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DETECTION OF A VERY BRIGHT SOURCE CLOSE TO THE LMC SUPERNOVA SN 1987A

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ABSTRACT

High angular resolution observations of the supernova in the Large Magellanic Cloud, SN 1987A, have revealed a bright source separated from the SN by approximately 60 mas with a magnitude difference of 2.7 at 656 nm (Hα). Speckle imaging techniques were applied to data recorded with the CfA two-dimensional photon counting detector (PAPA) on the CTIO 4 m telescope on March 25 and April 2 to allow measurements in Hα on both nights and at 533 nm and 450 nm on the second night. The nature of this object is as yet unknown, though it is almost certainly a phenomenon related to the SN.

Subject headings: interferometry — stars: supernovae

I. INTRODUCTION

The supernova SN 1987A in the Large Magellanic Cloud (LMC) is the closest unobscured event of its kind since 1604. This provides a unique opportunity for a detailed study of this extraordinary event using a wide variety of observational tools. At the 50 kpc distance of the LMC, high angular resolution interferometric techniques are capable of providing substantial information about the expanding shell and the environment around the SN.

On 1987 March 25 (30 days after the initial event) and on April 2, observations of the SN were made using the Cerro Tololo InterAmerican Observatory (CTIO) 4 m telescope and the Harvard-Smithsonian Center for Astrophysics (CfA) speckle imaging system. The planned purpose of the observations was to attempt to measure the angular diameter of the SN photosphere and to detect the relative position of the SN with respect to the Sanduleak B3 supergiant. At the time of these observations, it was uncertain whether this star still existed, though subsequent analysis of *IUE* spectral data has since shown (Kirshner *et al.* 1987) that the star probably cannot still be in its original form. Speckle observations could also be used to examine the region around the SN for possible light echos from surrounding dust or gas. Despite its expected angular size of only a few milliarcseconds (mas), measurement of the photospheric diameter appeared to be possible using aperture mask interferometry, since the high brightness of the source would provide very high signal-to-noise data. Details of this experiment will be included in a separate paper.

Conventional speckle data were recorded using the PAPA two-dimensional photon counting detector and a set of narrow band (10 nm half-power width) interference filters. Reduction of the data recorded at 656 nm (Hα) from both nights produced a totally unexpected result, showing a bright source only 2.7 mag fainter than the primary source, and separated from it by approximately 60 mas (Karovska *et al.* 1987). A nearly identical result was obtained from the Hα data from the observations on both nights and the source was also detected at 533 nm and 450 nm on the second night. This second object cannot possibly be the original Sanduleak star since it is about 6 mag brighter.

In this *Letter*, we will describe in more detail the observations and results, suggest possible interpretations, and discuss the follow-up observations needed to attempt to understand the mysterious nature of this second source.

II. OBSERVATIONS AND PROCESSING

Two nights, 1987 March 25 and April 2, were provided by the director of CTIO, Dr. R. Williams, for speckle observations of the SN. The speckle system used for these observations was constructed at CfA and has been described in detail elsewhere (Karovska, Nisenson, and Stachnik 1986). An important component of this system is the detector, the Precision Analog Photon Address detector (PAPA) (Papaliolios, Nisenson, and Ebstein 1985) which determines the *x-y* position and time of arrival of each detected photon. This detector has been shown to have the characteristics necessary for accurate speckle image reconstruction. The digital photon addresses are converted to a video signal and stored on VCR tape for later processing. The front-end optics package includes magnifying optics to match the telescope and detector resel scales, computer-controlled atmospheric dispersion correcting prisms, a set of narrow-band interference filters, and various neutral density filters.

The observations consisted of recording data sets of 5 minutes duration on the SN and three different reference stars. Data were recorded with four different filters centered on 400, 450, 533, and 656 nm, each with a bandwidth of 10 nm. Count rates for the data sets ranged from 40 to 70 thousand detected photons per second (neutral density filters were required to reduce the source brightness). The field size used for recording was 1".9 with 256×256 pixel sampling. This gives a 7 mas per resel which is more than adequate for sampling the diffraction limit of the 4 m telescope, which ranges from 20 mas at 400 nm to 33 mas at 656 nm. Since the observations were made when the telescope was pointed between 20° and 30° from the horizon, the data were not of the best quality. Seeing was approximately 2″, the atmospheric dispersion was not fully corrected at shorter wavelengths, and the telescope tracking was unsteady.

