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PROPERTIES OF THE SN 1987A CIRCUMSTELLAR RING AND THE DISTANCE TO THE LARGE MAGELLANIC CLOUD[1]

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ABSTRACT

We have determined the distance to SN 1987A by comparing the angular size of its circumstellar ring, measured from an *HST* image obtained in a narrow [O III] 5007 Å filter, with its absolute size derived from an analysis of the light curves of narrow UV lines (N V λ1240, N IV] λ1486, N III] λ1750, and C III] λ1909) measured with *IUE*. Our analysis confirms that the observed elliptical structure is indeed a circular ring seen at an inclination of $\langle i \rangle = 42\overset{\circ}{.}8 \pm 2\overset{\circ}{.}6$ and provides a determination of its absolute diameter of $(1.27 \pm 0.07) \times 10^{18}$ cm. Its ratio to the angular diameter of $1\overset{''}{.}66 \pm 0\overset{''}{.}03$ (Jakobsen et al.) gives an accurate determination of the distance to SN 1987A, i.e., $d(1987\text{A}) = 51.2 \pm 3.1$ kpc. Estimating the relative position of SN 1987A within the Large Magellanic Cloud on the basis of radial velocity data, the distance to the *center* of the LMC turns out to be 50.1 ± 3.1 kpc and its distance modulus 18.50 ± 0.13. This value agrees very well with the determinations obtained from light-curve analyses of variable stars.

Subject headings: galaxies: distances — galaxies: Magellanic Clouds — stars: circumstellar shells — stars: individual (SN 1987A) — stars: supernovae

1. INTRODUCTION

An accurate determination of the distance to the Large Magellanic Cloud (LMC) is an essential step for the determination of the cosmological distance scale because the LMC can be used as a sampling field in which to calibrate the luminosity of a number of standard candles.

The recent high-resolution imaging of the SN 1987A circumstellar ring (Jakobsen et al. 1991) combined with the results of several years of assiduous monitoring of the UV spectrum of SN 1987A with the *International Ultraviolet Explorer* (*IUE*) (Fransson et al. 1989; Sonneborn et al. 1990) has offered us a unique opportunity to obtain high-accuracy measurements of both the angular and the absolute size of the supernova circumstellar ring and, therefore, to determine the distance to SN 1987A with unprecedented accuracy.

2. *HUBBLE SPACE TELESCOPE* OBSERVATIONS IN THE [O III] 5007 Å LINE

The circumstellar ring around supernova 1987A was observed on 1990 August 24 with the *Hubble Space Telescope* (*HST*), using the European Space Agency's Faint Object Camera in the F/96 mode, with a narrow [O III] 5007 Å filter in a 1660 s exposure (Jakobsen et al. 1991).

The central portion of the processed (40 iterations with Lucy's algorithm; Panagia et al. 1991) image is shown in Figure 1 (Plate L1). The brightness *inside* the ring is much lower than at the rim. In particular, the brightness ratio between the rim and the inner region is everywhere much higher than 10 and reaches values as high as 100 for the bright knots. This implies that the bulk of the emitting gas is confined in a very narrow structure which is a genuine ring. A confirmation of a planar geometry comes from Crotts & Heathcote (1990) spectroscopy of optical emission lines. They find that the expansion of the bright nebulosity within 1″ of the supernova is confined to a plane and is not consistent with spherically symmetric expansion.

The major- and minor-axis angular diameters of the ring are $1\overset{''}{.}66 \pm 0\overset{''}{.}03$ and $1\overset{''}{.}21 \pm 0\overset{''}{.}03$, respectively (Jakobsen et al. 1991). The apparent elliptical shape can be explained in terms of an inclination of 43° ± 3° (Jakobsen et al. 1991). An argument in favor of the reality of a tilted-ring geometry, as opposed to the possibility of a *true* ellipse, is that it is *physically* very hard to produce a high-eccentricity elliptical structure *centered* on its source. Another point in favor is the close agreement of the inclination determined from the elliptical shape with the value derived from an analysis of the UV emission-line light curves (see next sections).

