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SN 1985f: DEATH OF A WOLF-RAYET STAR

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ABSTRACT

From an analysis of the optical spectrum of SN 1985f, we show that the supernova ejecta contain $\gtrsim 5\ M_\odot$ of oxygen and very little hydrogen. We suggest that the explosion resulted from the pair instability supernova of a $\sim 50\ M_\odot$ WO Wolf-Rayet star. The optical luminosity of the supernova is powered by the radioactive decay of ^{56}Co synthesized in the explosion. From the rate of decay of the optical emission we estimate that the explosion occurred ~ 350 days before it was discovered in 1985 February. We show that the peak luminosity at earlier epochs was considerably smaller than that of a typical supernova, because the progenitor lacked an extensive envelope and because the radioactive decay luminosity was trapped in the massive ejecta until $\gtrsim 100$ days after the explosion. We suggest that some of the oxygen-rich (Cas A type) supernova remnants may also have been produced by exploding WO stars.

Subject headings: nebulae: supernova remnants — stars: supernovae — stars: Wolf-Rayet

I. INTRODUCTION

Filippenko and Sargent (1985) discovered a supernova superposed on an H II region near the nucleus of the spiral galaxy NGC 4618. The spectrum of SN 1985f was unlike that of any previously observed supernova in that it was dominated by very broad, strong [O I] λλ6300, 6364 lines. Broad lines from hydrogen or helium were conspicuously absent.

In this *Letter*, we analyze the optical spectrum of the supernova and the rate of decline of its luminosity. We propose that SN 1985f is an example of a pair instability supernova, and that the progenitor was a massive WO Wolf-Rayet star.

II. ANALYSIS OF THE OPTICAL SPECTRUM

In addition to the very strong [O II] lines, other strong lines include Mg I] λ4562, Na I λλ5890, 5896, [Ca II] λλ7291, 7324, O I λ7774, and [C II] λ8730 (Filippenko and Sargent 1985; A. Filippenko, private communication). There is a weaker feature at λ4040, which we tentatively identify with Si I λλ3905, 4103. In addition, there are many weaker features, some at wavelengths of O I and N I lines. However, we caution that the line identifications of all except the strongest lines are very uncertain, since all of the lines are very broad ($\gtrsim 100$ Å), and there are features at almost all wavelengths from 4000 to 9000 Å. Many of the observed features therefore must be line blends. In addition to the discrete line features, the spectrum shows a very broad hump extending from 4000 to 5500 Å, which is very similar to the broad iron group feature in the spectra of Type I SN.

Using the observed line spectrum, we can constrain the conditions in the ejecta of SN 1985f. In doing this, we will assume that the primary energy source (which we will later argue is radioactive decay) merely heats and ionizes the gas and does not directly contribute to the observed line excitation. There are several arguments for this: first, fast electrons are more likely to lose energy in heating the plasma than in producing excitations; second, the excitations in a heavy element plasma are mainly to autoionizing and continuum states which produce ionization; third, the lines observed in the spectrum are primarily forbidden or nonresonance allowed lines which are difficult to excite directly. We assume that the gas is in kinetic equilibrium, and that the oxygen-line emitting region is sufficiently homogeneous that it can be characterized by a single electron temperature T and density n_e. We have adopted an extinction of $A_V = 0.7$ to the supernova; this extinction was derived from the Balmer line ratios in the H II region on which the supernova is superposed. We have adopted a distance of $10.64 d_{10.6}$ Mpc to the supernova to convert fluxes to luminosities. All luminosities, densities, ages, etc. are determined as of 1985 February 28, the date the SN was first observed. On that date, we estimate that the total luminosity of the SN was $3.4 \times 10^{41} d_{10.6}^2$ ergs s^{-1}.

The strongest lines in the spectrum, the [O I] λλ6300, 6364 lines, have a luminosity which we estimate to be $5.1 \times 10^{40} d_{10.6}^2$ ergs s^{-1}. If we assume that the supernova resulted from the disruption of a normal star, it is reasonable to assume that the total mass of oxygen in the remnant $M_{\rm O}$ is less than 100 $M_\odot$. Figure 1 shows the region of the (n_e, T) plane which is excluded by the requirement that $M_{\rm O} < 100 d_{10.6}^2\ M_\odot$.

