Displaying the heterogeneity of the SN 2002CX-like subclass of type IA supernovae with observations of the pan-starrs-1 discovered sn 2009ku

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DISPLAYING THE HETEROGENEITY OF THE SN 2002CX-LIKE SUBCLASS OF TYPE IA SUPERNOVAE WITH OBSERVATIONS OF THE PAN-STARRS-1 DISCOVERED SN 2009ku[*]

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ABSTRACT

SN 2009ku, discovered by Pan-STARRS-1, is a Type Ia supernova (SN Ia), and a member of the distinct SN 2002cx-like class of SNe Ia. Its light curves are similar to the prototypical SN 2002cx, but are slightly broader and have a later rise to maximum in g. SN 2009ku is brighter ($\sim$0.6 mag) than other SN 2002cx-like objects, peaking at $M_V = -18.4$ mag — which is still significantly fainter than typical SNe Ia. SN 2009ku, which had an ejecta velocity of $\sim$2000 $\mathrm{km\,s^{-1}}$ at 18 days after maximum brightness is spectroscopically most similar to SN 2008ha, which also had extremely low-velocity ejecta. However, SN 2008ha had an exceedingly low luminosity, peaking at $M_V = -14.2$ mag, $\sim$4 mag fainter than SN 2009ku. The contrast of high luminosity and low ejecta velocity for SN 2009ku is contrary to an emerging trend seen for the SN 2002cx class. SN 2009ku is a counter-example of a previously held belief that the class was more homogeneous than typical SNe Ia, indicating that the class has a diverse progenitor population and/or complicated explosion physics. As the first example of a member of this class of objects from the new generation of transient surveys, SN 2009ku is an indication of the potential for these surveys to find rare and interesting objects.

Subject headings: supernovae: general — supernovae: individual(SN 2009ku)

1. INTRODUCTION

Most Type Ia supernovae (SNe Ia) can be described by a single parameter that relates peak luminosity with light-curve shape (Phillips 1993), intrinsic color (Riess et al. 1996), and ^{56}Ni mass (Mazzali et al. 2007). There are examples of particular SNe Ia not following this parameterization (e.g., Li et al. 2001; Foley et al. 2010b), with a single, relatively large subclass of objects (see Foley et al. 2009 for a recent list of mem-

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bers) dominating the outliers. Members of this subclass, labeled "SN 2002cx-like" after the prototypical object (Li et al. 2003), have peak magnitudes $\sim$2 mag below that of normal SNe Ia and spectra that resemble the high-luminosity SN Ia 1991T (Filippenko et al. 1992; Phillips et al. 1992) at early and intermediate phases, except with significantly lower expansion velocities and having late-time ($\sim$1 yr after maximum) spectra which show low-velocity Fe II lines, few lines from intermediate-mass elements, and no strong forbidden lines (Jha et al. 2006; Sahu et al. 2008). The extreme characteristics of this class can be explained if the objects are full deflagrations of a white dwarf (WD) (Branch et al. 2004; Phillips et al. 2007). Because of their low velocities, which eases line identification, and probing of the deflagration process, which is essential to all SN Ia explosions, this subclass is particularly useful for understanding typical SN Ia explosions. For a review of this class, see Jha et al. (2006).

A recent addition to this class, SN 2008ha (Foley et al. 2009; Valenti et al. 2009; Foley et al. 2010a), was much fainter (peaking at $M_V = -14.2$ mag) and had a significantly lower velocity ($v \approx 2000$ $\mathrm{km\,s^{-1}}$) than the typical member. Although its maximum-light spectrum indicates that the object underwent C/O burning (Foley et al. 2010a), certain observations are consistent with a massive-star progenitor (Foley et al. 2009; Valenti et al. 2009; Moriya et al. 2010). SN 2008ha generated $\sim$10$^{-3}M_\odot$ of ^{56}Ni and ejected $\sim$0.3$M_\odot$ of material (Foley et al. 2010a), suggesting that the most plausible explanation was a failed deflagration of a WD that did not destroy the progenitor star (Foley et al. 2009, 2010a). Furthermore, another member of this class, SN 2008ge, was hosted in an S0 galaxy with no signs of star for-

mation or massive stars, including at the SN position in pre-explosion *HST* imaging (Foley et al. 2010c).

