

SN 1984A AND S ANDROMEDAE: TWO EXAMPLES OF RARE TYPE Ia SUPERNOVAE

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ABSTRACT

Supernova 1984A was a remarkable Type Ia event which exhibited extremely high-velocity material in its spectrum. The optical light curve of this supernova is marked by a rapid decline, which further distinguishes it from common Type Ia events, but the optical spectra are, apart from the persistent, unusually larger Doppler shifts, practically identical to previously well-observed Type Ia supernovae such as SN 1981B. In contrast to the extreme optical peculiarity of this supernova, the IR light curves are almost normal. Only one other Type I supernova is known to have a light curve which is as fast as SN 1984A—SN 1885 in M31, S Andromedae. S Andromedae has been classified as a peculiar Type I on account of its unusual light curve. But now that such a fast light curve is no longer unprecedented, we can classify S Andromedae as a Type Ia supernova.

Subject heading: stars: supernovae

I. INTRODUCTION

SN 1984A was discovered in NGC 4419 [type SB(s)a] by Kimeridze on 1984 January 4.096 (Askenov 1984), and was found independently by Rosino (1984a) on January 7. Rosino (1984b) reported spectra of the supernova on January 9, 10, and 11 which show that SN 1984A is a classical Type Ia supernova (SN Ia). However, Rosino also noted that the SN was unusual because of a general blueward displacement of the spectral features—for example, the Si II 6355 Å absorption which usually falls at 6130 Å (with $\sigma \approx 20$ Å) was at 6000 Å. Additional spectroscopy on January 10 by Wegner and McMahan (1987) confirms this spectral peculiarity, and high velocities continue to be in evidence ~ 20 days after maximum in spectra reported by Wheeler (1985).

The extreme nature of SN 1984A recently led Branch (1987) to discuss the near maximum light spectrum of Wegner and McMahan (1987) and to focus upon the high velocities exhibited by SN 1984A as a key piece of evidence in the debate regarding the homogeneity of SN Ia. SN 1984A demonstrates beyond doubt that not all SN Ia are identical.

In § II we compare the light curves, both optical and infrared, and the spectra of SN 1984A with the well-observed SN Ia, SN 1981B. In § II we also show that the rapidly declining optical light curve of SN 1984A is matched by that of the supernova of 1885, S Andromedae, and in § III we investigate the possibility that SN 1984A and S Andromedae are both rare examples of SN Ia with very fast light curves and high expansion velocities. Section IV compares the properties of SN 1984A and S Andromedae with more common SN Ia.

II. COMPARISON WITH OTHER SUPERNOVAE

a) Optical Light Curves

SN 1984A brightened from $m_{pg} = 16$ at discovery on January 4.096 (Askenov 1984) to $m_{pg} = 13.5$ 3 days later on January 7 (Rosino 1984a). The SN had increased to $B = 13.1$, with $B - V = 0.3$ on January 10, indicating that SN 1984A was approaching maximum light. [Using the transformation of Branch and Bettis 1978, $m_{pg} = B - 0.29 + 0.18(B - V)$ and so $m_{pg} = 12.9$]. When photometry was next reported on January 29.988 the SN had fallen to $m_{pg} = 13.0$ (Argyle 1984). Visual magnitude estimates by Verdenet (1984) through February and

March showed the supernova declining steadily at ~ 0.07 mag per day.

The epoch of optical maximum is well constrained by the steeply rising branch of the light curve. Comparison of SN 1984A with Pskovskii's (1977) compilation of early light curves indicates that the date of maximum must have occurred between JD 2,445,714 and 2,445,718. For practical purposes of comparing SN 1984A with other SN adoption of a date of $2,445,716 \pm 3$ will be satisfactory (cf. Branch 1987). The corresponding photographic magnitude at maximum would have been 12.1 ± 0.3 . Corrected for interstellar extinction within our Galaxy $m_{pg}^0 = 11.9 \pm 0.3$ (de Vaucouleurs, de Vaucouleurs, and Corwin 1976).

NGC 4419 lies in a direction toward the core of the Virgo Cluster, only $2^\circ 5'$ away from the center as defined by Sandage and Tammann (1976), and although NGC 4419 has a negative velocity, the Tully-Fisher relation for this galaxy indicates that it is a member of the Virgo Cluster (Helou, Salpeter, and Krumm 1979). The mean photographic magnitude, corrected for foreground extinction, at maximum for SN Ia in Virgo Cluster galaxies is 11.9 , $\sigma = 0.6$ (Branch and Bettis 1978), and consequently the optical brightness of SN 1984A is normal.

