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SN 1961V: AN EXTRAGALACTIC ETA CARINAE ANALOG?[1]

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ABSTRACT

We have obtained spectra of the site of the unique Type V supernova SN 1961V in NGC 1058, and of two nearby H II regions. Broad (FWHM $\approx$ 2100 km s^{-1}) Hα emission, with a luminosity of 2×10^{36} ergs s^{-1}, is detected at the position of SN 1961V. SN 1961V is thus the first historical extragalactic object classified as a supernova to be optically recovered. The "east H II region," about 1".6 northeast of SN 1961V, is a small high-excitation H II region, with strong [O II], [N II], and [S II] lines for its excitation, and no detectable continuum. The temperature of the ionizing star must be greater than 45,000 K, but the H II region requires only a small fraction of the ionizing flux that such a star would produce. We argue that the east region is probably ionized by the SN 1961V progenitor, some 60 pc distant, and intercepts only a fraction of the ionizing flux from that star. The nearby "west H II region" is an intermediate-age supernova remnant, similar in its optical and radio properties to the most luminous supernova remnants in M31 and M33, but is not obviously associated with SN 1961V.

We believe that SN 1961V was not a supernova (the explosion of a massive star at the end of its life) but the superoutburst of a luminous blue variable—an exaggerated η Carinae–type outburst of a very massive, evolved star near the end of core hydrogen burning. The long plateau in the light curve following outburst, at nearly the same brightness as the preoutburst star, suggests that the progenitor survived the outburst and was seen for more than 4 years afterward. It eventually faded because of the formation of optically thick dust in the ejecta, which amounts to only $\sim$1–10 $M_\odot$. The progenitor is one of the most massive and luminous known stars, with a zero-age main-sequence (ZAMS) mass $\gtrsim$240 $M_\odot$ and a current mass $\gtrsim$170 $M_\odot$. The major reduction in mass is a direct result of mass lost during core hydrogen burning through a wind, and perhaps previous large episodic events. The hot underlying star should therefore now be of type Of/WN, like the S Doradus star R127 in the Large Magellanic Cloud but several times more luminous. During outburst the star had the spectrum and colors of an F supergiant, formed in an extended optically thick wind, and was thus optically very bright, partly at the expense of a changing bolometric correction. In addition, considerable thermal radiation was apparently liberated from the material ejected by the star, resulting in the energetic outburst observed. Such a star can account for both the high excitation of the nearby east H II region and the extreme visual brightness of the progenitor without requiring an unreasonably high mass or luminosity.

Our observed Hα flux from the site of SN 1961V suggests a circumstellar extinction of $A_V \approx 5$ mag, if the surviving star resembles η Car. The present brightness of the star should be near $V \approx 27$ mag with a large uncertainty. The infrared brightness should be much higher.

Subject headings: nebulae: H II regions — stars: massive — stars: mass loss — stars: supernovae — stars: variables

I. INTRODUCTION

SN 1961V in the Sc galaxy NGC 1058 ($cz = 518$ km s^{-1}; Sandage and Tammann 1981) is the prototype, and the only generally recognized example, of the Type V supernovae (Zwicky 1965; Oke and Searle 1974). Its characteristics are clearly distinct from those of Type I and II events (Bertola 1963), and it is also the only supernova other than SN 1987A with a known progenitor star. An 18th magnitude star was visible at the supernova site on preoutburst plates dating back to 1937 October (Bertola 1964; Zwicky 1964). This progenitor was extraordinarily luminous, $M_{pg} = -12.1$ (dereddened) for a distance of 8 Mpc, making it easily the brightest star in NGC 1058 and possibly the brightest known individual star in *any* galaxy. The progenitor was last seen at this brightness on 1960 September 14 (Bertola 1963); by 1960 November 21 it was 2 mag brighter at $m_{pg} = 15.8$ (Bertola 1963; Zwicky 1964). The outburst was not discovered, however, until 1961 July, some 8 months later. By this time it had climbed to $m_{pg} = 14$, and it remained at this brightness for another 5 months.

The light curve of SN 1961V (Bertola 1964; Utrobin 1984; Doggett and Branch 1985) is remarkable both for its duration and structure. The star reached a brief maximum in 1961 December at $m_{pg} = 12.5$, half a magnitude brighter than the normal Type II-P supernova 1969L in the same galaxy (Ciatti, Rosino, and Bertola 1971; Kirshner *et al.* 1973). It then quickly faded to $m_{pg} = 17$, paused at this brightness for 6 months, then continued a rapid decline to $m_{pg} = 18.5$–19 by early 1963, over

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2 years after the beginning of the outburst and just over a year past maximum light. At this time the object was 0.5–1 mag fainter than the presupernova star. It remained near $m_{pg} = 19$ for another 4 years (!), through early 1967 (Bertola 1967). The star faded below visibility ($m_{pg} \gtrsim 22$) by 1968 September when only the faint H II regions near the supernova could be seen (Bertola and Arp 1970; Fesen 1985).

The spectra and colors of the outburst (Branch and Greenstein 1971) were as remarkable as the light curve. The spectrum of the supernova was unlike any seen before, displaying narrow emission lines of hydrogen, helium, and singly ionized iron that indicated an expansion velocity of only ~ 2000 km s^{-1}. These characteristics were more like those of a normal *nova* near maximum light. A He/H abundance ratio of at least 4 times solar is suggested by the strength of the He lines. The spectrum and continuum colors remained remarkably constant throughout the outburst, even after a 4.5 mag decline. In particular, during 18 months of monitoring, SN 1961V never underwent the dramatic transition to a "supernebular" spectrum (Wheeler *et al.* 1986), characteristic of old normal supernovae. Bertola (1965) obtained broad-band photoelectric photometry of the outburst for 4 months around maximum light. Again, the colors were remarkably constant, resembling those of an F supergiant or a normal nova near maximum light.

