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SUPERNOVA 2009kf: AN ULTRAVIOLET BRIGHT TYPE IIP SUPERNOVA DISCOVERED WITH PAN-STARRS 1 AND *GALEX*

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ABSTRACT

We present photometric and spectroscopic observations of a luminous Type IIP Supernova (SN) 2009kf discovered by the Pan-STARRS 1 (PS1) survey and also detected by the *Galaxy Evolution Explorer*. The SN shows a plateau in its optical and bolometric light curves, lasting approximately 70 days in the rest frame, with an absolute magnitude of $M_V = -18.4$ mag. The P-Cygni profiles of hydrogen indicate expansion velocities of 9000 km s^{-1} at 61 days after discovery which is extremely high for a Type IIP SN. SN 2009kf is also remarkably bright in the near-ultraviolet (NUV) and shows a slow evolution 10–20 days after optical discovery. The NUV and optical luminosity at these epochs can be modeled with a blackbody with a hot effective temperature ($T \sim 16{,}000$ K) and a large radius ($R \sim 1 \times 10^{15}$ cm). The bright bolometric and NUV luminosity, the light curve peak and plateau duration, the high velocities, and temperatures suggest that 2009kf is a Type IIP SN powered by a larger than normal explosion energy. Recently discovered high-z SNe ($0.7 < z < 2.3$) have been assumed to be IIn SNe, with the bright UV luminosities due to the interaction of SN ejecta with a dense circumstellar medium. UV-bright SNe similar to SN 2009kf could also account for these high-z events, and its absolute magnitude $M_{\rm NUV} = -21.5 \pm 0.5$ mag suggests such SNe could be discovered out to $z \sim 2.5$ in the PS1 survey.

Key words: stars: evolution – supernovae: general – supernovae: individual (2009kf)

Online-only material: color figures

1. INTRODUCTION

Type II supernovae (SNe) are hydrogen-rich explosions and fall into three main sub-classes. Type IIP events have plateaus in their optical and near-infrared (NIR) light curves, Type IIL events show a linear decay after peak, and Type IIn events present strong signatures of the presence of a dense circumstellar medium (CSM) and are characterized by narrow hydrogen emission lines superimposed on broad wings. The relative fractions of these SNe are now well measured in the nearby universe (see Smartt 2009, for a review of relative rates). The majority of these (around 60%) are IIP with typical mid-plateau magnitudes of $M_V \sim -17$ mag (Richardson et al. 2002). However, they are heterogeneous and span a factor of 100 both in luminosity and in mass of ^{56}Ni created explosively (Hamuy & Pinto 2002; Pastorello et al. 2003). The progenitor stars of several of the nearest IIP SNe have been discovered (Li et al. 2006; Smartt et al. 2009) and are the red supergiants (RSG) that both stellar evolutionary theory and light-curve modeling have predicted.

Type IIL and IIn SNe are significantly less frequent by volume making up about 3% and 4%, respectively, of the total core-collapse (CC) SNe (Smartt et al. 2009). The lack of an extended plateau suggests that Type IIL SNe have more massive progenitor stars that shed a considerable amount of their hydrogen envelope before explosion, but there are no progenitor detections that confirm this scenario. The progenitors of Type IIn SNe have likely undergone large mass ejection just before their explosion (Gal-Yam et al. 2007; Gal-Yam & Leonard 2009).

Type II SNe are now being searched for in medium- and high-redshift surveys for a variety of reasons. The IIP SNe appear to be reasonably standard candles and have produced precise distance estimates with different methods (Baron et al. 2004; Dessart et al. 2008), but the empirical correlation of plateau–luminosity and expansion velocity, the standardized candle method (SCM), seems a promising method of measuring the distances to large numbers of Type IIP SNe. The dispersion on the order of 0.2–0.3 mag (Hamuy 2003; Nugent et al. 2006; Poznanski et al. 2009), 0.1–0.15 mag in the NIR range (Maguire et al. 2010b), is potentially similar to Type Ia SNe but they are

