THE ASTROPHYSICAL JOURNAL, 421:L27–L30, 1994 January 20

A *HUBBLE SPACE TELESCOPE* ULTRAVIOLET SPECTRUM OF SN 1993J[1]

DAVID J. JEFFERY,[2] ROBERT P. KIRSHNER,[2] PETER M. CHALLIS,[2] CHUN S. J. PUN,[2] ALEXEI V. FILIPPENKO,[3] THOMAS MATHESON,[3] DAVID BRANCH,[4] ROGER A. CHEVALIER,[5] CLAES FRANSSON,[6] NINO PANAGIA,[7] ROBERT V. WAGONER,[8] J. CRAIG WHEELER,[9] AND ALEJANDRO CLOCCHIATTI[9]

Received 1993 September 13; accepted 1993 November 5

ABSTRACT

We obtained a *Hubble Space Telescope* ultraviolet spectrum of the Type II supernova SN 1993J in M81 on 1993 April 15. The ~1650–2900 Å region is smoother than observed for SN 1987A and SN 1992A and lacks strong P Cygni absorptions caused by iron peak element lines. Synthetic spectra calculated using a parameterized LTE procedure and a simple model atmosphere do not fit the UV region. Radio observations suggest that SN 1993J is embedded in a thick circumstellar envelope. The UV spectra of other supernovae that are believed to have thick circumstellar envelopes also have ~1650–2900 Å regions lacking in strong P Cygni absorptions. Interaction of supernova ejecta and circumstellar matter may cause the smooth UV spectrum. If so, UV observations of supernovae will provide insight into the circumstellar environment of the supernova progenitors.

Subject headings: circumstellar matter — stars: atmospheres — supernovae: individual (SN 1993J) — ultraviolet: stars

1. INTRODUCTION

We report a *Hubble Space Telescope* (*HST*) UV spectrum of SN 1993J in M81 (NGC 3031) taken on 1993 April 15 UT (~18 days after the explosion [Schmidt et al. 1993; Wheeler et al. 1993]). This spectrum and an optical April 15 spectrum from Lick Observatory appear in Figure 1. The *HST* spectrum was taken in three exposures at UT times 8:56 (1800 s), 10:32 (1800 s), and 12:08 (1300 s) using the G160L, G270H, and G400H gratings of the Faint Object Spectrograph (FOS) red side and the 4".3 × 1".4 aperture. The *HST* spectrum reveals the UV region with much higher signal-to-noise ratio than *IUE* spectra (Wamsteker et al. 1993; Sonneborn et al. 1993). The optical spectrum was taken on the Lick 3 m Shane reflector with the Kast double spectrograph using Reticon CCD detectors and a 2" slit at the parallactic angle. Five exposures of 300–800 s duration were needed to obtain coverage over the range 3120–9910 Å; the exposures were done in the interval 5:71–7:54 UT. The resolution is ~6 Å. The optical spectrum is not photometrically accurate, and so has been scaled to match the coeval V magnitude, 10.94 mag (Schmidt et al. 1993). The shapes of the *HST* and Lick spectra are in good agreement in the region of overlap (3120–4780 Å). The longest wavelength FOS segment was lower by 30% than the scaled Lick spectrum; this discrepancy may arise from a pointing error in the FOS slit. We have scaled this segment to match the Lick spectrum and joined them at ~4500 Å. The shorter wavelength FOS segments agree with each other and the Lick spectrum, and so were not scaled.

The SN 1993J spectrum in Figure 1 has been corrected for extinction using $E(B-V) = 0.1$ mag and the standard ($R_V = 3.1$) extinction law of Cardelli, Clayton, & Mathis (1989). The $E(B-V)$ value was suggested by the earliest *IUE* spectra (Wamsteker et al. 1993) which show a broad depression centered near 2200 Å that we attribute to the 2175 Å bump in the interstellar extinction law. This depression is eliminated with $E(B-V) \approx 0.1$ mag and becomes an artificial emission with $E(B-V) \approx 0.2$ mag. Because the UV extinction can deviate strongly from the standard extinction law, this argument is not conclusive, but other observations are consistent with $E(B-V) = 0.1$ mag. Galactic foreground stars have a mean $E(B-V)$ of $\sim 0.09 \pm 0.02$ mag (Wheeler et al. 1993). The interstellar Na I D lines in high-resolution optical spectra of SN 1993J suggest total $E(B-V)$ values in the range 0.1–0.4 mag (Benetti et al. 1993; Wheeler et al. 1993). An $E(B-V)$ value of 0.15 ± 0.02 mag has been found by Wheeler et al. (1993) from the early spectra and colors of the supernova itself.