Using the time of maximum and peak brightness found above we have compared the photographic and visual light curves of SN 1984A with the well-observed Type Ia SN 1981B (Figs. 1 and 2), assuming a distance modulus relative to Virgo of $\Delta\mu = 0.4$ which is consistent with both the distance to NGC 4536 according to the infall model of Aaronson *et al.* (1982) and the photographic magnitude of SN 1981B at maximum ($m_{pg}^0 = 11.49$; Buta and Turner 1983). Initially the brightness is exactly as expected. However, by day 50 it is clear that SN 1984A faded faster than SN 1981B. During the interval 20–70 days, the mean rate of decline is 0.065 ± 0.007 mag day $^{-1}$ for SN 1984A, but only 0.04 mag day $^{-1}$ for SN 1981B. During the same interval SN 1984A declined faster in the visual than even SN I 1986G which was a well-observed photometrically “fast” supernova with $\beta = 12$, and $\lambda_{Si II} = 6148$ Å (Phillips *et al.* 1987). (β is Pskovskii's photometric speed class which is the initial rate of post peak decline in 0.01 mag day $^{-1}$).

The fast decline of SN 1984A may be unprecedented among supernovae observed in this century, but the visual light curve of SN 1984A bears a close resemblance to that of another rare

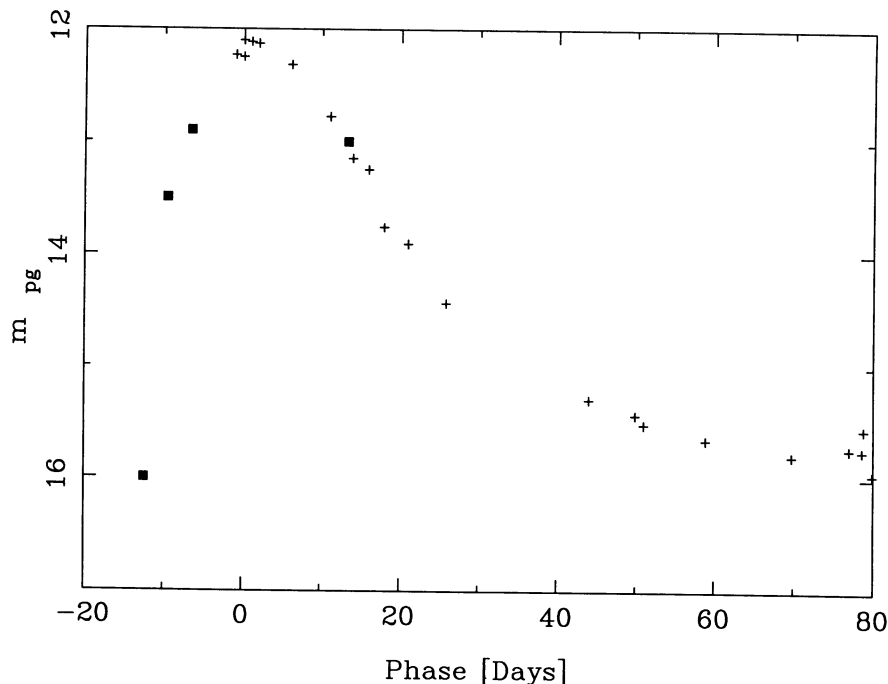


FIG. 1.—The m_{pg} light curve of SN 1984A (solid squares) is compared with SN 1981B (crosses). A relative distance modulus of 0.4 mag has been assumed.

Type I supernova, S Andromedae, the supernova of 1885. From over 500 magnitude estimates, de Vaucouleurs and Corwin (1985) have presented a definitive visual light curve of the supernova which is plotted along with data for SN 1984A in Figure 3. This figure constitutes convincing evidence that the light curves of these two supernovae were very similar. To find the apparent brightness difference between S And and SN 1984A, we have used the date of photographic maximum found above to align the light curves in time and then fitted the SN

1984A observations to de Vaucouleurs and Corwin's analytic formula which gives a smooth interpolation to the mean points on the light curve of S And. This yields $\Delta m = 4.6 \pm 0.3$ mag.