3. OBSERVATIONS OF NARROW EMISSION LINES

Narrow emission lines of highy ionized species were detected in the short-wavelength *IUE* spectrum beginning in late 1987 May, i.e., no later than 3 months after explosion (Wamsteker et al. 1987).

After reaching a maximum around 400 days, the line intensities decreased for about 300 days, then stabilized to a roughly constant value or declined at a much slower rate. Figure 2 shows the light curve for lines of three ionization stages of nitrogen, N V λ1240, N IV] λ1486, N III] λ1750, and for C III] λ1909 (Sonneborn et al. 1990; Sanz Fernandez de Cordoba 1990).

The most obvious interpretation of the delayed start and the peak of the light curves around day 400 is in terms of light-travel effects combined with monotonic decay of the intrinsic emission. With a tilted-ring geometry, the intensity is expected

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1991ApJ...380L..23P

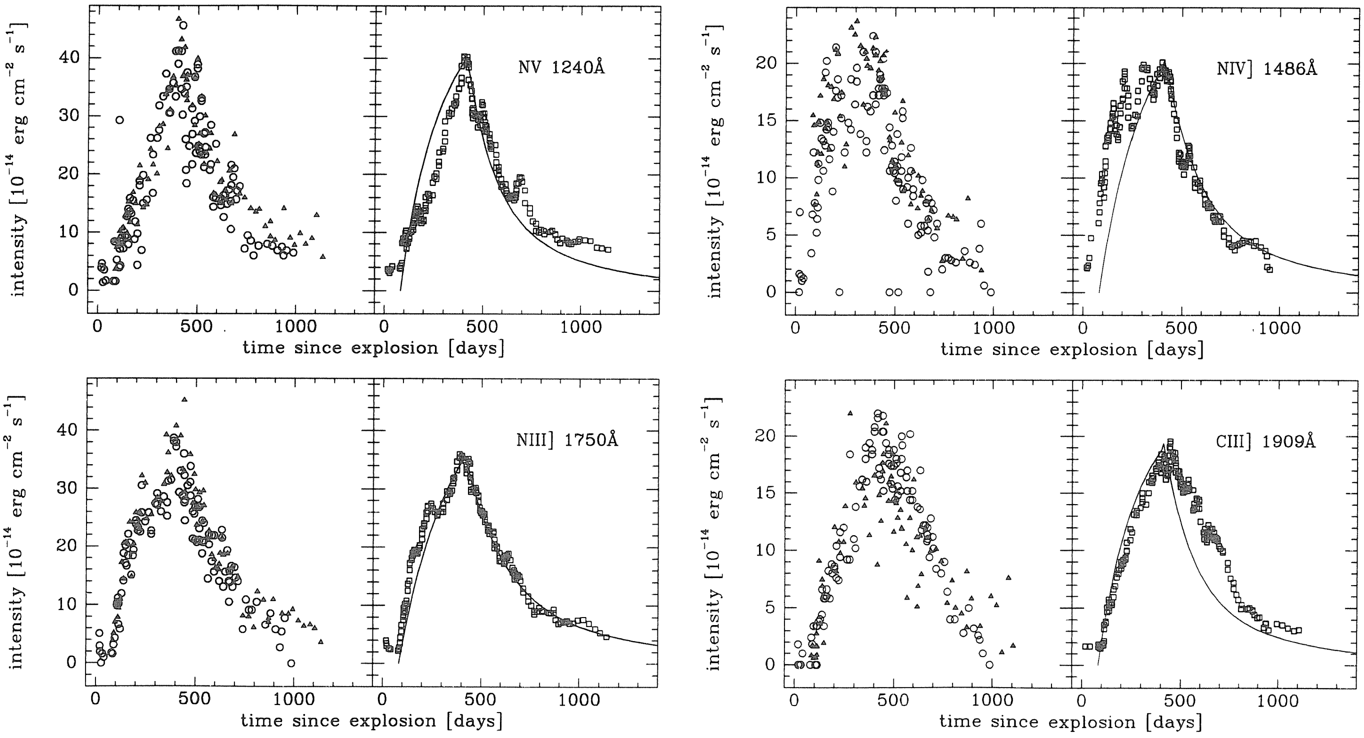

FIG. 2.—Evolution of the narrow UV emission-line intensities compared with our model calculations. For each line, the observational data are shown in the left-hand panel: filled triangles and open circles denote *IUE* data obtained at GSFC and VILSPA observatories, respectively. The right-hand panel shows the 8 point boxcar-smoothed light curve and the theoretical curve computed for $t_{\max} = 413$ days.

to be zero for an initial period of time given by

$$t_0 = (R_{\rm ring}/c)(1 - \sin i) , \quad (1)$$

where i is the inclination of the ring. Then the intensity rises until it reaches a maximum at a time

$$t_{\max} = (R_{\rm ring}/c)(1 + \sin i) \quad (2)$$