Aldering, Humphreys, & Richmond (1993) suggest on the basis of preexplosion observations that the SN 1993J progenitor was probably a K star coincident with a late O or early B star or an OB association. The *IUE* spectra of SN 1993J decrease in flux by a factor of ~2 between mid-April and late April, so any contamination of our *HST* spectrum from early-type stars is no more than 50% of the flux. Further *HST* observations will set a more stringent upper bound on any contamination.

In Figure 1 we have labeled some of the prominent P Cygni absorptions. The velocities of the absorption minima are in the

[1] Partially based on observations with the NASA/ESA *Hubble Space Telescope*, obtained at the Space Telescope Science Institute, which is operated by AURA, Inc., under NASA contract NAS 5-26555.

[2] Harvard-Smithsonian Center for Astrophysics, MS-19, 60 Garden Street, Cambridge, MA 02138.

[3] Department of Astronomy and Center for Particle Astrophysics, University of California, Berkeley, CA 94720.

[4] Department of Physics & Astronomy, University of Oklahoma, Norman, OK 73019.

[5] Department of Astronomy, University of Virginia, P.O. Box 3818, Charlottesville, VA 22903.

[6] Stockholm Obsrvatory, S-133 36 Saltsjöbaden, Sweden.

[7] Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218. Affiliated with the Astronomy Division, Space Science Department of ESA. Also University of Catania, Italy.

[8] Department of Physics and Center for Space Science and Astrophysics, Stanford University, Stanford, CA 94305-4060.

[9] Department of Astronomy, University of Texas at Austin, Austin, TX 78712.

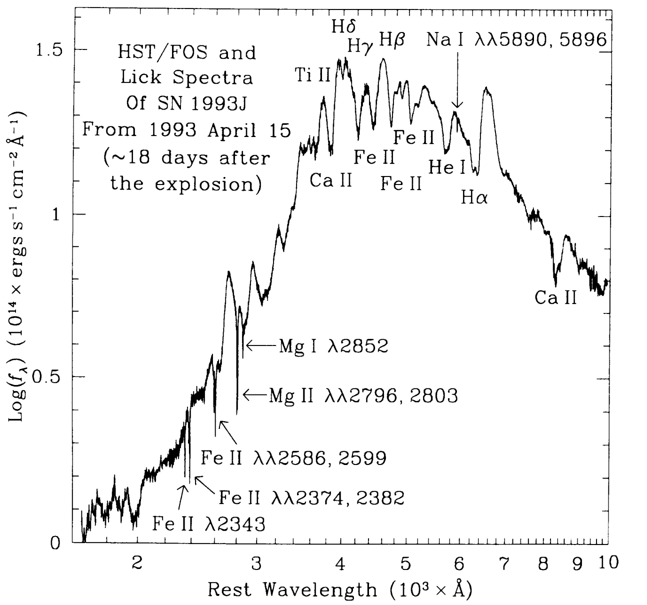

FIG. 1.—Combined *HST* FOS and Lick Observatory optical spectrum of SN 1993J from 1993 April 15. The spectrum has been corrected for extinction (see text). The wavelengths have been corrected for the heliocentric velocity of M81.

range ~ 7000–11,000 km s^{-1}. As is usually the case with supernovae (e.g., Panagia 1985), the region blueward of ~ 3700 Å exhibits a UV flux deficiency relative to a blackbody fit to the optical spectrum. The UV flux deficiencies of supernovae are caused by heavy line blanketing mainly by lines from iron peak elements (Wheeler et al. 1986; Harkness 1991). Supernova UV blanketing and flux deficiency decrease with increasing temperature. When atmospheric temperatures are sufficiently high ($\gtrsim 12,000$ K for solar composition [e.g., Wagoner, Perez, & Vasu 1991]), no UV flux deficiency is expected. Because of the blanketing, identification of features in supernova UV spectra requires synthetic spectrum analysis.

The interstellar lines in Figure 1 (indicated with arrows) are typical low-ionization UV interstellar lines (e.g., de Boer, Jura, & Shull 1987) and are identifiable in the early SN 1993J *IUE* spectra (Wamsteker et al. 1993). They are all resonance lines arising from the absolute ground states of their ions. High-resolution *IUE* and optical spectra of the interstellar lines show multiple components with velocity offsets in the range -140 to $+181$ km s^{-1} (Wamsteker et al. 1993; Wheeler et al. 1993); the components are caused by gas in our Galaxy, M81, and, perhaps, other sources along the line of sight.

