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THE RISE TIMES AND BOLOMETRIC LIGHT CURVE OF SN 1994D: CONSTRAINTS ON MODELS OF TYPE Ia SUPERNOVAE

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ABSTRACT

Using published photometry and an empirical model of the temporal evolution of the apparent magnitudes in the *UBVRI* passbands, we have constructed a continuous optical bolometric, or "quasi-bolometric," light curve of the well-observed Type Ia supernova SN 1994D. The optical bolometric light curve is found to have a maximum luminosity of about $8.8 \times 10^{42} \times (D/13.7 \text{ Mpc})^2$ ergs s^{-1}, which is reached ~18 days after the explosion. In addition, the optical bolometric light curve exhibits an inflection, or "shoulder," about 25 days after maximum. This inflection corresponds to the secondary maximum observed in all filter light curves redder than *B*. The individual filter curves have rise times similar to that of the optical bolometric light curve; other Type Ia supernovae are found to have similar rise times. Our fits indicate that the peak bolometric luminosity and the maxima in the *B*, *V*, and *R* light curves all occur within a day of one another. These results can be used to place constraints on theoretical models of Type Ia events. For example, most current theoretical models predict rise times to peak luminosity which are significantly shorter than that estimated for SN 1994D.

Subject headings: supernovae: general — supernovae: individual (SN 1994D)

1. INTRODUCTION

To compare theoretical models for the temporal evolution of the emitted flux from Type Ia supernovae (SN Ia's) with observations, it is necessary either to calculate the predicted light curves in the various observational passbands from the models or to construct bolometric light curves from the data. Attempts have been made to calculate the filter light curves from models with elaborate hydrodynamics codes (e.g., Höflich & Khokhlov 1996; Eastman 1996), but a consensus on the correct treatment of the radiation transfer has yet to be reached (Eastman 1996; Pinto 1996; Höflich 1996). Accurate filter light curves are difficult to calculate in this manner, as they require synthesization of the entire spectrum on a large number of wavelength points at every stage in the evolution of the explosion. On the other hand, the construction of truly bolometric light curves from observations requires numerous simultaneous measurements across the entire electromagnetic spectrum, including the satellite ultraviolet, the optical *UBVRI* passbands, the near-infrared *JHK* passbands, and longer wavelengths. No SN Ia event has ever been observed extensively in all of these bands; few have a substantial number of observations even in the optical passbands. Nevertheless, with a few assumptions regarding the amount of energy emitted at unobserved wavelengths, approximate bolometric light curves can be derived from observed photometric data. In this manner, preliminary bolometric light curves for a few well-observed SN Ia's (e.g., SN 1992A) have been constructed by Suntzeff (1996). As an observationally derived estimate of the total thermal energy radiated from a SN Ia, a bolometric light curve provides a crucial link between theory and observations by allowing model predictions to be directly compared with observational results. The value of a bolometric light curve, assembled from observations, to constrain SN explosion models has been clearly demonstrated in the case of SN 1987A (Suntzeff et al. 1991; Bouchet, Danziger, & Lucy 1991).

SN 1994D was a Type Ia event that occurred in NGC 4526, an S0 galaxy located about 5° from M87 in the Virgo Cluster.[2] Accurate and extensive observations of SN 1994D have been reported by Richmond et al. (1995), Patat et al. (1995), and Meikle et al. (1996). Höflich (1995) compared optical filter light curves predicted from theoretical models with unpublished photometry from the Cerro Tololo Inter-American Observatory (CTIO) and the Center for Astrophysics (CfA). Although the models were able to reproduce the general characteristics of the filter light curves, the detailed shapes of the curves could not be matched.

SN 1994D was an unusual SN Ia in several respects: it displayed an unusually blue color near maximum, appeared to be overluminous at maximum compared to other SN Ia's and deviated from the decline-luminosity relation observed for Type Ia events (Richmond et al. 1995; Patat et al. 1995). Near maximum, the spectrum of SN 1994D exhibited a strong P Cygni line near 1.05 μm that is possibly due to He I ($\lambda_0 = 1.083$ μm; Meikle et al. 1996). The degree to which SN 1994D represents a truly peculiar SN Ia, as opposed to a minor variant of a "normal" SN Ia, is still to be determined, however. In particular, the derived luminosity is somewhat uncertain due to uncertainty about the distance to NGC 4526, and the spectral region observed by Meikle et al. (1996) has not been observed for any other SN Ia at a similar phase.