If we extrapolate the visual light curve of SN 1984A using observations of S And, then $V = 10.4 \pm 0.4$, and $B - V = 1.9 \pm 0.5$ at maximum. This unusually red color for a SN Ia near maximum is confirmed by Rosino (1984b) who reported that $B - V = 0.3$ 5 days before maximum, on January 10. Near maximum, Type Ia supernovae typically have $B - V \approx 0$; SN

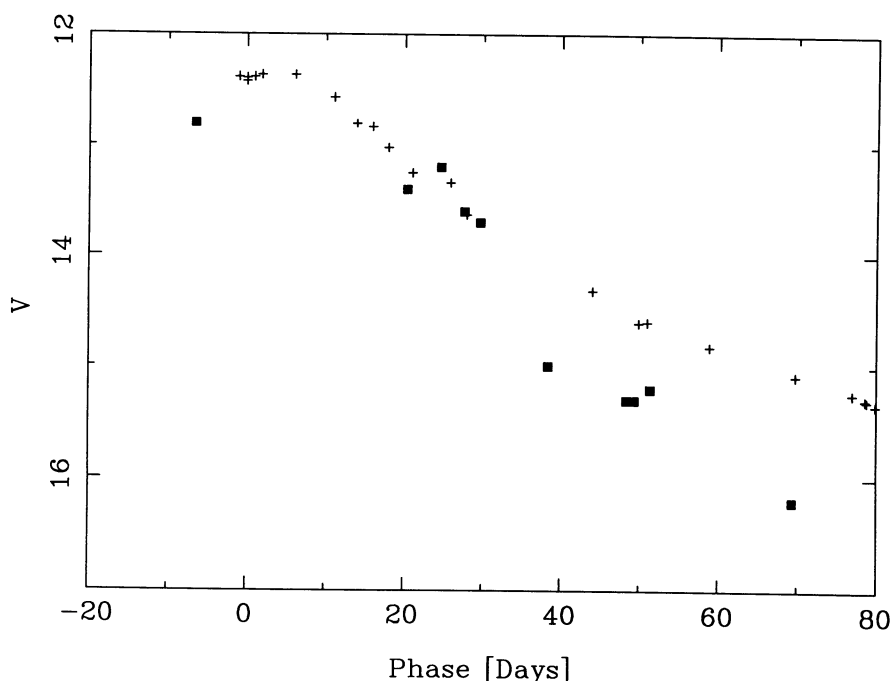


FIG. 2.—The visual light curve of SN 1984A (solid squares) is compared with SN 1981B (crosses). A relative distance modulus of 0.4 mag has been assumed. The comparison shows that SN 1984A declined much faster than SN 1981B.

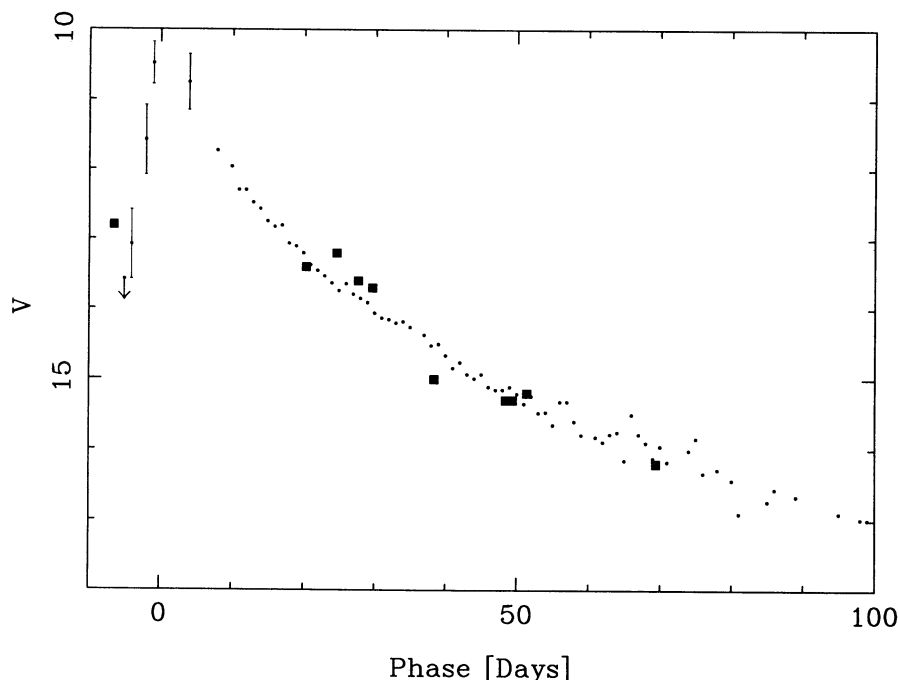


FIG. 3.—The visual light curve of SN 1984A (solid squares) is compared with S Andromedae (small circles)

