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THE NATURE OF S ANDROMEDAE (SN 1885A)

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ABSTRACT

The available data on SN 1885A in M31 indicate that it was a Type I supernova, but that its light curve had a rapid rise to maximum, a rapid postmaximum decline, and a large magnitude difference between maximum and 150 days postmaximum, compared to other Type I events. We argue that it was a low-mass explosion, ejecting 0.1–0.3 $M_\odot$ of matter, mostly in the form of ^{56}Ni. This suggests that it left a compact remnant, either a neutron star or a white dwarf. A model by Woosley, Taam, and Weaver involving He detonation on the surface of a white dwarf gives an excellent fit to the observed light curve. In this model, there is a white dwarf remnant, the fast-moving gas is Fe rich, and the total energy is 4×10^{50} ergs, all of which differ from models for Type Ia supernovae. If a hot white dwarf is present in the remnant of SN 1885A, it might produce observable line emission from the expanding nebula.

Subject headings: nebulae: supernova remnants — stars: supernovae — stars: white dwarfs

I. INTRODUCTION

Two major classes of Type I supernovae have been identified and are generally designated Type Ia (SN Ia) and Type Ib (SN Ib) events. The SN Ia are well modeled as the carbon deflagration of white dwarfs with a mass of 1.4 $M_\odot$; there is good agreement of light curves and both early and late spectra (Woosley and Weaver 1986 and references therein). No compact remnant is expected. The nature of SN Ib is more uncertain, but recent observations suggest that they are the explosions of the cores of massive stars with a range of He, C, and O abundances (Wheeler *et al.* 1987). The optical light curves of SN Ia and SN Ib are similar and spectroscopy and infrared photometry were necessary to distinguish the two classes.

A number of supernovae show deviations from the standard properties of the two classes and have been designated peculiar. Among these is the second brightest supernova of the past 300 yr: S Andromedae or SN 1885A in M31. Although there have been excellent discussions of the extensive observations of this event (de Vaucouleurs and Corwin 1985 and references therein, hereafter dVC; van den Bergh 1986), there has been little theoretical discussion in terms of recent supernova models. Here we address this problem and conclude that SN 1885A belongs to a supernova class distinct from SN Ia and SN Ib. Most other peculiar Type I supernovae appear to be closer to SN Ia and SN Ib than to this third class, although SN 1939B and SN 1965I may be related events.

II. SN 1885A

The spectral information on SN 1885A is poor, but dVC were able to deduce the wavelengths of major peaks in the spectrum from the old records. The hydrogen Balmer lines are not clearly present, which strongly suggests that the supernova was of Type I. Also, the supernova occurred in the bulge of M31 at a separation of 16″ from the nucleus. It was associated with an old stellar population.

The most detailed information on SN 1885A is the V light curve and Figure 1 shows the final result of dVC's work. For this plot, we have taken a distance modulus to M31 of 24.07 (dVC) and an extinction $A_v = 0.5$. De Vaucouleurs and Corwin note that the extinction due to the Galaxy is probably ~ 0.3 mag. The extinction due to M31 is uncertain; dVC do note that there are no observable dust clouds in the vicinity of the supernova. Their preferred value is $A_v = 1.0$ along the whole line of sight, but this is primarily based on bringing the $B-V$ color and absolute magnitude of SN 1885A into rough accord with the properties of SN Ia. We believe that SN 1885A was not a SN Ia event. Also, the column density of hydrogen to the bulge X-ray sources in M31 is consistent with just the column density expected from our Galaxy (Van Speybroeck *et al.* 1979).

Also shown in Figure 1 are the V light curves for the SN Ia events SN 1984A (Kimeridze and Tsvetkov 1986; Graham 1988 and references therein) and SN 1986G (Phillips *et al.* 1987). SN 1984A is taken to be in the Virgo Cluster at 21 Mpc (Tammann 1987) with $A_v = 0.9$ (Kimeridze and Tsvetkov 1986) and the distance to SN 1986G in NGC 5128 is taken to be 7.9 Mpc (Sandage and Tammann 1975) with $A_v = 2.7$ (Phillips *et al.* 1987). With these estimates, SN 1885A at maximum is fainter than the SN Ia events by 2 mag, but our distances to SN 1984A and SN 1986G are based on the long distance scale so the difference could be smaller.