Using a small sample of SN 2002cx-like objects, McClelland et al. (2010) suggested that their peak luminosities correlated with light-curve shapes and ejecta velocity (with more luminous SNe having faster ejecta and slower declining light curves). These correlations are similar to that of the relationship between light-curve shape and peak luminosity in "normal" SNe Ia (Phillips 1993) and suggest that SN 2002cx-like objects can possibly be described by a single parameter.

As part of the Medium Deep Survey (MDS) SN 2009ku was discovered by Pan-STARRS-1 (PS1) on 2009 Oct. 4.83 (UT dates are used throughout this paper) at mag 19.9 (Rest et al. 2009) in APMUKS(BJ) B032747.73-281526.1, an Sc galaxy with a redshift of 0.0792 in the MD02 field (coincident with the CDF-S field). Spectroscopy showed that it was a SN Ia similar to SN 2002cx (Rest et al. 2009). From the discovery magnitude and redshift alone, SN 2009ku had a peak magnitude of $M_r \lesssim -18$ mag, similar to that of SN 2002cx, but much brighter than SN 2008ha. With our full light curves, we measure its peak brightness below. We also show that the spectra of SN 2009ku are similar to SN 2002cx and most similar to those of SN 2008ha, with both objects having small expansion velocities.

We present and discuss our observations in Section 2. In Section 3, we place SN 2009ku in the context of other objects in the SN 2002cx-like subclass and typical SNe Ia. We discuss our results and summarize our conclusions in Section 4. Throughout this work, we use the concordance cosmology of $(H_0, \Omega_m, \Omega_\Lambda) = (70, 0.3, 0.7)$.

2. OBSERVATIONS AND DATA REDUCTION

SN 2009ku was discovered before maximum brightness by the 1.8 m PS1 telescope on Haleakala as part of the rolling MDS search. Unfortunately, PS1 coverage of SN 2009ku was interrupted on 1 October 2009, shortly after maximum brightness, for engineering work on the telescope.

To supplement the PS1 light curve, we obtained *gri* photometry with GMOS on the Gemini-South 8 m telescope (Hook et al. 2004), RATCam on the Liverpool 2 m telescope, and Suprime-Cam on the Subaru 8.2 m telescope. Late-time *griz* photometry was resumed with PS1 beginning 15 December 2009.

The images were de-biased, flat-fielded, and astrometrically registered by pipelines developed specifically for each imager. PS1 Gigapixel Camera (GPC1) data was processed with the Pan-STARRS Image Processing Pipeline[11]. GMOS data was reduced using the Gemini IRAF[12] package. RATCam and Suprime-Cam data was processed by a modified version of the SuperMacho pipeline (Rest et al. 2005).

Following preliminary processing, we used the Super-Macho pipeline for photometry and difference imaging. Photometric catalogs of secondary standard stars were produced by first matching the GPC1 MDS fields 03–

[11] http://svn.pan-starrs.ifa.hawaii.edu/trac/ipp/wiki/ .
[12] IRAF: the Image Reduction and Analysis Facility is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc. (AURA) under cooperative agreement with the National Science Foundation (NSF).
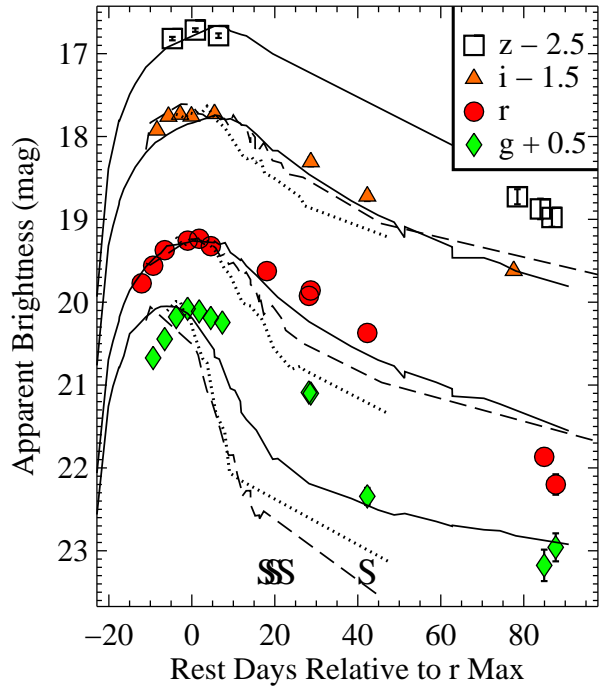

FIG. 1.— *griz* light curves of SN 2009ku. The uncertainties for most data points are smaller than the plotted symbols. Also plotted are comparison light curves of SNe 2002cx (*VRI*; dashed lines), 2005hk (*griz*; solid lines), and 2008ha (*VRI*; dotted lines) after applying a magnitude offset to match the peak in each band. The epoch of each spectrum is marked with an 'S.'

