Sk $-69^{\circ}202$ have column densities substantially higher than this

(Chevalier 1987). Thus, it seems unlikely that a substantial, even if lumpy, shell exists beyond 2–3 pc from SN 1987A unless it can be shown that the dust in such shells has very unusual characteristics.

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