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PROPERTIES OF STAR 2, ONE OF THE SN 1987A COMPANIONS, DERIVED FROM *HUBBLE SPACE TELESCOPE*–FAINT OBJECT SPECTROGRAPH OBSERVATIONS[1]

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ABSTRACT

We present and discuss the *Hubble Space Telescope* Faint Object Spectrograph observations of Star 2, one of the two companions of SN 1987A, in the range 1200–8000 Å. Our analysis, based on a comparison of the observed spectrum with spectra of O and B type stars and with model atmospheres, confirms that Star 2 is a B2III star. The extinction toward Star 2 is mostly of LMC origin and amounts to an $E(B-V) = 0.19 \pm 0.02$. The detailed extinction curve has a 2200 Å bump less pronounced than the average LMC extinction law. Star 2 has an effective temperature of $T_{\rm eff} = 22{,}000 \pm 2000$ K and a luminosity of $\log L/L_{\odot} = 4.38 \pm 0.11$. Also, Star 2 appears to rotate with an equatorial velocity of $v \sin i = 250 \pm 50$ km s^{-1} and is presently undergoing mass loss at a range of $\log \dot{M} \simeq -7.0 \pm 0.5$ $M_{\odot}$ yr^{-1}. Judging from its position in the H-R diagram and its present parameters, Star 2 had an original mass of about 13 $M_{\odot}$ and was born less than 13 Myr ago, which makes Star 2 coeval to the SN 1987A progenitor Sk 69°202.

Subject headings: binaries: visual — dust, extinction — stars: early-type — stars: evolution — stars: fundamental parameters — supernovae: individual (SN 1987A)

1. INTRODUCTION

Star 2 is one of the two bright, close companions of SN 1987A in the Large Magellanic Cloud. Since they appear to be physically associated with the supernova progenitor, Sk −69°202 (van den Bergh 1987), the study of the characteristics of these stars can provide important insights on the nature and origin of the progenitor itself and on the environment in which the progenitor of SN 1987A evolved.

The first classification of Star 2 was made by Gilmozzi et al. (1987) and by Kirshner & Gilmozzi (1989), who, on the basis of *IUE* spectra, estimated a spectral type B0V for star 2. Recently Walborn et al. (1993), using new ground-based spectroscopic observations in the blue region of the spectrum, classified Star 2 as a B2III. The difference in the classification is large and warrants further study, especially in view of the widely different evolutionary scenarios that the two classifications would imply: a recently formed star, say, 5 Myr old on the one hand, and a rather evolved star, possibly as old as 20 Myr on the other hand. So an accurate determination of the physical properties (such as effective temperature, bolometric luminosity, and mass) of Star 2 is fundamental in assessing the problem of its companionship to the supernova progenitor.

Furthermore, Star 2 is so close to the line of sight of SN 1987A (offset ∼2″.5) that an extinction curve obtained directly from an analysis of its spectrum will represent the best estimate of the reddening toward the supernova. This, of course, is crucially important for the study of numerous phenomena directly or indirectly related to the supernova (energetics, luminosity at maximum, physical parameters of the circumstellar rings, etc.).

In this paper we present and discuss the ultraviolet and optical spectrum of Star 2, obtained with the *HST*-FOS, from which we determine the stellar parameters of the star as well as an accurate estimate on the interstellar extinction toward Star 2. Also we determine that the initial mass of Star 2 was about 13 $M_{\odot}$ and its age is less than 13 Myr, so that Star 2 turns out to be coeval to Sk −69°202.

2. OBSERVATIONS

The observations were made on 1992 March 30 with the Faint Object Spectrograph (FOS) of the *Hubble Space Telescope* with a resolution of $\lambda/\Delta\lambda \simeq 1300$. Both the blue and the red side detectors were used with the G130H, G190H, G270H, G400H, G570H, and G780H gratings. The B-3 (0″.86) aperture was used for all observations. The exposure times were 800 s with the G130II, 600 s with the G190H, and 300 s with all of the other gratings. A detailed description of the instrumentation can be found in Allen & Angel (1982) and in the FOS Instrument Handbook (Kinney 1992). The observations were obtained as a part of the *HST* Supernova INtensive Study (SINS) GO program.

Routine calibration of the data was carried out by the science data-processing pipeline system maintained by the Space Telescope Science Institute. The calibration process is discussed by Koratkar (1993). Because of the poor signal-to-noise ratio we do not consider the region with $\lambda >$ 8000 Å.

The observed spectrum of Star 2 is shown in Figure 1. The optical spectrum shows Hα clearly in emission and Hβ partially filled in. The Balmer series is visible up to H13. Several He I lines are also clearly visible (3927, 4009, 4026, 4471 Å).

Many of the lines observable in the UV are of interstellar origin, in particular Mg I λ2852, Mg II λλ2795, 2803, Fe II λλ2343, 2374, 2382, 2586, 2599, O III λλ1175, 1334, and Si II λλ1260, 1526. Only few stellar lines (e.g., the Fe III multiplet in the 1900 Å region, Si II λ1264 shown in Fig. 1, below) can

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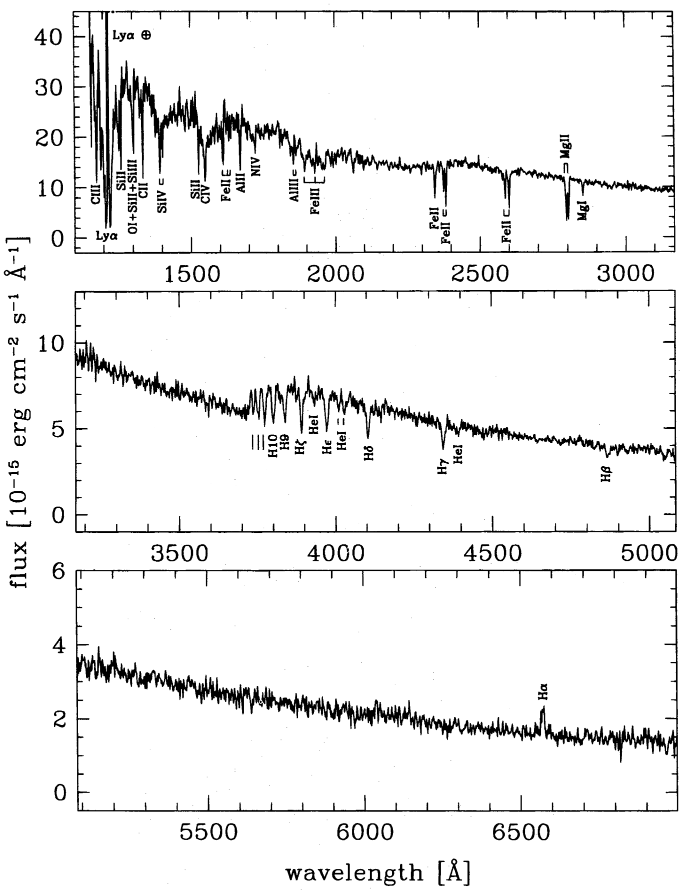

FIG. 1.—The spectrum of Star 2. The strongest lines in absorption and/or in emission are shown. The Balmer series is labeled down to H10, while H11, H12, and H13 are indicated by vertical lines. The spectrum shown in figure has been obtained by 10 point averaging of the original spectrum and rebinning into 1 Å intervals.

be entirely photospheric. All of the others have interstellar lines superimposed on their photospheric components. These lines are Al III λ1671, Al III λλ1855, 1863, C IV λλ1548, 1551, the Si II and Si III multiplet at 1300 Å, Si IV λλ1394, 1403, and the Fe II multiplet at ~1600 Å.