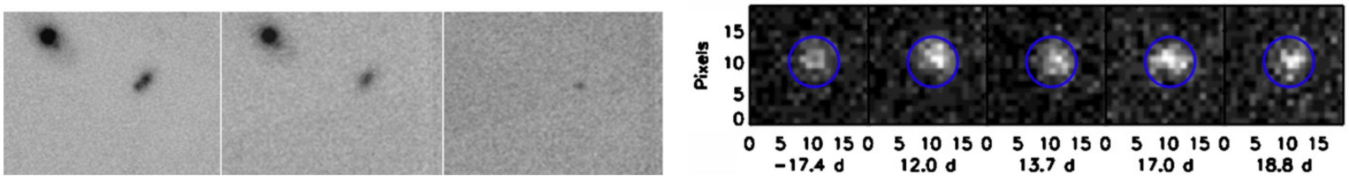

Figure 1. Left panel: discovery image of SN 2009kf (*r* band) in MD08 sky field, template, and difference images. Right panel: *GALEX* NUV images of the host galaxy pre-SN and with SN 2009kf in the rest frame. The phase is with respect to the explosion date (JD = 2, 454, 989.5 ± 3). Blue circles show the 6 arcsec (4 pixel) radius aperture used to measure the fluxes.

(A color version of this figure is available in the online journal.)

significantly fainter, restricting their use with current surveys to $z < 0.3$.

Although this is CC, SNe of all varieties have been used to estimate the star formation rate (SFR) out to $z \sim 0.2$ (Botticella et al. 2008; Bazin et al. 2009) and $z \sim 0.7$ (Dahlen et al. 2004). Recently the highest redshift SNe ($0.7 < z < 2.3$) have been found and proposed to be UV bright IIn SNe (Cooke et al. 2009). Cooke (2008) suggested that this type of SNe could be used to probe the SFR of the universe out to $z \sim 2$ in upcoming surveys.

The Pan-STARRS 1 (PS1) survey has the potential to discover thousands of SNe between $0 < z \leqslant 1$ (Young et al. 2008). The 7 deg^2 camera and 1.8 m aperture could allow IIP SNe to be used as cosmological probes at $z \sim 0.2$ and the brightest events to be found out to $z \sim 2$. One of the first discoveries of PS1, SN 2009kf (Young et al. 2009), is a very bright SN that shares some characteristics with IIP SNe with its luminous plateau and broad P-Cygni features. Simultaneous *Galaxy Evolution Explorer* (*GALEX*) images show that it is also remarkably bright in the near-ultraviolet (NUV). We discuss the implication of this rare SN for understanding the explosions and the use of Type IIP events for probing cosmology and SFR at high redshifts. We adopt the cosmological parameters $H_0 = 70\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$, $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$.

2. DISCOVERY AND OBSERVATIONAL DATA

SN 2009kf ($\alpha_{\rm J2000} = 16^{\rm h}12^{\rm m}54^{\rm s}.05$, $\delta_{\rm J2000} = +55°38'13''.7$) was discovered on 2009 June 10.9 UT by PS1 during the course of the Medium Deep Survey (10 extragalactic fields observed nightly using 25% of the telescope time) in the sky-field MD08 (Figure 1). The last non-detection was on 2009 June 04.9 UT so we adopt an explosion date JD = 2,454,989.5 ± 3. The reported phases are with respect to the explosion date and in the SN rest frame. The PS1 MD08 coverage provided g, r, i, z photometry, and we supplemented this with images from the Liverpool Telescope (LT), William Herschel Telescope (WHT), and Gemini-North Telescope (GN). The PS1 images were reduced with the custom built Image Processing Pipeline while LT, WHT, and GN images were reduced with IRAF[12] tasks. The instrumental magnitudes were derived from host galaxy template subtracted images using point-spread function (PSF) fitting techniques (as in Botticella et al. 2009). A local sequence of Sloan Digital Sky Survey (SDSS) stars was used to measure the relative magnitude for each observation. The uncertainties in the measurements are estimated by combining in quadrature the error of the photometric calibration and the error in the PSF fitting. Apparent and absolute magnitudes reported in this Letter are in the AB and Vega systems, respectively.