Images of the site of SN 1961V taken shortly after the star had faded from view showed a faint H II region in an outlying spiral arm of NGC 1058 roughly coincident with the site of the supernova (Bertola and Arp 1970). More recent observations (Fesen 1985) revealed two faint H II regions near the site, aligned almost east–west and $\sim 4''$ apart. Neither, however, is perfectly coincident with the location of SN 1961V. The supernova apparently occurred on the southwest corner of the eastern H II region (hereafter "the east region"); a faint knot of Hα emission was seen there in the images of Fesen, barely resolved from the H II region. A combined spectrum of the two H II regions showed only Hα and [O III] emission, with [O III] λ5007/H$\alpha \approx 1.0$–1.5, typical of outlying H II regions in late-type spirals. Additional optical imaging by Cowan, Henry, and Branch (1988) has confirmed Fesen's observations, reaching about 2 mag deeper but with much poorer seeing.

Radio images made at 20 cm with the VLA at $1\farcs2$ resolution by Branch and Cowan (1985) revealed only two detectable radio sources in NGC 1058, the western radio source being coincident with the west H II region and the eastern source being coincident with the supernova position. Additional 6 cm observations by Cowan, Henry, and Branch (1988) showed that both sources are nonthermal.

The interpretation of the observations of this remarkable object depend upon two additional quantities: (1) the distance to NGC 1058 and (2) the bolometric correction (BC) to the apparent magnitude, in particular before the outburst. Estimates of the distance to NGC 1058, a face-on Sc II–III galaxy, range from ~ 12 Mpc applying the Baade-Wesselink method to SN 1969L (Kirshner and Kwan 1974; Schurmann, Arnett, and Falk 1979) to 5.3 Mpc for the average of three galaxies in the NGC 1003 cluster (Bottinelli *et al.* 1985) using the method of "sosie" galaxies. As a compromise we adopt 8 Mpc below, although we stress that the *qualitative* features of our model do not hinge upon the precise value of the distance. Previous analyses of SN 1961V (Chevalier 1981; Utrobin 1984) applied a BC of approximately -4 to the progenitor on the assumption that massive stars always appear as hot O stars. Below, however, we argue that the SN 1961V progenitor may have been in a phase dominated by an optically thick wind with the colors of an A or F supergiant (and a correspondingly small BC), both *before and after outburst*. This assumption is important because it leads to a large difference in the derived values of both the luminosity and the mass of the progenitor.

The extreme duration of the outburst, the luminosity of the progenitor star, and its association with a high-excitation H II region led Utrobin (1984) to model SN 1961V as the explosion of a 2000 $M_\odot$ star. The progenitor was suggested by Utrobin to be similar to the supposed supermassive star R136a in 30 Dor (Feitzinger *et al.* 1980; Cassinelli, Mathis, and Savage 1981; Savage *et al.* 1983), and, like R136a, to be surrounded by a giant H II region—in this case a fossil H II region created by the supernova progenitor. More recent observations, however, have demonstrated that R136a is not a single "supermassive" star but rather a compact cluster of relatively massive stars (Walker and O'Donoghue 1984; Moffat, Seggewiss, and Shara 1985; Weigelt and Baier 1985; Melnick 1985; Neri and Grewing 1988). The loss of R136a as an analogous object weakens Utrobin's proposal that the progenitor of SN 1961V was a "supermassive" star. In addition, realistic models of very massive supernova explosions do not produce light curves or compositions (and hence spectra) that look like those of SN 1961V (Stringfellow and Woosley 1988).

Our observations of the SN 1961V site were undertaken to study the environment in which this outburst occurred. Analysis of the data and reinterpretation of many previous observations suggest that SN 1961V was not the explosion of a star of extreme mass, nor indeed even a supernova.[3] We propose instead that the site, and SN 1961V itself, can be explained with nearby luminous blue variable (LBV) analogs: the SN 1961V environment is similar to the Gum Nebula, while the star itself is similar to the hot S Doradus stars like R127 in the LMC, Var 83 in M33, and with what we believe is the best analog, η Car. Our observations are presented in § II, while § III discusses the results for the H II regions. Our model for the progenitor of SN 1961V and the observed outburst are discussed in § IV. A brief version of this study was reported by Stringfellow *et al.* (1988).

II. OBSERVATIONS

Spectra of the SN 1961V environment were obtained with the Cassegrain CCD spectrographs on the 3 m Shane telescope of Lick Observatory (Miller and Stone 1987; Miller, Robinson, and Goodrich 1988). A sensitive Texas Instruments 800 × 800 pixel^2 CCD was the detector, and various gratings and grisms were used to obtain spectra in the wavelength ranges and resolutions listed in Table 1. We used the transmission spectrograph for the 1986 January spectrum and the UV Schmidt spectrograph for all subsequent spectra. Also, the 1986 January data were obtained through the spectropolarimetry optics, which split the light into two beams and recorded them separately. The extra optics allow minimal light loss, still enable us

[3] Here we define a *supernova* to be the final explosion *at the end of a star's life*, brought about either by core collapse and a subsequent bounce or by nuclear incineration of the entire star. If a remnant remains after the explosion, it is a collapsed degenerate core and not an underlying star still undergoing nuclear burning in its center. Mere ejection of the outer envelope, even if associated with high luminosities and large kinetic energies, is not a supernova if the star basically survives the outburst. This is not an empirical definition but rather a "theoretical" one, which we adopt here for clarity, since we are interested in the nature of the outburst and the underlying object. This definition is consistent with both Type I and Type II supernovae.