Regarding the Hα emission, we have considered the possibility of contamination of Star 2 spectrum by the emission from the supernova ejecta or from the circumstellar rings. One can immediately exclude any major contamination by the rings because in addition to Hα emission, one should see forbidden lines, such as [N II] λ6548 and λ6584 or [O II] λλ3727, 3729), with an intensity at least as strong as the Hα line (Panagia et al. 1996a), whereas they are not present in the spectrum of Star 2. About contamination by the supernova itself, despite the fact that these are pre-COSTAR data, the expected contamination is very low. In fact, the flux emitted at Hα by the ejecta is approximately the same ($\sim 2 \times 10^{-15}$ ergs cm^{-2} s^{-1} $Å^{-1}$) as that detected in the spectrum of Star 2 (Panagia et al. 1996b), so that at the distance of Star 2 (2″.5), the flux contributed by the supernova in the FOS aperture is less than 5% and, therefore, no correction needs to be applied.

3. SPECTRAL CLASSIFICATION

Star 2 has been classified as B2III by Walborn et al. (1993) on the basis of its optical spectrum. Following the criteria outlined by Rountree & Sonneborn (1991) we have tried to classify Star 2 using its ultraviolet spectrum. Our spectral resolution is about 4 times lower than the one used by Rountree & Sonneborn but we believe that this does not affect our conclusions appreciably. Figure 2 shows the region of interest for a UV spectral classification. Using the atlas of interstellar lines toward SN 1987A (Blades et al. 1988), we identified the lines in the UV spectrum of Star 2 that are contaminated by interstellar components. In Figure 2 we show the positions of the photospheric lines which can be used for the spectral classification. Starting from the consideration that Star 2 its a blue star but not an O spectral type we restricted the comparison only to B stars. It is immediately clear that early luminosity class I can be ruled out on the basis of the absence of P Cygni profiles in the C IV λλ1548, 1551, Si IV λλ1394, 1403 and N V λλ1239, 1243 doublets, which, due to the presence stellar winds, are expected to be very strong in these objects, and then, despite of the interstellar contamination, should be clearly observable.

A closer inspection to Figure 2 then reveals that

1. The absence of N III λλ1748, 1751 suggests a spectral type later than B0.5III.
2. The absence of N IV λ1718 argues in favor of a spectral type later than B1III.
3. The He II λ1640 line is very weak and possibly blended with a Fe II line indicating a B2III type or later.
4. The ratio Si II λ1264/C III λ1247 is ~1 indicating a spectral type B1.5III–B2III.
5. Finally, the C IV λλ1548, 1551, Si IV λλ1394, 1403 and possibly N V λλ1239, 1243 doublets are visible very clearly in absorption with no evidence of a P Cygni profile, suggesting a spectral type later that B0III (we must notice, however, that these lines are contaminated by interstellar lines).

It is clear that the analysis of the UV spectrum argue in favor of Star 2 being a B2III type, thus confirming and adding weight to Walborn et al. (1993) classification.

Further information on the spectral classification of Star 2 can be obtained from the optical spectrum outside the wavelength interval considered by Walborn et al. (1993). In particular, the Hα line (Fig. 1) is in emission with an equivalent width of $W_{eq} = -5.0 \pm 0.8$ Å and a half-power full width of HPFW = 10 Å. The *working* (i.e., purely morphological) definition of a Be star is "a non-supergiant B star whose spectrum has or had at one time one or more hydrogen line in emission" (Jaschek, Sletteback, & Jaschek 1981). So from this point of view Star 2 *has* to be classified as a Be star. Jaschek et al. (1980) defined a classification scheme based on spectrum characteristics using a sample of 140 stars. They subdivided Be stars in five different groups. The only groups which contain B2III stars are group I, which actually defines the classical Be stars, and group V, which contains objects that changed from normal B to Be or vice versa. Star 2 can only belong to group V because if it does not display the characteristics typical of group I objects (Balmer lines in emission up to Hζ at least, Fe II emission lines and/or IR excess). As a member of group V, Star 2 is most likely to display variability on relatively short scale (Jaschek et al. 1980), which so far has never been detected.

In conclusion, the morphological dichotomy between "normal" B and Be stars, unlike the UV or optical spectral classification, does not appear to add valuable information

