

# FIRST RESULTS FROM THE FAINT OBJECT CAMERA: SN 1987A<sup>1</sup>

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## ABSTRACT

We present the first images of SN 1987A taken on day 1278 after outburst with the Faint Object Camera on board the *Hubble Space Telescope*. The supernova is well detected and resolved spatially in three broad-band ultraviolet exposures spanning the 1500–3800 Å range and in a narrow-band image centered on the [O III] λ5007 line. Simple uniform disk fits to the profiles of SN 1987A yield an average angular diameter of  $\theta \approx 170 \pm 30$  mas, corresponding to an average expansion velocity of  $v \approx 6000$  km s<sup>-1</sup>. The derived broad-band ultraviolet fluxes, when corrected for interstellar absorption, indicate a blue ultraviolet spectrum corresponding to a color temperature near 13,000 K. The luminosity of SN 1987A in the ultraviolet,  $L \approx 2 \times 10^{36}$  ergs s<sup>-1</sup>, is comparable to that emitted in the visible-through-infrared portion of the spectrum. Finally, the narrow-band [O III] image reveals that the circumstellar nebula known to surround SN 1987A has the shape of a thin, tilted ring having a radius 0.20 pc and a thickness  $\approx 2 \times 10^{-2}$  pc.

**Subject headings:** stars: circumstellar shells — stars: individual (SN 1987A) — stars: supernovae — ultraviolet: general

## 1. INTRODUCTION

As well as being of great intrinsic interest, SN 1987A should present a challenging test of the resolution capability of the *Hubble Space Telescope*. Expanding at velocities of order  $v \approx 10^4$  km s<sup>-1</sup> for three and one-half years since the explosion, the ejected outer envelope of SN 1987A is expected to have reached an angular size of order  $\theta \approx 100$  mas. Spectroscopic observations obtained from *IUE* spectra and ground-based imaging have also revealed the presence of an  $\approx 1''$  sized circumstellar nebula surrounding SN 1987A. Moreover, due to

contamination from neighboring stars located a few arc-seconds away in the field, the light curve of SN 1987A has become increasingly difficult to monitor, both from the ground and with *IUE*, now that SN 1987A has faded some six orders of magnitude from its peak brightness.

For these reasons SN 1987A was selected to be observed with the Faint Object Camera (FOC) on board the *Hubble Space Telescope* as part of the science assessment program designed to test the scientific performance of the observatory given the optical problems with the primary mirror of the telescope.

## 2. OBSERVATIONS AND ANALYSIS

SN 1987A and its immediate surroundings were observed with the f/96 camera of the FOC (Macchetto et al. 1982) on 1990 August 23–24 UT (JD 2,448,127.6; day 1277.8). Three exposures were obtained in the broad-band UV filters, F175W (1676 s), F275W (838 s), and F346M (575 s), and one 1660 s exposure in the narrow-band F501N [O III] λ5007 filter (see Parescé 1990 for a description of the filters and other details of the FOC). A 512 × 512, 0".022 × 0".022 pixel detector format was used, providing a field of view of 11" × 11". All exposures were taken in coarse track.

The supernova is well detected and resolved spatially in all exposures obtained. Portions of the F275W and F501N images containing SN 1987A and its two UV bright companion stars are shown in Figure 1 (Plate L19). The images displayed in Figure 1 were flat-fielded and resampled to correct for the FOC detector distortion, but are otherwise unprocessed. In particular, the faint  $\approx 4''$  diameter halos caused by the spherical aberration of the telescope can be seen surrounding the image cores of the two bright ( $V \approx 14.9$  and  $V \approx 15.6$ ) stars 2 and 3 located 2".9 and 1".6 from SN 1987A (e.g., Walker & Suntzeff 1990). The image of SN 1987A is clearly visible within the outer halo of star 3 in both images. The F501N exposure also shows the curious circumstellar ring known to surround

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SN 1987A (Crotts, Kunkel, & McCarthy 1989; Wampler et al. 1990). The F346M and F175W exposures are very similar in appearance to the F275W image and show little, if any, trace of the ring.