1975A was observed 5 days before maximum light when $(B - V)_0 = -0.15$ (Kirshner, Arp, and Dunlap 1976). Red colors near maximum are a feature which SN 1984A shares with SN Ib and S And. According to de Vaucouleurs and Corwin's (1985) analysis of reports of the color of S And, $B - V \approx 1.3$ at maximum light.

b) Optical Spectra

Branch (1987) has discussed the premaximum spectrum of SN 1984A of Wegner and McMahan (1987) and has used synthetic spectrum calculations to show that the photospheric velocity of SN 1984A exceeds that of SN 1981B at maximum by 4300 km s^{-1} . (Colgate, Pearce, and Petschek 1987) has argued that the high velocity of SN 1984A is due to the fact that the supernova was observed much earlier before maximum light than suggested by Branch (1987) or above. However, later observations of the spectrum rule out this possibility.

Blue and red spectra of SN 1984A were obtained on 1984 February 6 and 9 (22 and 25 days after maximum light) by Levreault and Garnett (reported by Wheeler 1985). Comparison of SN 1984A with SN 1981B 20 and 24 days past maximum confirms the general pattern of blueshifting of the features in SN 1984A found earlier. The blueshift is especially clear for the lines of Ca II 3968 + 3933 and Fe II 4568 (multiplet 38) and Si II 6355. From measurements of line positions in these spectra we find $v_{\text{phot}}(84A)/v_{\text{phot}}(81B) = 1.22 \pm 0.05$ (cf. 1.34 ± 0.04 before maximum). The position of the Si II absorption has moved redward to $6100 \text{ \AA}$ indicating an expansion velocity, for this stage of evolution, which is still significantly higher than SN 1981B ($\lambda_{\text{Si II}} = 6145 \text{ \AA}$) or any of the SN Ia in Branch's (1981) compilation. Despite the different Doppler shift exhibited by SN 1984A and SN 1981B, the spectra of these two events, as judged by the relative strength of lines and the shape of the emission and absorption features, bear a striking similarity to one another. The similarity is such that it is

probably fair to note that the blue spectrum of SN 1984A on February 6 ($t = 22$ days) bears a greater resemblance to the spectrum of SN 1981B 29 and 35 days after maximum than it does to earlier observations. Apparently SN 1984A evolved faster than SN 1981B, a natural consequence of a greater expansion velocity which leads to formation of the photosphere in deeper layers of the ejecta sooner than normal and mimicking an older SN.

c) IR Data

Graham *et al.* (1987) have recently presented and discussed new IR photometry of SN 1984A and made a detailed comparison with SN 1981B. The IR evolution of the H ($1.65 \mu\text{m}$) and K ($2.2 \mu\text{m}$) flux and the $H - K$ colors of the two SN are practically indistinguishable. The H magnitude of SN 1984A 20 days after optical maximum, $H_{20} = 13.35 \pm 0.05$ is consistent with $H_{20} = 13.14$, $\sigma = 0.29$ for SN Ia in Virgo inferred from a sample of six supernovae with distances well known relative to Virgo (Elias *et al.* 1985). Although the H and K light curves appear quite normal, there is evidence that the J ($1.25 \mu\text{m}$) light curve deviates from standard behavior. The J light curve decays faster than usual which is reflected by a distinct development of the $J - H$ color (Fig. 4).

