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EARLY OBSERVATIONS OF SN 1993J IN M81 AT McDONALD OBSERVATORY

J. C. WHEELER, E. BARKER, R. BENJAMIN, J. BOISSEAU, A. CLOCCHIATTI, G. DE VAUCOULEURS, N. GAFFNEY, R. P. HARKNESS, A. M. KHOKHLOV, D. F. LESTER, B. J. SMITH, V. V. SMITH, AND J. TOMKIN
Department of Astronomy, University of Texas at Austin, RLM 15.308, Austin, TX 78712-1083
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ABSTRACT

The visual light and color curves of SN 1993J show behavior unlike that of other Type II supernovae. The initial flash peaked at $V = 10.7$ on JD = 2,449,076.8, 3 days following the shock outbreak which is estimated to have occurred at JD 2,449,074.5 = March 28.0 UT. High-dispersion spectra show 10 velocity components in each of the Na D lines. Early optical and IR spectra show a nearly blackbody continuum cooling from 14,900 ± 1000 K to 11,800 ± 700 K from March 31.2 to April 1.2 UT. Superposed on this continuum are broad, weak Balmer, Paschen, and He I lines. From blackbody fits to early spectra the color excess is estimated to be about $E(B-V) = 0.15 \pm 0.02$. The V light curve is reproduced by a model based on a 3.3 $M_\odot$ helium core of which the outer 0.4 $M_\odot$ is 20% hydrogen by mass. The recession of the photosphere through the thin H layer is completed at the first minimum. The second peak at $V = 10.86$ on JD 2,449,095.5 = April 18.0 is powered by radioactive heating. The subsequent decreasing rate of decline of the light curve may indicate the presence of a constant-luminosity source of about 10^{41} ergs s^{-1}. Application of the expanding photosphere method to the early spectra gives a distance estimate of 4.2 ± 0.6 Mpc, or DM = 28.1 ± 0.4, but the result will depend on the detailed structure of the atmosphere.

Subject headings: galaxies: individual (M81) — galaxies: ISM — supernovae: individual (SN 1993J)

1. INTRODUCTION

SN 1993J was discovered by F. García of Lugo, Spain, on March 28.9 = JD 2,449075.4 in M81 = NGC 3031 at $m_v \simeq 10.8$ (Ripero 1993). Observations at McDonald Observatory commenced on March 31.1 UT and consisted of high- and low-dispersion spectroscopy in the optical and IR (see Swartz et al. 1993) and optical spectropolarimetry (see Tammell, Hines, & Wheeler 1993). Photometry obtained elsewhere has also been analyzed. In this *Letter* we report some of the early observations and present some preliminary analysis. Details of the observational methods will be given elsewhere.

2. LIGHT AND COLOR CURVES

The V-band light curve in Figure 1 is based on compilations of photoelectric and CCD photometry kindly communicated by T. Kato, B. Granslo, A. M. J. Wijers, W. Herbst, and P. Prugniel. The magnitudes have been corrected after correspondence with the observers. With the negative prediscovery image-tube record by J.-C. Merlin (1993, private communication), JD 2,449,074.41, $m > 17.0$, the first positive prediscovery CCD observation by Neely (1993a, b; 1993, private communication), JD 2,449,074.8, $V = 13.45 \pm 0.15$, and the magnitude of the putative precursor ($V = 20.8$ after Aldering, Humphreys, & Richmond 1993), the observations narrowly constrain the onset time to t_0 = JD2,449, 074.5 ± 0.05 = March 28.0. A provisional mean V system was defined by the observations of Kato (Kyoto), Richmond (Berkeley), Prugniel (Haute-Provence), Herbst (Van Vleck), and Mikolajewski (Torun), to which other data sets were reduced, if and as needed, by small zero-point corrections (less than ±0.1 mag). A few aberrant values (residuals ≥0.1) were rejected.