The asymmetric shape of the image cores of stars 2 and 3 (especially obvious in the F275W image) is caused by the peak count rates exceeding the linearity limit of the photon-counting FOC detector ( $\approx 2$  counts  $\text{s}^{-1}$  pixel $^{-1}$  for point sources). This saturation, although local in effect, distorts the core of the point-spread function and severely affects the photometric integrity of the stellar images in a not easily quantifiable manner. For this reason stars 2 and 3 were not used as photometric or spatial references in the analysis of the data.

Fortunately, the  $11'' \times 11''$  field of view of the images also includes the fainter star 4 (Walker & Suntzeff 1990) located  $5''.5$  west of SN 1987A. This faint ( $V = 18.2$ ) and very blue ( $B - V = -0.11$ ) star is of comparable brightness to SN 1987A in all bands. The F275W and F501N images of star 4 are shown as inserts in Figure 1. It should be noted that the optical layout of the FOC does not have a central obscuration, so the spherical aberration of the telescope does not lead to the point-spread function changing with position within an FOC image. The constancy of the FOC point-spread function has been confirmed by in-orbit tests. A comparison between the images of star 4 and SN 1987A shows the supernova to be obviously extended. This is seen more clearly in Figure 2, which shows a detailed comparison between the point-spread function represented by the image of star 4 and SN 1987A for the F275W exposure. The stellar image has a FWHM of  $\approx 3$  pixels or  $\approx 66$  mas, whereas the FWHM of the supernova image is  $\approx 7.5$  pixels or  $\approx 165$  mas. Similar extensions are seen in the SN 1987A images in the other three bandpasses.

In order to derive an objective measure of the angular size of the SN 1987A images, we have numerically convolved the star 4 point-spread function with a uniform disk, and least-squares fitted the smoothed point-spread function to the supernova images. For the F275W and F346M data we obtain best-fit disk diameters of  $\theta \approx 190 \pm 30$  mas and  $\theta \approx 155 \pm 30$  mas using this technique. The best-fit diameters derived from the lower signal-to-noise ratio F175W and F501N exposures are slightly smaller,  $\theta \approx 110 \pm 65$  mas and  $\theta \approx 135 \pm 50$  mas, respectively. The weighted average diameter is  $\theta \approx 170 \pm 30$  mas. However, we note that the simple uniform disk model does not provide a particularly good fit near the center of the SN 1987A images, which are more strongly peaked than the smoothed point-spread function. This suggests that the

expanding debris is strongly limb-darkened or, alternatively, that a central pointlike core may be present in the image.

We have also derived absolute, broad-band fluxes for SN 1987A by carrying out digital aperture photometry on the images, and referencing to separate matching calibration exposures of the UV spectrophotometric standard star BPM 16274 (Bohlin et al. 1990). The gap in dynamic range between the bright ( $V = 14.20$ ) standard star and the faint ( $V > 17$ ) linear domain of the FOC was spanned by use of preflight-calibrated neutral density filters. Effective attenuation factors as well as effective wavelengths and monochromatic reference fluxes for the filters used were derived numerically by folding the preflight FOC sensitivity curves with the *IUE* spectrum of BPM 16274. For the aperture photometry a square box of size  $29 \times 29$  pixels centered on the stellar images was used. This box contained approximately 40% of the total light in the images. In measuring the counts contained in the images of SN 1987A special care was taken to subtract the underlying background from the spherical aberration halo of star 3 by measuring and averaging the background in three different positions at the same radial distance from the star as SN 1987A. The background correction ranged from 16% of the total signal in the case of the F275W and F346M exposures to 41% in the case of the lowest S/N F175W exposure. The resulting absolute total fluxes are shown in Figure 3. The statistical uncertainties of the derived fluxes are less than 2% in all cases. Based on in-flight experience gained so far on the absolute sensitivity of the FOC, we estimate that the absolute uncertainty on our fluxes is less than  $\pm 30\%$ .