A strong diagnostic of the physical conditions in the gas is the ratio of the higher excitation [O I] λ5577 line to the λλ6300, 6364 lines. There is a weak feature in the spectrum near 5577 Å (rest); taking the intensity in this feature as an upper limit to the λ5577 intensity, we have that $L(5577)/$

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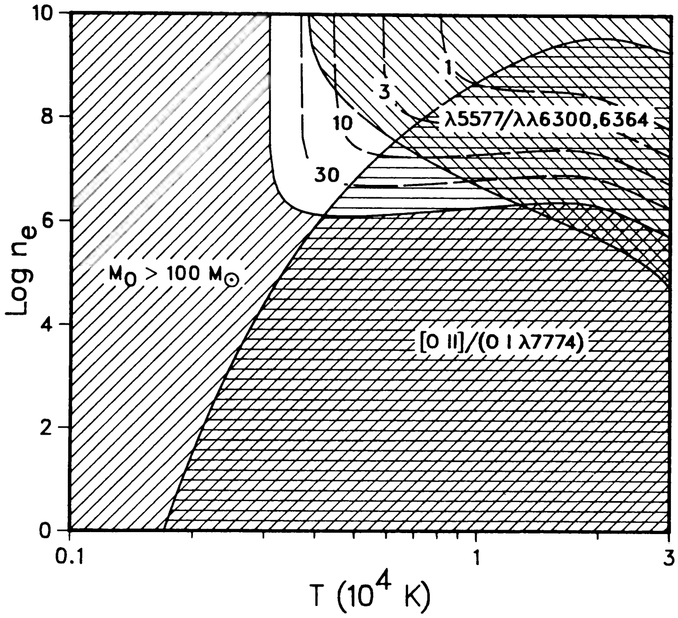

FIG. 1.—The unshaded portion of this figure shows the range of electron densities n_e and temperatures T allowed by the observed optical line intensities of SN 1985f. The shaded regions show the portions of the (n_e, T) plane which are excluded by the requirements that the oxygen mass not exceed 100 $d_{10.6}^2$ $M_\odot$, that the observed [O I] λ5577/λλ6300, 6364 ratio not exceed the observed upper limit, and that the [O II] λλ3727, 3729/(O I λ7774) ratio not exceed its observed upper limit. The numbered dashed curves are loci of fixed oxygen mass (the numbers give the masses in $d_{10.6}^2$ $M_\odot$).

$L(6300, 6364) < 0.05$. This limit excludes high densities and temperatures, as shown in Figure 1.

Lines from O^+ and O^{+2} are not seen in the spectrum of SN 1985f. This is presumably due to the relatively low ionization of the gas. However, there are lines observed at the wavelengths of some highly excited allowed lines of O^0, the clearest case being λ7774. Other highly excited allowed lines, such as λ8449, could be present but are at wavelengths where they blend with strong lines. It is unlikely that these lines are excited by thermal collisions as the required temperatures would produce stronger λ5577 than is observed. The λ7774 line is a transition between $S = 2$ levels, and thus cannot be directly excited from the ground state ($S = 1$) by radiation or by fast particles. The most likely excitation mechanism for these lines appears to be the recombination of O^+. In that case, the rate of emission of this line and of the unobserved [O II] λλ3727, 3729 lines are all proportional to the amount of O^+. Thus, the observed limit on the intensity of the [O II] lines relative to the λ7774 line gives another constraint on the density and temperature, if these lines are produced in the same region as the [O I] lines. Since the [O II] lines are easily collisionally suppressed and have a high excitation energy, high temperatures and low densities are excluded, as shown in Figure 1. The ratio of λ7774 to [O I] emission can be used to determine the ionization fraction O^+/O^0 in the gas; unfortunately, this line ratio is quite temperature and density sensitive, and the ionization is only constrained to lie in the range $10^{-3} \lesssim O^+/O^0 \lesssim 3$.

A final constraint on the electron density results from assuming that the mass of ejecta is less than 100 $M_\odot$ and that the age of the supernova is more than several months (as suggested by its slow decline in luminosity); then $n_e \lesssim 10^{10}$ cm^{-3}. Combining these constraints, we find that the density and temperature must lie in the unshaded region in Figure 1, with $3000 \leq T \leq 6000$ K, and $10^6 \lesssim n_e \lesssim 10^{10}$ cm^{-3}. For the densities and temperatures in this region, the electron density is greater than the critical density for the [O I] line to be collisionally suppressed. Thus, the strength of the line is determined only by the mass of O^0 and the temperature. Figure 1 shows lines of constant oxygen mass M_O, derived form the intensities of the [O I] and O I lines. For densities and temperatures in the allowed region, the mass of oxygen is $M_O \geq 5.6 d_{10.6}^2 M_\odot$.