TABLE 1

OBSERVATION LOG

UT Date 1986	Wavelength Range (Å)	Resolution (Å)	Exposure (minutes)	Slit	sec z
Jan 11	4200–6900	8.0	30	2".0	1.0
Oct 9	6120–6920	3.0	60	2.0	1.0
	6120–6920	3.0	83	2.0	1.1
Oct 10	3340–4920	5.6	60	2.0	1.1
	4300–5100	2.8	55	2.0	1.2
Dec 26	6130–6940	4.2	60	3.2	1.0
Dec 27	6130–6940	4.2	70	3.2	1.1
	4300–5100	3.8	40	3.2	1.3

to flux-calibrate the spectra accurately, and have the advantage of providing two independent spectra. The slit in all exposures was aligned east–west to include both H II regions, yet remain close to the parallactic angle (Filippenko 1982) during observations made at considerable zenith angles.

Data reduction included bias subtraction, flat-fielding, wavelength calibration, and flux calibration using the standard stars in Stone (1977). Isolated emission lines and blends were measured on the low-resolution spectrum; the high-resolution spectra were subsequently used to deblend more accurately the Hα + [N II] and [S II] composites. The [O II]/Hβ and [Ne III]/Hβ line intensity ratios were measured from the UV spectra. All resulting line fluxes are presented in Table 2, and the composite low-resolution spectrum is shown in Figure 1.

The mean east–west separation of the two H II regions is 3".7, with the east region having a seeing-corrected diameter of $\sim$2".8 and the west region being unresolved. In all of our well-exposed spectra we detect a weak blue continuum 1".6 west of the east region, and near the site of SN 1961V. The continuum fluxes are rather uncertain, especially considering possible centering errors in the slit, but are measured as 9.2 at 4350 Å and 9.0 at 6330 Å in units of 10^{-18} ergs s^{-1} cm^{-2} Å^{-1}. This continuum source was found in B images which Utrobin (1987) has presented. Its brightness and color are consistent with a small cluster containing from 5 to 10 early O stars, or a larger number of early B main-sequence stars, with a combined absolute magnitude of $M_V \approx -7$.

The high-resolution spectra also show a broad component of Hα at a position coincident with SN 1961V, and having the same redshift as the narrow lines. The FWHM of this emission is about 46 Å (2100 km s^{-1}), comparable to the reported width of the emission lines during the 1961 outburst. Figure 2 presents the Hα spectra for the east and west H II regions and the SN 1961V position. Much of the narrow Hα seen at the supernova position is due to some overlap of the east region along the slit, and similarly the spectrum of the east region is partly contaminated by light from the supernova's position.

TABLE 2

EMISSION-LINE FLUXES

LINE	OBSERVED East	OBSERVED West	DEREDDENED[a] East	DEREDDENED[a] West
[O II] λ3727	4.91	3.81	5.88	4.19
[Ne III] λ3869	0.58	0.59	0.68	0.64
Hβ λ4861	1.00	1.00	1.00	1.00
[O III] λ4959	1.22	1.52	1.20	1.51
[O III] λ5007	3.81	4.62	3.72	4.56
[O I] λ6300	0.25:[b]	0.48	0.21:[b]	0.44
[N II] λ6548	0.31	0.28	0.26	0.25
Hα λ6563	3.56	3.34	2.90	3.00
[N II] λ6584	0.94	0.83	0.77	0.74
[S II] λ6716	0.44	0.64	0.35	0.57
[S II] λ6731	0.37	0.64	0.30	0.57
Absolute Hβ flux (10^{-15} ergs cm^{-2} s^{-1})	0.32	0.29	0.60	0.40

[a] $E_{B-V} = 0.19$ mag for the east region, 0.10 mag for the west region.

[b] The measured [O I] flux in the east region may be quite uncertain, as explained in the text.

III. THE H II REGIONS

The optical spectra of the east and west H II regions are superficially rather similar. Both have high [O III]/Hβ ratios characteristic of high-excitation regions. The west region, however, has relatively strong [O I] λ6300 and [S II] $\lambda\lambda$6716, 6731 lines, often indicative of a shock contribution. The radio data of Branch and Cowan (1985) and of Cowan, Henry, and

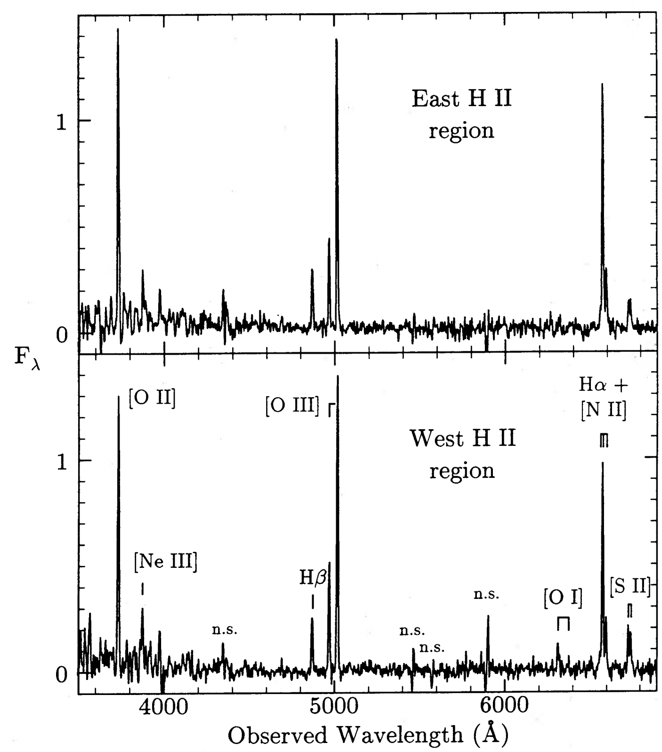

FIG. 1.—Low-resolution optical spectra of the two H II regions adjacent to the site of SN 1961V. The ordinate is in units of 10^{-16} ergs cm^{-2} s^{-1} Å^{-1}. The prominent [O I] and [S II] lines in the west region, in conjunction with the radio data of Cowan, Henry, and Branch (1988), confirm the presence of a supernova remnant there, while the strong [O III], [Ne III], and [O II] lines in the east region indicate a hot ionizing source, with $T_* \gtrsim 45{,}000$ K. Incompletely subtracted night-sky emission lines are indicated by "n.s."