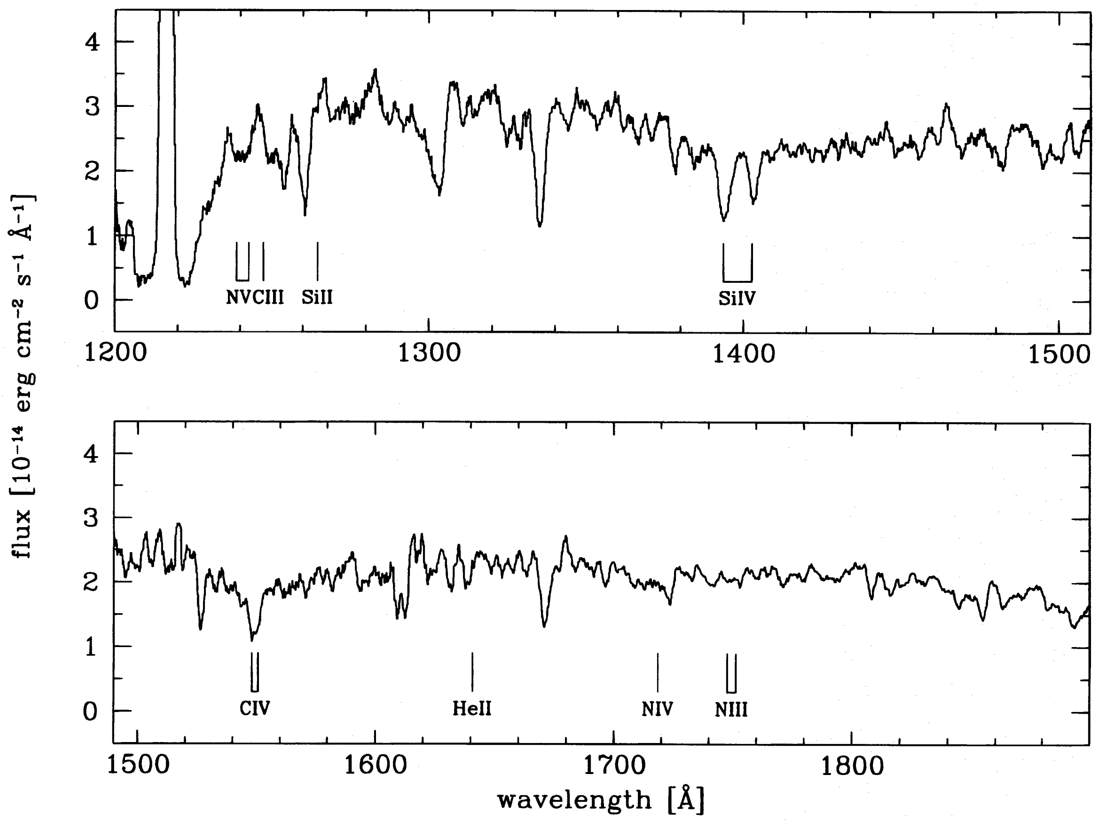

FIG. 2.—Ultraviolet region of the spectrum of Star 2 containing the lines suited for a spectral classification. The vertical lines show the positions of the following spectral lines N V λλ1239, 1243, C III λ1247, Si II λ1264, Si IV λλ1394, 1403, C IV λλ1548, 1551, N IV λ1718, N III λλ1748, 1751.

on the physical properties of Star 2. We will further discuss the implications of Star 2 being a B2IIIe star in paragraph 6 on the Hα line.

4. THE EXTINCTION CURVE AND THE SPECTRAL ENERGY DISTRIBUTION OF STAR 2

The determination of the reddening toward Star 2 has double significance, in that both it allows to correct the spectral energy distribution of the star, and, due to the proximity to SN 1987A, it provides the best and most direct estimate of the reddening along that line of sight to SN 1987A.

Previous estimates of the reddening toward SN 1987A, which were based either on the preoutburst colors of Sk −69°202 (Panagia et al. 1987; Fitzpatrick & Walborn 1990; Walborn et al. 1993) or on the colors of main-sequence stars and supergiants within few arcminutes from SN 1987A (Walker & Suntzeff 1990; Fitzpatrick & Walborn 1990) gave values in the range 0.16–0.20 in $E(B-V)$ with uncertainties of ± 0.02.

The canonical procedure to obtain the extinction curve is to compare the spectral energy distribution of a star with that of an unreddened star with the same physical properties ($T_{\rm eff}$, log g, chemical composition). We know that Star 2 is B2IIIe in spectral type, so the next logical step would be to compare Star 2 with a LMC star of the same spectral type not reddened. Unfortunately such spectra, covering the same wavelength interval, are not available. But, more important, as discussed extensively by Walborn et al. (1993), the spectral type—effective temperature calibrations are rather uncertain, in the sense that stars of the same spectral type may have considerably different temperatures. As a consequence, their intrinsic spectral distributions are poorly constrained, thus making the determination of the reddening through their comparison rather problematic.

Since we need to determine both the reddening and the spectral energy distribution in order to characterize the properties and the evolutionary stage of Star 2 properly, one viable alternative is to use model atmosphere calculations as reference spectra to compare with the energy distribution of Star 2. Indeed, this is the standard procedure to calibrate the effective temperatures of unreddened stars (see, for example, Gray 1992). The main sources of uncertainty inherent to such method are (1) the accuracy of the measurements, (2) the realism of the model, and (3) the interstellar reddening. If a star is reddened, this procedure can still be applied successfully if one introduces the reddening as an explicit fitting parameter in the comparison and adds complementary criteria, such as spectral lines analysis and/or the Balmer jump, to help selecting the appropriate model.

In the case of Star 2, one can use the Balmer jump to define an acceptable range of models with different temperatures, gravities, and chemical compositions. Then one can further constraint the models by selecting the ones that, once reddened, better represent the observed spectral distribution. The last step is to assume an extinction curve and allow the reddening to vary until the best fit is achieved for a particular model.

We have used two sets of model atmospheres (Kurucz 1992) with metallicities $Z = Z_\odot$ and $Z = Z_\odot/3$, respectively. A comparison of the two sets with each other reveals that the lower metallicity models have somewhat bluer continua, although the differences are rather small, i.e., about 1% throughout the entire spectrum except for $\lambda < 2000$ Å where they are of the order of 2%–3%.

For hot stars the Balmer jump is sensitive to temperature and gravity and almost intensitive to the chemical composition. We limited our comparison to models with $\log g = 3.0, 3.5, 4.0$. The temperature derived on this basis was 21,000 K ($\log g = 3.5$) with an uncertainty, due to measurement errors and to the range of adopted gravities, of about 2000 K. Therefore, for the next step of comparing reddened models with the spectrum of Star 2, we explored a temperature range of about 2 σ, i.e., ± 4000 K, around 21,000 K.

We assumed the reddening to be a combination of the galactic and the 30 Dor average extinction laws as compiled by Savage & Mathis (1979) and Fitzpatrick (1986), respectively. We kept the relative contribution of each law as a free parameter and searched for the best value of $E(B-V)$ which yielded the optimum match of the spectrum of Star 2 with each spectrum of the models within the range selected from the Balmer jump analysis. The galactic contribution was allowed to vary between 0% and 40% of the total reddening in the V band in steps of 5%. Varying the galactic contribution has effects both on the strength of the 2200 Å feature in the extinction curve and in the slope of its far-ultraviolet region, given that the 30 Dor extinction curve is steeper than the galactic one. The 2200 Å feature, however, does not represent a good indicator of the goodness of a fit, in terms of amount of extinction, because its strength is *related to the chemical composition of the interstellar grains more than to their total amount.* Furthermore, even the shape of the far-UV extinction curve displays significant scatter toward different lines of sight (Savage & Mathis 1979; Fitzpatrick & Savage 1984). All of this makes the comparison between reddened models and Star 2 not very sensitive to the exact percentage of the galactic contribution.

The results of this analysis are (1) Star 2 effective temperature based on Balmer jump and on the whole energy distribution is $T_{\rm eff} = 22{,}000$ K with an uncertainty of ± 1000 K. We would like to note that ± 1000 K is the error calculated only on the base of statistical arguments; however, the uncertainties in the shape of the adopted extinction curve and the fact that the procedure is model dependent suggest adoption of a more conservative value of ± 2000 K. (2) The corresponding color excess is $E(B-V) = 0.19$ with an error of ± 0.02. The percentage of galactic contribution is 30%, corresponding to a galactic foreground extinction of about $E(B-V) = 0.06$ (Bessell 1991; Schwering & Israel 1991). (3) There is not significant difference in the quality of the fit with either $Z = Z_\odot$ or $Z = Z_\odot/3$, although the solar abundance spectrum gives a marginally better fit to the observations.