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[2] With a velocity of ~533 km s^{-1} (Binggeli, Sandage, & Tammann 1985), NGC 4526 is clearly a member of the Virgo Cluster. Recent reports of the distance modulus for the Virgo Cluster range from 31.1 (Freedman et al. 1994; Saha et al. 1996) to 32.0 (Sandage et al. 1996). We will adopt the distance modulus for NGC 4526 of 30.68 (13.7 Mpc) favored by Richmond et al. (1995) and Patat et al. (1995), but will scale all luminosities accordingly.

TABLE 1

DERIVED PARAMETERS FOR SN 1994D LIGHT CURVES

Band	Δt_{30} (days)	$T_{\max}$ [a] (day)	$m_{\max}$ (mag)	Δm_{15} (mag)	s_2 (mag day^{-1})
U	16.1 ± 0.7	431.70 ± 0.14	11.31 ± 0.02	1.82 ± 0.03	0.0166 ± 0.0032
B	17.6 ± 0.5	432.90 ± 0.15	11.85 ± 0.01	1.47 ± 0.03	0.0166 ± 0.0002
V	20.1 ± 0.6	433.41 ± 0.15	11.90 ± 0.01	0.83 ± 0.02	0.0311 ± 0.0003
R	19.3 ± 0.6	432.21 ± 0.21	11.87 ± 0.02	0.81 ± 0.03	0.0342 ± 0.0002
I	20.0 ± 3.0	429.79 ± 0.25	12.10 ± 0.02	0.64 ± 0.04	0.0523 ± 0.0001
Bolometric	17.8 ± 1.7	432.35 ± 0.27	12.04 ± 0.02	1.17 ± 0.03	0.0305 ± 0.0008

[a] JD − 2,449,000.

Using the high-quality observations and an empirical model to fit the optical filter light curves, we derive a continuous optical bolometric light curve for SN 1994D. Our model and fitting procedure are described in § 2. With this continuous model of the filter light curves, bolometric magnitudes can be calculated even when simultaneous measurements in all filter passbands are unavailable. The method used to compute the optical bolometric light curve is presented in § 3. We also estimate the rise time to bolometric maximum in § 4. The rise time and shape of the optical bolometric light curve are briefly compared with predictions from various models in § 5.

2. THE EMPIRICAL MODEL

The shapes of the observed SN Ia light curves (Leibundgut et al. 1991a; Riess, Press, & Kirshner 1996) suggest a simple analytical form. We model the time evolution of the observed brightness (in magnitudes in a given filter band) as a Gaussian (for the peak phase) atop a linear decay (for the late-time decline, ~50 days past maximum light). A second Gaussian is introduced to fit the secondary maximum that is observed in the *V*, *R*, and *I* light curves about 25 days after the initial peak (Ford et al. 1993; Suntzeff 1996). To account for the rising (i.e., premaximum) segment of the light curves, we multiply this model by a function which rises exponentially and approaches unity near the peak of the first Gaussian. The model parameters for the light curves in each of the available passbands are determined by a least-squares fitting technique. This simple approximation, with between 5 and 10 free parameters, yields a surprisingly accurate representation of the optical filter light curves observed for most SN Ia's (Vacca & Leibundgut 1996a). The model has the advantage of being completely independent of any assumptions regarding the nature of Type Ia events or possible similarities or differences from one event to another. Further discussion of the empirical model and the fitting procedures will be presented in a forthcoming paper (Vacca & Leibundgut 1996b).

We have used this empirical model to fit the light-curve data for SN 1994D. In Figure 1 (Plate L3), we show the model fits to the *U*, *B*, *V*, *R*, and *I* light curves for this supernova. The fits were restricted to within ~100 days of the maximum because many SNs have exhibited changes in the late-time decline several hundred days after maximum (Doggett & Branch 1985; Leibundgut et al. 1991a). Errors on the data points in the *BVRI* passbands were assumed to be those given by Richmond et al. (1995); errors on the *U*-band data were taken from Patat et al. (1995). The residuals from the fits are shown below each panel. Although our model fits the observed light-curve data far better than the standard Type Ia templates of Leibundgut (1988), close inspection of the residuals reveals additional small-amplitude structure in the observed light curves. A flux excess relative to our model is present about 5 days after maximum in the *V*, *R*, and *I* light curves; this feature, which has never been reported before, is also seen in the unpublished data from CTIO and the CfA (Höflich 1995).