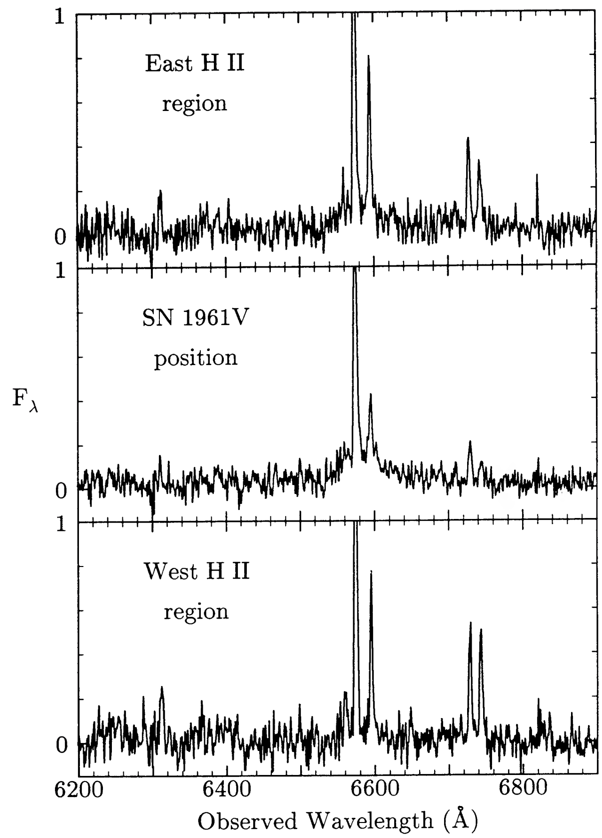

FIG. 2.—High-resolution red spectra of the H II regions and the SN 1961V site. The ordinate is in relative flux units. Note the broad Hα at the base of the narrow Hα and [N II] lines at the supernova position. These wings are absent in the west region. Because the east region and the SN position overlap slightly in the long-slit spectra, the broad Hα is also present in the top panel, and much of the narrow emission at the SN site may be due to the east H II region. Inspection of the two-dimensional long-slit data show that the broad Hα is indeed centered at the SN position. The FWHM of the broad emission feature is ~ 2100 km s^{-1}.

Branch (1988) have already shown that the west region probably contains a supernova remnant, and our optical spectra support this. At 8 Mpc the flux level reported by Branch and Cowan for the west region is about a third of the intrinsic radio luminosity of Cas A. The reddening of $E_{B-V} = 0.10$ mag in Table 2 is derived from the Hα/Hβ ratio assuming the intrinsic value of 3.0 typical of shocks or of recombination following photoionization. Our high-resolution Hα spectra indicate that the FWHM of the narrow Hα emission lines in both the west and the east region is less than 150 km s^{-1}.

We suspect, but cannot prove, that part of the [O I] present in the east region high-resolution spectrum of Figure 2 is due to incomplete night-sky subtraction. The [O I] emission is absent, or very weak, in the low-resolution spectrum of Figure 1. Bearing this in mind, the east region has less [O I] and weaker [S II] lines than the west region; it is probably a photoionized H II region relatively uncontaminated by shocks. Comparing the data in Table 2 with the published models of McCall, Rybski, and Shields (1985) and unpublished models of G. A. Shields and D. Garnett (1988, private communication), we note that the high [O III]/Hβ ratio can be produced only if the temperature of the exciting star is $T_* \gtrsim 45{,}000$ K, at least as hot as a typical O3 star. However, the Hα luminosity indicates that the total ionizing photon flux is $\sim 6 \times 10^{49}$ s^{-1}. This value is comparable to that expected for a single embedded O3 star, and a factor of at least 100 less than the ionization requirements of 30 Dor. The strong [O II] emission indicates that the east region is ionization-bounded and not density-bounded, so it is probably ionized by a very dilute radiation field; one possibility is that the weak OB cluster found by Utrobin (1987) is the energy source. The projected distance of the east region from both SN 1961V and the OB cluster (nearly coincident with SN 1961V) is ~ 60 pc, and we estimate that the region intercepts a maximum of 25% of the light from these two sources. The emission rate of ionizing photons from 10 O3 stars is $\sim 6 \times 10^{50}$ s^{-1}, sufficient to provide the energy to the east region, but such a cluster is rare and would be evident in, for example, the spectra. For stars cooler than O3, however, there are too few ionizing photons to produce the observed Hα.

An alternative energy source is the SN 1961V progenitor itself. The recombination time scale for the east region is ~ 2000 yr, while the light travel time is ~ 200 yr. According to this interpretation the progenitor must have been a very hot O or Wolf-Rayet star in the very recent past. It should be noted that model 9 of Utrobin (1984) produces 5×10^{51} ionizing photons each second, a factor of almost 25 too much (including the covering factor). Slit losses affecting the Hα flux cannot account for this large discrepancy, and hence this provides another argument against the large BC used by Utrobin and others.

The suggested analogy of the SN 1961V *environment* to that of 30 Dor (Utrobin 1984) is also not supported by our observations. The H II regions near SN 1961V are about a factor of 100 less luminous and less massive than 30 Dor, and there is little evidence for any very massive stars except for the SN 1961V progenitor itself. We suggest that a better analogy is with the Gum Nebula region (Chanot and Sivan 1983), except that the Gum Nebula is density-bounded rather than ionization-bounded and is larger (260 pc). The ionizing source of the Gum Nebula, ζ Pup, is a very luminous O4 If star with $L \approx 10^6\ L_\odot$, $T_{\rm eff} = 42{,}000$ K, current mass 36 $M_\odot$, and ZAMS mass 70–90 $M_\odot$ (Bohannon *et al.* 1986). Zeta Pup is not obviously associated with any other O stars, although several B associations (analogous to the apparent cluster close to SN 1961V) are nearby. The bright emission patches of the Gum Nebula extend some 100 pc from ζ Pup, without having any obvious ionizing stars inside them. Finally, there is even an intermediate-age supernova remnant (the Vela SNR) nearby, analogous to the west H II region.