If the λ7774 line is indeed produced by recombination, then the excitation rate of this line is comparable to the rate of excitation of Hβ for similar ionized oxygen and hydrogen abundances. Moreover, the ionizations of hydrogen and oxygen in the gas will be similar, since they have nearly equal ionization potentials and since charge exchange will drive the ionization of the less abundant species to $H^+/H^0 = (8/9)(O^+/O^0)$. Thus, the absence of detectable broad Hβ leads to a limit on the relative abundance of hydrogen and oxygen, $H/O \leq 1/2$.

With the high density and low temperature in the supernova ejecta, low-excitation allowed and semiforbidden lines are expected to be relatively strong, since the forbidden lines will be at least partially collisionally suppressed. This may account for the strength of the Na I and Mg I] lines.

III. THE PROGENITOR AND ITS DEMISE

We believe that SN 1985f resulted from the explosion of a massive Wolf-Rayet star in its WO phase and that it is an example of a "pair instability supernova" (Prantzos *et al.* 1985; Fowler and Hoyle 1964). The large mass of oxygen inferred in § II, plus the fact that SN 1985f is projected against an H II region, suggest that the progenitor of the supernova was a massive Population I star. The absence of hydrogen indicates that the progenitor was an evolved star which had lost its outer layers prior to the explosion. The possible identifications of Si I lines and a broad iron group feature suggest that substantial nucleosynthesis beyond oxygen occurred prior to or during the explosion. A WO star is an evolved Population I star in which all layers outside the oxygen core have been lost. Evolutionary calculations (Prantzos *et al.* 1985; Doom 1985; Maeder 1983) incorporating strong mass loss have shown that very massive O stars ($M > 50$ $M_\odot$) may reach the WO phase via the WN and WC phases. At the end of helium core burning, a WO star is very similar to the oxygen core of a "very massive object" (VMO) (Bond, Arnett, and Carr 1982, 1984; Ober, El Eid and Fricke 1982, 1983; El Eid, Fricke, and Ober 1983; and Woosley and Weaver 1982), and it should share the same fate. VMOs with core masses in the range 30 $M_\odot \lesssim M \lesssim 100$ $M_\odot$ are expected to explode as pair supernovae. The debris from SN 1985f presumably lies in this range (cf. Fig. 1).

By analyzing the blue side of the [O I] λ6300 line in the published spectrum (the red side may be blended with other lines) assuming that the emissivity is proportional to density, we estimate that the kinetic energy of the ejecta can be characterized by an rms velocity $v_{\rm rms} \approx 3300$ km s^{-1}, where the kinetic energy is $Mv_{\rm rms}^2/2$. Bond, Arnett, and Carr (1984) find that the kinetic energy of a pair supernova is a sensitive (increasing) function of M, with our estimated $v_{\rm rms}$ corresponding to $M \approx 50\ M_\odot$. In the Bond *et al.* models, a 50 $M_\odot$ supernova would eject $\sim 40\ M_\odot$ of oxygen, $\sim 10\ M_\odot$ of silicon group elements, and $\sim 1\ M_\odot$ of ^{56}Ni.

Measurements of the peak [O I] flux at three epochs revealed a mean rate of decline of ~ 0.015 mag per day during the 4 months following discovery, with some evidence for a steepening of the light curve with time (A. Filippenko, private communication). The slowness of the decline indicates that energy is being fed into the remnant continuously, presumably through the radioactive decay of ^{56}Co (which in turn is the decay product of ^{56}Ni synthesized during the explosion). The half-life of ^{56}Co is 78.5 days, corresponding to a rate of decline of 0.0096 mag per day in the rate of energy *release*. The instantaneous bolometric luminosity is the rate at which this energy is *absorbed* by the ejecta, and may be characterized by the rate of energy release times a "deposition function" $D(t) \leq 1$ (Colgate, Petschek, and Kriese 1980). If the measured rate of decline for [O I] parallels the decline in the bolometric luminosity, then D must be decreasing with time. Gamma-rays carry 97% of the energy released during ^{56}Co decay, and the increasing transparency of the remnant to these photons probably accounts for the variation of D. In the range $0.03 \ll D \ll 1$, $D \propto t^{-2}$, giving a light curve with