The light curve consists of two separate components: (1) the "flash," an initial, very fast rise from $V = 20.8$ at t_0 to a first maximum at $V = 10.7$ on $T_1 = t_1 - t_0 = 2.3$ days (JD 2,449,076.8 = March 30.3), followed by a rapid decline to an intermediate minimum at $V = 11.87$ on $t - t_0 = 8.3$ (JD 2,449,082.8 = April 5.3), and (2) a second peak $V = 10.86$ on $T_2 = t_2 - t_0 = 21.1$ days (JD 2,449,095.6 = April 18.1). The supernova then faded at a progressively slower rate of decline to below $V = 12.5$ after day 60. The $B-V$ color curve, also shown in Figure 1, reveals three distinct phases. When first observed with filtered CCDs on JD 2,449,076.7 ($T = 2.2$ days) the supernova was already reddening rapidly at a rate of 0.1 mag day^{-1}, consistent with a minimum at $B-V = -0.2$ at $T \leq 1$ day. On the second rise, the rate of reddening slowed to 0.015 mag day^{-1}. On the second decline, the reddening rate increased again to 0.06 mag day^{-1}, with $B-V$ reaching +1.3 on $t - t_0 = 36$ (JD 2,449,110) as V declined to the value of the first minimum. The $B-V$ color remained stationary with a color temperature about 4000 K until day 54 (JD 2,449,128), when it started to become slowly bluer.

The mean *foreground* (Galactic) reddening in the M81 field was estimated from the $U-B$, $B-V$ colors of 10 field stars to be on average $E(B-V) \simeq 0.09 \pm 0.02$. The *total* color excess derived from the $U-B$, $B-V$ color-color relation for the first 6 days is $E(B-V) \simeq 0.16$ (de Vaucouleurs 1993). If the total color excess were greater than 0.3, it would be difficult to account for the initial colors, which, after correction, would be too blue for a blackbody at any temperature.

Modeling of the visual light curve of Figure 1 suggests that the radius of the progenitor must have been $\simeq 3 \times 10^{13}$ cm in order to account for the width of the decline to a minimum about 9 days after shock breakout. Figure 1 also shows a theoretical V light curve, and the $B-V$ color curve based on the 3.3 $M_\odot$ helium core model of Shigeyama et al. (1990). This model had 1.8 $M_\odot$ of ejecta, 1.4 $M_\odot$ of He, and 0.4 $M_\odot$ of metals, including 0.08 $M_\odot$ of ^{56}Ni. The model was homologously contracted from 20 days after explosion to 1 day and then reexpanded with radioactive deposition and flux-limited diffusion to compute the light curve (see Swartz, Wheeler, &