In § 2, we give a synthetic spectrum analysis of the April 15 spectrum. In § 3, we compare this spectrum to the combined UV and optical spectra of other supernovae. The conclusions are given in § 4.

2. SYNTHETIC SPECTRUM ANALYSIS

We have done a parameterized LTE synthetic spectrum analysis of the combined *HST* and optical April 15 spectrum using procedures similar to those of Kirshner et al. (1993). Radiative transfer is treated with the Sobolev method. We adopted a model for the supernova with an inner boundary at 6500 km s^{-1} that radiates like a blackbody at 7750 K in the comoving frame. The temperature decreases outward from the inner boundary but beyond 8000 km s^{-1} becomes constant at 6000 K. The (comoving) density profile was adapted from one for SN 1987A; above 8000 km s^{-1}, the profile decreases exponentially with *e*-folding velocity 1500 km s^{-1}. The inner boundary density is 6.3×10^{-14} g cm^{-3}. SN 1993J is thought to have a thin hydrogen envelope of mass less than 1 $M_\odot$ above a helium core (Nomoto et al. 1993; Podsiadlowski et al. 1993). Adopting this picture, we use a hydrogen envelope of 0.16 $M_\odot$ with solar composition above a helium core. The interface between the hydrogen envelope and helium core is at 8000 km s^{-1}. Our radiative transfer calculations are not very sensitive to the helium core since most line formation occurs above 8000 km s^{-1}. The electron opacity optical depth $\frac{2}{3}$ is at ~ 9500 km s^{-1} where the density is $\sim 1 \times 10^{-14}$ g cm^{-3}. We impose an outer boundary at 16,400 km s^{-1} as a crude way of keeping the Ca II H and K line absorption from being too broad. The blue edge of the Hα absorption shows, however, that some ejecta move at $\sim 19,000$ km s^{-1}.

Figure 2 shows synthetic spectra calculated with full and restricted line lists matched to a smoothed April 15 spectrum. The restricted calculations show the contributions of individual ions to the spectrum formation. The inner boundary temperature of 7750 K with an uncertainty of 1000 K is adequate to account for the optical continuum. If $E(B-V)$ is 0 mag or 0.2 mag, then inner boundary temperatures of $\sim 7000 \pm 1000$ K and $\sim 9000 \pm 1000$ K, respectively, would account for the optical continuum.

Overall, the full-line calculation reproduces the observed optical spectrum rather well. There are, however, some notable discrepancies. The Hα line is not well fitted; to reproduce the observed net emission requires a NLTE calculation. The He I λ5876 line is not produced at all in the synthetic spectrum.

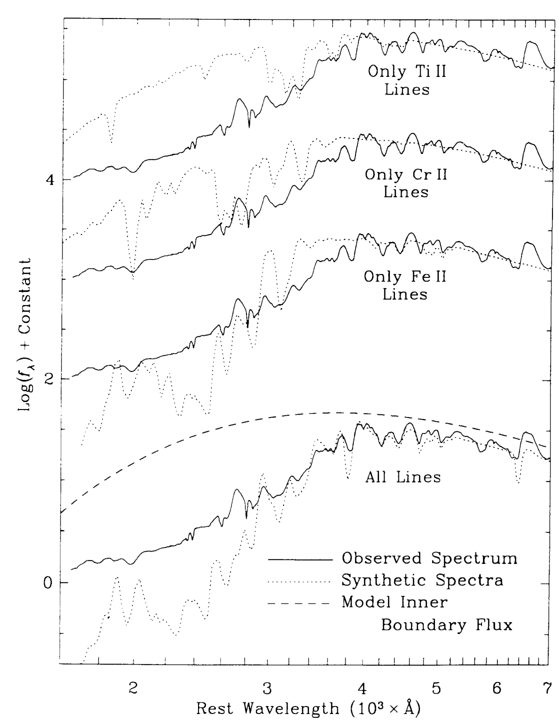

FIG. 2.—The April 15 SN 1993J spectrum and synthetic spectra calculated with restricted and full line lists. The observed spectrum has been corrected for extinction and redshift as in Fig. 1 and been given a 20 Å boxcar smoothing.