The first step in the data processing is flat-fielding, which corrects for nonuniformities in the photocathode and the camera. The photons are grouped into frames and then Fourier-transformed (FT). The optimum frame time was determined by integrating short sets of data with several different frame times and measuring the variance in the high frequency region of the FT. The frame time for the SN data turned out to be 5 ms. Approximately 60,000 frames were available for each data set. Complex correlations are calculated from the FT of each frame (Knox and Thompson 1974) to average both the amplitude and phase in the FT; these correlations are then summed over all the frames. Similar operations are applied to the reference star data, and division of the SN data by the reference star data in Fourier space performs an operation equivalent to deconvolution, eliminating the effects of the atmospheric transfer function and telescope aberrations. The inverse FT of the complex spectrum results in the reconstruction of an image. The transform of the squared modulus reconstructs an autocorrelation image (AC); the AC generally has better signal-to-noise ratio and is used for determining the magnitude difference of the two components. In the case of a simple object such as a binary star, the image is needed only to eliminate the 180° ambiguity in the position of the second component.

III. RESULTS

Figure 1 (Plate L1) shows the results from the data processing. Figure 1*a* is a single input frame, showing the position of each detected photon in a single input frame. Flat fields were recorded by pointing the telescope at an illuminated screen on the dome, and the amplitudes in each frame were scaled by the integrated flat field, thereby correcting for system and detector nonuniformities. Figure 1*b* displays the power spectrum from the integrated transform of the 656 nm data recorded on April 2. Despite the noise in the display, one can see broad, low-contrast bands, which are the fringes characteristic of a close double star with unequal magnitude components. Figure 1*c* shows the image of an unresolved reference star, and Figure 1*d* shows the SN reconstructed image. The size of the displayed spots is indicative only of their relative brightness.

Data for nearby comparison stars recorded close in time through the same filters produced clean, pointlike images, with no significant structure at the separation and position angle of the second source in the SN images. Figure 2*a* plots the Hα AC, and Figure 2*b* shows the AC at 533 nm. These two ACs were generated using the central 128 × 128 pixels in the field (7 mas sampling, 0″.95 field) which gives a somewhat better definition of the reconstructed peaks. Figure 2*c* shows the AC at 450 nm, reconstructed by averaging the finest pixels to produce a 1″.9 (128 × 128) field with 14 mas sampling. Figure 2*d* plots the reference star ν Doradus which was recorded with the 450 nm data, also reconstructed at the larger scale. The averaging generally gives better signal-to-noise ratio, needed for the 450 nm reconstruction, but may result in an image which is slightly less sharp. It is clear that the double structure in the SN is well above the background noise level, particularly in Hα, and the reference star AC has no substantive structure at a comparable scale and position. The ACs, which are reconstructed from only the amplitudes in the transform, have better signal-to-noise ratio than the image, because of the more severe requirements on the quality of the data for the image reconstruction process. Therefore, they were used to measure the parameters of the reconstructed sources.

The separation of the two sources measured in Hα on both nights was 0″.059 ± 0″.008, and the magnitude difference was 2.7 ± 0.2. Since the visual magnitude of the SN at the time of the observations ranged from 4.0 (March 25) to 3.8 (April 2), this source has an apparent magnitude of about 6.5. The errors in our magnitude estimates are slightly too large (0.2) to allow a determination whether the second source changed in brightness by the same amount as the SN during the eight days between our observations. The measurement at 533 nm (April 2) gave a separation of 0″.052 ± 0″.007, and the measured magnitude difference was 3.0 ± 0.5. In both the Hα and 533 nm measurements, the position angle of the secondary source relative to the primary was 194° ± 2°. The 180° ambiguity normally associated with speckle interferometry measurements was eliminated using the image reconstruction. Reconstructions from data recorded at 450 nm show a feature at approximately the same position with a 3.5–4.0 mag difference from the primary. Residual atmospheric dispersion produced elongation in the reconstructions, and this was an increasingly severe problem at shorter wavelengths. Thus either residual dispersion or the red color of the source might explain the uncertainty of its detection at 450 nm. The elongation appears to be somewhat greater in the SN images than in the comparable reference stars, despite their having been close in position on the sky. This suggests that the elongation may be in the object, though the signal-to-noise ratio in the detection is too low to be sure.

IV. DISCUSSION

The detection of the second bright source on two different nights, 8 days apart, combined with the reported detection of this source by a group at Imperial College performing speckle observations on the Anglo-Australian Telescope (Matcher, Meikle, and Morgan 1987) on April 14, leaves little doubt that the source really exists. Since this second source was almost 5 mag brighter than any known preexisting source in the field (the B3 Sanduleak star), it is clear that its appearance must be related to the SN. Reconstructions from the data recorded at 400 nm, where the SN was reduced sufficiently in brightness so that the magnitude difference between the SN and the B3 star would have been small enough to detect their separation, showed no extension of the primary source to an accuracy of about 20 mas. The 60 mas separation of the two bright sources would correspond to about 3000 AU at the distance of the LMC (50 kpc), perpendicular to the line of sight. This corresponds to 2 lt-weeks, and the first observation occurred 30 days after the SN explosion.