There are three properties of the shape of the light curve of SN 1885A that are of particular importance. First, as summarized by dVC, there was a rapid rise to maximum light which is estimated to have occurred on the night of August 21. The supernova was definitely not observed on the night of August 16, implying that it was at least 3 mag fainter than at maximum. The rise time from 3 mag below maximum to maximum is thus ~ 4 days. From a compilation of photographic light curves of other SN I (Pskovskii 1977), this time scale is $\sim 14 \pm 2$ days. Since SN I are observed to be reddening at maximum light, the corresponding time scale for the V band is larger by a few days. Second, the rate of decline after maximum is rapid. Van den Bergh (1986) notes that at 20 days after maximum, SN 1885A declined at 0.10 ± 0.01 mag day^{-1} while the mean rate of decline for 8 SN I with photoelectric photometry was 0.065 ± 0.007 mag day^{-1}. Normal SN I have their maximum rate of decline at this time; for SN 1885A, the decline was even more rapid closer to maximum light. Finally, the magnitude change from maximum to 150 days after maximum, Δm_{150}, is unusually large. From Figure 1, for SN

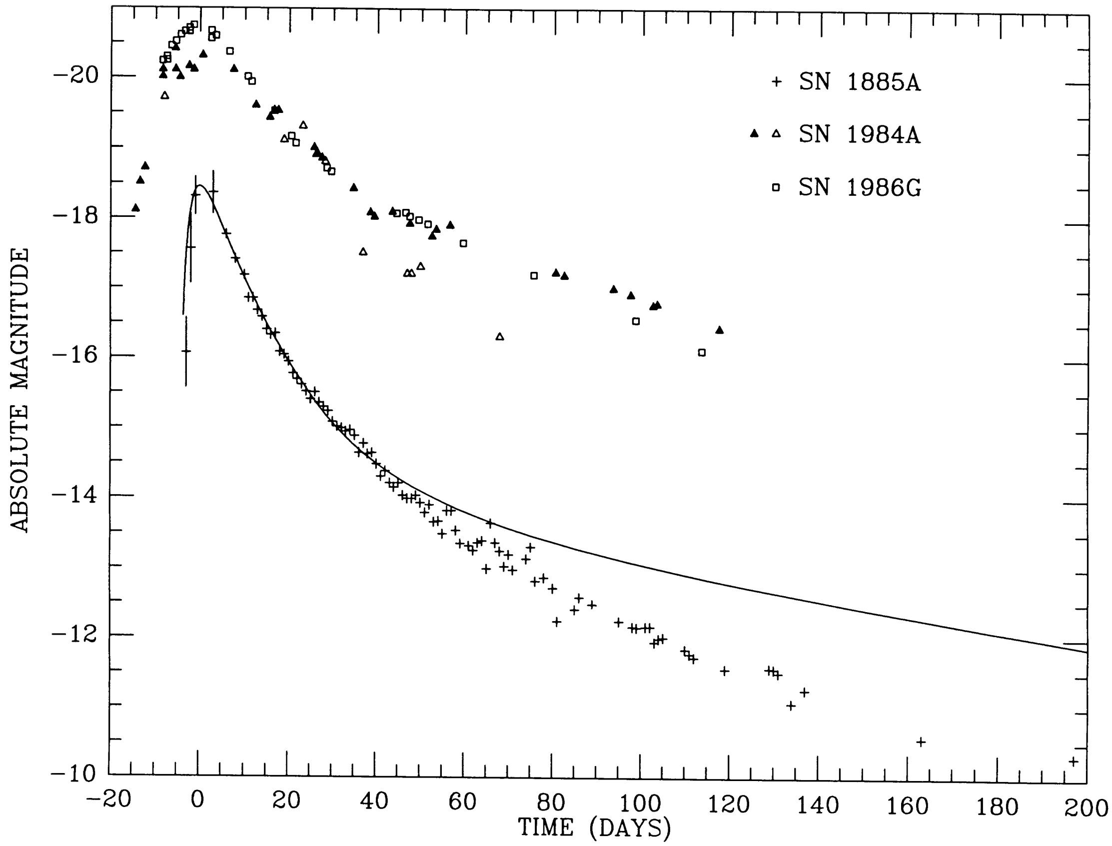

FIG. 1.—The observed V light curves of SN 1885A, SN 1984A, and SN 1986G compared to absolute bolometric magnitude evolution of model 1 of WTW (*solid line*). The sources of the data and the assumed distances and extinctions are given in the text. For SN 1984A, the closed triangles refer to data from Kimeridze and Tsvetkov (1986) and the open triangles to the compilation of Graham (1988). The time $t = 0$ refers to maximum V light, which is taken to be 1885 August 21 for SN 1885A, 1984 January 18 for SN 1984A, and 1986 May 13 for SN 1986G.

1885A, $\Delta m_{150} = 7.5$ mag at V, while for combined data on SN 1972E and SN 1986G, $\Delta m_{150} = 5.3$ mag.