$$\frac{dm_{\rm bol}}{dt} = 1.09\left(\frac{1}{\tau_{\rm Co}} + \frac{2}{t}\right), \qquad (1)$$

where $\tau_{\rm Co} = 113.45$ days is the *e*-folding time for ^{56}Co decay and t is the time elapsed since the explosion (assumed to be much greater than the 8.8 day *e*-folding time for ^{56}Ni decay). If $dm_{\rm bol}/dt \approx 0.015$ approximately 2 months after discovery, then the age at discovery would have been $t_{\rm disc} \approx 350$ days. The initial mass of ^{56}Ni required to produce the estimated bolometric luminosity at the epoch of discovery is

$$M_{\rm Ni} \approx 0.03\, D^{-1} \exp\left(t_{\rm disc}/\tau_{\rm Co}\right) d_{10.6}^2\, M_\odot \sim 0.7\, D^{-1}\, M_\odot, \qquad (2)$$

where the last value follows if we adopt the estimate above for $t_{\rm disc}$. The precise value of D is uncertain because of uncertainties in the γ-ray opacity and in the distribution of matter within the ejecta. It is unlikely that D drops below 0.03, corresponding to the complete escape of γ-rays but full absorption of positron energy. A crude estimate using Axelrod's (1980) formula yields $D \approx 1$. Thus the turnover from complete to partial deposition of the γ-ray energy could have accounted for the steepening of the light curve.

A small mass of ^{56}Ni is consistent with theoretical predictions of nucleosynthesis in pair supernovae, provided that M is not much larger than our estimated 50 $M_\odot$. For $M < 50\ M_\odot$, the yield of ^{56}Ni predicted by Bond, Arnett, and Carr (1982) drops precipitously below 5%; they point out that their calculations seriously *overestimate* the yield (Bond, Arnett, and Carr 1984). A larger ^{56}Ni mass (and larger total mass M) would be consistent with the observed luminosity if the deposition factor were much smaller than 1 or if the supernova were older than 350 days at the time of discovery. In the former case the maximum possible mass of ^{56}Ni would be $\approx 18\ M_\odot$. In the latter case, the age could range from 470 days ($D = 0.03$) to 860 days ($D = 1$) for a theoretical maximum ^{56}Ni mass of 50 $M_\odot$. The value of $dm_{\rm bol}/dt$ would then be smaller than 0.015, and the discrepancy between $dm_{\rm bol}/dt$ and the rate of decline in the [O I] luminosity would signify the decreasing importance of [O I] as a coolant. Whatever the cause of the difference between $1.09/\tau_{\rm Co}$ and $dm_{\rm bol}/dt$, the fact that its amplitude is ≈ 0.005 mag per day suggests that the remnant was several hundred days old when it was discovered.

IV. DISCUSSION

The properties of SN 1985f are consistent with its origin as an exploding WO star. We propose that the explosion resulted from the pair instability of a massive ($\sim 50\ M_\odot$) oxygen core, followed by thermonuclear detonation. Such an explosion is not believed to produce any compact remnant, and so we predict that no pulsar or compact X-ray source will be observed within SN 1985f. We estimate that the explosion occurred approximately 350 days before the supernova was discovered on 1985 February 28. The estimated electron density at the time of discovery falls comfortably within the allowed region of Figure 1.

Photographic plates taken at various times during 1984 and early 1985 reveal no stellar object brighter than $m_V \approx 12.5$ at the position of SN 1985f (Wenzel 1985). This is not surprising if our estimates for the age of the SN and the initial mass of ^{56}Ni ($\sim 1\ M_\odot$) are correct. The light curve of a supernova powered by radioactive decay is determined by the competition between the energy input, which decreases monotonically, and photon trapping, which inhibits the escape of radiation and causes the light curve to rise at early times (Arnett 1982). In Type I supernovae, photons become untrapped within the first 1–3 weeks, and the light curve has a luminous peak dominated by nickel decay. However, the more massive envelopes and lower expansion speeds of pair supernovae cause the duration of trapping to rise roughly in proportion to $(M/v)^{1/2}$. In SN 1985f, we estimate that photons may have been trapped for $\gtrsim 100$ days, and that the light curve peaked during the cobalt decay phase, with a maximum intensity only $\sim$ 2–3 mag brighter than the discovery magnitude. The peak resulting from nickel decay would have been missing entirely. With a peak brightness of $m_V \approx$ 13–14 [$M_V \approx (-17) - (-16)$], SN 1985f would have escaped detection. In general, we would expect pair supernovae to be $\sim$ 2–4 mag fainter at peak brightness than typical Type I and Type II supernovae. As originally suggested by Chevalier (1976) for Cas A, we argue that the optical emission from the shock break-out was faint and short-lived because the progenitor Wolf-Rayet lacked an extended envelope.