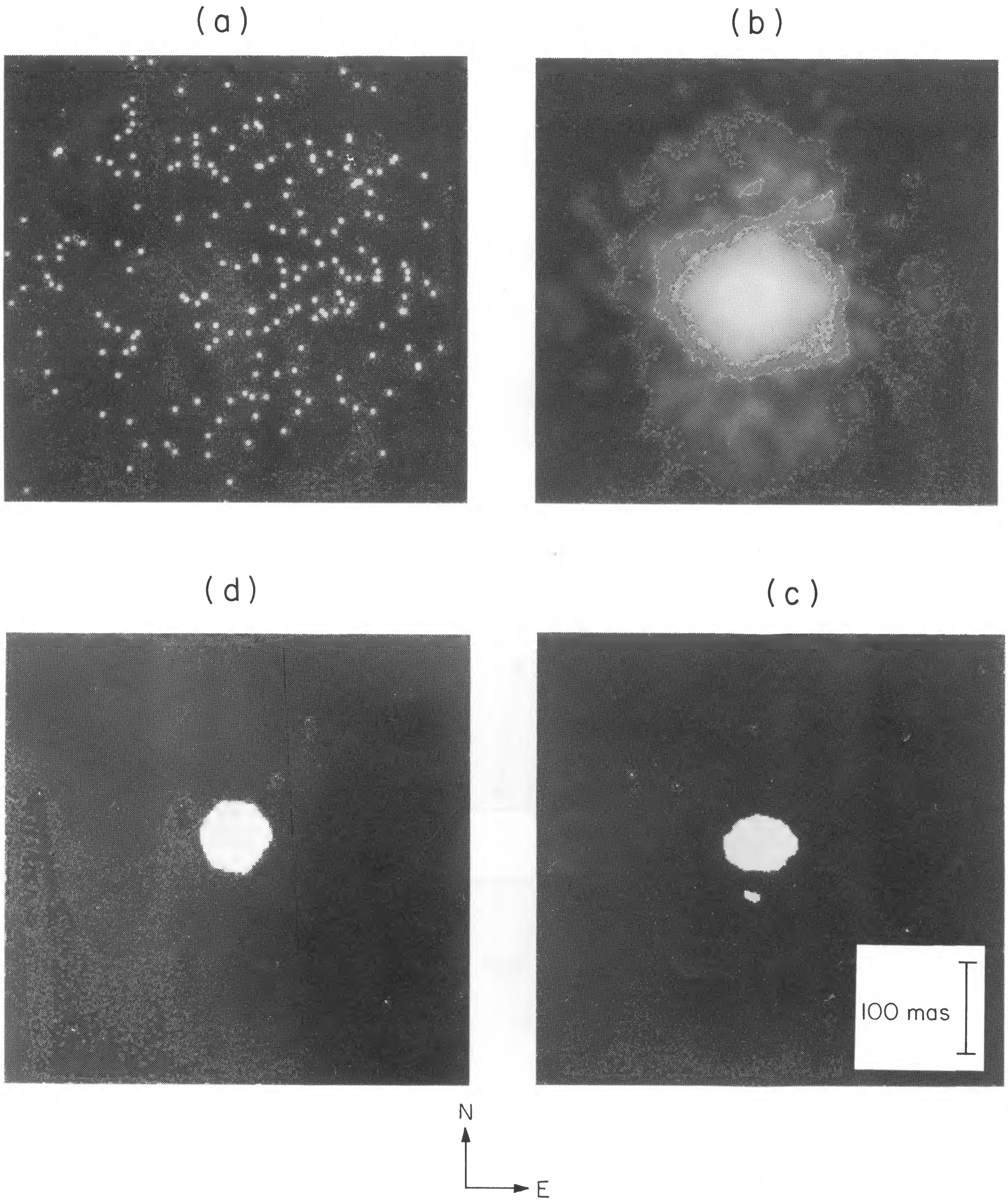

FIG. 1.—Speckle imaging reconstruction in Hα of the region around SN 1987A showing the bright secondary source. (*a*) Single 5 ms frame (*b*) reconstructed power spectrum from 60,000 frames. (*c*) Reconstructed image of the reference star ν Doradus. (*d*) Reconstructed image of the SN.