With the supernova atmosphere temperatures prevailing on April 15, this line requires nonthermal effects to be as strong as observed; we estimate that the line is $\sim 10^8$ times stronger than LTE predicts. The nonthermal excitation may be caused by X-rays from the shock interaction of the supernova ejecta and a circumstellar envelope (see below) or by γ-rays and positrons produced by the ^{56}Ni decay chain. The radioactive ^{56}Ni would have been synthesized and mixed outward during the explosion. The absorptions of Hα and the He I λ5876 line have peculiar shapes that consist of two components. We do not fit these peculiar shapes and cannot explain them; an asymmetry in the ejecta is a possibility (Schmidt et al. 1993), but then we would expect other lines to be affected.

The dashed line if Figure 2 is the model inner boundary flux. The full-line synthetic spectrum is everywhere reduced from this. At optical wavelengths the deficiency mainly results from electrons which scatter flux back to the interior. The deficiency in the UV region is much larger because of the heavy UV line blanketing that is typical of supernova atmospheres (see § 1). The line blanketing either absorbs flux or scatters it back to the interior. The Fe II line calculation shows that Fe II lines cause most of the blanketing. The Ti II and Cr II line calculations show that these lines have a lesser effect; similar calculations with lines of Mn II, Co II, and Ni II show that those ions are of comparable importance to Ti II and Cr II. As can be seen from Figure 2, the observed spectrum has a smaller UV flux deficiency than the synthetic spectrum. This discrepancy is not necessarily caused by a defect of the model. It takes great physical and numerical accuracy to calculate large flux deficiencies correctly; such accuracy is too much to demand of a parameterized LTE Sobolev method calculation.

The observed spectrum does not show the complex structure seen in the UV region of the synthetic spectra blueward of $\sim$2900 Å. This structure results from a complex blend of P Cygni absorptions caused by the strongest iron peak element lines. It is probable that the bumps at $\sim$2950 Å and $\sim$3200 Å in the observed spectrum are largely shaped by iron peak lines as the synthetic spectrum suggests. The bump at $\sim$2730 Å is probably a NLTE Mg II λ2798 emission line. This feature stands a factor of $\sim$1.5 above the local continuum and *IUE* spectra show that it grows to a factor of $\sim$3 above the local continuum by April 30. The feature is blueshifted from the rest wavelength of the Mg II line because the ejecta are very optically thick. A similar, though narrower, emission feature developed in the Type II supernova SN 1979C at $\sim$50 days after the explosion (Benvenuti et al. 1982; see also Fig. 3 below).

The structure seen in the synthetic spectra blueward of $\sim$2900 Å was a constant feature of our calculations. Thus the relatively smooth $\sim$1650–2900 Å region of the observed spectrum requires an explanation. It has been suggested that the smoothness may be caused by a relatively flat outer density profile that results from the interaction of the ejecta and a circumstellar envelope (Höflich 1993). That SN 1993J had a thick circumstellar envelope has been inferred (e.g., Lundqvist, Fransson, & Chevalier 1994) from radio emission from the supernova (e.g., Van Dyk et al. 1993). The origin of the envelope is probably a circumstellar wind from the progenitor. Synthetic spectrum calculations using flatter density profiles (while decreasing the density in the ejecta below 10,000 km s^{-1} to keep the photosphere in the same location) produced some smoothing of the UV region, but the synthetic optical Fe II lines became too weak. Detailed spectral modeling using density profiles calculated with circumstellar interaction are needed to further the investigation.