IV. WHAT WAS SN 1961V?

a) The Progenitor

With our adopted distance of 8 Mpc and our measured reddening of $A_{\rm pg} \approx A_B \approx 0.6$ mag, the absolute brightness of the SN 1961V progenitor was about $M_{\rm pg} \approx M_B \approx -12.1$. The progenitor was clearly the most luminous individual star in NGC 1058. Normal supergiants are observed to have $M_V \gtrsim -10$, while *luminous blue variables* (LBVs; Conti 1984) do in fact have magnitudes in this range, as seen in Table 3. Examples of LBVs include η Car, S Doradus–type stars, and the Hubble-Sandage (Hubble and Sandage 1953) variables. Lamers (1987) has recently reviewed the characteristics and categorized the different types of LBVs. Of interest here are those defined as having *large eruptions*, with variations $\Delta m_V \geq 3$ mag, or obvious nebulosities surrounding them due to previous outbursts. Both properties have been observed for η Car.

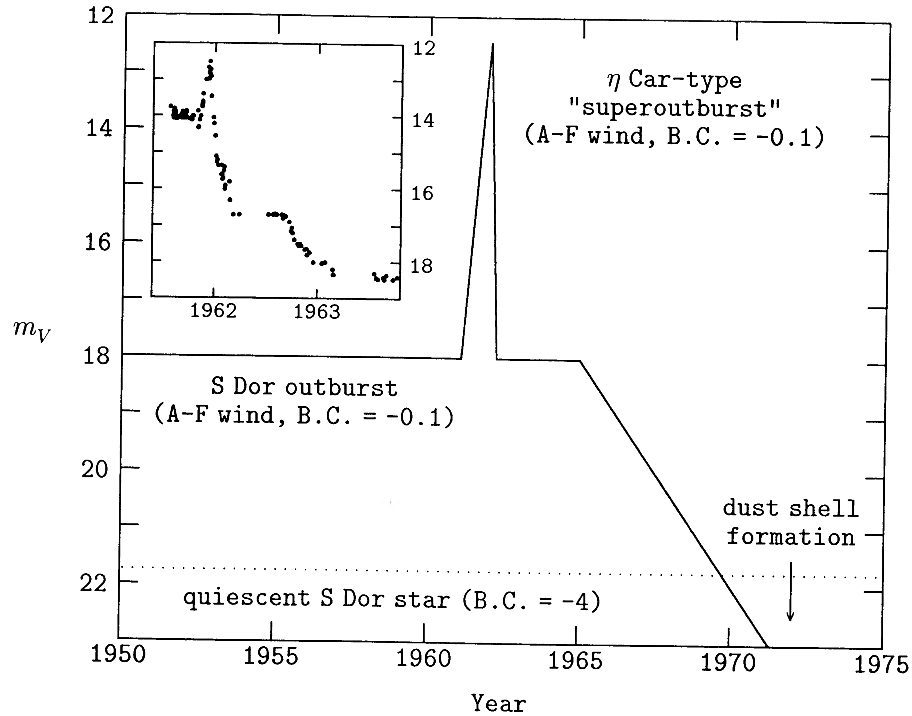

FIG. 3.—Schematic diagram of the SN 1961V light curve and our interpretation of the events. The inset shows data from Bertola (1963, 1965) covering the maximum, to demonstrate the complex structure in this part of the light curve. The progenitor, observed since 1937 October at $m_{pg} \approx 18$, is proposed to have been a massive S Doradus star in a normal outburst (optically thick wind) phase. The observed "supernova" outburst was analogous to the η Car superoutburst which occurred in the 1840s. The star subsequently returned more or less to its preoutburst state, remaining there for 4 yr. The formation of optically thick dust within the ejected material then caused a steady decline in the light curve after early 1965. The very uncertain brightness of the underlying, "quiescent" S Doradus star with an intrinsic BC ≈ -4 mag is also shown.

In the case of more moderate changes of $\Delta m_V \approx 1$–2 mag, which are also the most common photometric variations observed in LBVs, $M_{\rm bol}$ appears to remain nearly constant during outburst while M_V increases dramatically (Lamers 1987 and references therein). Because of the sizable change in M_V and the (near) constancy of $M_{\rm bol}$, this implies a similar large change in the BC; $M_{\rm bol} = M_V + {\rm BC} \approx$ constant. However, this has been observed only for a few LBVs with moderate outbursts, and is unconfirmed for large outbursts. In fact, η Car apparently increased its M_{bol} by 1 mag or so, accompanied by the usual increase in M_V (Davidson 1987*a*). We do not know the time history of $M_{\rm bol}$ for any LBV during a large eruption.