[12] IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

The *GALEX* Time Domain Survey (TDS) detected SN 2009kf in monitoring observations of the MD08 field. The host galaxy was detected in the pre-explosion TDS observations between JD = 2,454,960.7 and 2,454,968.9 with NUV = 21.58 ± 0.15 mag. This is corrected for the flux enclosed in a 6″ radius aperture (Morrissey et al. 2007), and the error is measured from the dispersion of measurements between the observations. The SN was detected in five observations with exposure times of 1.0–1.5 ks from JD = 2,455,003.7 to 2,455,013.8, with a peak magnitude of NUV = 22.34 ± 0.38 mag. The SN magnitude was measured by subtracting the flux of the host galaxy from the total flux enclosed in a 6″ radius aperture centered on the host galaxy NUV centroid as determined in the pre-discovery images. The errors in the SN magnitude include both the error in the host galaxy magnitude and the error in the observed magnitude, which is measured empirically as a function of magnitude from the dispersion of 4275 matched sources between observations in bins of 0.5 mag.

Spectroscopic follow-up was obtained with Gemini Multi-Object Spectrographs at GN on JD = 2,455,061.7 and 2,455,094.7 and with Andalucia Faint Object Spectrograph and Camera at the Nordic Optical Telescope (NOT) on JD = 2,455,117.6. Spectra were reduced using the Gemini pipeline and standard routines within IRAF for the NOT spectrum. The spectra of the host galaxy SDSS *J*161254.19 + 553814.4 provided a redshift measurement of $z = 0.182 \pm 0.002$ from the nebular emission lines, in agreement with the SDSS photometric redshift of 0.185 ± 0.065.[13] A reddening coefficient of $C(\mathrm{H}\beta) = 1.3 \pm 0.25$ was derived from the $\mathrm{H}\alpha/\mathrm{H}\beta$ emission line ratio, which corresponds to a host galaxy extinction of $E(B - V) = 0.9$ mag, while the Galactic extinction is negligible ($E(B - V) = 0.009$ mag; Schlegel et al. 1998). The N II and O III N II line ratio methods of estimating metallicity were employed (Pettini & Pagel 2004), giving 12 + log(O/H) abundance of 8.50 ± 0.1 dex.

3. PHOTOMETRIC AND SPECTROSCOPIC EVOLUTION

The r, i, z light curves of SN 2009kf (Figure 2) display a plateau which is similar to that observed in Type IIP SNe (Hamuy 2003). However, there are differences in that SN 2009kf shows a relatively slow rise to peak, and a clear maximum, which occurs progressively earlier from the red to the blue bands. In the last observation at about 280 days after explosion, we estimated an upper limit of $i > 24$ mag.

To meaningfully compare the light curves of SN 2009kf with those of nearby Type IIP SNe, we estimated extinction and redshift corrections, the latter requiring time dilation correction and *K*-correction. We adopted a redshift of 0.182 ± 0.002

[13] Information on the host galaxy is available at http://cas.sdss.org/astrodr7

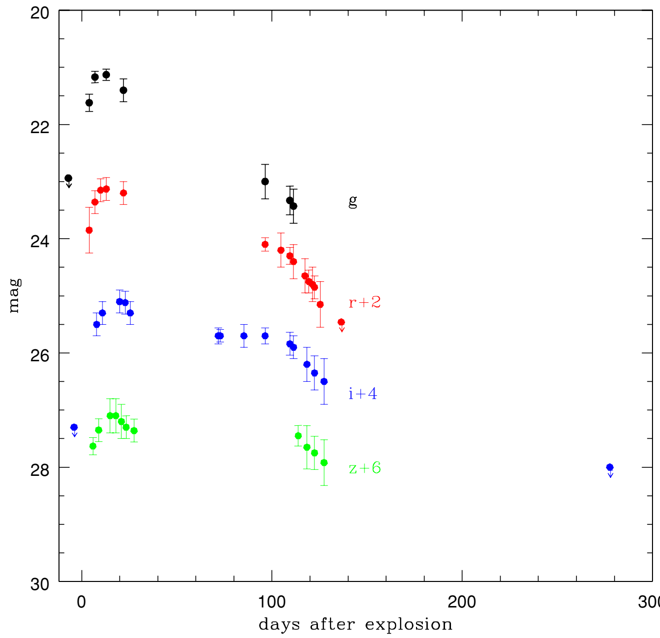

Figure 2. g, r, i, z light curves of SN 2009kf in the observer frame. The magnitudes are not corrected for extinction. The phase is with respect to the explosion date.