07 to images obtained by the Sloan Digital Sky Survey (SDSS) and then extrapolating the zero points to observations of the MD02 on the same night.

We performed template subtraction to remove the underlying host-galaxy light and measure the SN flux. A set of reference *griz* images were constructed from deep stacks of GPC1 images obtained in photometric conditions in late January 2010. This procedure allows a reference set to be constructed from homogeneous imaging while being sufficiently deep for difference imaging with telescopes of much larger aperture.

HOTPANTS[13] was used to determine a convolution kernel and subtract this reference image from each image. A modified version of DoPHOT (Schechter et al. 1993) was then used to measure the flux of the SN.

Comparing our reference images to deep stacks produced from the last available PS1 epoch, we found low-level residual flux at the position of the SN. As this flux is not detected in single images and at this epoch SN 2009ku is more than 80 days past maximum brightness, we do not believe that this residual flux significantly affects the photometry. Nonetheless, an offset is added to all photometry to account for the residual flux.

We present the *griz* light curves in Figure 1 and Table 1.

We obtained two low-resolution spectra of SN 2009ku with GMOS (Hook et al. 2004) on Gemini-South (PI Berger; Program GS-2009B-Q-30) and one with the

[13] http://www.astro.washington.edu/users/becker/hotpants.html .

Julian Date −2455000	Passband	Magnitude[a]	Telescope
84.12	r	19.77(03)	PS1
87.10	g	20.17(03)	PS1
87.12	r	19.56(02)	PS1
88.10	i	19.42(02)	PS1
90.11	g	19.94(02)	PS1
90.13	r	19.37(02)	PS1
91.09	i	19.26(01)	PS1
92.11	z	19.32(02)	PS1
93.11	g	19.68(02)	PS1
94.11	i	19.23(02)	PS1
96.07	g	19.58(02)	PS1
96.09	r	19.26(01)	PS1
97.06	i	19.25(01)	PS1
98.09	z	19.21(02)	PS1
99.08	g	19.61(02)	PS1
99.09	r	19.23(02)	PS1
102.10	g	19.69(02)	PS1
102.11	r	19.32(02)	PS1
103.07	i	19.22(02)	PS1
104.12	z	19.28(03)	PS1
105.10	g	19.74(02)	PS1
116.68	r	19.62(02)	Gemini-S
127.62	g	20.59(05)	Liverpool
127.62	r	19.92(04)	Liverpool
128.08	r	19.86(06)	Subaru
128.10	g	20.60(06)	Subaru
128.11	i	19.81(06)	Subaru
142.81	g	21.84(11)	Gemini-S
142.81	r	20.37(03)	Gemini-S
142.81	i	20.22(06)	Gemini-S
180.90	i	21.12(03)	PS1
181.85	z	21.23(10)	PS1
187.84	z	21.37(13)	PS1
188.82	g	22.68(21)	PS1
188.83	r	21.87(10)	PS1
190.83	z	21.48(12)	PS1
191.82	g	22.46(18)	PS1
191.83	r	22.20(13)	PS1
213.79	i	22.85(76)	PS1
214.80	z	22.99(63)	PS1
219.76	i	23.86(86)	PS1
220.76	z	22.98(68)	PS1

[a] Uncertainties are reported in hundredths of a magnitude

ALFOSC spectrograph[14] on the 2.5 m Nordic Optical Telescope. We also obtained a medium-resolution spectrum of SN 2009ku with the MagE spectrograph (Marshall et al. 2008) on the Magellan Clay 6.5 m telescope. A journal of observations can be found in Table 2. Standard CCD processing and spectrum extraction were performed with IRAF. The data were extracted using the optimal algorithm of Horne (1986). Low-order polynomial fits to calibration-lamp spectra were used to establish the wavelength scale, and small adjustments derived from night-sky lines in the object frames were applied. For the MagE spectrum, the sky was subtracted from the images using the method described by Kelson (2003). We employed our own IDL routines for flux calibration and telluric line removal (except for the ALFOSC spectrum) using the well-exposed continua of spectrophotometric standard stars (Wade & Horne 1988; Foley et al. 2003, 2006, 2009). Our spectra of SN 2009ku are presented in Figure 2.