One of the most useful aspects of a continuous model of the light-curve shapes is that additional interesting quantities can be objectively derived from it. In particular, we determine the rise time, Δt_{30} (see below); the time of maximum brightness, $T_{\max}$; the peak apparent magnitude, $m_{\max}$; the magnitude difference between the peak and 15 days after the peak, Δm_{15}; and the slope of the late-time decline, s_2. The values of these parameters, derived from our fits to the data for SN 1994D in each photometric band, are given in Table 1.[3] Except for s_2, whose error was calculated as part of the least-squares fitting routine, the uncertainties on all parameters derived from the best-fit model (e.g., $T_{\max}$ and $m_{\max}$) were estimated using a Monte Carlo procedure. We simulated data points drawn from the best-fit model at the same phases as the observed data points and with uncertainties estimated from the rms deviation of the observed data from the best fits. The errors given in Table 1 correspond to the standard deviations measured after 1500 simulations.

3. THE OPTICAL BOLOMETRIC LIGHT CURVE

Using the results from the fits to the light-curve data in the *UBVRI* passbands, we constructed an optical bolometric, or "quasi-bolometric," light curve for SN 1994D. For this calculation we used the normalized passband transmission curves given by Bessell (1990), and zero points derived from the Kurucz (1992; see also Castelli & Kurucz 1994) model spectrum of Vega scaled to match the observed flux of Vega in the *V* band given by Hayes (1985). The integrated flux in each band was approximated by the mean flux multiplied by the effective width of the passband. We corrected for the partial overlap of the *V*, *R*, and *I* bands, and interpolated between the fluxes in the *U*, *B*, and *V* bands in order to fill the small wavelength gaps between these passbands. We corrected the fluxes for extinction by adopting the extinction values advocated by Richmond et al. (1995). The resulting quasi-bolometric light curve, the construction of which is greatly facilitated by our continuous model of the individual filter light curves, is shown at the bottom right of Figure 1. This curve represents the temporal evolution of the flux between ~3280 and ~8810 Å. The secondary maximum observed in the *V*, *R*, and *I* data carries through to the optical bolometric light curve. A similar feature is seen in the bolometric light curve of SN 1992A and possibly in SN 1991T (Suntzeff 1996). In fact, the shape of the

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[3] The results presented in Table 1 supersede the values given in Vacca & Leibundgut (1996a).