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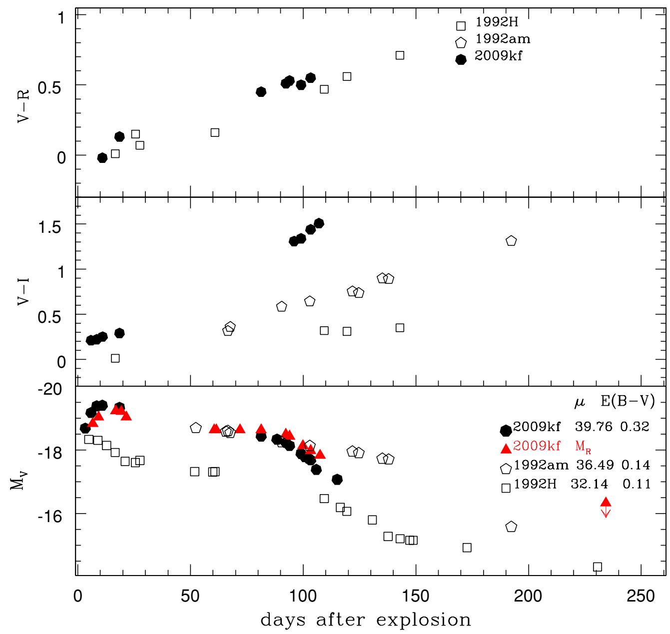

Figure 3. Top and middle panels: temporal evolution of rest-frame $V-R$ and $V-I$ colors of SNe 2009kf, 1992H (Clocchiatti et al. 1996), and 1992am (Schmidt et al. 1994; Hamuy 2003). The colors of SN 2009kf are not corrected for host galaxy extinction while the colors of SNe 1992H and 1992am have been corrected. The phases in the rest frame are relative to explosion epoch. In the bottom panel, the V-band absolute light curves of SNe 2009kf, 1992H, and 1992am have been compared. The absolute magnitudes have been corrected by internal and Galactic extinction. The phases in the rest frame are relative to explosion epoch. The R-band absolute light curve of SN 2009kf is also illustrated.

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($\mu = 39.76$ mag) and determined the K-correction from observed riz AB magnitudes to rest-frame VRI Vega magnitudes using the spectra of SN 2009kf, a sample of spectra of different Type II SNe, and employing the IRAF package *synphot*.

The comparison of color evolution with that of similar SNe for which the color excess has been previously determined can be used to estimate the extinction correction. Figure 3 shows the evolution of the $V-R$ and $V-I$ colors not corrected for internal extinction for SN 2009kf and of the intrinsic colors for SNe 1992H and 1992am (Clocchiatti et al. 1996; Schmidt et al. 1994; Hamuy 2003). The intrinsic color $V-I$ of Type IIP SNe in the plateau phase appears fairly homogeneous, due to the photospheric temperature being close to that of hydrogen recombination. Olivares et al. (2010) suggest that this temperature leads to an intrinsic $(V-I)_0 = 0.66 \pm 0.05$ mag at the end of the plateau phase and that $E(V-I)$ can be used to determine the extinction correction. SN 2009kf has $V-I = 1.3 \pm 0.4$ mag at this epoch which implies a value of $A_V = 1.6 \pm 1$ mag. We also compared the $V-R$ color of SN 2009kf with that of SN 1992H (Clocchiatti et al. 1996) since these SNe are similar both in the photometric and spectroscopic evolution. We measured, at the same epoch, $V-R = 0.55 \pm 0.4$ mag for SN 2009kf and $V-R$ 0.25 mag for SN 1992H, which implies a value of $A_V = 1 \pm 1.4$ mag. The absorption component of the Na I doublet ($\lambda\lambda$5890, 5896) from the host galaxy in the spectra of SN 2009kf is not detected, and we set an upper limit of EW(Na I D) < 1.4 Å. The relation by Munari & Zwitter (1997) then gives an upper limit on extinction of $E(B-V) \lesssim 0.3$ mag. The integrated host galaxy extinction, as measured from the $c(\mathrm{H}\beta)$ index is $E(B-V) = 0.9$ mag. While this is not directly applicable to the line of sight of SN 2009kf, it does suggest that areas of high extinction are plausible. While the uncertainties prevent a definitive and consistent determination of reddening, the *VRI* colors of 2009kf suggest a reddening of $A_V \simeq 1$ mag ($E(B-V) = 0.32 \pm 0.5$ mag assuming $R_V = 3.1$) is applicable.