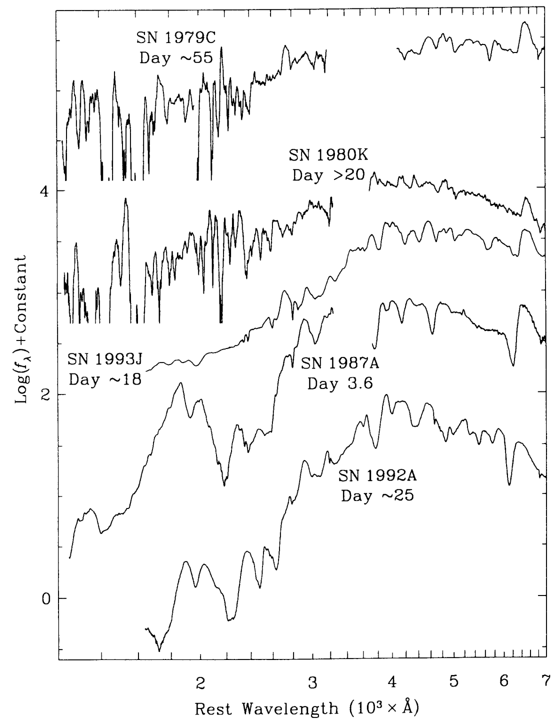

FIG. 3.—Combined UV and optical spectra of supernovae SN 1979C, SN 1980K, SN 1992A, and SN 1993J. The spectra have been corrected for redshift and extinction. The $E(B-V)$ values used are 0.1 mag and 0.32 mag for SN 1979C and SN 1980K (Panagia 1985), 0.15 mag for SN 1987A (Hamuy et al. 1988), 0 mag for SN 1992 A (Kirshner et al. 1993), and 0.1 mag for SN 1993J (see § 1). The standard extinction law of Cardelli et al. (1989) has been used, except for the SN 1987A UV region where the extinction law of Fitzpatrick (1986) for the 30 Doradus region of the LMC has been used. Estimated times from explosion are given, except for SN 1987A where the exact time is known and for SN 1980K where only a lower limit is given. The UV spectrum for SN 1979C comes from 10 days before the optical spectrum; the time since explosion is an average estimate. In the other cases, the time differences between UV and optical regions are negligible.

3. COMPARISON OF SPECTRA

Figure 3 compares our SN 1993J spectrum with spectra of Type II supernovae SN 1979C, SN 1980K, and SN 1987A, and the Type Ia supernova SN 1992A. The comparison UV spectra come from the *IUE*, except for SN 1992A UV spectrum which is from the *HST* (Kirshner et al. 1993). For the type II supernovae, we chose spectra from epochs when the optical region resembles the SN 1993J optical region.

We have done a 20 Å boxcar smoothing of all the UV spectra and most of the optical spectra. In the cases of the UV spectra of SN 1979C and SN 1980K, the 20 Å boxcar smoothing is insufficient to remove coherent noise. A real intrinsic continuum exists in these *IUE* spectra blueward of $\sim$2600 Å, but the structure seen there is not well measured.

The most striking aspect of Figure 3 is that the SN 1987A and SN 1992A UV regions resemble each other and resemble the UV region of the full-line synthetic spectrum shown in Figure 2. The SN 1979C and SN 1980K UV regions resemble the SN 1992J UV region in showing no obvious broad absorptions. Earlier UV spectra of SN 1979C and SN 1980K also lack obvious broad absorptions.

Radio observations imply that SN 1979C and SN 1980K have thick circumstellar envelopes shed by the progenitors (Weiler et al. 1986) that are comparable in density with the circumstellar envelope of SN 1993J (Lundqvist et al. 1994). SN 1987A was also detected in the radio, but was intrinsically fainter by about three orders of magnitude at peak radio luminosity (Turtle et al. 1987) and had circumstellar densities that are estimated to be ~10–100 times smaller than those of SN 1979C and SN 1980K (Chevalier 1987; Lundqvist & Fransson 1987). Since no Type Ia supernova has ever been detected in the radio, presumably much less circumstellar material surrounds SN 1992A than SN 1979C, SN 1980K, and SN1993J. These facts, together with Figure 3, suggest that a smooth UV spectrum lacking broad absorptions is a characteristic of supernovae with thick circumstellar envelopes.

For SN 1979 C and SN 1980K, emission lines blueward of ~2000 Å and flux excesses in the far-UV ($\lesssim$1500 Å) are apparent in earlier spectra than those we show. These features have been explained by Comptonized flux from the shock interaction of supernova ejecta with a circumstellar envelope (Fransson 1982; Fransson et al. 1984). Comptonized flux is a small effect redward of ~1500 Å and thus does not explain the shape of our SN 1993J UV spectrum.

The spectra of SN 1987A, SN 1992A, and SN 1993J show definite UV flux deficiencies relative to blackbody fits to the optical. SN 1980K and probably SN 1979C show UV flux deficiencies redward of ~1500 Å; blueward of ~1500 Å, the far-UV flux excesses may still be present, but the spectra are poor. Detailed modeling is needed to understand the UV flux deficiencies. If circumstellar interaction can eliminate absorptions, then it may have a large effect on the degree of UV flux deficiency as well.