and starts declining afterward. Combining these equations and solving for sin i, we obtain an independent determination of the inclination:

$$\sin i = (t_{\max} - t_0)/(t_{\max} + t_0) . \quad (3)$$

With approximate values of $t_0 < 90$ days and $t_{\max} \sim 400$ days, the inclination of the ring turns out to be greater than ~40°, which is virtually coincident with the value derived from the ring elliptical shape. A more precise estimate is given in § 4, where t_0 and $t_{\max}$ are derived from a quantitative analysis of the light curves. In any case, since the two determinations are independent, their close agreement is clear evidence that the ring is quite circular indeed.

High-resolution observations of the C III] 1909 Å doublet (Cassatella et al. 1991) show that the derived density is slowly decreasing with time, indicating that there are density fluctuations in the emitting gas.

Observations of optical narrow emission lines (e.g., [O III] λλ5007 and 4363, Hα, [N II] λλ6548–6583, etc.) show the same trend already detected at UV wavelengths. Figure 3 displays the available data for [O III] λλ5007 and 4363 as collected from literature (Wampler, Richichi, & Baade 1989 and references therein; Menzies 1990; Jakobsen et al. 1991). The intensity ratio of λ4363 to λ5007 indicates that the electron temperature in the ring was around 50,000 K in late 1987 and decreased steadily, being around 20,000 K in early 1989 (Fransson et al. 1989; Wampler et al. 1989).

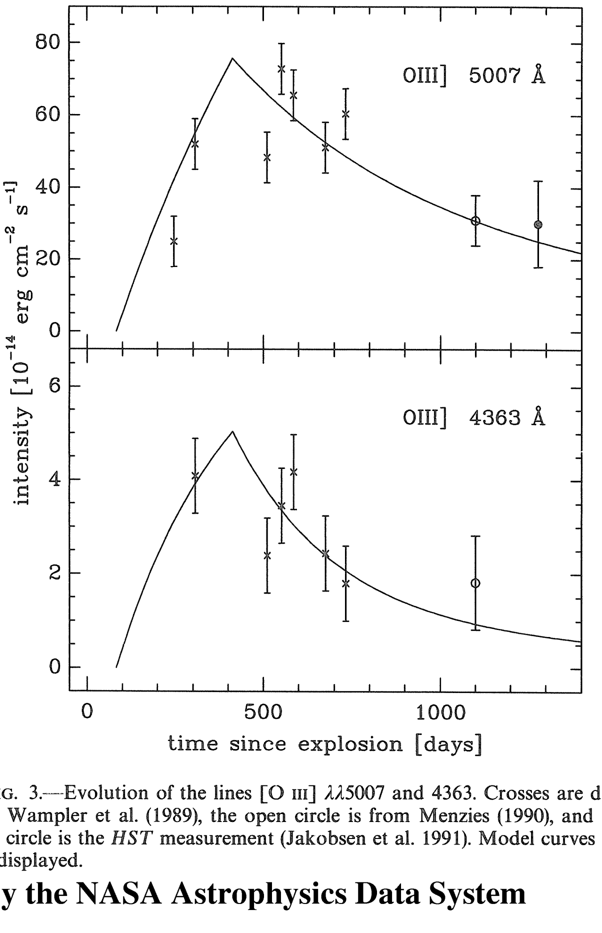

FIG. 3.—Evolution of the lines [O III] λλ5007 and 4363. Crosses are data from Wampler et al. (1989), the open circle is from Menzies (1990), and the filled circle is the *HST* measurement (Jakobsen et al. 1991). Model curves are also displayed.