The similarity between the observed properties of LBVs undergoing large eruptions ($\Delta m_V \geq 3$ mag) and SN 1961V suggests that the SN 1961V progenitor was an LBV which experienced a large outburst; see Figure 3. Such stars at maximum light normally have the colors and spectra of A–F supergiants, again similar to the color observed for the supernova *after* the outburst (Walborn and Liller 1977; Leitherer *et al.* 1985; Stahl *et al.* 1985; Stahl and Wolf 1986). (No colors for the progenitor were measured.) The underlying stars are of course much hotter, but they are enshrouded in an optically thick He-rich wind which has the appropriate recombination temperature. Under this assumption, then, we adopt an intrinsic $(B - V)_0 = 0.3$ mag and a bolometric correction BC $\lesssim -0.1$ mag. We further justify these values by noting that the brightness of the star during the 4 yr plateau in the light curve after the outburst was approximately the same as the progenitor's observed brightness prior to 1960 September 14, and at this time the colors were again those of an F supergiant. This value for the BC gives a luminosity for the progenitor of $\sim 6.4 \times 10^6$ $L_\odot$, about the same as that of the most luminous known stars such as η Car (Davidson 1971; van Genderen and Thé 1984), Var 83 in M33 (Humphreys *et al.* 1984), R99 in the LMC (Stahl

TABLE 3

PROPERTIES OF THE MOST LUMINOUS KNOWN LBVs

Property	SN 1961V	η Car	ζ Pup	R99	R123	R127	Var 83
$M_{\rm bol}$	−12.3	−12.1	−10.1	−12.2	−12.14	−11.0	−11.7
M_V	...	...	−6.0	...	−9.05	−7.8	−8.7
BC	−0.1	∼0	−4.0	...	−3.1	−3.2	...
$M/M_\odot$	≥170	≥ 150	38	≥ 135	≥ 100	≥ 60	...
$R/R_\odot$	...	...	18	45	70	48	...
$T_{\rm eff}$ (K)	≥ 45,000	30,000	42,000	40,000	34,000	33,000	37,000
$B - V$	...	...	−0.26	0.25–0.37	0.13	0.0–0.1	∼0.05
$L/L_\odot$ (10^6)	6.4	5.3	0.85	5.9	5.5	1.9	3.7

SOURCES.—η Car: van Genderen and Thé 1984; ζ Pup: Bohannon *et al.* 1986; R99: Stahl *et al.* 1984; R123: van Genderen, Groot, and Thé 1983; R127: Stahl *et al.* 1983; Var 83: Humphreys *et al.* 1984.

et al. 1984), and R123 in the LMC (van Genderen, Groot, and Thé 1983). For comparison, properties of the most luminous LBVs (during quiescence) are given in Table 3. Entries in Table 3 have been taken from the sources noted. The properties of SN 1961V and η Car are those preceding outburst. The Eddington limit mass for our luminosity is about 140 ± 20 $M_{\odot}$, allowing for reasonable uncertainties in the He abundance. The outburst, however, was surely super-Eddington, and applying the Eddington limit would overestimate the mass of the star. It is clear that there is no need to postulate an extraordinary progenitor star. Arguments based on the Eddington limit yield only an approximate value of the mass, and comparisons with detailed models are preferred.

Maeder (1980) has presented models in the mass range of interest to us. The constraints which must be met by his models in order to derive a mass are the following: (1) the helium abundance must be at least 4 times solar; (2) the star is evolved and must be at least near the end of core hydrogen burning; (3) $\log (L/L_{\odot}) \gtrsim 6.8$; and (4) $T_{\rm eff} > 45{,}000$ K. It appears that a star of ZAMS mass $\gtrsim 240$ $M_{\odot}$ near core H exhaustion provides a good fit to the SN 1961V progenitor. At this evolutionary stage the surface He abundance of Maeder's 240 $M_{\odot}$ model is about 5 times solar, and the stellar surface temperature is about 40,000 K; similar values have been deduced for η Car by Davidson *et al.* 1986. Higher mass models would apparently have somewhat higher temperatures. The mass of the star at this stage is about 170 $M_{\odot}$, which is the value given in Table 3, and the mass loss (during core hydrogen burning) has occurred through a wind. It is also possible that large episodic mass-loss events have occurred in the recent past (see below). In the previous section we have already indicated that the ionization of the east H II region requires a stellar temperature of $\gtrsim 45{,}000$ K. The total number of ionizing photons from the Maeder 240 $M_{\odot}$ model is $\sim 3.4 \times 10^{49}$ s^{-1}, while more massive stars at temperatures above 45,000 K will have more ionizing photons.

b) The Outburst

Utrobin (1984) modeled SN 1961V as the outburst of a 2000 $M_{\odot}$ star. One of the parameters forcing him to such a high mass was the duration of the outburst, although he did not try to fit the last 4 yr of the light curve when the star remained nearly constant in brightness some 6.5 mag below maximum. In fact his model ran out of energy after only 27 months, when the recombination cooling wave reached the center of the remnant. He suggests that the subsequent behavior of the light curve was a result of the outburst ejecta interacting with material previously lost via winds. The explosion model also has considerable difficulty reproducing the remarkable constancy of the spectra and colors of the outburst. As the cooling wave eats into the chemically differentiated interior, one expects corresponding changes in both the spectra and the colors, as observed in the late-time spectra of, for example, Type Ib supernovae (Filippenko and Sargent 1986; Gaskell *et al.* 1986). The observed spectra of SN 1961V, however, had remarkably uniform line strengths and continuum shape throughout the outburst (Greenstein and Minkowski 1973). All of this suggests that in SN 1961V we did not see such a cooling wave, but rather saw a fairly constant-velocity, chemically homogeneous wind of varying strength, as in slow novae (see, e.g., Zwicky 1965).

The stellar model used by Utrobin (1984) was also not an evolutionary model but simply one constructed to match the observations with the simplified physics he used. For example, he had hydrogen at the surface because hydrogen lines were observed in the spectra of SN 1961V. However, evolutionary calculations show that all stars with ZAMS masses $\gtrsim 40$ $M_{\odot}$ die as Wolf-Rayet stars, at which point they have lost almost their entire hydrogen envelope in the form of a wind (Schild and Maeder 1984; Maeder 1984; Humphreys 1984; Langer and El Eid 1986; Langer 1987). Such supernovae would be classified as Type I events (no hydrogen), although their light curves may be dramatically different from those of typical Type I events. The SN 1961V progenitor was almost certainly more massive than 40 $M_{\odot}$, yet it retained some of its hydrogen envelope. More recent models by L. M. Ensman (1988, private communication), done in the spirit of the Utrobin calculations, show that the light curve of SN 1961V is not well reproduced by the explosion of a supermassive star.