The circumstellar "ring" seen in the F501N image shown in Figure 1 appears as a near-perfect ellipse centered on SN 1987A. The ring is reasonably well detected at  $\approx 25$  counts pixel $^{-1}$  on the rim compared to  $\approx 8$  counts pixel $^{-1}$  of background in adjacent areas. We do not confirm the  $0''.1$  offset between the center of the ellipse and the supernova reported by Wampler et al. (1990). The measured major and minor semi-axes of the ring are  $830 \pm 15$  mas and  $605 \pm 15$  mas, respectively. The position angle of the major axis is  $80^\circ \pm 5^\circ$ . The width of the ring appears to be resolved marginally at best over most of its length. We estimate the angular width to be less than 4 pixels, or 88 mas. Factor 4–5 intensity fluctuations are seen along the ellipse. We detect only barely the fainter outer parts of the loops seen both north and south of the ring by Crotts et al. (1989) and Wampler et al. (1990). However, since these outer structures are an order of magnitude fainter in [O III] than the inner loop, this is consistent with the expected

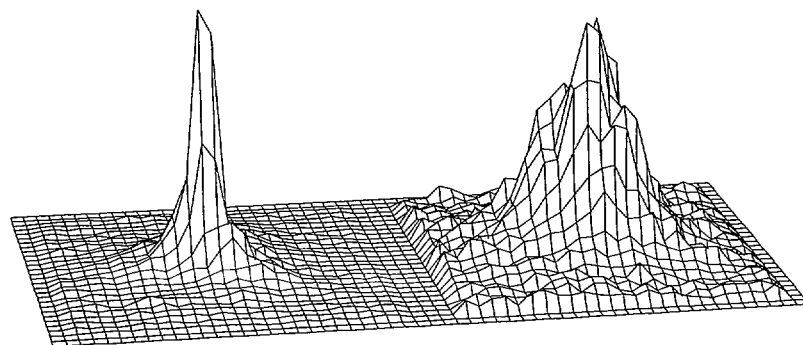


FIG. 2.—Detailed comparison between the point-spread function of the comparison star 4 (left) and the image of SN 1987A (right) taken from the F275W exposure. The vertical scale is arbitrary, but linear in counts per pixel. The stellar image has a FWHM of  $\approx 3$  FOC f/96 pixels or  $\approx 66$  mas, whereas the FWHM of the supernova image is  $\approx 7.5$  pixels or  $\approx 165$  mas.

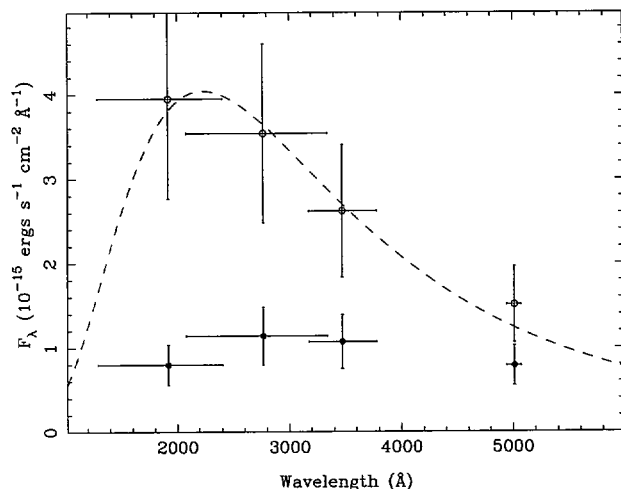


FIG. 3.—Observed broad-band absolute ultraviolet fluxes of SN 1987A (filled symbols). The open symbols mark the fluxes corrected for interstellar extinction assuming  $E(B - V) = 0.2$  (see text). Also shown is the  $T \approx 13,000$  K best-fit blackbody curve.

lower sensitivity to diffuse emission given the f/96 focal ratio of the FOC.

Last, we have attempted to measure the total energy flux of the ring by means of aperture photometry. We arrive at a value of  $F \approx 3 \times 10^{-13}$  ergs s $^{-1}$  cm $^{-2}$ . Because of the obvious difficulties associated with measuring the flux of a non-point-source object of a size comparable to the full  $\approx 4''$  extent of the aberrated *Hubble Space Telescope* point-spread function, we estimate that this value is probably uncertain by a factor of at least 2.

### 3. DISCUSSION

With an adopted distance of 50 kpc to the LMC (Eastman & Kirshner 1989), the average angular diameter of SN 1987A of  $\theta \approx 170$  mas observed on day 1277.8 corresponds to a linear radius of  $R \approx 2.1 \times 10^{-2}$  pc and an expansion velocity of  $v \approx 6000$  km s $^{-1}$ . This average velocity is well within the 2000–30,000 km s $^{-1}$  range of ejection velocities seen in the spectrum of SN 1987A (Cassatella 1987; Kirshner et al. 1987; Hanuschik & Dachs 1988; Phillips et al. 1988).