Figure 3 displays the best-fit model ($T_{\rm eff} = 22{,}000$ K, $\log g = 3.5$ and $Z = Z_\odot$) together with the observed spectrum. Figure 4 shows the actual extinction curve (*open dots*) and its the best fit (*solid line*) in terms of a combination of average galactic and LMC extinction curves in a ratio 1:2. As one can see the agreement between the model and the open dots is very good overall except in the region around

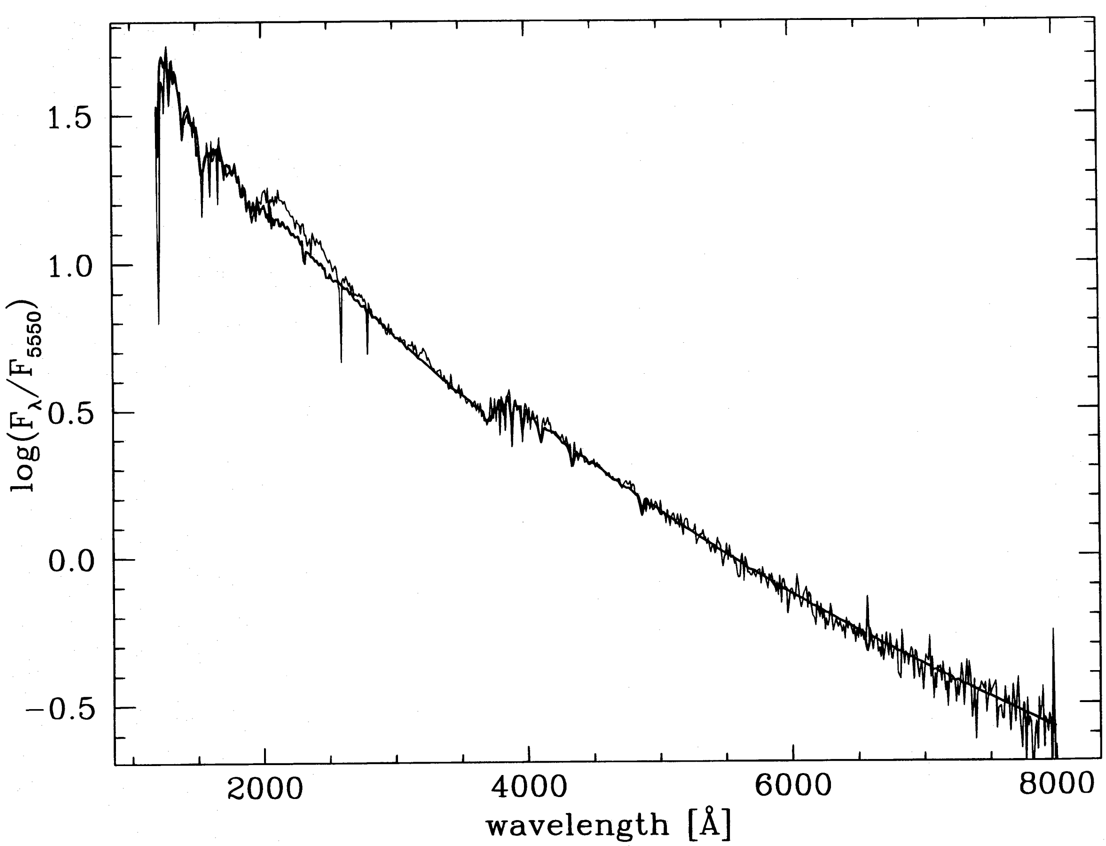

FIG. 3.—Comparison between the spectrum of a model atmosphere with $T_{\rm eff} = 22{,}000$ K, $\log g = 3.5$, $Z = Z_\odot$ (*heavy line*), and the spectrum of Star 2 (*light line*) dereddened using a value of $E(B-V) = 0.19$ and a galactic contribution of 30%. The apparent overcorrection around 2000 Å reveals that the 2200 Å bump, along the line of sight toward Star 2, is less strong than predicted by the combination of LMC and Galactic average extinction curves (see text).

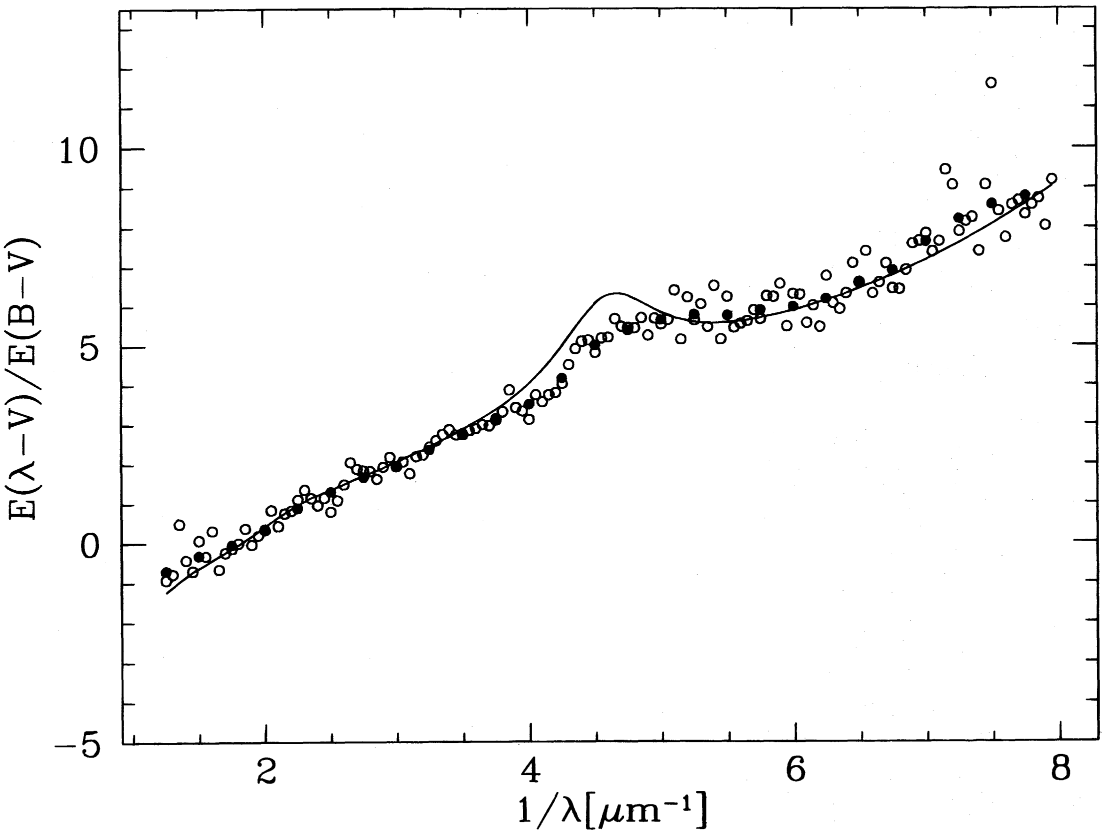

FIG. 4.—Extinction curve (*open dots*) obtained from the ratio of the theoretical spectrum from a model atmosphere with T_{eff} = 22,000 K, log g = 3.5, $Z = Z_{\odot}$ to the observed spectrrum of Star 2. The solid line is a composite extinction curve calculated using the best-fit reddening parameters. The solid line is a composite extinction curve calculated using the best-fit reddening parameters. The filled dots are average over 10 observed points. The extinction curve has been binned into 0.05 μm^{-1} intervals.

the 2200 Å bump. Also, there is a larger dispersion in the far-UV and in the red. In the far-UV this is clearly due to the presence of stellar lines, which are not well reproduced by the model (e.g., the Fe III multiplet at ~1900 Å) and to the presence of interstellar absorption lines that the models cannot reproduce and that cannot easily be disentangled from the stellar components (see Fig. 2). In the near IR the larger dispersion is entirely due to the lower S/N ratio.