Evolutionary models of very massive stars (e.g., Woosley and Weaver 1986 and references therein) predict that stars with initial masses greater than ~ 65 $M_{\odot}$ die as pair-creation supernovae. Stars with main-sequence masses from about 65 to 100 $M_{\odot}$ undergo core collapse after several precursor pulsations, while stars with masses in the range 100–300 $M_{\odot}$ explode once and for all. Stars with even larger masses collapse to black holes without exploding, if rotation is neglected. The inclusion of rotation, however, modifies this latter conclusion (Stringfellow and Woosley 1983, 1988; Stringfellow, Woosley, and Bodenheimer 1986; Glatzel, El Eid, and Fricke 1985), so the possibility exists for complete explosions of even very massive stars. These explosions (for helium core masses > 100 $M_{\odot}$) are very energetic, with expansion velocities $\gtrsim 10{,}000$ km s^{-1}. They also synthesize great quantities of ^{56}Ni, producing an optical display very much more luminous than any Type I supernova, and certainly nothing at all like SN 1961V (Stringfellow and Woosley 1988). In fact, rotation (or some equivalent mechanism) is crucial to Utrobin's model if the star is to explode at all. If the star is significantly less massive, so that little ^{56}Ni is produced in the explosion, then the light curve is predominantly powered by recombination in the ejecta (Schaeffer, Cassé, and Cahen 1987), resulting in a short-lived outburst with a total duration of only 3–4 months. In either case, SN 1961V appears extremely unlikely to have been the *explosion* of a very massive star.

We propose instead that the SN 1961V outburst can best be understood as a continuous, optically thick wind from an evolved star of initial mass $\gtrsim 240$ $M_{\odot}$ and similar to that seen in slow novae. The postoutburst plateau in the light curve then has a straightforward explanation. *The object seen after the outburst was the same star that was there before, at approximately the same brightness*!

We emphasize that the rather uncertain distance to NGC 1058, while playing a role in determining the quantitative values in our model, is not the major factor in our discussion. More important is the *color* of the observed progenitor, and the consequent value of the bolometric correction. A second important factor is the *outburst mechanism*; while the explosion of a very massive star may release vast quantities of energy, the decay of this energy with time (and the observed light curve) is quite different from that which might be expected from an outburst or a wind. Conversely, winds can act as radiation traps, temporarily storing radiative energy before releasing it in some type of outburst whose duration is longer than that of supernovae, thus somewhat mimicking a more massive and luminous star. This may in fact explain the excess luminosity

($\Delta M_{\rm bol}$ increasing by ~ 1 mag) apparently observed in the η Car outburst (Davidson 1987*a*).

Many of the instabilities proposed to explain outbursts in massive, luminous stars have, when investigated, not been successful. Notably, the numerical simulations of Stothers and Chin (1983) have shown that nuclear instabilities in the hydrogen- or helium-burning shells or core flashes cannot account for the observed photometric variations. While pulsational instabilities in a near-Eddington limit stellar envelope are not entirely excluded, the most likely mechanism involves rapid, episodic mass-loss events, with mass-loss rates exceeding 0.1 $M_{\odot}$ yr^{-1}. Instability mechanisms have recently been reviewed by Appenzeller (1986), who also reaches the same conclusion. In particular, Appenzeller suggests that radiation pressure due to metal lines can result in large outbursts in LBVs.

Lamers and Fitzpatrick (1988) have recently compared the location, within the H-R diagram, of the most luminous observed stars with that of the Eddington limit and find remarkable agreement between the two. As a massive star evolves, the rate at which mass is lost increases, resulting in the star expanding and cooling while diminishing in mass. The star does this at near-constant luminosity and eventually runs into the Eddington limit, $L_{\rm Edd} = 4\pi cGM/\kappa$. Utilizing new opacities (κ) which incorporate the full effects of metal lines in the ultraviolet, Lamers and Fitzpatrick have shown that the Eddington limit shifts to higher effective temperatures as the mass of the star decreases; the opacity decreases with increasing temperature. The only apparent resolution of this dilemma is for the star to somehow attain a higher surface temperature (the star must move back to the left in the H-R diagram), thereby achieving greater stability. The star seems to accomplish this feat by losing a considerable amount of mass quickly, exposing regions of higher temperature interior to the mass being ejected. This may be the mechanism which powers the large outbursts observed in LBVs.

Davidson (1987*b*) presents a simplified model of an opaque wind which, depending on the mass-loss rate, emulates the observed features of the various classes of LBV outbursts. In the case of a large outburst where the mass-loss rate becomes quite high, the wind is opaque and the temperature does not fall below about 7000 K. During this phase the BC is small. Excessive mass loss can occur without much further change in the visual appearance of the star. Davidson draws the analogy between his findings and two particular LBV events: the moderate outburst of P Cyg and the large outburst observed for η Car. Van Genderen and Thé (1984) and Lamers (1987) also discuss and compare these two cases. We discuss here the similar behavior exhibited by SN 1961V and η Car, both having been large LBV outbursts.

Zwicky (1964) originally called both SN 1961V and the outburst of the remarkable Galactic variable star η Car the prototypical examples of the Type V supernovae. At that time, η Car was considered to have been a slow, peculiar supernova. We now know, however, that η Car did not blow up in its great 1843 eruption. The underlying star is still ejecting shells of material, powering a dense circumstellar H II region, and heating the circumstellar dust shroud produced in the great eruption. Eta Car is now the brightest 10 μm and 20 μm infrared source in the sky (Westphal and Neugebauer 1969); its bolometric luminosity is about 5.3×10^6 $L_{\odot}$ (corrected for a distance of 2500 pc), of which more than 90% is in the infrared (van Genderen and Thé 1984). This luminosity is nearly identical with that of the SN 1961V progenitor derived here. In addition, the absolute visual magnitude of the η Car "progenitor" (i.e., the star that was visible both before the outburst and prior to the subsequent formation of dust in the ejecta) was nearly identical with that of the SN 1961V progenitor. With $M_{\rm bol} = -12.1$, and an F supergiant spectrum (BC $\lesssim -0.1$), as was actually observed for η Car in a subsequent brightening in the 1890s (Walborn and Liller 1977), η Car would have had $M_V \approx -12$. With a line-of-sight extinction of $A_V \approx 1.5$ mag (van Genderen and Thé 1984; Davidson 1987*a*), the apparent visual brightness should have been $V \approx 1.5$ at normal maximum light during quiescence. This is comparable to its observed apparent magnitude in the decade immediately preceding the great outburst of the 1840s.