In considering models for the light curve of SN 1885A, we concentrate on ones in which the light is powered by the radioactive decay chain $^{56}\mathrm{Ni} \rightarrow {}^{56}\mathrm{Co} \rightarrow {}^{56}\mathrm{Fe}$. These models are the most successful in reproducing the light curves of normal SN I, especially the late tail. The early light curve is determined by two time scales: a diffusion time for the release of radiative energy, τ_d, and the ^{56}Ni decay time, τ_{Ni}. The time τ_d is found by equating the age with the diffusion time and is $\tau_d = (\alpha \kappa M / c V_e)^{1/2}$, where α is a dimensionless constant that depends on the density distribution, κ is the opacity, M is the ejected mass, c is the speed of light, and V_e is an effective velocity. For a given density distribution, V_e is proportional to $(E/M)^{1/2}$, where E is the net explosion energy. The early evolution is determined by the dimensionless ratio $\tau_d/\tau_{\mathrm{Ni}}$. Arnett (1982) has derived analytic solutions for early light curves depending on the constant y which is proportional to $\tau_d/\tau_{\mathrm{Ni}}$. Models for SN Ia require y in the range 0.6–0.75. In order to fit the rapid rise of SN 1885A, y of ~ 0.15 is needed; the peak in the model bolometric luminosity then occurs at an age of 4 days. For small values of y, the model postmaximum decline approximates that of ^{56}Ni decay, i.e., 0.12 mag day^{-1}. If escape of γ-ray energy occurs, a steeper decline is possible. This result is in rough accord with the observations. We are comparing the model bolometric luminosity with the observed V luminosity, but this should be adequate because the $B - V$ color is red and fairly constant near maximum light. Most of the light is probably in the V band. If SN 1885A and SN Ia have comparable density distributions, $\kappa M / V_e$ may be about one order of magnitude smaller in SN 1885A than in SN Ia. Since burning of much of the mass to Fe-peak elements is likely in both cases, κ may be comparable, although the intermediate mass elements in SN Ia may lower κ by a factor of 2–3. In thermonuclear models, V_e does not depend strongly on the event because the amount of energy produced is proportional to the burned mass. The implication is that SN 1885A was a low-mass explosion. The late luminosity ($t \gtrsim 100$ days) depends on the fraction of the ^{56}Co γ-ray and positron power that is deposited in the expanding gas. For a given density distribution the deposited fraction of γ-rays is proportional to M/V_e^2 so that a low-mass event is expected to be relatively faint at late times, as observed for SN 1885A.

In the radioactive decay model, the mass of ^{56}Ni synthesized in the explosion can be estimated from the luminosity at maximum light (Arnett 1982). With peak absolute V magnitude of -18.5 to -19.2, corresponding to $A_v = 0.3$ to 1.0 (dVC) at an age of 4.5 days and a bolometric correction of 0 mag, the ^{56}Ni mass is in the range 0.13–0.25 $M_{\odot}$. The bolometric correction does introduce some uncertainty in this result.

The apparent low mass of the SN 1885A event and the old population progenitor suggests that the progenitor was a white dwarf in a binary system. Ciardullo *et al.* (1987) note that the distribution of novae in M31 follows that of the bulge light to within 10″ of the nucleus. Although novae may not lead to SN

I, the position of the supernova is appropriate for a white dwarf binary progenitor.

One possible class of models is a thermonuclear detonation in a white dwarf (Woosley, Taam, and Weaver 1986, hereafter WTW, and references therein). Some of these involve low ejected mass, e.g., model 1 of WTW which involves the detonation of He on the surface of a white dwarf. Figure 1 shows that the bolometric light curve of model 1, calculated as described in WTW, provides an excellent fit to the V light curve of SN 1885A over the first 50 days. At later times, it is plausible that the bolometric correction becomes large. The parameters for model 1 are an ejected mass of 0.26 $M_{\odot}$, a ^{56}Ni mass of 0.19 $M_{\odot}$, a net energy of 0.38×10^{51} ergs, and a remnant white dwarf of mass 1.17 $M_{\odot}$. This model applies to a relatively low He accretion rate (10^{-9} $M_{\odot}$ yr^{-1}); a higher accretion rate leads to a more energetic explosion with greater mass ejection.

Another possible explosion mechanism is the collapse of a white dwarf to a neutron star. A particularly promising mechanism of this type is the accretion onto an O-Ne-Mg white dwarf in a binary system; this is a possible formation mechanism for the bulge X-ray sources (Baron *et al.* 1987). The requirement for SN 1885A is that ~ 0.2 $M_{\odot}$ of matter be ejected, most of which is ^{56}Ni. It has never been demonstrated that this can occur as a result of core collapse, but it cannot be definitely ruled out. The explosions of massive stars, like the progenitor of SN 1987A, appear to synthesize less ^{56}Ni, but the absence of matter outside the white dwarf may facilitate the ejection of ^{56}Ni.