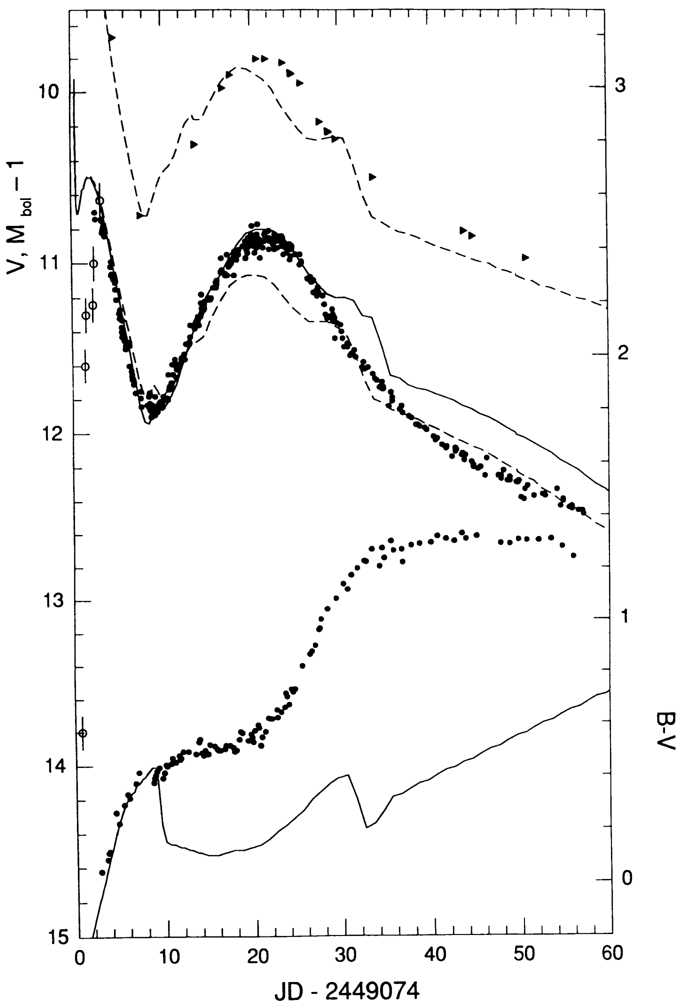

FIG. 1.—Observed V and $B-V$ curves are shown as a function of epoch since JD 2,449,074.0 near shock breakout. Prediscovery and discovery points are shown as open circles. The bolometric data of Schmidt et al. (1993) are shown as triangles. Also shown are the theoretical light curves for the models described in the text. The solid lines represent V and $B-V$ for the model with 0.8 $M_\odot$ of ^{56}Ni. The dashed lines represent V and M_{bol} for a model with 0.05 $M_\odot$ of ^{56}Ni and a constant source of luminosity of 10^{41} ergs s^{-1}. The bolometric light curves are displaced 1 mag for clarity. Theoretical curves assume DM = 27.7.

Harkness 1991 for details). The outer 0.4 $M_\odot$ was converted to a hydrogen mass fraction of $X = 0.2$. Tables of expansion opacities for the outer H layer, the helium layer, and the inner, metal-rich layers were computed by averaging the Rosseland opacity of lines from the list of 42×10^6 from R. L. Kurucz (private communication) in bins of 40 Å in the comoving frame. The construction of this model is incapable of predicting the initial temperature. A value of $T = 10^5$ K was assigned. The V-magnitude computed in this way cannot reproduce the first rise but is quite good for the subsequent 30 days. At that point the metal core becomes transparent and the computation loses validity. The color curve does not behave as well once the photosphere recedes through the H at the first minimum and at virtually the same time through the helium. The colors are simply computed from blackbodies at the photospheric temperature, and the excessive blue luminosity might be moderated with a proper account of resonance scattering. This light-curve calculation gave a preference to the 3.3 $M_\odot$ model over that of 4.0 $M_\odot$ favored by Swartz et al. (1993) for modeling the onset of helium lines, so the preferred configuration might lie somewhere between.

Unlike SN 1987A, which was constant in U but steadily declining in redder bands after the radioactive peak, SN 1993J shows a decrease in the slope of the light curves in $BVRI$ (Schmidt et al. 1993). This might be the indication of a buried source of constant luminosity in addition to the radioactive decay. Figure 1 also shows a model with an added constant source of 10^{41} ergs s^{-1} and 0.05 $M_\odot$ of ^{56}Ni along with the bolometric data of Schmidt et al. (1993). Such a source cannot be ruled out at this time. If present, it would correspond to a pulsar with a period of $P = 5$ ms $B_{12}^{1/2} r_6^{1/2}$ for a standard dipole mechanism (Gunn & Ostriker 1969), but it could also be due to particle emission.

3. HIGH-DISPERSION SPECTROSCOPY

The high-resolution spectra were obtained with the 2.1 m Struve telescope and the Sandiford Cassegrain echelle spectrometer (McCarthy 1993) on April 2 and 5. We are able to identify a minimum of 10 components of Na I with heliocentric velocities: -140, -125, -120, -61, -55, -6, 0, $+117$, $+122$, and $+134$ km s^{-1}. The strong components at -6 and 0 are presumably from the Galactic disk. The weaker components at -120 to -140 correspond to interstellar H I velocities in M81 in the vicinity of the supernova (Rots & Shane 1975). The component at ~ -60 corresponds nearly to the rest frame of M81 but could represent inflow in the Galaxy. The strongest extragalactic component is that with very high positive velocities and may represent flow in the M81-M82 group.