The total mass of the ejecta of SN 1987A is believed to be of order  $M \approx 10 M_{\odot}$  (e.g., Arnett et al. 1989), in which case a lower limit on the total column density through the ejected shell is  $N_T > (M/m_H 4\pi R^2) \approx 2 \times 10^{23}$  cm $^{-2}$ . In view of the uncertain amount of clumping and dust formation in the ejecta, it is not obvious whether this column density corresponds to optically thin or optically thick conditions. Our data suggest marginally that the angular extent of SN 1987A changes with wavelength. If real, this could be interpreted as being due to wavelength-dependent opacity effects.

Our broad-band ultraviolet fluxes for SN 1987A corrected for interstellar extinction are shown as the open symbols in Figure 3. A total reddening of  $E(B - V) = 0.20$  to SN 1987A was assumed, with  $E(B - V) = 0.05$  arising in the Milky Way and  $E(B - V) = 0.15$  in the LMC (Panagia et al. 1987; Gilmozzi et al. 1987). The average extinction curve of Savage & Mathis (1979) was used, except for the shortest wavelength F175W flux, where a value of  $A_{\lambda}/E(B - V) = 8.6$  was adopted in order to take into account the steeper ultraviolet extinction curve of the 30 Doradus region (Fitzpatrick 1986). The intrinsic

broad-band ultraviolet spectrum of SN 1987A is seen to be rather blue.

The best-fit blackbody curve shown in Figure 3 indicates an ultraviolet color temperature of  $T \approx 13,000$  K. The absolute ultraviolet fluxes of SN 1987A, combined with the measured angular diameter of  $\theta \approx 170$  mas, indicate that SN 1987A is radiating in the ultraviolet at an apparent surface brightness a factor  $\approx 5 \times 10^{-11}$  below the blackbody limit corresponding to the color temperature. This is presumably a manifestation of the fact that the ultraviolet flux is almost certainly not a true continuum spectrum but in the form of numerous emission lines, combined with the strongly non-LTE conditions in the outer envelope of the ejecta where resonance scattering in numerous Doppler-broadened atomic transitions is believed to be the dominant opacity source (Fransson et al. 1987; Lucy 1987; McCray, Shull, & Sutherland 1987).

By using the best-fit blackbody curve shown in Figure 3 as a convenient interpolation device, we derive a total vacuum ultraviolet luminosity for SN 1987A of  $L(\lambda < 3300 \text{ \AA}) \approx 2 \times 10^{36}$  ergs s $^{-1}$ . This ultraviolet energy output equals  $\approx 30\%$ – $40\%$  of the corresponding visible-through-infrared ( $U$  to  $K$ ) luminosity obtained by extrapolation of the day 793–1204 light curve obtained by Caldwell et al. (1990). Although the ultraviolet emission represents a significant correction to the combined ultraviolet-through-infrared luminosity, this radiative energy output can still be accounted for by the total radioactive decay luminosity of SN 1987A predicted for day 1278 (Woosley, Pinto, & Hartmann 1989; Caldwell et al. 1990).

The existence of the circumstellar nebula detected in our F501N, [O III]  $\lambda 5007$  exposure was first deduced from the narrow emission lines detected in *IUE* spectra of SN 1987A since day  $\approx 80$  (Fransson et al. 1989). It was later imaged directly by Crotts et al. (1989) and Wampler et al. (1990). As discussed by the latter authors, the ring is definitely a physical line-emitting object and not merely a light echo. Moreover, because of its large distance from the supernova ( $R \approx 0.20$  pc), the ring cannot be material ejected in the explosion, but must have been created prior to the event, presumably through several episodes of stellar-wind-generated mass loss during the evolution of the blue supergiant progenitor star, Sk  $-69^{\circ}202$ . This circumstellar material was then rapidly photoionized when the ultraviolet flash from SN 1987A reached it some 240 days after the explosion.