On the other hand, the discrepancy around the 2200 Å feature appears to be statistically significant. This means that in this region the best-fit model cannot represent the reddening law toward Star 2 adequately. Actually, the observed bump is less pronounced than in the average LMC curve. The filled dots in Figure 3 represent the 10 point averages of the observed extinction curve.

Adopting $R = 3.1$, we computed the absolute extinction curve for the line of sight toward Star 2. We believe that this represents the most accurate determination of the extinction curve toward Star 2 and, because of its association with Sk −69°202 (see § 7), toward SN 1987A. In Table 1 we report the derived extinction. The values for $1/\lambda > 4.0$ μm^{-1} and $1/\lambda > 5.5$ μm^{-1} are those obtained from the best fit in terms of a combination of 30% galactic and 70% LMC laws, whereas around the 2200 Å bump ($4.0 \le 1/\lambda \le 5.5$ μm^{-1}) we give the actual average values as displayed in Figure 3.

The measured strength of the 2200 Å bump is confirmed independently from the analysis of the emission lines in the spectrum of the inner circumstellar ring of SN 1987A (Panagia et al. 1996b). In particular, the line intensity ratios

TABLE 1

EXTINCTION CURVE TOWARD STAR 2

$1/\lambda$ (μm^{-1})	λ (Å)	A_λ	A_λ / [$E(B-V)$]	Method
1.25......	8000	0.35	1.86	Fit
1.50......	6667	0.47	2.47	Fit
1.75......	5714	0.56	2.96	Fit
2.00......	5000	0.67	3.52	Fit
2.25......	4444	0.77	4.07	Fit
2.50......	4000	0.85	4.46	Fit
2.75......	3636	0.91	4.80	Fit
3.00......	3333	0.98	5.16	Fit
3.25......	3077	1.05	5.55	Fit
3.50......	2857	1.14	5.99	Fit
3.75......	2667	1.23	6.48	Fit
4.00......	2500	1.25	6.60	Obs
4.25......	2353	1.38	7.26	Obs
4.50......	2222	1.58	8.31	Obs
4.75......	2105	1.61	8.49	Obs
5.00......	2000	1.66	8.75	Obs
5.25......	1905	1.69	8.88	Obs
5.50......	1818	1.68	8.86	Obs
5.75......	1739	1.67	8.80	Fit
6.00......	1667	1.71	8.99	Fit
6.25......	1600	1.76	9.24	Fit
6.50......	1538	1.81	9.55	Fit
6.75......	1481	1.88	9.89	Fit
7.00......	1429	1.96	10.3	Fit
7.25......	1379	2.03	10.7	Fit
7.50......	1333	2.13	11.2	Fit
7.75......	1290	2.22	11.7	Fit

[N II] 6548+6584/[N II] 5755 and [N II] 2140+2144/[N II] 6548+6584 are both temperature indicators. Given that the two ratios must give the same temperature and that the UV lines fall in the 2200 Å region, the comparison between the temperatures derived from the two ratios is a valuable diagnostic tool to test the extinction around the 2200 Å bump. The results of the analysis show that the amount of extinction needed to obtain one and the same temperature agrees perfectly with the estimate obtained from this study, whereas the adoption of a more "standard" 2200 Å bump would produce temperature discrepancies that are well beyond the measurements errors.

To complete our analysis of the line of sight toward Star 2, we have measured the neutral hydrogen column density to Star 2 by fitting the interstellar Ly α absorption line. We obtain

$$N(\text{H I}) = (4.0^{+1.0}_{-0.8}) \times 10^{21}\ \text{cm}^{-2}\ .$$

This leads to a ratio

$$E(B-V)/N(\text{H I}) = (4.8^{+1.3}_{-1.1}) \times 10^{-23}\ \text{cm}^2\ ,$$

which is 3–6 times lower than in our Galaxy, just reflecting the lower metallicity of the LMC where most of the extinction originates (see also Fitzpatrick 1986).

The effective temperature we obtain is somewhat higher than the canonical values for galactic B2 giants (see, e.g., Schmidt-Kaler 1982). The lower metallicity of the LMC could cause stars of a given spectral type to have a higher temperature than the corresponding stars in our Galaxy. Also, the spectral type—effective temperature calibrations are rather uncertain (see discussion in Walborn et al. 1993), and, therefore, we conclude that an effective temperature of $T_{\text{eff}} = 22{,}000 \pm 2000$ K is entirely appropriate for Star 2 being a B2III.

5. STELLAR PARAMETERS

The stellar radius was determined by comparing the dereddened spectrum of Star 2 with a model atmosphere at $T_{\text{eff}} = 22{,}000$ K, $\log g = 3.5$, $Z = Z_\odot/3$ and by adopting a distance to SN 1987A of 51 kpc (Panagia et al. 1991). Because of spherical aberration and of pointing problems, only a fraction of the stellar flux was actually measured with the adopted FOS aperture. A direct estimate of the correction factor was derived by comparing the magnitudes of Star 2, as measured by Walborn et al. (1993) in the U, B, V, and R bands, with the corresponding average fluxes as measured with the FOS. The correction factor turned out to be virtually independent of the wavelength, with an average value of 1.31 ± 0.05. Including this correction, we calculate a radius

$$R = 10.8 \pm 0.8\ R_\odot\ .$$

Correspondingly, the bolometric luminosity is

$$\log L/L_\odot = 4.38 \pm 0.11\ .$$

The fit of the continuum with model atmospheres, as discussed in § 3, allows one to estimate the effective temperature of Star 2 rather accurately but leaves its gravity poorly constrained. To determine the gravity we have used the Hγ line, which is a sensitive function of gravity. The observed Hγ equivalent width is $W_{\text{obs}}(\text{H}\gamma) = 3.0 \pm 0.5$ Å. To compare this value with classical model atmosphere we have had to correct it for the emission produced in the stellar wind (see § 5). With the wind parameters deduced from the analysis of the Hα emission and following the prescriptions of Panagia (1991) and Scuderi et al. (1992), the correction amounts to $\Delta W = +0.4$ Å, which makes the intrinsic Hγ equivalent width at the stellar atmosphere $W_{\text{atm}}(\text{H}\gamma) = 3.4 \pm 0.6$ Å. Comparing this corrected value with the non-LTE calculations of Mihalas (1972) we estimate a value of $\log g = 3.33 \pm 0.17$. A similar procedure applied to the Hβ line gives $\log g = 3.31 \pm 0.29$, the uncertainty being larger because the wind emission correction is larger.