4. CONCLUSIONS

We have obtained a *HST* spectrum of SN 1993J on 1993 April 15 from 1650 to 4780 Å. Our synthetic spectrum calculations account for the optical features of this spectrum and those of its ground-based extension, but not for the lack of strong iron peak element line absorptions in the ~1650–2900 Å region. The UV behavior may result from the interaction of the supernova ejecta with a thick circumstellar envelope. One possibility is that the interaction changes the density profile of the outer ejecta and thereby affects the radiative transfer in that region. Other supernovae with thick circumstellar envelopes have UV spectra that also lack strong absorptions. Thus a relatively smooth UV spectrum appears to be a signature of supernovae whose ejecta interact with thick circumstellar envelopes. Detailed UV modeling is needed to investigate this possibility and to extract information on progenitor mass loss.

We thank the energetic staff of the Space Telescope Science Institute, especially Brett Blacker, for their efforts in making the *HST* observation in a timely way. We also thank Robert Harkness, Peter Höflich, and Brian Schmidt. D. J. Jeffery thanks Peter Sutherland and McMaster University for their hospitality. Support for this work was provided by NASA through grant GO-2563.01-87A from the Space Telescope Science Institute which is operated by AURA under NASA contract NAS 5-26555, and by NSF grants AST 92-18475 and AST 91-15174 and NASA grants NAG 5-841 and NAGW-1789.

REFERENCES

Aldering, G., Humphreys, R. M., & Richmond, M. 1993, preprint
Benetti, S., Contarini, G. Gratton, R., & Turatto, M. 1993, IAU Circ., No. 5751
Benvenuti, P., Sanz Fernandez de Cordoba, L., Wamsteker, W., Macchetto, F., Palumbo, G. C., & Panagia, N. 1982, An Atlas of UV Spectra of Supernovae (Noordwijk: ESA)
Cardelli, J. A., Clayton, G. C., & Mathis, J. S. 1989, ApJ, 345, 245
Chevalier, R. A. 1987, in ESO Worskhop on the SN 1987A, ed. I. J. Danziger (Garching: ESO), 481
de Boer, K. S., Jura, M. A., & Shull, J. M. 1987, in Exploring the Universe with the *IUE* Satellite, ed. Y. Kondo (Dordrecht: Reidel), 485
Fitzpatrick, E. L. 1986, AJ, 92, 1068
Fransson, C. 1982, A&A, 111, 140
Fransson, C., Benvenuti, P., Gordon, C., Hempe, K., Palumbo, G. G. C., Panagia, N., Reimers, D., & Wamsteker, W. 1984, A&A, 132, 1
Harkness, R. P. 1991, in ESO/EIPC Workshop: SN 1987A and Other Supernovae, ed. I. J. Danziger & K. Kjär (Garching: ESO), 447
Hamuy, M., Suntzeff, N. B., González, R., & Martin, G. 1988, AJ, 95, 63
Höflich, P. 1993, private communication
Kirshner, R. P., et al. 1993, ApJ, 415, 589
Lundqvist, P., & Fransson, C. 1987, in ESO Workshop on the SN 1987A, ed. I. J. Danziger (Garching: ESO), 495
Lundqvist, P., Fransson, C., & Chevalier, R. A. 1994, in preparation
Nomoto, K., Suzuki, T., Shigeyama, T., Kumagai, S., Yamaoka, H., & Saio, H. 1993, Nature, 364, 507
Panagia, N. 1985, in Supernovae as Distance Indicators, ed. N. Bartel (Berlin: Springer-Verlag), 14
Podsiadlowski, P., Hsu, J. J. L., Joss, P. C., & Ross, R. R. 1993, Nature, 364, 509
Schmidt, B. P., et al. 1993, Nature, 364, 600
Sonneborn, G., Rodriguez, P. M., Wamsteker, W., Fransson, C., & Kirshner, R. P. 1993, IAU Circ., No. 5754
Turtle, A. J., et al. 1987, Nature, 327, 38
Van Dyk, S. D., Weiler, K. W., Rupen, M. P., Sramek, R. A., & Panagia, N. 1993, IAU Circ., No. 5759
Wagoner, R. V., Perez, C. A., & Vasu, M. 1991, ApJ, 377, 639
Wamsteker, W., Rodriguez, P. M., Gonzalez, R., Sonneborn, G., & Kirshner, R. P. 1993, IAU, Circ., No. 5738
Weiler, K. W., Sramek, R. A., Panagia, N., van der Hulst, J. M., & Salviati, M. 1986, ApJ, 301, 790
Wheeler, J. C., et al. 1993, ApJ, 417, L71
Wheeler, J. C., Harkness, R. P., Barkat, Z., & Swartz, D. 1986, PASP, 98, 1018