The relative darkness of the interior of the ring with respect to the exterior suggests that the object is indeed a circular annulus or “equatorial belt,” and not a limb-brightened shell. If so, then the angle between the normal to the ring and the line of sight given by the ratio of the minor and major axes is  $\alpha = 43^{\circ} \pm 3^{\circ}$ . Emission from the front of the ring should have started to become visible after  $t = R/c(1 - \sin \alpha) \approx 76$  days. The complete ring should have been visible after  $t = R/c(1 + \sin \alpha) \approx 400$  days. These predictions are remarkably consistent with the time evolution of the narrow emission lines seen in the *IUE* spectra of SN 1987A by Fransson et al. (1989). The ultraviolet emission lines first appeared on day  $\approx 80$  and grew gradually in intensity until day  $\approx 400$ , after which they decreased. We note that our data reveal no obvious difference in brightness between the northern and southern limbs, from which it follows that the current O III recombination time in the ring gas must be less than the light crossing time,  $t = 2R/c \sin \alpha \approx 325$  days. This is consistent with the behavior of the N IV and N V lines in the more recent *IUE* observations (Sonneborn et al. 1990).

The density of  $n_e \simeq 2 \times 10^4 \text{ cm}^{-3}$  for the ionized circumstellar gas derived by Fransson et al. (1989) from the ultraviolet line diagnostics is also consistent with a ring geometry. For an adopted angular width of  $\theta = 88 \text{ mas}$  ( $\Delta R \simeq 2 \times 10^{-2} \text{ pc}$ ), our measured total ring flux quoted above corresponds to an observed average extinction-corrected  $[\text{O III}] \lambda 5007$  line surface brightness of  $I_l \simeq 2 \times 10^{10} \text{ photons s}^{-1} \text{ cm}^{-2} \text{ sr}^{-1}$ . Equating this with the predicted  $[\text{O III}] \lambda 5007$  emissivity calculated assuming a density of  $n_e \simeq 2 \times 10^4 \text{ cm}^{-3}$ , a current temperature of  $T \simeq 2 \times 10^4 \text{ K}$  (Wampler, Richichi, & Baade 1989), unity ionization correction, and the depleted oxygen abundance of  $[\text{O}/\text{H}] = 1.7 \times 10^{-5}$  derived by Fransson et al. yields an emission measure of  $\int n_e^2 dR \simeq 2 \times 10^6 \text{ cm}^{-6} \text{ pc}$  and a unit-filling-factor line-of-sight thickness of  $\Delta R \simeq 7 \times 10^{-3} \text{ pc}$  for the ring. The close factor  $\simeq 3$  agreement between the estimates of the tangential and line-of-sight thicknesses of the ring is almost certainly fortuitous given the huge uncertainties, but nevertheless does add further support to the concept of a ring geometry.

The total mass of the ring calculated for a ring diameter of  $R \simeq 0.20 \text{ pc}$ , thickness  $\Delta R \simeq 2 \times 10^{-2} \text{ pc}$ , and density  $n_e \simeq 2 \times 10^4 \text{ cm}^{-3}$  is  $M \simeq 0.2 M_\odot$ . This mass could easily be accu-

mulated on a time scale of  $t \simeq 10^5\text{--}10^6 \text{ yr}$  at typical supergiant mass-loss rates. How the material was collected and shaped into such a well-defined thin ring is less obvious, although scenarios involving a slow red supergiant wind phase followed by a fast asymmetrical blue supergiant wind phase could conceivably create such an object given suitable anisotropies in the winds. Nonetheless, this "equatorial belt" surrounding SN 1987A is presumably aligned with the rotation axis of the progenitor star, Sk  $-69^\circ 202$ . This may be of relevance if and when a pulsar is seen emerging from the debris of SN 1987A.

The Faint Object Camera is the result of many years of hard work and important contributions by a number of highly dedicated individuals. In particular, we wish to thank ESA/HST Project Manager Robin Laurance, the ESA/HST Project Team, and the European contractors for building an outstanding scientific instrument. The FOC IDT Support Team, D. Baxter, P. Greenfield, R. Jedrzejewski, and W. B. Sparks, acknowledge support from ESA through contract 6500/85/NL/SK. P. Crane and I. R. King acknowledge support from NASA through contracts NAS5-27760 and NAS5-28086.