The de-reddened V- and R-band absolute light curves are illustrated in Figure 3. In Figure 4, the pseudo-bolometric and absolute NUV light curves of SN 2009kf are compared with those of other Type IIP SNe. The pseudo-bolometric light curve was obtained by first converting g, r, i, z magnitudes into monochromatic fluxes, then correcting these fluxes for the adopted extinction according to the law from Cardelli et al. (1989), and finally integrating the resulting spectral energy distribution (SED) over wavelength, assuming zero flux at the integration limits. The pseudo-bolometric light curve clearly displays a plateau, from day 20 to day 90, which is shorter than the 100–120 days typical of IIP SNe. However, it is significantly more luminous than all other IIP SNe for which a good estimate of bolometric luminosity is available. The upper limit luminosity estimated at about day 280 suggests that the mass of radioactive ^{56}Ni deposited in the ejecta is $M(^{56}\mathrm{Ni}) < 0.4\ M_\odot$. The absolute NUV light curve is obtained by correcting the *GALEX* data for the redshift and extinction discussed above. The absolute magnitude is incredibly bright at 10–20 days after explosion in comparison with other well-studied IIP SNe (Dessart et al. 2008). The NUV flux and optical emission can be reproduced satisfactorily with a blackbody fit with a temperature dropping from ∼16,000 K to ∼13,000 K from 10 to 20 days (as illustrated in Fig 4). The radius of the blackbody fit implies an expansion velocity of about 10,000 km s^{-1}, which is similar to the measured velocities from absorption lines. The evolution of the temperature, radius, and luminosity of the blackbody fit is also different from normal Type IIP SNe that are characterized by smaller values and different declines. We note that it would also be possible to reproduce the SED