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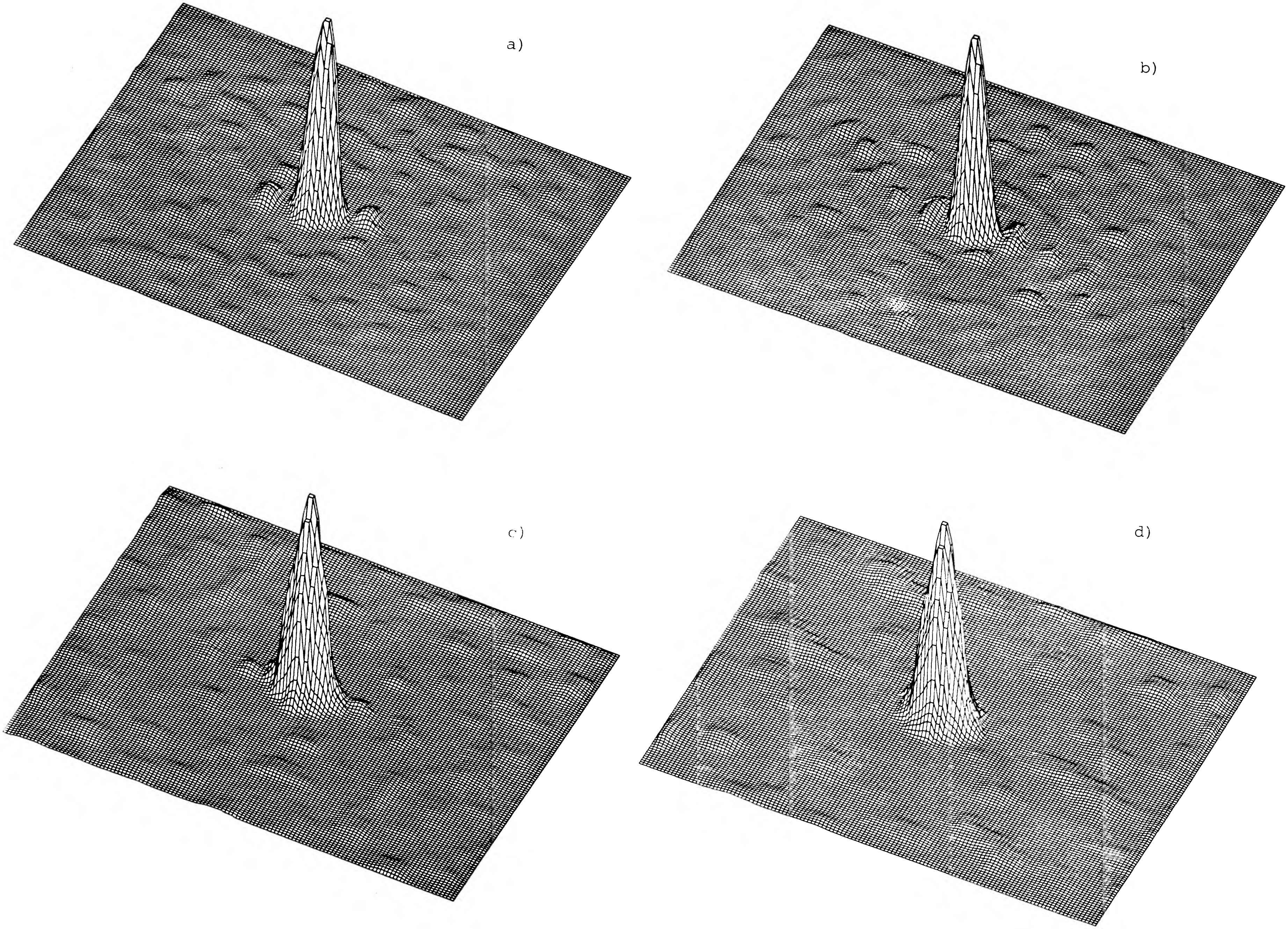

FIG. 2.—Speckle autocorrelation images of the region around SN 1987A in three wavelengths and a comparison star. (*a*) Autocorrelation in Hα. (*b*) Autocorrelation at 533 nm. (*c*) Autocorrelation at 450 nm. (*d*) Autocorrelation of the reference star ν Doradus at 450 nm.

One possible explanation for the existence of the second source is that it could be a large cloud of dust or gas reflecting light from the SN. However, the brightness of the second source would require that the cloud subtend a minimum of 1 sr as seen from the SN (the source is 10% as bright as the SN), even with an albedo of unity. This would be an enormous cloud, probably spatially resolved by our measurements. It is also unlikely that such a cloud could exist in the neighborhood of a B3 supergiant. Another possibility is that the second source was a very bright star wrapped in a dust shell which was blown away by the SN flash. However, such a source would be nearly the brightest star in the LMC (improbable) and would have been very bright in the IR. No such source existed in that position in the *IRAS* survey of infrared sources.

While there are many other more exotic possibilities to explain these results, it is clear that more data are needed to sort them out. Measurement at a later date should determine whether their relative positions have remained stationary and whether the second source has brightened along with the SN. Measurement at other wavelengths should determine what the relative color of the two sources is, and whether the second source is an emission-line object. New observations are planned at the end of 1987 May and in early July. It is hoped that they will shed new light on this extraordinary object.

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