We also measured the rotational velocity by comparing the observed Hγ profile with the theoretical profiles calculated by Mihalas (1972) (see Fig. 5), adding a wind emission component as appropriate from scaling the Hα line. Attributing the difference between theoretical and observed profiles to rotational broadening, we obtain

$$v \sin i = 250 \pm 50\ \text{km s}^{-1}\ .$$

The values of log g derived above represent the effective gravity, which include both the true gravity and the effect of centrifugal force. For a present mass of Star 2 of about 12 $M_\odot$ (see § 7) and a stellar radius of 10.8 $R_\odot$, the breakup velocity is 460 km s^{-1}. If one assumes $\sin i = 1$, rotation has the effect to reduce the effective gravity by 22% at the equator and about 10% averaged over the whole stellar surface. For lower values of the inclination the reduction

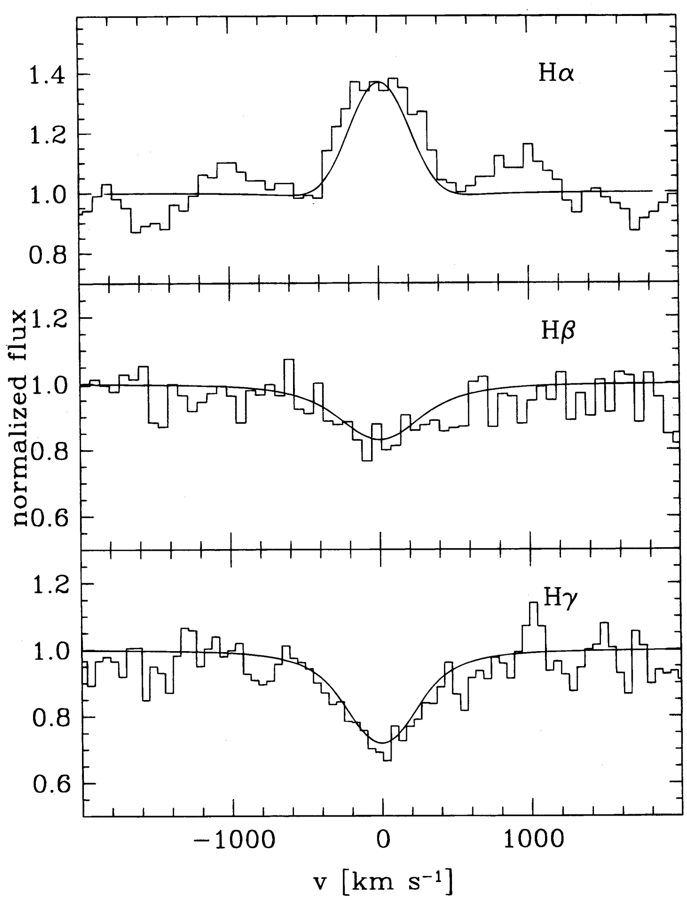

FIG. 5.—Comparison of the observed and theoretical profiles for the Hγ, the Hβ, and the Hα hydrogen lines of Star 2.

TABLE 2

STELLAR PARAMETERS OF STAR 2

Parameter	Value
Spectral type	B2 III
T_{eff}	$22,000 \pm 2000$ K
log g	$\geq 3.37 \pm 0.17$
Radius	$10.8 \pm 0.8\ R_{\odot}$
$\log(L/L_{\odot})$	4.38 ± 0.11
$v \sin i$	250 ± 50 km s^{-1}
$\log[\dot{M}/(M_{\odot}\ yr^{-1})]$	-7.0 ± 0.5
Initial mass	$\geq 13\ M_{\odot}$
Age	≤ 13 Myr

would be larger. Therefore, the true gravity of Star 2 is higher than measured from the Hγ and Hβ profiles and is likely to be $\log g \simeq 3.37$ or higher.

Table 2 summarizes the stellar parameters of Star 2.

6. Hα EMISSION AND MASS LOSS

Mass loss may affect the evolution of a star rather strongly. The mass-loss rate is then an important parameter that has to be determined for a correct characterization of the evolutionary stage of a star.

The Hα line provides one of the most powerful tools to extract this information (see, e.g., Klein & Castor 1978; Leitherer 1988; Scuderi et al. 1992, 1994). The interpretation of the Hα emission in terms of a stellar wind in the case of Star 2 may, however, not be straightforward due to the possible Be nature of the object.

In fact, if Star 2 were a classical Be star, then part of the Hα emission would originate from material orbiting around the star and part from material escaping the surface of the object, i.e., a wind. As Star 2 seems to be rather peculiar as a Be object, in the sense that the only clear evidence of its nature is the Hα emission, we will also explore the possibility that all of this emission is due to outflowing material.

In the latter scenario an estimate of the mass-loss rate can be obtained fitting the Hα profile. Our analysis follows the method outlined by Scuderi et al. (1992, 1994) with some modifications to allow for rotational broadening. The expected difference relative to the case of a purely radially flowing wind is a broadening and flattening of the profile, which is especially important at low velocities, i.e., for the layers closest to the surface of the star were the effect of the rotation is dominant with respect to that produced by the radial outward motion of the wind. To take into account the broadening due to the rotation, we first calculated an Hα profile that includes only the effects of the presence of a wind, and then we convolved this profile with a suitable rotational profile.

The wind profile was calculated using the model described in Panagia (1991) and Scuderi et al. (1992). The wind is assumed to be stationary, spherically symmetric, fully ionized, and isothermal. The velocity field is assumed to have a truncated power-law dependence with radius

$$v(r) = v_0\left(\frac{r}{R_*}\right)^{\gamma}, \quad \frac{r}{R_*} \leq \left(\frac{v_\infty}{v_0}\right)^{1/\gamma};$$

$$v(r) = v_\infty, \quad \frac{r}{R_*} > \left(\frac{v_\infty}{v_0}\right)^{1/\gamma}; \qquad (1)$$

where R_* is the radius of the star, v_0 and v_∞ are the initial and the terminal velocity of the wind, respectively. The temperature in the wind was assumed to be $0.85 \times T_{eff}$, hydrogen and helium are singly ionized with He/H = 0.1 by number, and the departure coefficient for level 2 of hydrogen is $b_2 = 3$ (H. J. G. L. M. Lamers, private communication). The terminal velocity is assumed to be $v_\infty = 1200$ km s^{-1}, as appropriate for a star with $T_{eff} =$ 22,000 K (see, e.g., Panagia & Macchetto 1982).

Then, for a given set of wind parameters, i.e., v_0, γ, and $\dot{M}$, we calculate a wind emisson profile. This purely emission profile is combined with a photospheric profile and with an appropriate P Cygni scattering profile in the way described by Scuderi et al. (1992).