During the great outburst, η Car reached about $V = -1$, or $M_V = -14.5$, about 10 times as luminous as it was before (and after) the outburst (van Genderen and Thé 1984; Davidson 1987*a*). Since the star was probably nearly Eddington-limited before outburst, it was significantly super-Eddington during the outburst, and remained so for some 15 yr or more. During this time, the star ejected most of the circumstellar envelope which now enshrouds it. Analyses of the thermal radio emission, optical emission spectrum, X-ray absorption, and infrared dust emission are all in agreement that the total ejected mass was around 3 $M_{\odot}$ (Jones 1985; Allen, Jones, and Hyland 1985; Chlebowski *et al.* 1984; Hyland *et al.* 1979), with a characteristic ejection velocity of ~ 750 km s^{-1}. The actual mass ejected depends primarily on the average mass-loss rate presumed during outburst. Estimates range from 5×10^{-3} to 10^{-1} $M_{\odot}$ yr^{-1}, yielding a total mass ejected for η Car of 0.15–3 $M_{\odot}$ for the 30 yr duration of the outburst. The SN 1961V outburst was apparently more energetic (2100 km s^{-1}) and more luminous than in the η Car case, but also quicker. Thus, to within an order of magnitude, the total mass ejected by SN 1961V (probably between 1 and 10 $M_{\odot}$) is equivalent to that ejected by η Car. Assuming 3 $M_{\odot}$, the highest value estimated for the ejected mass, the kinetic energy of the η Car ejecta is about 2×10^{49} ergs, while the light radiated in excess of the normal formidable stellar luminosity was $\sim 9 \times 10^{49}$ ergs. SN 1961V appears to have been about 10 times as luminous as η Car at maximum light. However, the η Car outburst lasted about 10 times as long, so the total amounts of light radiated during the two events were comparable. The η Car outburst apparently produced somewhat more energy in radiation than in the kinetic energy of the ejecta (by a factor of a few), while for SN 1961V the kinetic and radiated energies were roughly comparable. For both SN 1961V and η Car, this is in stark contrast to normal supernovae, where the kinetic energy of the ejecta is larger than the radiated energy by typically a factor of ~ 100. The two Type V events, η Car and SN 1961V, thus radiated supernova-like luminosities, while the total energies involved may have been some 1–2 orders of magnitude less than in a typical Type II event (3–4 orders of magnitude if energy lost by neutrino emission is included).

As noted, the SN 1961V progenitor was seen for more than 4 yr after the end of the outburst, but it did eventually fade from view. Eta Car, of course, underwent a similar decline, largely because of the formation of dust in the dense ejecta. Lamers (1987) and Davidson (1987*a*) describe such behavior for the outburst of P Cyg during the seventeenth century. The same fate may have befallen the SN 1961V star (Fig. 3). The intrinsic Hα luminosity of the outflowing H II region around η Car is about 10^{38} ergs s^{-1} (Allen, Jones, and Hyland 1985). We detect broad Hα emission from the site of SN 1961V with a luminosity (corrected only for the foreground extinction) of about 2×10^{36} ergs s^{-1}. It is unclear whether this is really the ejecta of the outburst or a continuing wind being photoionized by the surviving star. In either case, we expect that the source of luminosity is largely the ionizing radiation emitted by the star. As we have shown, this is perhaps 3.4×10^{49} s^{-1} for the SN 1961V progenitor, while a similar figure has been derived for η Car (Allen, Jones, and Hyland 1985), so we expect the intrinsic Hα luminosity of the two stars to be comparable. Interpretation of the broad Hα flux as being due to a light echo seems quite unlikely. Our measured value of the extinction in the blue is small ($A_B < 1$) and the decline in m_B by 150 days past maximum light was large ($\sim$4.5 mag). These data are at variance with the criteria, outlined by Schaefer (1987), necessary to sustain a significant light echo at late times. Note also that our reddening is consistent with that of SN 1969L, a typical Type II supernova located even farther out beyond the optical disk of NGC 1058 than SN 1961V.

Comparison of our observed Hα flux with that of η Car therefore suggests a current circumstellar extinction of $A_V \approx 5$ mag for the surviving SN 1961V star. If the wind phase of the underlying star has stopped and it now looks like a more normal O star, then a BC ≈ -4 is expected and the star should currently have visual magnitude about $V \approx 27$. If instead the wind phase is still active and BC $\lesssim -0.1$, then the star should have $V \approx 23$. These magnitudes are of course quite uncertain, but they bring up the possibility that the star may be visible with the Hubble Space Telescope. The existence of the OB cluster in the region would make identification more difficult, but would also make imaging with the HST interesting. Perhaps an even better opportunity exists in the infrared, where the star should be a $\sim$5 mJy source at 10 μm, and hence the brightest point thermal IR source in NGC 1058. We have checked the *IRAS Point Source Catalog*, and nothing is detected to an upper limit of 0.5 Jy, but a 5 mJy source would easily be detected by SIRTF and the Keck Ten Meter Telescope. SN 1961V may help us answer important questions on the nature of variability in LBVs and their subclasses, in particular those with large outbursts such as η Car and P Cyg, the most massive stars known today.

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