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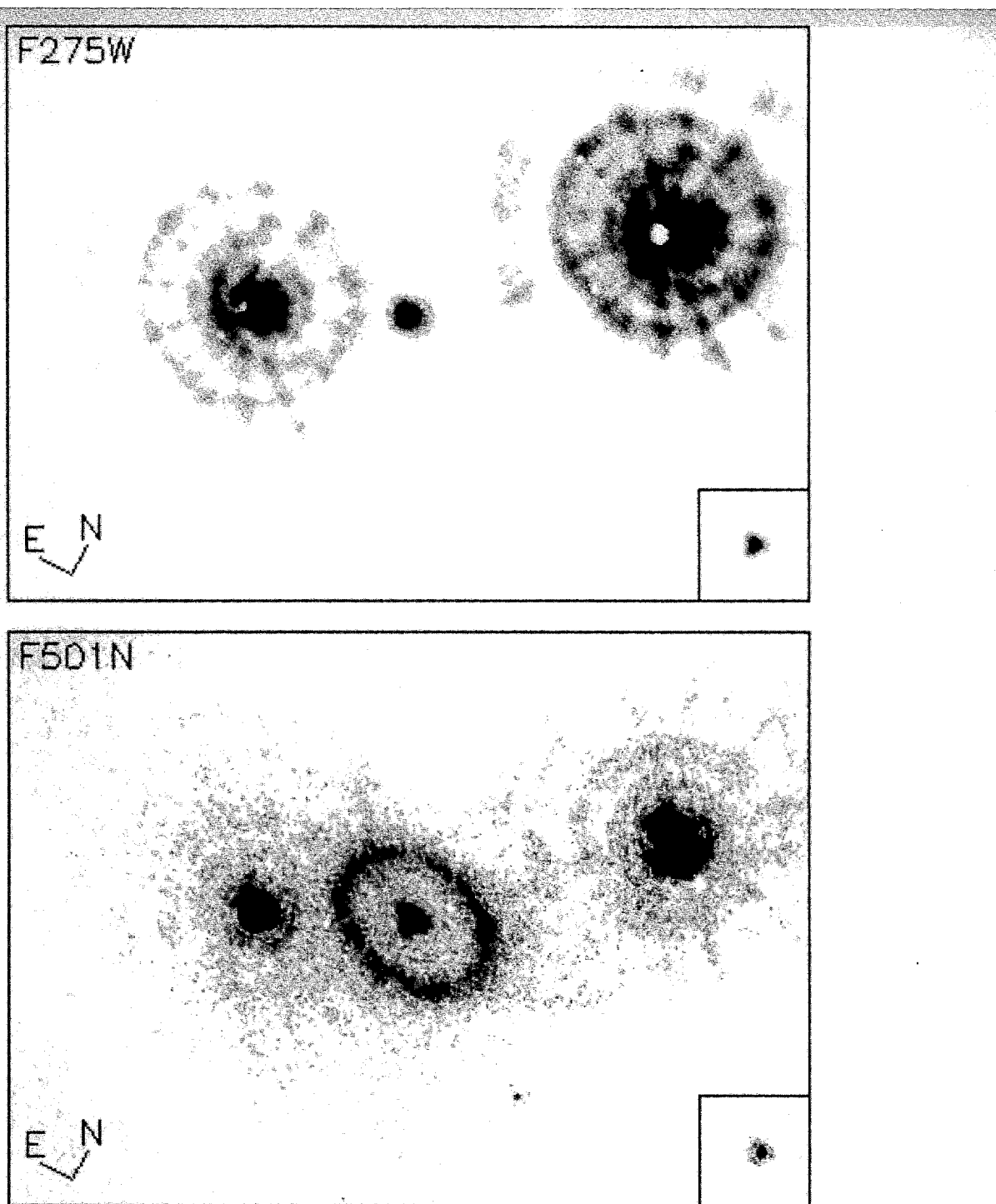


FIG. 1.— $8''.4 \times 5''.9$  segments of the F275W exposure (*upper frame*) and F501N exposure (*lower frame*) showing SN 1987A and its two companion stars 2 and 3. The images from the same exposures of the  $V = 18.24$  reference star 4 located  $5''.5$  west of SN 1987A are shown as inserts.

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