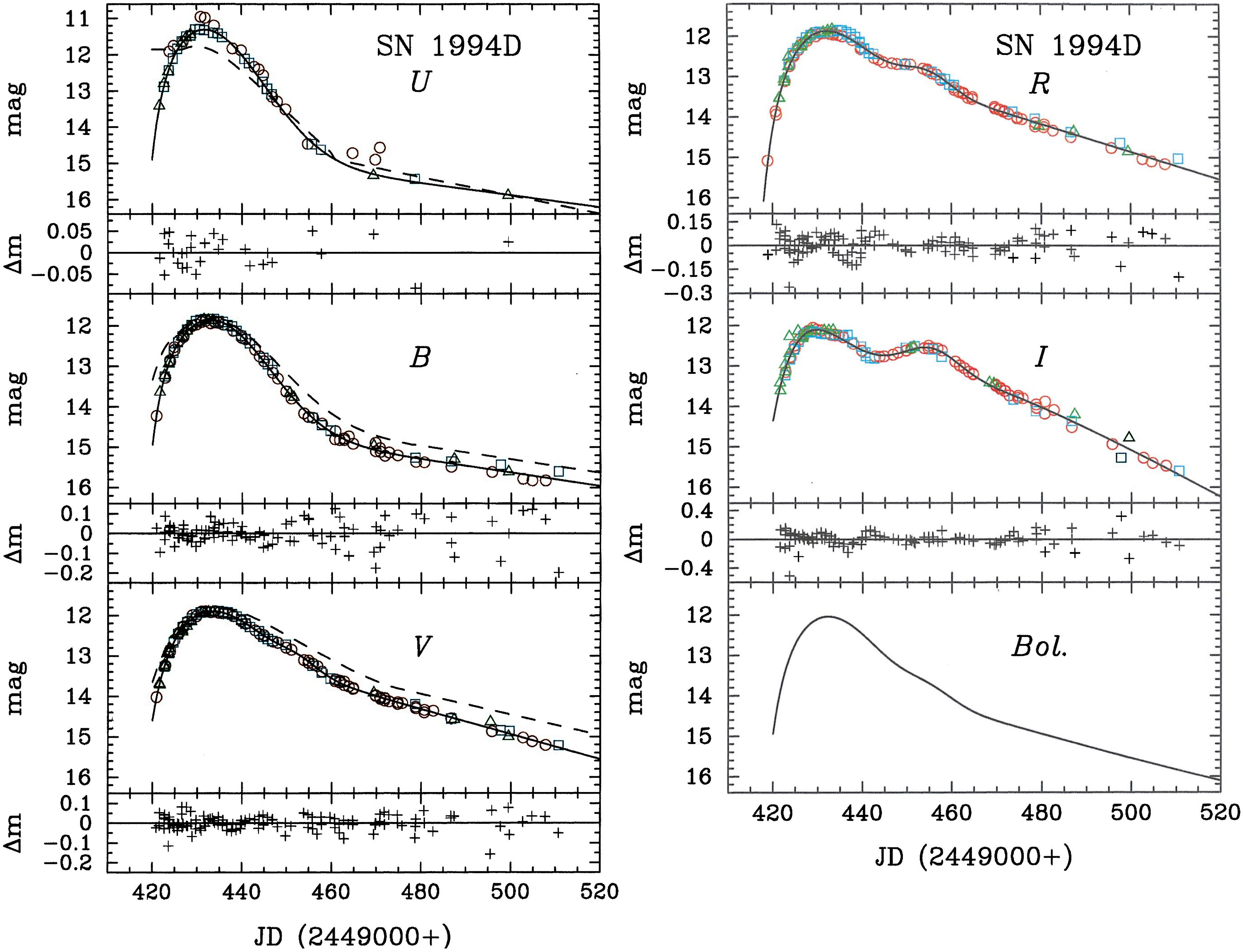

FIG. 1.—*U*, *B*, *V*, *R*, *I*, and bolometric light curves of SN 1994D. Symbols are the observed data from Richmond et al. 1995 (*circles*), Patat et al. 1995 (*squares*), and Meikle et al. 1996 (*triangles*). The solid lines are the best-fitting models to the data points in each passband. Residuals are shown below each panel. The dashed lines are the light-curve templates of Leibundgut (1988) normalized to the time and magnitude of the maximum light in *B*.

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bolometric and filter light curves of SN 1994D are very similar to those of SN 1992A. We fitted the optical bolometric light curve with our model and determined its parameters and their uncertainties, which are listed in Table 1. The empirical model reproduces the quasi-bolometric light curve to better than 0.01 mag over the entire temporal range.

The maximum flux for the quasi-bolometric light curve was found to be $3.9(\pm 0.1) \times 10^{-10}$ ergs cm^2 s^{-1}. For a distance of 13.7 Mpc (Richmond et al. 1995; Patat et al. 1995), this implies a maximum luminosity of $8.8(\pm 0.2) \times 10^{42}$ ergs s^{-1}. As shown by Suntzeff (1996), the flux in the U through I photometric bands comprises ~80% of the thermal energy radiated by a SN Ia between 2000 and 22000 Å, and very little additional flux is expected to be emitted at wavelengths $\lambda < 2000$ Å and $\lambda > 22000$ Å (Blair & Panagia 1987).[4] From the results given by Suntzeff (1996) for SN 1992A, the flux in the near-infrared wavelength bands is expected to contribute less than ~15% to the total flux even at 80 days after maximum. From the J, H, and K magnitudes given by Richmond et al. (1995) corresponding to about 6 days after the maximum of the quasi-bolometric curve, we estimate that the flux in these near-infrared bands represents less than 3% of the total flux in the combined optical bands. Based on assumed intrinsic colors, Leibundgut (1996) estimated that the infrared contributes less than 5% near maximum light. An upper limit to the true bolometric correction can be estimated from the total flux for a blackbody with optical colors equal to those observed for SN 1994D. We fitted the observed fluxes in the *UBVRI* passbands with a Planck spectrum and derived a bolometric correction from the best-fit temperature. Although a blackbody spectrum is generally a poor fit to the observed spectral energy distributions, we use it only to obtain a rough estimate of the bolometric correction. At the optical bolometric maximum, the blackbody effective temperature was found to be ~14,000 K and the bolometric correction, in terms of the ratio of total flux to flux in the optical passbands, is a factor of ~2.7. With this value we can place limits on the peak bolometric flux from SN 1994D of $42.9 < \log [L_{\rm bol}(D/13.7\ {\rm Mpc})^2] < 43.3$. We note that during those phases when the Planck function did provide a good fit to the observations (during the premaximum rise), the bolometric correction was found to be about a factor of 2. It should also be noted that although we have not accounted for energy lost due to freely escaping gamma rays in our calculations, we expect this energy loss to represent only a very small fraction of the bolometric luminosity at maximum (Leibundgut & Pinto 1992).