Rotation is allowed for by convolving the resulting line with a rotational profile, which is assumed that appropriate for a layer with radius such as half of the wind emission originates from gas inside that radius. Such a radius occur very close to the stellar atmosphere. For example, with velocity slopes of $\gamma = 1$ and $\gamma = 0.5$, the radii which enclose the 50% emission region are 1.26 and 1.41 the stellar radius, respectively. Assuming momentum conservation, the corresponding rotational velocities are 0.79 and 0.71 the equatorial velocity. Since the rotational velocity changes so little over most of the emitting region, our approximation is certainly adequate.

Finally, the resulting profile is convolved with an instrumental profile (i.e., a Gaussian with an HPFW = 5.7 Å; Kinney (1992) and compared with the observed profile (see Fig. 5). Adopting a rotational velocity of $v_{rot} = 250$ km s^{-1}, the best fit is achieved for

$$\gamma = 0.5 \pm 0.5\ ,$$

$$v_0 = 130 \pm 30 \text{ km s}^{-1}\ ,$$

$$\dot{M} = 2.6 \times 10^{-7}\ M_{\odot}\ \text{yr}^{-1}\ .$$

We have to bear in mind that the mass-loss rate is a rather sensitive function of the wind radial velocity field. On the other hand, our analysis shows that rotational broadening is the dominant factor in determining the shape of the profile, and, therefore, the radial velocity field of the wind is not perfectly determined. This implies that the mass-loss rate may be uncertain by as much as a factor of ~ 3.

We note that the wind parameters derived from the analysis of the Hα line provide an excellent fit to the Hβ and of Hγ, too. In fact, not only can the observed equivalent widths of Hβ and of Hγ be accounted for, but also the profiles are fitted quite satisfactorily (cf. Fig. 5).

On the other hand, as we noted at the beginning of the section, the mass-loss rate obtained so far is a upper limit if the Hα emission is in part produced by material not escaping from the star. Mass-loss rates of classical Be stars have been measured from far-infrared measurements using appropriate disk + wind models (Waters, Coté, & Lamers 1987). For giant stars of similar spectral type as Star 2 they found $\dot{M} \simeq 5 \times 10^{-8}\ M_{\odot}$ yr^{-1} to within a factor of 3. Assuming the mass-loss rate proportional to the equivalent width of the Hα (see, for example, Scuderi et al. 1992), one obtains $\dot{M} \simeq 3 \times 10^{-8}\ M_{\odot}$ yr^{-1} for Star 2 under the hypothesis of it being a "classical" Be star.

Clearly, the truth has to be intermediate between the "pure wind hypothesis" and the "classical Be" hypothesis. Thus, considering that the estimates in either case are uncertain to a factor of 3, we conclude that Star 2 has a mass-loss rate of about $10^{-7}\ M_{\odot}\ \mathrm{yr}^{-1}$.

7. STELLAR MASS, AGE, AND RELATIONSHIP TO SN 1987A

To determine the mass of Star 2 we used two independent methods: (1) a spectroscopic determination and (2) a determination based on stellar evolution.

As discussed in § 4, the true stellar gravity derived from the Hγ and Hβ equivalent widths after allowance for rotation and for the presence of a wind, is $\log g \geq 3.37 \pm 0.17$ and the stellar radius is $R = 10.8 \pm 0.8\ R_{\odot}$. It follows that

$$M_{\mathrm{spectr}} \geq 10.1^{+4.5}_{-3.0}\ M_{\odot}$$

The evolutionary mass of Star 2 can be estimated from its position in the H-R diagram. With $T_{\mathrm{eff}} = 22{,}000 \pm 2000$ K and $\log(L/L_{\odot}) = 4.38 \pm 0.11$, and using the evolutionary model calculations of Schaller et al. (1992), which include mass loss, the initial mass and the age of Star 2 would appear to be

$$M_{\mathrm{evol}} = 11.8 \pm 1.5\ M_{\odot}$$

and $(15 \pm 2) \times 10^6$ yr, respectively (see, Fig. 6). Because of mass loss, the present mass is found to be a little lower than the initial one, i.e.,

$$M_{\mathrm{present}} \simeq 11.7\ M_{\odot}$$

In Figure 6 we also display the evolutionary tracks of Schaerer et al. (1993) calculated for stars with a lower metallicity ($Z = 0.008$). As one can see, in the early phases of the post–main-sequence evolution, even a big change in metallicity affects the evolutionary tracks only marginally.

The two determinations of the stellar mass are in excellent agreement with each other, especially considering that

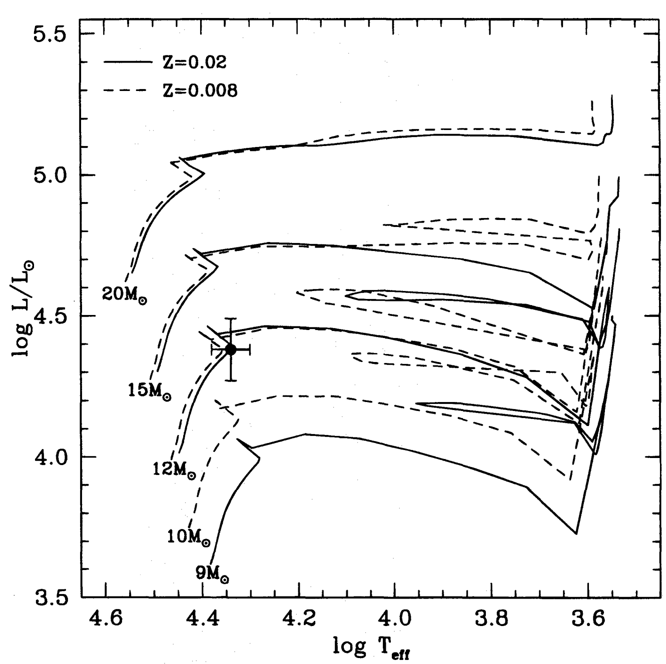

FIG. 6.—Theoretical H-R diagram for stars with masses between 9 and 20 $M_{\odot}$. Solid lines ($Z = 0.02$) are from Schaller et al. (1992). Dashed lines ($Z = 0.008$) are from Schaerer et al. (1993). The position of Star 2 is indicated by the filled dot.