Column densities of Na I were estimated assuming Gaussian line profiles to determine the equivalent width of each component and to deblend lines. The classical doublet-ratio method (Spitzer 1968) was used to estimate the saturation in these lines, and column densities were then calculated using the identified components of the weaker of the Na I lines (5896 Å). Most of the column density arises from strong absorption systems at -6 and 0 km s^{-1} and at $+117$, $+122$, and $+134$ km s^{-1}. The -6 km s^{-1} doublet is both strongly saturated and contaminated by telluric Na I emission, so its contribution is uncertain. The sums of the column densities derived from each component give what we believe to be conservative lower limits to total Na I along the line of sight, $\sim 4 \times 10^{13}$ cm^{-2} in the Galaxy and $\sim 1 \times 10^{13}$ cm^{-2} externally. Using results from Hobbs (1976, 1978) for column densities of Na I through various lines of sight with determined color excesses, we estimate that the total color excess toward SN 1993J must be (conservatively) within the range $E(B-V) = 0.1$–0.4, consistent with the results from the photometry and low-dispersion spectroscopy.

4. LOW-DISPERSION OPTICAL SPECTROSCOPY

The low-dispersion optical spectroscopic observations were obtained on 1993 March 31.18 and April 1.14, using the Craf Cassini CCD on the ES2 grating spectrograph on the 2.1 m Struve telescope. Sky conditions were photometric on both nights. The good seeing (smaller than 2″) and very wide slit (12″) ensure that the observed spectra do not suffer from systematic light losses due to atmospheric differential refraction. On each night several exposures of the supernova and the standard star Feige 34 (Stone 1977) were obtained.

The resulting spectra are shown in Figure 2, where it is seen that the spectrum of SN 1993J was nearly Planckian on both nights, although there are some wide and shallow features superposed on the continuum. The interstellar Na I D line

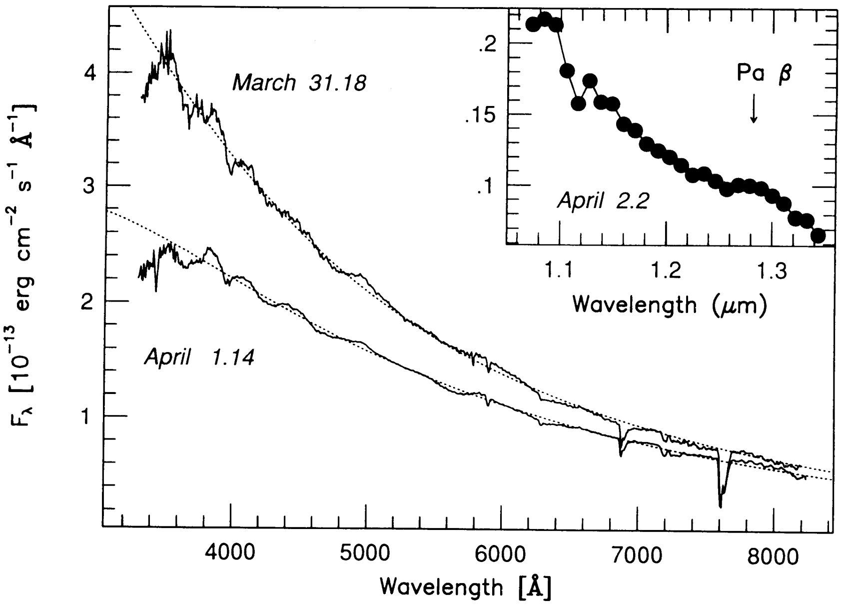

FIG. 2.—Low-resolution optical spectra of SN 1993J. The solid lines give the spectra observed on the dates indicated by the labels close to the curves. The dotted lines give as a reference the reddened blackbody curves which best fit the observations (see text). The inset shows the J-band spectrum obtained on April 2.2. The vertical flux scale is the same as for the optical spectra.