The luminosity range derived above extends up to $\log L_{\rm bol} < 43.5$ and 43.8 for Virgo distance moduli of 31.1 and 32.0, respectively. This range encompasses all luminosity predictions for models of the explosion of Chandrasekhar-mass white dwarfs (Woosley & Weaver 1994, 1995; Höflich & Khokhlov 1996; Eastman 1996). For the Virgo Cluster distance modulus favored by Sandage et al. (1996), SN 1994D would be highly overluminous with respect to the current models for Type Ia explosions.

4. RISE TIMES AND TIMES OF MAXIMUM

The rise time, defined here as the difference (in days) between the time of maximum brightness and the time when the supernova was 30 mag below maximum, Δt_{30}, was found to be 17.8 ± 1.7 days for the optical bolometric light curve. Similar values are found for the rise times of the individual filter light curves (Table 1). The magnitude difference was chosen to correspond roughly to the difference in luminosity between the pre-explosion white dwarf and the peak of a typical SN Ia. Because the light curve is so steep before maximum, the estimated rise time is relatively insensitive to the precise value of the magnitude difference chosen. It is critically dependent on the assumed shape of the light curve prior to maximum, however. We have assumed that the light curve rises (that is, the apparent magnitudes decrease) exponentially with time. It is certainly possible that the premaximum light curves of SN Ia's rise faster than this, in which case our procedure will yield an overestimate of the rise time. Additional premaximum data for other SNs, as well as comparisons with detailed model calculations, will be needed to determine whether our assumed form is an accurate representation of the premaximum segment of SN Ia light curves.

We note that our estimate of the rise time of the B light curve for SN 1994D is very similar to the value determined for SN 1990N (17–20 days) by Leibundgut et al. (1991b) using a different method. (A bolometric light curve constructed for SN 1990N that includes satellite ultraviolet data was found to have a bolometric rise time of about 14–18 days; Leibundgut 1996.) We applied our fitting procedure to the B data for SN 1990N and derived a rise time of ~19 days, a result which indicates that we are not grossly overestimating the rise time with our procedure and provides some confidence in our values for SN 1994D. Furthermore, based on the estimated time of maximum and the first observation of SN 1994D in the R band, the rise time in R must be longer than ~13.3 days. We find a similarly long rise time when we apply our procedure to the B data for SN 1991T (~18.5 days; Vacca & Leibundgut 1996b). The rise times of the V light curves for SN 1994D and SN 1992A are also found to be approximately the same (~20 days).

For SN 1994D, the estimated rise time corresponds to an explosion date of ~1994 March 3 (JD 2,449,414.6), consistent with the values obtained from the individual filter curves. The first observation on 1994 March 7 was therefore only 4–5 days after the explosion. Our estimated explosion date agrees surprisingly well with that found by Höflich (1995), although our estimate of the rise time to bolometric maximum is ~3 days longer.

Contrary to the expectations from the models or the template light curves of Leibundgut (1988), we find only small differences between the times of the maxima in the B, V, R, and bolometric light curves. They all occur within ~1 day of one another (Table 1). In addition, the U and B maxima are separated by only ~1 day. Similarly small differences in the times of maximum for the various filter light curves are found for several other well-observed SN Ia's (e.g., SN 1989B and SN 1990N; see Vacca & Leibundgut 1996a, 1996b). Interestingly, the dim and fast-declining events SN 1986G and SN 1991bg exhibit a delay of about 2 days between the maxima in B and V.