4. LIGHT-CURVE ANALYSIS

The emission-line evolution has been analyzed by using a simple model which not only explains the shape of the "light curves" of UV lines but can also correctly describe the evolution of optical lines with no need of additional assumptions (Panagia & Gilmozzi 1991). This model assumes the following:

1. The emitting gas is distributed in a narrow ring which is inclined at an angle i.
2. The ionization of the various ions remains constant with time. Thus, the intrinsic evolution is entirely due to cooling of the emitting gas.
3. The temperature decreases inversely with time, $T \propto t^{-1}$, being of the order of 50,000 K around 300 days after explosion.
4. In order to account for the observed density fluctuations, the presence of two coexisting components is assumed, one with an electron density around 2.5×10^4 cm^{-3} (Fransson et al. 1989) and another with a density 4 times lower. Accordingly, the temperature evolution of the latter component occurs on time scales 4 times longer than for the former.

These assumptions are naturally suggested by the observations themselves: for example, the fact that N V λ1240 and N III] λ1750 evolve quite similarly to each other (cf. Fig. 2) indicates clearly that recombinations do not play an important role.

For the sake of simplicity the ring emissivity has been approximated with a constant fraction of that of a spherical shell of equal radius. This assumption introduces only a minor inaccuracy in the overall light curve (of the order of 10%) and does not affect the location of the starting point or that of the peak of the light curve (Panagia & Gilmozzi 1991).

In our analysis we use the data presented by Sonneborn et al. (1990), which are the measurements obtained from the GSFC *IUE* Observatory, and the preliminary measurements of the line intensities obtained from the set of observations made from VILSPA (Sanz Fernandez de Cordoba 1990). The observed flux at all times is dominated by the continuous emission of stars 2 and 3, and, therefore, the uncertainty for each line is about the same at all epochs. We adopt 1 σ errors of 8, 4, 4, and 3 (10^{-14} ergs cm^{-2} s^{-1}) for N V λ1240, N IV] λ1486, N III] λ1750, and C III] λ1909, respectively. Referred to the maximum intensities, they correspond to relative errors of the order of 10% for N III], 15% for N V and C III], and 20% for N IV] lines, respectively. Since the errors on individual data points are rather large, we determine the starting time and the time of the peak independently of each other, using different procedures.

In the available data, the intensity of a line is either positive, if some signal is believed to be detected, or zero if no line is apparent. Therefore, the average of the data obtained until an epoch earlier than t_0 is expected to decrease with time because one is progressively averaging the positive values of noise (apparent detections) with null data (no detection). However, as soon as real signal is detected, the average is expected to rise sharply. Therefore, the starting time for each line, t_0, has been estimated as the time at which a sharp rise of the time-averaged intensity begins. The uncertainty is due both to the coarse sampling (observations were made approximately once a week) and to measurement errors. We estimate the overall uncertainty to be of the order of 10 days in each case. The values of t_0 for the four lines are reported in Table 1 together with their adopted uncertainties. The weighted average is $t_0 = 83 \pm 6$ days.