III. SN 1984A AND S ANDROMEDAE

Although there is good reason to identify S And as a Type Ia supernova, the unusual light curve and colors have made precise classification of this supernova impossible. However, it now appears that the photometric properties of S And are not unprecedented for a SN Ia. The chief evidence for classifying S And comes from descriptions of the spectrum. On the basis of these records de Vaucouleurs and Corwin (1985) classify S And as a Type I. However, as the light curve is unusual, the classification is modified to Type I peculiar. De Vaucouleurs and Corwin (1985) allude briefly to the possibility that S And might belong to the subclass of Type I supernovae, SN Ib,

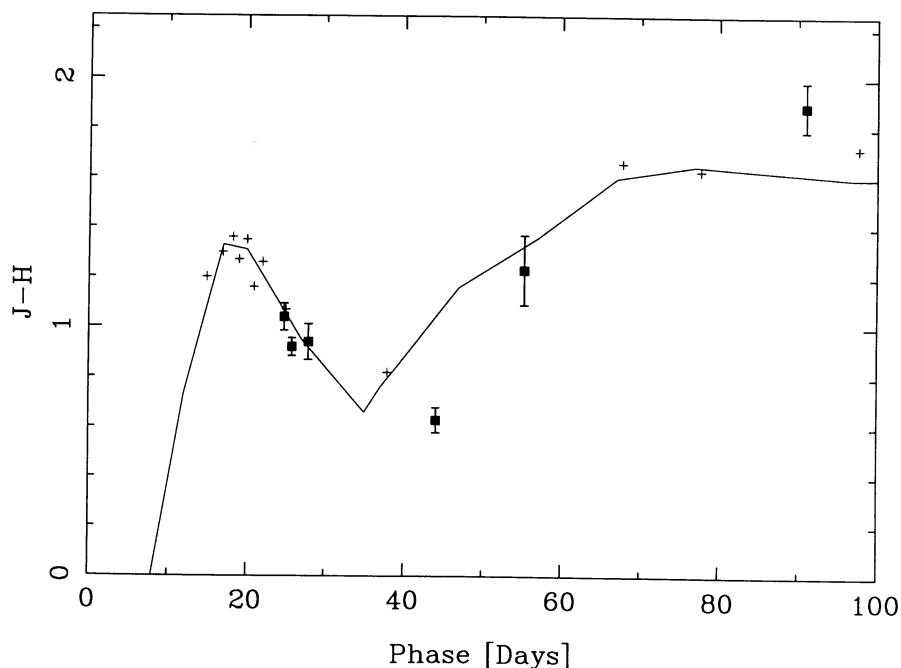


FIG. 4.—The $J-H$ colors of SN 1984A (solid squares) are compared with SN 1981B (crosses) showing anomalous evolution. The solid line is the standard color evolution of SN Ia according to Elias *et al.* (1985). The data for SN 1984A are from Graham *et al.* (1987). The point for $t = 55$ is mean of three observations, and the $t = 91$ days is the mean of 2.

which is exemplified by SN 1962L, 1964L, and more recently by SN 1983N and SN 1984L. Type Ib supernovae constitute a distinct, well-defined, class of Type I's. Clearly it is important to investigate the possibility that the supernova of 1885 was a Ib.

A comparison of the light curves of the above mentioned SN Ib with S And confirms that neither evolution nor the light curve of S And is consistent with the classification SN Ib. The visual spectroscopic observations of S And leave little reason to doubt that SN 1885 was a classical SN Ia (de Vaucouleurs and Corwin 1985) and even less reason to suspect that it was a SN Ib. We have compared the descriptions of the spectrum of S And with spectra of the SN Ib SN 1962L, SN 1983N, and SN 1984L 20–30 days from maximum (Bertola 1964; Panagia *et al.* 1987; Wheeler and Levreault 1985). Apart from the emission peaks either side of the 5700 Å absorption which SN Ia and SN Ib share, the visual observations of S And seem to bear little resemblance to SN Ib. A similar exercise has been carried out for the spectra of SN 1984A and SN 1981B (Wheeler 1985; Branch *et al.* 1983). All of the major peaks in the spectra of these SN Ia from 4700 to 7000 Å have been recorded, and only two of the eight reported emission features in S And do not appear to have notable counterparts in modern spectra. The recording of a strong peak in the spectrum of S And at 6568 Å is particularly significant as we can identify this as the emission associated with the Si II 6355 line. The Si II line is the principal identifying feature of a SN Ia near maximum light, and there is no comparable feature in the SN Ib spectrum with which this may be confused. Thus it appears that we can be fairly confident that S And was a SN Ia.