[14] http://www.not.iac.es/instruments/alfosc .

Phase[a]	UT Date	Telescope / Instrument	Exposure (s)	Observer[b]
18.1	2009 Oct. 12.2	Gemini-S/GMOS	2×1200	EC
19.9	2009 Oct. 14.1	NOT/ALFOSC	3600	SM, EK
22.8	2009 Oct. 17.2	Magellan/MagE	3×1800	RF
42.3	2009 Nov. 7.3	Gemini-S/GMOS	2×1200	LF

[a] Rest-frame days since r maximum, 2009 Sept. 22.7 (JD 2,455,097.2).
[b] EC = E. Christensen; LF = L. Fuhrman; EK = E. Kankare; RF = R. Foley; SM = S. Mattila

3. ANALYSIS

3.1. *Photometric Analysis*

Figure 1 shows the *griz* light curves of SN 2009ku. Also plotted are the *VRI* light curves of SNe 2002cx and 2008ha and the *griz* light curves of SN 2005hk, a well-observed SN extremely similar to SN 2002cx (Phillips et al. 2007). Each light curve has been shifted to have r (or R) maximum correspond to $t = 0$ days and so that each comparison curve peaks at the same magnitude as SN 2009ku.

Although its light curve is sparse after maximum, relative to SNe 2002cx, 2005hk, and 2008ha, SN 2009ku clearly peaked significantly later in g than in r and i and had a slower decline in all bands. Although the light curves are sparse, we measure $\Delta m_{15} = 0.53 \pm 0.27$, 0.32 ± 0.05, and 0.18 ± 0.09 mag in *gri*, respectively. The uncertainty in these measurements is relatively large due to the gap between measurements after maximum light. As long as the the light curves are smooth during this period, our measurements of Δm_{15} should not be significantly affected. In particular, at $t = 17.9$ days, the r band had declined by 0.37 mag from peak, which is a strict upper limit on $\Delta m_{15}(r)$.

Since SN 2009ku was not observed in B and most comparison objects were not observed in g, we have focused on the r/R observations, in which we expect objects to have a similar light-curve shapes. However, using the relationships between the decline rates of *gri* and B for SN 2005hk and scaling the decline rates for SN 2009ku, we have determined that SN 2009ku had $0.51 \leq \Delta m_{15}(B) \leq 0.67$ mag, with an average value of 0.59 mag. This is an extremely small value of $\Delta m_{15}(B)$ for any SN Ia. Although SN 2009ku has a slower decline than other SN 2002cx-like objects in *gri*, the uncertainty in converting from decline rates in *gri* to B and the sparsely sampled post-maximum light curves of SN 2009ku make us question the accuracy of the derived value of $\Delta m_{15}(B)$.

3.2. *Spectral Analysis*

Despite contamination by host-galaxy light, all spectra of SN 2009ku exhibit clear SN features. These features are at low velocity, and there are no obvious hydrogen or helium features (except from narrow galactic emission lines).