TABLE 1

BEST-FIT PARAMETERS FOR UV LINES

Line	t_0 (days)	$t_{\max}$ (days)
N V λ1240	86 ± 11	408 ± 54
N IV] λ1486	81 ± 12	399 ± 60
N III] λ1750	84 ± 9	412 ± 37
C III] λ1909	81 ± 10	428 ± 54
Weighted average	83 ± 6	413 ± 24

The time of the maximum is determined by model fitting, adopting a fixed value of $t_0 = 83$ days. Moreover, since the late evolution of the light curve is entirely insensitive to the early time evolution, and the relative error is large for points with low intensities, for each line we limit our model fitting to data above $I_{\max}/2$. The free parameters in the fitting procedure are the time of the peak and the peak intensity. The individual light curves are analyzed independently: Table 1 reports the derived values and their uncertainties that are obtained with a minimum χ^2 procedure. The individual estimates of the time of the maximum range between 399 days for N IV] and 428 days for C III]. The weighted average is 413 days with an uncertainty of ±24 days.

The model curves obtained with the best-fit set of parameters are presented in Figure 2, superposed on the observational points. It is clear that the overall agreement between models and observations is excellent. Most of the apparent discrepancies are well within the uncertainties, which are rather large. This is especially true in the case of the N IV] line and explains why an eyeball inspection of Figure 2 may give the impression that its intensity reached a maximum at a considerably earlier epoch. To facilitate the comparison, in addition to the observational points, in Figure 2 we show also the 8 point boxcar smoothed light curves, which agree with the model calculations quite closely, especially in the position of the peak.

With the derived values of t_0 and $t_{\max}$, equation (3) yields an inclination of $i = 42° \pm 5°$. This value is fully consistent with the one determined from the ring elliptical shape and confirms that we are dealing with a genuine ring structure. We combine the two determinations to obtain $\langle i \rangle = 42\overset{\circ}{.}8 \pm 2\overset{\circ}{.}6$, which inserted into equation (2) leads to a value of the ring *absolute* diameter $(1.27 \pm 0.07) \times 10^{18}$ cm.

It is worth noting that the success of our model in describing the observations, both in the UV and in the optical (see Fig. 3), implies that the ionization remains virtually constant over the period covered by the observations, i.e. more than 3 yr. Since the recombination time is definitely less than 1 yr even considering just radiative recombinations (e.g., Fransson et al. 1989), a steady source is required to maintain the ionization at a level comparable to that established by the initial burst of UV radiation, while still letting the gas cool rather quickly. The characteristics of the implied ionization "source" are similar to those of the central star of a planetary nebula like NGC 7027, i.e., an effective temperature in excess of 10^5 K and a luminosity of several thousand $L_\odot$. Being so hot, its bolometric correction amounts to several magnitudes and its *optical* luminosity is much lower than the present level of the supernova optical continuum. If such a source is a stellar remnant, eventually, when the supernova fades away, it could be detected as a pointlike source with $m_V \simeq 20$ and $(B-V)_0 = -0.35$.

A detailed account of the model calculations and a comparison with observations will be presented in a forthcoming paper (Panagia & Gilmozzi 1991).

5. DISTANCE TO THE LARGE MAGELLANIC CLOUD

There is little doubt that the material of the ring so well defined in the radiation of [O III] λ5007 is indeed the same gas responsible for the UV lines because C III, N III, and O III are ions that coexist with each other. Moreover, the same model that provides a good match of the UV line light curves can also account quite well for the light curves of the optical [O III] lines λλ5007 and 4363 (see Fig. 3). Actually, *IUE* observations have detected a faint O III] line at 1666 Å (Fransson et al. 1989), which evolves in a similar fashion to the other UV lines, but its low intensity makes it impossible to use it to determine the size of the O III emitting region directly. Therefore, it is quite legitimate to compare the *angular* size of the ring derived from the [O III] λ5007 image with the *absolute* size derived from the UV line light curves and determine the distance to SN 1987A. Since the ring absolute diameter is $(1.27 \pm 0.07) \times 10^{18}$ cm and its angular diameter is 1″.66 ± 0″.03 (Jakobsen et al. 1991), we estimate a *distance* to SN 1987A: $d(1987A) = 51.2 \pm 3.1$ kpc. We like to stress that 3.1 kpc represents the *total* error and is not just the standard deviation of the mean. This latter would be considerably smaller, ~2.1 kpc or 4.1%, essentially reflecting the dispersion of the individual $t_{\rm max}$ determinations.