discussed in § 3 is seen in absorption at 5897 Å. A shallow P Cygni feature appears on both nights extending from ~4500 to ~5110 Å, which we associate with Hβ. The minimum at $\lambda \sim 4680$ Å implies an expansion velocity of ~11,200 km s^{-1}. There is excess emission extending from ~5700 to ~6100 Å on March 31.18 with no sign of corresponding absorption, and a P Cygni profile with minimum at $\lambda \sim 5593$ Å and maximum at 6020 Å on April 1.14. This feature can be associated with the He I λ5876 transition with the absorption representing a blueshift of 14,500 km s^{-1}. On March 31.18 there is an asymmetric feature with a sharp blue edge between 6265 and 6285 Å. This asymmetry is also present in another spectrum taken almost simultaneously (H. E. Ann and P. Garnavich, 1993, private communication). This feature can be associated with Hα, but the core may be dominated by a telluric line at 6280 Å. The profile changes substantially by the next night to reveal a shallow absorption feature extending from $\lambda \sim 6060$ to 6550 Å. The minimum located at $\lambda \sim 6285$ Å implies an expansion velocity of ~12,650 km s^{-1}, but because of the telluric feature this velocity may not be reliable. There is no sign of emission at the rest wavelength of Hα. Finally, two other P Cygni features with minima at $\lambda \sim 3965$ and 4220 Å can be identified with Hδ and Hγ blueshifted by 10,000 and 9600 km s^{-1}, respectively. Since the Hγ feature appears flattened at both maximum and minimum, the velocity was taken at the bluest edge of the minimum. The calibration errors are as big as the "features" blueward of ~4000 Å, so the identification of Hδ is uncertain.

5. LOW-DISPERSION INFRARED SPECTROSCOPY

IR spectra of SN 1993J were obtained on March 31.2 (1.0–1.3 μm, 1.9–2.5 μm), April 1.2 (1.0–1.8 μm), and April 2.2 (1.0–1.3 μm, 1.9–2.2 μm) using the infrared grating spectrometer (Lester et al. 1990) on the 2.7 m reflector. The continua are consistent with thermal blackbody emission with a color temperature of $T \sim 10{,}000$ K and the following approximate IR magnitudes: March 31.2, $J = 10.9 \pm 0.3$, $K = 10.6 \pm 0.2$; April 1.2, $J = 10.6 \pm 0.2$, $H = 10.2 \pm 0.5$; April 2.2, $J = 10.7 \pm 0.3$, $K = 10.6 \pm 0.2$. Paβ 1.282 μm emission was detected on April 1.2 and 2.2, but not convincingly so on March 31.2, owing to poor cancellation of the atmospheric absorption. The J-band spectrum for April 2.2 is shown in the inset in Figure 2. We estimate the line center to be 1.287 ± 0.006 μm, with a total velocity width of $v \sim 11{,}000$ km s^{-1}.

6. DISCUSSION

SN 1993J has shown marked dissimilarities from other Type II supernovae (SNe II). The light curve has some morphological similarities to that of SN 1987A, with a shock breakout phase and then a secondary peak, but the whole evolution has been much more rapid. Models of the light curve and spectra computed here and elsewhere (Shigeyama et al. 1993; Podsiadlowski et al. 1993; Ray, Singh, & Sutaria 1993; Swartz et al. 1993; Woosley et al. 1993; but see Höflich, Langer, & Duschinger 1993) suggest an ejecta mass of about 2–3 $M_\odot$, with only about 0.4 $M_\odot$ in the outer hydrogen envelope, much less than in the case of SN 1987A, but with an initial radius of several hundred solar radii. Given that the shock breakout phase may have been missed in other events, the secondary maximum may be compared with the observed maxima of other observed supernovae.