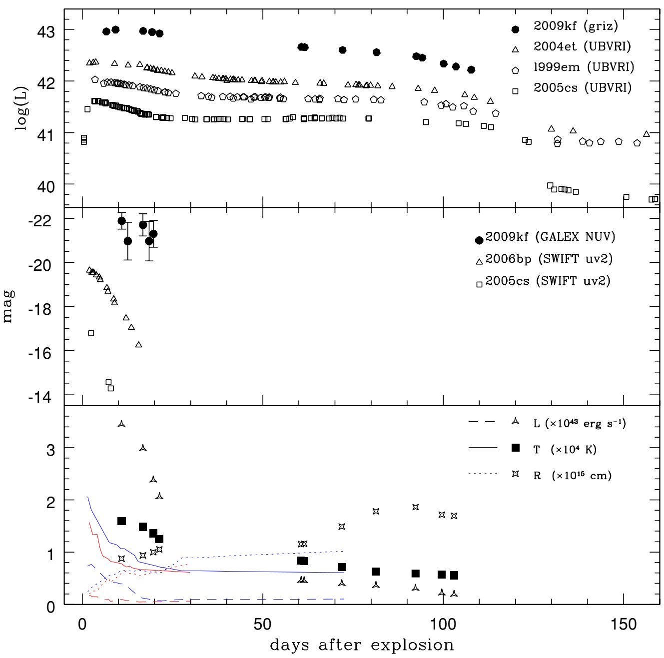

Figure 4. Top panel: pseudo-bolometric light curves of SNe 2009kf, 2004et (Maguire et al. 2010a), 1999em (Hamuy et al. 2001), and 2005cs (Pastorello et al. 2009). The light curves are in the SN rest frames and the phases are relative to explosion epoch. Bottom panel: absolute UV light curves of SNe 2009kf, 2006bp, and 2005cs (Dessart et al. 2008). The light curves are in the SN rest frames and the phases are relative to explosion epoch. The NUV magnitudes of SN 2009kf are in Vega mags and not *K*-corrected. The central wavelength of the NUV filter in the SN rest frame is about 1960 Å. Bottom panel: temporal evolution of the temperature, radius, and luminosity of the blackbody fit for SNe 2009kf (black), 2006bp (blue), and 2005cs (red) (Dessart et al. 2008).

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with low extinction and a temperature of $T_{\rm eff} \sim 9600$ K, but this would then require an expansion velocity of about 12,000 km s^{-1} maintained to 20 days, which is unusually high for a normal IIP.

The spectra of SN 2009kf show strong Hα and Hβ P-Cygni profiles, and a P-Cygni feature in the region around 5800 Å that may be attributed to He I (λ5876), Na I ($\lambda\lambda$5889, 5896) or their blend. However, the peak of the emission is blueshifted from the rest wavelength of He I by 100 ± 300 km s^{-1} and from that of Na I by 1000 ± 300 km s^{-1}. We suggest that this is He I since there are no prominent metal lines in the spectrum. The presence of He I is consistent with the high energy and temperature inferred by the NUV/optical light curves assuming an extinction of about $A_V = 1$ mag. Between 61 and 89 days after explosion, the continuum becomes redder (Figure 5) and there is little evolution in the Balmer features. Fitting Gaussian profiles to these features we determine expansion velocities of 9000 ± 1000 km s^{-1} from Hα on day 61 and of 7800 ± 1000 km s^{-1} from Hα and Hβ on day 89 after discovery. There is more evolution in He I, which becomes stronger by day 89 due to an increasing contribution of Na I. The expansion velocity from this line decreases from 7200 ± 1000 km s^{-1} on day 61 to 6500 ± 1000 km s^{-1} on day 89. The spectra of SN 2009kf show similarities to SNe 1992H and 1992am (Clocchiatti et al. 1996; Schmidt et al. 1994; Hamuy 2003; see Figure 5).

4. DISCUSSION

The high luminosity, both in the optical and UV, short plateau duration and large expansion velocity of SN 2009kf have important implications for understanding the origins of

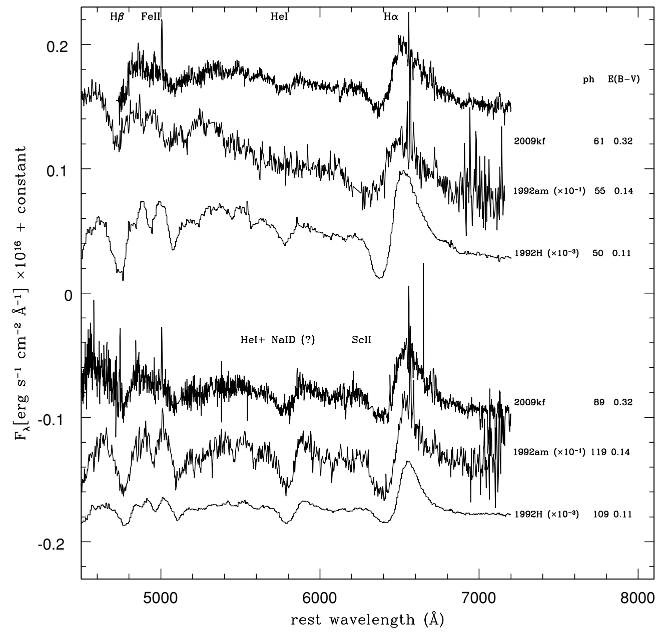

Figure 5. Spectra of SNe 2009kf, 1992H (Clocchiatti et al. 1996), and 1992am (Schmidt et al. 1994; Hamuy 2003) at two different epochs. The spectra have been corrected for host galaxy recession velocities and for reddening. The phases in the rest frame are relative to explosion epochs.