The comparison of the spectra of SN 2009ku to those of other SNe is aided by the addition of galaxy template spectra to the comparison SN spectra. In Figure 2, we compare SN 2009ku to SNe 2002cx and 2008ha at similar phases. Although the features in the SN 2009ku spectra
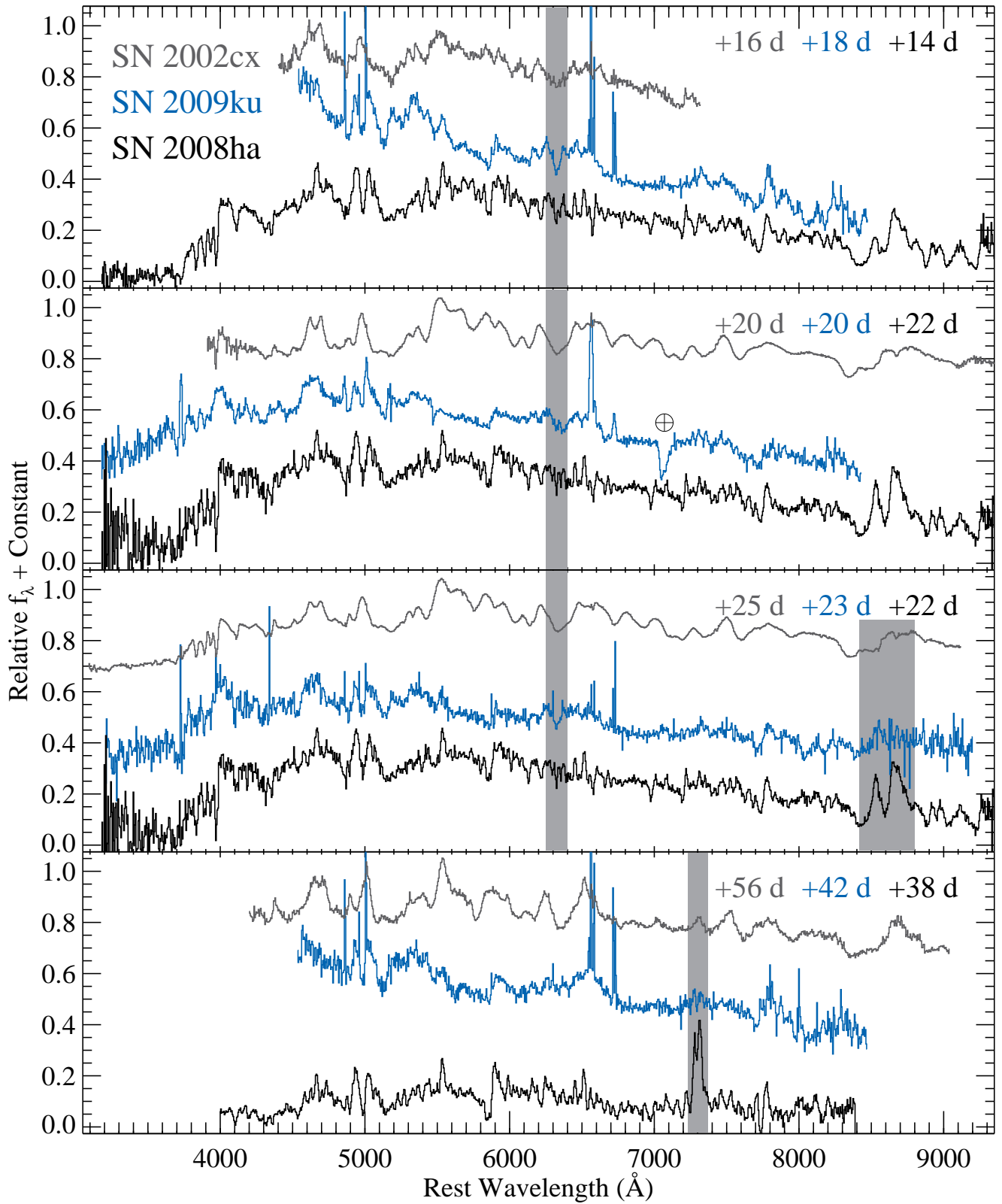
FIG. 2.— Optical spectra of SN 2009ku (blue curves in the middle of each panel) denoted by their phase relative to maximum brightness. The grey and black curves (top and bottom in each panel) are of spectra of SNe 2002cx and 2008ha. For visual comparison, an Sc template galaxy spectrum has been added to each SN 2002cx and SN 2008ha spectrum. The regions corresponding to Si II λ6355, [Ca II] $\lambda\lambda$7291, 7324, and the Ca II NIR triplet are shaded grey. Incomplete telluric correction in the second spectrum is marked.

are relatively weak, they match those of SN 2008ha to a high degree. There is some similarity to SN 2002cx, but also clear differences. Some of these differences are the result of different line velocities and widths, while others are likely differences in the composition and/or opacity of the ejecta. By comparing SN 2009ku to SNe 2002cx and 2008ha, it is clear that there are several features in the spectra of SN 2009ku corresponding to Cr II, Fe II, and Co II (see Foley et al. 2009 for a synthetic spectrum identifying these features). Additionally, the spectra of SNe 2008ha and 2009ku evolve similarly. From the spectral comparisons, we determine that the ejecta velocity of SN 2009ku is similar to that of SN 2008ha, although perhaps slightly lower (i.e., the O I λ7774 line is at a lower velocity at similar epochs in SN 2009ku); SN 2009ku must have had a very low ejecta velocity near maximum.