In the case of the He detonation mechanism, the burning proceeds to Fe-peak elements and intermediate weight elements end up at a high velocity ($>30{,}000$ km s^{-1}). This is not what is observed in SN Ia spectra, which is the main reason for ruling out detonation models for these events (Chevalier 1981; Woosley and Weaver 1986). There are some spectroscopic descriptions of SN 1885A, particularly 20–40 days after maximum light, and dVC find that most of the spectral peaks correspond to peaks observed in the spectra of normal SN I. In the detonation model, intermediate elements should not be prominent, but these are usually identified as absorption features in the spectra of normal SN I so it is difficult to deduce the elements present in SN 1885A. The fact that the $B-V$ color of SN 1885A was very red at maximum and remained about constant until 20 days after maximum suggests spectral differences with normal SN I. In normal events, the $B-V$ color is moderately blue near maximum and reddens over the next 20 days; this temperature decrease is the cause of the postmaximum luminosity decrease. The fact that SN 1885A declined sharply in V magnitude while maintaining a constant color index is unusual. If it radiated as an approximate blackbody, this would require a rapid decrease in photospheric radius, which could be achieved by the opacity having a high power dependence on temperature (as occurs in SN II) or by a dense shell turning optically thin. Alternatively, the radiation does not approximate a blackbody and there are either absorption features in the B band or emission features in the V band near maximum light.

Our conclusion on the nature of SN 1885A disagrees with that of Graham (1988), who claimed that SN 1885A was a fast SN Ia based on the similarity of the V light curve to that of the Type Ia SN 1984A. However, Graham did not take into account the extensive photometry of Kimeridze and Tsvetkov (1986), which is clearly compatible with the light curves of normal SN Ia like SN 1981B or SN 1986G (see Fig. 1) but is incompatible with the light curve of SN 1885A. We believe that the five data points on SN 1984A over the period 40–70 days past maximum light from Verdenet (1984), which are included by Graham (1988), are likely to be in error (Fig. 1). All the other data on SN 1984A, including spectroscopy and infrared photometry, are consistent with a normal SN Ia event.

We have examined the light curve compilations of Rust (1974) and Pskovskii (1977, 1984) and have not found any supernovae with the extreme properties of SN 1885A, although SN 1939B and SN 1965I may be related objects. Photographic photometry of SN 1939B was obtained by Baade and by Shapley and is compiled by Rust (1974). De Vaucouleurs and Corwin noted that SN 1939B apparently had a postmaximum decline in photographic magnitude that was steeper than the B decline of SN 1885A. In addition, SN 1939B had a rapid rise, ~ 9 days to photographic maximum and a large drop in photographic magnitude between maximum and late times. While most SN I drop by ~ 5.6 mag between the time of maximum and an age of 220 days (e.g., data in Rust 1974), SN 1939B dropped by ~ 6.7 mag over this time interval. This combination of properties is suggestive of a low-mass explosion, but less extreme than was the case for SN 1885A. Model 2 of WTW, which is He detonation on a white dwarf with an accretion rate of 2×10^{-9} $M_{\odot}$ yr^{-1}, has a net energy of 1.17×10^{51} ergs, ejected mass of 0.80 $M_{\odot}$, and a ^{56}Ni mass of 0.49 $M_{\odot}$. This model reaches bolometric maximum in 8 days and may be the type of explosion that can give the properties of SN 1939B. Like SN 1939B, SN 1965I showed a moderately steep rise and decline, but no data at late times are available (Rust 1974).

III. THE REMNANT OF SN 1885A

The lack of detected emission from the remnant of SN 1885A (dVC) suggests that most of the ejecta is in a cool, free expansion phase. The ejecta may be heated and ionized by the central compact object that is predicted by our model. While a central neutron star is a possibility, a white dwarf remnant has a firmer theoretical basis. Model 1 of WTW predicts a white dwarf with luminosity 8×10^{36} ergs s^{-1} and effective temperature 2.9×10^{5} K, so the flux peaks at 100 Å. The optical depth of the nebula at 100 Å is ~ 0.2 if it is composed of low ionization stages of Fe. Therefore, a significant fraction of the stellar radiation may be converted to lower energy line emission, as in a planetary nebula. The predicted composition is mainly Fe with some slow moving C and O (WTW). Spectroscopy at the well-determined position of the supernova (dVC) is probably warranted.

The rate of supernovae related to SN 1885A is difficult to determine given the small number of events and the relative difficulty of finding fast, faint supernovae (Fig. 1). The fact that the only supernova in M31 in over 100 yr was of this type suggests a nonnegligible rate. The explosion energy of the model for SN 1885A, 4×10^{50} ergs, is about a factor of 3 smaller than the expected explosion energy of a SN Ia so that information on the numbers of such events might be obtained if the total energies of supernova remnants can be accurately determined.

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