There are now several known cases of supernova remnants (SNRs) containing rapidly expanding (2000–5000 km s^{-1}) oxygen-rich knots. Cas A is the prototype of this class, but other possible examples include G292.0 + 1.8 in our Galaxy, N132D and 0540 − 69.3 in the LMC, 1E0102.2 − 7219 in the SMC (Dopita and Tuohy 1984), and the very spectacular SNR in NGC 4449 (Blair, Kirshner, and Winkler 1983). We suggest that some of these remnants may also have resulted from the pair supernovae of WO stars. (Filippenko and Sargent 1985 originally pointed out the possible relationship between Cas A and SN 1985f.) Cas A has very rapidly expanding knots composed primarily of oxygen, with essentially no hydrogen or helium, but also containing silicon group elements and iron (Chevalier and Kirshner 1978). Although the mass of optically emitting knots is small, their composition is very similar to that we have derived for the ejecta in SN 1985f, and a much higher mass of ejecta is observed in X-ray emission (Murray *et al.* 1979; Markert *et al.* 1983). There are also more spatially extended, slow moving "quasi-stationary flocculi" which are enriched in He and N. We suggest that these are due to the interaction of the supernova ejecta with circumstellar matter deposited by the Wolf-Rayet stellar wind. Despite its estimated age of ~ 300 yr and its proximity to Earth, Cas A was not observed as an optical supernova. We suggest that the peak optical emission from the supernova was diminished by the same mechanisms described above for SN 1985f (see also Filippenko and Sargent 1985). Finally, no pulsar or point X-ray source is seen within Cas A (Murray *et al.* 1979), suggesting that the supernova did not involve a core collapse which formed a neutron star. (Conversely, we note that 0540 -69.3 in the LMC contains a pulsar [Seward, Harnden, and Helfand 1984] and thus cannot have formed by the scenerio we have described.)

Surveys for Wolf-Rayet stars are relatively complete for the region within ~ 2.5 kpc of the Sun (Conti *et al.* 1983), and for the Magellanic Clouds (Breysacher 1981; Azzopardi and Breysacher 1979). Forty-four and 101 WRs have been identified in the solar neighborhood and in the LMC, respectively; the SMC is relatively much poorer in WRs (Massey 1985). Adopting a mean WR lifetime of 3×10^5 yr, we estimate the mean WR formation rate in the LMC to be $\gtrsim 1$ WR per 3000 yr. The estimated age of N132D is ~ 3000 yr (Lasker 1978), so we are forced to require that a substantial fraction of WRs in the LMC end their He core-burning phases with masses $\gtrsim 30\ M_{\odot}$, if we are to identify this SNR as the result of a pair of instability supernovae. It would be difficult to reconcile a high fraction of massive WRs with the observed population of O-stars in the solar neighborhood (assuming that all WRs evolve from O stars), although there is evidence suggesting that the IMF is skewed toward more massive stars in the LMC (Garmany 1984). NGC 4618, which hosts SN 1985f, appears to be undergoing a modest starburst in its nuclear regions. In such an environment, the formation rate of very massive stars may be enhanced still further.

Masses for WRs have been estimated in only a handful of cases. Massey's (1982) estimates for 16 WRs with O star companions yield only one case with a mass well over the threshold for pair supernovae, although uncertainties in the analysis could push the mass over the limit in at least two other cases. It is not at all clear how representative the WR + O binary sample is of the general mass function for WRs. If Massey's result represents a (pessimistic) estimate of the true abundance of massive WRs, then the probability of observing a pair supernova remnant at the distance of Cas A is still a few percent. Remnants as young as Cas A, however, should be quite rare (probability $\lesssim 1\%$).

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