the value of M_{spectr} is possibly a lower limit. Also, it is important to realize that the spectroscopic mass is a measurement of the present mass, whereas the mass deduced from evolutionary tracks is the initial mass of a star. Actually, we note that the measured mass-loss rate of Star 2 is an order of magnitude higher than the one adopted for the calculation of the evolutionary tracks (Schaller et al. 1992). Considering that the stellar luminosity is the main stellar parameter that affects the mass loss (Scuderi 1994; Scuderi & Panagia 1996), one expects that Star 2 has changed its mass-loss rate by no more than a factor of 2 or 3 since it was on the main sequence. Therefore, we can extrapolate back from the present and estimate that Star 2 has lost about 1 $M_{\odot}$ during its lifetime. Since the present temperature and luminosity of Star 2 indicate a *present* mass of about 12 $M_{\odot}$, we conclude that the initial mass of Star 2 was

$$M_{\mathrm{initial}} \geq 13\ M_{\odot}$$

and its age was

$$\mathrm{age} < 13 \times 10^6\ \mathrm{yr}\ .$$

All of this can be used to clarify the relationship of Star 2 to the progenitor of SN 1987A. Its mass has been estimated to be about $19 \pm 3\ M_{\odot}$ (Arnett et al. 1989). Adopting again Schaller et al. (1992) evolutionary calculations, the corresponding lifetime would be $(11 \pm 2) \times 10^6$ yr. On the other hand, the mass-loss rate just before explosion ($8.8 \times 10^{-6}\ M_{\odot}\ \mathrm{yr}^{-1}$, Chevalier & Fransson 1987) was about 3 times lower than the mass loss adopted for the evolutionary tracks. If the pre-explosion value is representative of the average mass-loss rate in the late phases of evolution, the total mass lost is somewhat lower than what is implied by the models, and, therefore, the lifetime of the progenitor of SN 1987A is likely to be somewhat longer than 11×10^6 yr. In any case, we conclude that the formation of Star is essentially coeval to that of the progenitor of SN 1987A well within the uncertainties. Furthermore, as the projected distance on the sky is about 2″5 it is very likely that the two stars, being formed at the same time, were physically associated (see also van den Bergh 1987).

8. CONCLUSIONS

From an analysis of *HST*-FOS spectra of Star 2, one of two companions of SN 1987A, we have determined its stellar parameters:

1. Star 2 is a B2III star, which is reddened by $E(B-V) = 0.19 \pm 0.02$.
2. Its effective temperature is $T_{\mathrm{eff}} = 22{,}000 \pm 2000$ K and its luminosity is $\log L/L_{\odot} = 4.38 \pm 0.11$.
3. Star 2 has a rotation velocity of $v \sin i = 250 \pm 50$ km s^{-1} and a mass-loss rate of $\log \dot{M} \simeq -7.0 \pm 0.5\ M_{\odot}\ \mathrm{yr}^{-1}$.
4. These stellar parameters imply that Star 2 had an original mass of about 13 $M_{\odot}$ and was born less than 13 Myr ago, which makes it coeval to the SN 1987A progenitor Sk $-69°202$.

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REFERENCES

Allen, R. G., & Angel, J. R. P. 1982, Proc. SPIE, 331, 259
Arnett, D. W., Bahcall, J. N., Kirshner, R. P., & Woosley, S. E. 1989, ARA&A, 27, 629
Bessell, M. S. 1991, A&A, 242, L17
Blades, J. C., Wheatley, J. M., Panagia, N., Grewing, M., Pettini, M., & Wamsteker, W. 1988, ApJ, 334, 308
Chevalier, R. A., & Fransson, C. 1987, Nature, 328, 44
Fitzpatrick, E. L. 1986, AJ, 92, 1068
Fitzpatrick, E. L., & Savage, B. D. 1984, ApJ, 279, 578
Fitzpatrick, E. L., & Walborn, N. R., 1990, AJ, 99, 1483
Gilmozzi, R., Cassatella, A., Clavel, J., Fransson, C., Gonzales, R., Gry, C., Panagia, N., Talavera, A., & Wamsteker, W. 1987, Nature, 328, 318
Gray, D. F. 1992, in The Analysis of Stellar Photospheres (Cambridge: Cambridge Univ. Press)
Jaschek, M., Hubert-Delplace, A. M., Hubert, H., & Jaschek, C. 1980, A&AS, 42, 103
Jaschek, M., Slettebak, A., Jaschek, C. 1981, Be Newsletter, 4, 9
Kinney, A. L. 1992, *Hubble Space Telescope* Faint Object Spectrograph Handbook (Baltimore: STScI)
Kirshner, R. P., & Gilmozzi, R. 1989 in Exploring the Universe with the *IUE* Satellite, ed. Y. Kondo, (Dordrecht: Reidel), 771
Klein, R. I., & Castor, J. I. 1978, ApJ, 220, 902
Koratkar, A. 1993, in Calibrating *Hubble Space Telescope*, ed. J. C. Blades & S. J. Osmer (Baltimore: STScI), 143
Kurucz, R. L. 1992, in IAU Symp. 149, The Stellar Population of Galaxies, ed. B. Barbuy & A. Renzini (Dordrecht: Kluwer), 225
Leitherer, C. 1988, ApJ, 326, 356
Mihalas, D. 1972, NCAR-TN/STR-76
Panagia, N. 1991, in the Physics of Star Formation and Early Stellar Evolution, ed. C. J. Lada & N. D. Kilafis (Dordrecht: Kluwer), 565
Panagia, N., Gilmozzi, R., Clavel, J., Barylak, M., Gonzales Riesta, R., Lloyd, C., Sanz Fernandez de Cordoba, L., & Wamsteker, W. 1987, A&A Letters, 177, L25
Panagia, N., Gilmozzi, R., Macchetto, F., Adorf, H. M., & Kirshner, R. P., 1991, ApJ, 380, L23
Panagia, N., & Macchetto, F. 1982, A&A, 106, 226
Panagia, N., Scuderi, S., Gilmozzi, R., Challis, P. M., Garnavich, P. M., & Kirshner, R. P. 1996a, ApJ, 459, L17
Panagia, N., Scuderi, S., Gilmozzi, R., & Kirshner, R. P. 1996b in preparation
Rountree, J., & Sonneborn, G. 1991, ApJ, 369, 515
Savage, B. D., & Mathis, J. S., 1979, ARA&A, 17, 73
Schaerer, D., Meynet, G., Maeder, A., & Schaller, G. 1993, A&AS, 98, 523
Schaller, G., Schaerer, D., Meynet, G., & Maeder, A. 1992, A&AS, 96, 269
Schmidt-Kaler, T. 1982, in Landolt-Bornstein, New Series: Astronomy and Astrophysics, Vol. 2b (Berlin, Heidelberg, New York: Springer), 451
Schwering, P. B. W., & Israel, F. P. 1991, A&A, 246, 231
Scuderi, S. 1994, Ph.D. thesis, Univ. of Catania
Scuderi, S., Bonnano, G., Di Benedetto, R., Spadaro, D., & Panagia, N. 1992, ApJ, 392, 201
Scuderi, S., Bonanno, G., Spadaro, D., Panagia, N., Lamers, H. J. G. L. M., & de Koter, A. 1994, ApJ, 437, 465
Scuderi, S., & Panagia, N. 1996 in preparation
van den Bergh, S. 1987, in ESO Workshop on SN 1987A, ed. I. J. Danziger (Garching: ESO), ESO-CWP No. 26, 677
Walborn, N. R., Phillips, M. M., Walker, A. R., & Elias, J. H. 1993, PASP, 105, 1240
Walker, A. R., & Suntzeff, N. B. 1990, PASP, 102, 131
Waters, L. B. F. M., Coté, J., & Lamers, H. J. G. L. M. 1987, A&A, 185, 206