Type IIP SNe, using them as cosmological distance indicators and detecting CC SNe at high redshift.

The bolometric light curve of SN 2009kf is similar to normal IIP SN but with three striking differences: it has a slow rising peak in the first 20 days, has a short plateau phase, and is significantly more luminous. The NUV luminosity is also remarkably higher and exhibits a slower evolution with respect to normal Type IIP SNe (Gal-Yam et al. 2008). The source of the observed luminosity at 10 days after the explosion can be modeled with a hot photosphere of $T_{\rm eff} \sim 16{,}000$ K and a radius of around 1×10^{15} cm. The photospheric temperature remains high for an unusually long period, as we see He I (λ5876) up to about 89 days and the normal metal lines are weak. The expansion velocity as measured from the Hβ absorption is similar to SN 1992am and extreme for an IIP type event, 7800 km s^{-1} at 89 days after discovery, compared with 4500 km s^{-1} for a typical IIP. In conclusion, 2009kf is both luminous and extremely blue, and hence extends the luminosity and energy range of IIP SNe.

This peculiarity raises the question of whether the standard model for Type IIP SNe with an RSG progenitor of 8–20 $M_{\odot}$ and an explosion energy of (0.1–2) × 10^{51} erg (Utrobin & Chugai 2009; Maguire et al. 2010a) is valid for this event. The luminosity, plateau duration, and expansion velocity mainly depend on the explosion energy, envelope mass, and radius of the progenitor star at the moment of the explosion, and the characteristics of SN 2009kf could be explained with a large explosion energy or a very large progenitor radius, but a lower than usual hydrogen envelope mass. The analytical models of Kasen & Woosley (2009) and numerical simulations of Young (2004) would require explosion energies in excess of 10 × 10^{51} erg, or progenitor radii of greater than 1000 $R_{\odot}$. Alternative explanations could be a different mass distribution of H and He in the envelope, or possibly interaction of the ejecta with a surrounding shell. A detailed model of SN 2009kf has the potential to provide insight into the diversity of Type IIP SNe, in particular as concerns their use as standard candles.

The bright visual magnitude of SN 2009kf and its apparent plateau means that such events may be preferentially selected in cosmology surveys. However, the distance modulus obtained from the *I*-band relation by Nugent et al. (2006) is $\mu = 40.63 \pm 0.5$, compared to the distance modulus of $\mu = 39.76$ for a ΛCDM cosmology. Further work on these high-luminosity and fast expansion velocity events is required to understand if this discrepancy for one event is statistical or systematic and if they can be reliably used for the SCM method applied to IIP SNe.

The discovery of SN 2009kf demonstrates the exciting potential of the *GALEX* TDS observing campaign which is coordinated with PS1 to both probe shock breakout (Gezari et al. 2008; Schawinski et al. 2008) and the nature of UV-bright Type II SNe. During the first PS1 phases, three confirmed SNe discoveries had simultaneous *GALEX* imaging within ±10 days of the PS1 discovery, but only SN 2009kf was detected. The transients discovered at high-z by Cooke et al. (2009) were interpreted as Type IIn SNe, as up until now the only SNe that had such high UV luminosities were interacting events. SNe 2008es and 2009kf are the brightest SN in the UV known so far ($M_{\rm NUV} = -22.2$ and -21.5 mag, respectively), but SN 2008es (Gezari et al. 2009; Miller et al. 2009) is a Type IIL SN and did not have obvious signs of CSM interaction. SN 2009kf is of similar brightness to the inferred NUV fluxes of Cooke et al. (2009) high-z SNe. The NUV light curves of all types of CC SNe are not well quantified, hence it is quite possible that some fraction of the Cooke et al. (2009) high-z SNe are UV bright Type II SNe similar to 2009kf. The seasonal stacked PS1 Medium-Deep Survey images will allow 2009kf-like UV bright SNe to be detected beyond $z \sim 2$, where the NUV band would be redshifted to the r band and use these events to probe the cosmic star formation history. The rate of these SNe at low redshift, their progenitor scenarios, and their UV evolution are key areas that we need to understand before we can confidently use them to probe the SFR at high redshift.

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