Our estimate of the distance to SN 1987A is somewhat higher than various determinations obtained with the Baade-Wesselink method, which range between 45 and 49 kpc with uncertainties greater than 10% (e.g., Eastman & Kirshner 1989; Schmutz et al. 1990). In view of the considerably larger uncertainties that affect those determinations, we do not believe that the discrepancies between our value and theirs are significant.

To determine the distance to the *barycenter* of the LMC, we have estimated the relative position of SN 1987A within the body of the LMC from the supernova radial velocity. The radial velocity measured for the narrow UV lines is 284 ± 6 km s^{-1} (Panagia et al. 1987). The highest velocity component observed in the UV interstellar spectrum of SN 1987A occurs at 282 ± 6 km s^{-1} (Blades et al. 1988). In the optical the last strong absorption component is observed at 280.1 ± 0.5 km s^{-1}, and a very weak component is detected for Ca II and Na I at a velocity of ~292 km s^{-1} (Vidal-Madjar et al. 1987).

On the other hand, Blades (1980), studying the Ca II and Na I interstellar absorption lines in the spectra of three sources in the 30 Doradus region, namely, R136, R139, and R145, finds three strong absorption components of comparable strength at approximate velocities of 250, 280, and 300 km s^{-1}. This suggests that SN 1987A lies behind two main gaseous layers in the LMC but is just at the near side of the third one. Incidentally, we note that this implies that the bulk of the 30 Dor region is at a somewhat larger distance than SN 1987A or, conversely, that the supernova is on the near side of that big complex.

Furthermore, 21 cm line measurements show that the bulk of the LMC neutral hydrogen extends its emission in the range 225–340 km s^{-1}, with three conspicuous components detected at 243, 273, and 300 km s^{-1} (McGee & Milton 1966; Radhakrishnan et al. 1972). Therefore, it is clear that SN 1987A is embedded in approximately two-thirds of the main body of the LMC. More quantitatively, assuming that the radial velocity distribution varies linearly with the depth in the LMC, we estimate that SN 1987A is embedded at 0.66 ± 0.04 of the depth of the LMC. Since the observed diameter of the LMC is 7°.7 (Allen 1973, p. 287), assuming its depth to be comparable to its transverse dimension, we conclude that SN 1987A is 1.1 ± 0.3 kpc farther away than the center of the LMC, whose distance, therefore, is $d(\text{LMC center}) = 50.1 \pm 3.1$ kpc. This corresponds to a distance modulus of $(m - M) = 18.50 \pm 0.13$.

6. CONCLUSIONS

We have determined the distance to SN 1987A by comparing the angular size of its circumstellar ring, measured from an *HST* image obtained in a [O III] 5007 Å filter (Jakobsen et al. 1991), with its absolute size derived from an analysis of the light curves of narrow UV lines monitored with *IUE* (Sonneborn et al. 1990).

First we have ascertained that the observed elliptical structure is indeed a circular ring seen at an inclination of $\langle i \rangle =$ 42°.8 ± 2°.6. Then, from the angular diameter of 1″.66 ± 0″.03 (Jakobsen et al. 1991) and the absolute diameter of $(1.27 \pm 0.07) \times 10^{18}$ cm, we have derived a distance to SN 1987A of 51.2 ± 3.1 kpc.

Estimating the relative position of SN 1987A within the LMC with a discussion of radial velocity data of the supernova, the neutral H gas, and other discrete sources in the 30 Dor region, we have concluded that the distance to the *center* of the LMC is 50.1 ± 3.1 kpc, or, conversely, that its distance modulus is 18.50 ± 0.13. This value agrees very well with the determinations obtained from light-curve analyses of variable stars (cf. Feast & Walker 1987), while it appears to contradict the lower estimates obtained from H-R diagram fits. However, since the latter are declaredly affected by relatively large uncertainties (0.2 mag or more; Feast & Walker 1987), such a discrepancy is not really significant.

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