IV. SN 1984A, SN 1885, AND THE PROPERTIES OF SN Ia

Branch (1981) and Pskovskii (1977) have reviewed optical spectroscopic and light curve data for a large number of SN I's and conclude that there is dispersion in their properties. The

parameters discussed are the rate of decline of the photographic light curve from maximum β , typically 9–10 (0.01 day^{-1}), and the velocity of material at the photosphere as inferred from the wavelength of the Si II 6355 Å absorption, which is on average found at 6130 Å. The most significant correlation (significant at the 99% level) is between the photometric speed class β and the wavelength of the Si II 6355 Å absorption. The sense of the relationship is such that the SN I with the fastest decaying light curves exhibit the slowest ejecta velocities. According to these correlations a SN such as SN 1984A with unusually high-velocity material should have slower than average blue and visual light curves. This does not appear to be the case. SN 1984A demonstrates that either there is no unique relation between light curve decay rate and expansion velocity, or that the relation is well-defined, but not single-valued. This latter alternative is more attractive theoretically since at extremely high velocities one might expect the rapid expansion to dominate the more subtle effects which may determine the light curve decay rate at lower velocities (Graham 1987).

The apparent brightness difference between SN 1984A and S And is 4.58 ± 0.28 mag. The visual extinction toward S And is estimated to be 0.6 ± 0.3 mag (de Vaucouleurs and Corwin 1985). Assuming that SN 1984A and S And had the same luminosity, the distance to NGC 4419 and the absolute magnitude of SN 1984A may be found. Correcting for foreground extinction toward NGC 4419 and adopting $\mu = 24.1$ for M31 (de Vaucouleurs 1978) the distance modulus for NGC 4419 is 29.1 ± 0.4 and $M_{\text{pg}} = -17.2 \pm 0.4$ at maximum. Estimates of the distance modulus for Virgo yield $\mu \approx 31.0$ (Hodge 1981), and therefore if NGC 4419 is a cluster member, then either the extinction to S And has been underestimated, or S And was less luminous than SN 1984A.

We have established that the optical and IR brightness of SN 1984A at maximum is entirely consistent with it being a common Type Ia supernova at the distance of Virgo. Perhaps,

since SN 1984A was a very rare SN Ia, this is only fortuitous, and NGC 4419 is a foreground galaxy. Let us investigate the consequences of this assumption.

Using de Vaucouleurs's (1979) distance measurements Branch (1982) finds that the relation between the absolute magnitude at maximum and the speed class is given by $M_{pg} = -18.7 + 0.19(\beta - 10.5) + 5 \log_{10} (H_0/100 \text{ km s}^{-1} \text{ Mpc}^{-1})$. For S And $\beta = 18$ (de Vaucouleurs and Corwin 1985) and since $M_{pg} = -17.2 \pm 0.4$, this implies $H_0 = 110 \pm 20 \text{ km s}^{-1} \text{ Mpc}^{-1}$. Unfortunately, it is probably unreasonable to expect the correlation between luminosity and photometric speed class to be linear over such a large range of β , and extrapolation from S And ($\beta = 18$) to common SN Ia ($\beta \approx 10$) will undoubtedly lead to error. It has already been shown that SN 1984A does not conform to the $\lambda_{Si II}/\beta$ correlation defined by more common SN Ia, and it is just as likely that one cannot extrapolate the M/β relation either.

There is a large uncertainty in the Tully-Fisher distance for NGC 4419 because of contamination by Galactic H I emission, and it is not entirely impossible on these grounds that NGC 4419 is closer than Virgo, yet there appears to be no good reason to deny the cluster membership of this galaxy. If SN

1984A and S And have the same luminosity, then it is likely that NGC 4419 is a member of Virgo, and the extinction toward S And has been underestimated.

V. CONCLUSIONS

The light curve of the Type Ia supernova SN 1984A is a good match to that of the supernova of 1885, S Andromedae. A reexamination of the observations of S And and comparison with SN 1984A suggests that there is now little reason to doubt that S And was a Type Ia event. Consequently, SN 1984A and S And are rare examples of the SN Ia phenomenon with unusually fast light curves. The identification of S And as a SN Ia may give us hope that we may use this supernova to calibrate SN Ia as standard candles, but the properties of SN 1984A suggest that the behavior of such rare supernovae are not readily related to more common Type Ia events. Therefore, this calibration cannot be reliable until more statistics are available to determine the M/β correlation for supernovae with such fast light curves.

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