SN 1993J is not behaving like a classical SN II of the "plateau" light-curve variety, presumably because, while the progenitor was a red supergiant with a large radius, the ejecta mass in SN 1993J was rather small. SNe II of the "linear" light-curve class have different, nearly continuous, spectra at maximum and different postpeak light curves. SN 1987K had a rather narrow maximum and showed evidence for Hα near maximum, but no evidence for H later on (Filippenko 1988). At the second maximum of SN 1993J, the strong H emission was unmistakable and rather different from that of SN 1987K. SN 1987K was probably beginning to show lines of He I before it was lost behind the Sun (Filippenko, Matheson, & Ho 1993), so it is likely to be closely related to SN 1993J. SN 1993J may bear some physical connection to other supernovae and especially to SN 1987K, but it is surely not identical to any other observed SN II.

The temperatures assigned to the spectra on the first two nights can be used to make an estimate of the distance to SN 1993J based on the expanding photosphere method (Schmidt, Kirshner, & Eastman 1992 and references therein). If we assume that the emission was nearly Planckian in the early phase, as suggested by the spectra and the *UBV* photometry, then the angular diameter is given by

$$\theta = \frac{R}{D} = \left[\frac{F_\lambda}{\zeta^2 \pi B_\lambda(T)}\right]^{1/2} , \quad (1)$$

where ζ is a correction for scattering and geometry. If we assume that the velocity at the photosphere does not vary substantially between March 31 and April 1 and that the initial radius is negligible (a 10% effect), then the distance can be estimated to be

$$D = \frac{v \Delta t}{\theta_2 - \theta_1} . \quad (2)$$

We have computed θ from the observed spectra shown in Figure 2 corrected for different values of the reddening (using $0.1 < A_V < 0.9$ and a mean absorption law) and have found that it is most free of overall trend and curvature on both nights for $E(B-V) = 0.15 \pm 0.02$ mag, again suggesting that this is approximately the right color excess, giving $A(V) = 0.5 \pm 0.08$ mag. For this value $E(B-V)$, the best-fitting blackbody curves give temperatures $T = 14{,}900 \pm 1000$ K on March 31.18 and $T = 11{,}800 \pm 700$ K on April 1.14. Blackbody curves of these temperatures, reddened by $E(B-V) = 0.15$, are also given in Figure 2. These temperatures are in good agreement with the values $T = 15{,}300$ K and $T = 11{,}300$ K derived from the $U-B$, $B-V$ colors.

The resulting distance is $D = 4.2 \pm 0.6 v_4 \zeta$ Mpc, where v_4 is the photospheric velocity in units of 10^4 km s^{-1}. Taking $v_4 = \zeta = 1$ as an illustration, this distance corresponds to an absolute distance modulus of 28.1 ± 0.4, which, within errors, agrees with other methods (27.7 ± 0.1; Jacoby et al. 1989; Tonry 1991; de Vaucouleurs 1993; Freedman et al. 1993).

We have computed sample spectra to check on the potential variation in this result due to the effects of scattering and geometric structure in the atmosphere. Atmospheres with power-law density profiles $\rho \propto r^{-n}$ with $n = 10$ and 40 and gray temperature distribution were constructed with a solar abundance of H, He, and heavy elements and a luminosity of $L = 3 \times 10^{42}$ ergs s^{-1}. For $n = 40$, a steep structure that can result when a reverse shock decelerates matter in an extended envelope, we find $T = 13{,}500$ K in all bands 5 days after the explosion and $\zeta = 0.98$, 0.98, and 1.00 in *V*, *R*, and *I*, respectively. For this "brick-wall" atmosphere, neither geometric nor scattering effects are significant. For $n = 10$, however, we find $T = 14{,}570$, 13,750, and 14,250 K and $\zeta = 0.54$, 0.55, and 0.55 in *V*, *R*, and *I*, respectively (*T* at *R* is suppressed slightly because it contains the P Cygni absorption of Hα). For this value of ζ the distance could be reduced by a factor of 2!. This serves to show that while the expanding photosphere method can be useful, the effects of geometry must be carefully evaluated (Branch 1979). At this early phase one must also be concerned with nonhomologous expansion, circumstellar interaction, and lack of sphericity.

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