5. DISCUSSION AND CONCLUSIONS

The extensive photometric observations of SN 1994D, along with a fairly simple empirical fitting procedure applied to the individual filter light curves, have allowed us to construct a continuous "quasi-bolometric" light curve and to estimate the rise time for this SN Ia. The fits yield a far more objective

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[4] This provides some justification for our use of the term "quasi-bolometric."

means of quantifying the parameters describing the light curves than the standard templates can provide. Because the procedure can be applied to the filter light curves of any individual SN Ia, it also can provide an independent test of the commonly adopted assumption that all SN Ia's are members of a single family (Hamuy et al. 1995; Riess et al. 1996). While providing a close approximation to the light-curve data, the fits can also reveal small-amplitude (<0.05 mag) substructure in the light curves that might escape notice if the light-curve templates were adopted.

Our fit to the optical bolometric light curve of SN 1994D yields a peak luminosity in the wavelength range 3300–8800 Å of $8.8(\pm 0.2) \times 10^{42}(D/13.7 \text{ Mpc})^2$ ergs s^{-1}. After accounting for possible bolometric corrections, we find the peak bolometric luminosity to be in the range $42.9 < \log\,[L_{\text{bol}}(D/13.7 \text{ Mpc})^2] < 43.3$. This corresponds to a mass of ^{56}Ni produced in the explosion of $0.4\ M_\odot < M_{\text{Ni}} < 1.1\ M_\odot$ (Arnett, Branch, & Wheeler 1985). The bolometric light curve also exhibits a very long rise time to maximum of ∼18 days and an inflection or "shoulder" about 25 days after the primary peak (∼40 days after the explosion).

Although the estimated peak bolometric luminosity for SN 1994D is in good agreement with the range of model predictions, it is not clear whether any of the current explosion models can reproduce the estimated rise times or the detailed structure of the observed filter or bolometric light curves for SN 1994D. Most current explosion models have difficulty in reproducing the long rise times found for SN 1994D and SN 1990N. Direct detonation and deflagration models yield rise times which are on the order of 7–14 days (e.g., Khokhlov, Müller, & Höflich 1993). Delayed detonations may have rise times as long as ∼15 days, but only pulsating delayed detonation models or detonation models incorporating a low-density damping envelope have rise times as long as that determined for SN 1994D (Höflich & Khokhlov 1996). None of the delayed detonation models considered by Höflich (1995) or the pulsating delayed detonation models investigated by Höflich, Khokhlov, & Wheeler (1995) can reproduce both the slow rise time and the peak bolometric luminosity of SN 1994D (unless it was substantially closer than 13.7 Mpc). The opacity and the treatment of the radiative transfer problem during the initial stages of the explosion have a critical influence on the rise times in the various models. However, because of poorly known oscillator strengths and incomplete line lists, the opacity is a source of uncertainty in the model calculations (Khokhlov et al. 1993; Eastman 1996). Unless damping envelopes are fairly common, the long rise times found for the light curves of SN 1994D and other SN Ia's may indicate that the opacity has been greatly underestimated.

The inflection seen in the bolometric light curves of SN 1994D and SN 1992A about 25 days after maximum is reproduced in some of the pulsating delayed detonation models for the explosion of Chandrasekhar-mass white dwarfs (Höflich et al. 1995; Eastman 1996). The presence of this "shoulder" in the predicted light curves from the explosions of sub–Chandrasekhar-mass white dwarfs depends on the details of the model calculations (Eastman 1996; Höflich & Khokhlov 1996).

Although beyond the scope of this paper, a detailed comparison between the bolometric light curve we have constructed for SN 1994D and those predicted by theoretical models would clearly represent an important test of various Type Ia explosion models. As the data for SN Ia's continue to improve in quality and quantity, the features observed in the light curves of SN Ia's, and their variation from one supernova to another, will ultimately provide a means of distinguishing the correct models for these events. Our light-curve–fitting method, by providing a quantitative description of the characteristics of individual observed light curves, should make the comparison between observations and models very straightforward.

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