Examining the spectra in detail, there are a few obvious differences between SNe 2008ha and 2009ku. SN 2009ku has a clear feature at $\sim$ 6325 Å until at least 23 days after maximum brightness. We interpret this feature as Si II λ6355, the hallmark of SNe Ia, blueshifted by $\sim$1400 km s^{-1}. This feature is present in SN 2008ha at maximum brightness (Foley et al. 2010a), but is not clearly present a week later (Foley et al. 2009). This feature is present, but weak, in SN 2002cx until around 15 days after maximum brightness (Li et al. 2003; Branch et al. 2004). For SN 2002cx, a feature at a similar wavelength persists until at least 25 days after maximum brightness, but this has been interpreted as Fe II (Branch et al. 2004).

Additionally, SN 2008ha has strong emission from the Ca II NIR triplet at 23 days after maximum brightness, but this feature is much weaker in SN 2009ku at a similar epoch, being very similar to that of SN 2002cx. At $\sim$40 days after maximum brightness, SN 2008ha has strong [Ca II] $\lambda\lambda$7291, 7324 emission, while SNe 2002cx and 2009ku have weak or absent [Ca II] emission at this epoch. These differences may indicate that SN 2009ku burned more material to Si and less to Ca than SN 2008ha, making its nucleosynthesis more similar to SN 2002cx.

3.3. *Comparison to Other Objects*

Although the number of SN 2002cx-like objects has grown such that properties of the class can be examined, few comprehensive studies have been performed. Jha et al. (2006) was the first to compile several members, showing that the relatively small sample of objects had "striking spectral homogeneity." SN 2008ha, if a true member of this class, is an outlier in this regard (e.g., the maximum-light spectrum of SN 2008ha shows strong Si II, which the other members do not; Foley et al. 2010a). McClelland et al. (2010) suggested (using SNe 2002cx, 2005hk, 2007qd, and 2008ha) that there were correlations between peak luminosity, light-curve shape and ejecta velocity.

SN 2009ku challenges that assertion. In Figure 3, we plot $\Delta m_{15}(R)$ (or $\Delta m_{15}(r)$ for SNe 2007qd and 2009ku), ejecta velocity $\sim$10 days after maximum, and M_V at peak for several SN 2002cx-like objects and typical SNe Ia. We assume that since SNe 2008ha and 2009ku have a similar ejecta velocity at 18 days after maximum brightness that they have a similar velocity a week earlier. Using SN 2005hk, the light curves of SN 2009ku were trans-
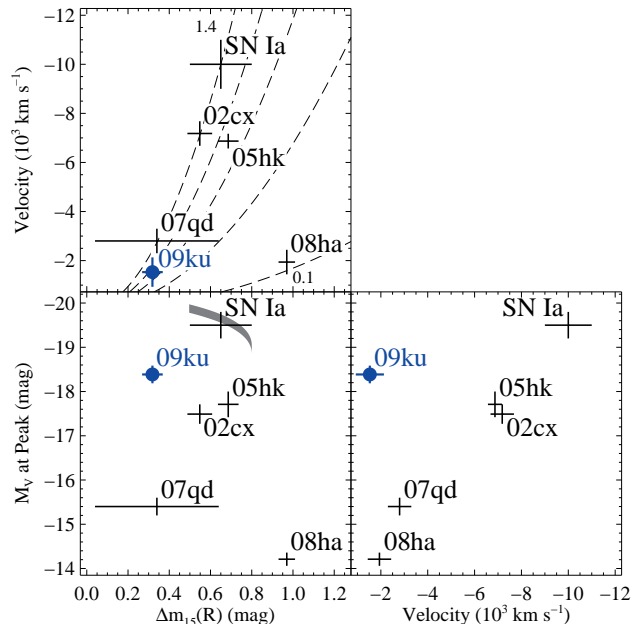

FIG. 3.— A comparison of $\Delta m_{15}(R)$, M_V at maximum, and the photospheric velocity at $\sim$10 days after maximum (derived from the minimum of O I λ7774) for various objects in the SN 2002cx-like class. The grey band represents the width-luminosity relationship for SNe Ia (in the M_V vs. $\Delta m_{15}(R)$ plot) and typical values for a Branch-normal SN Ia. The dashed lines represent the relationship between ejecta velocity and Δm_{15} for (from bottom-right to top-left) 0.1, 0.4, 0.7, 1.0, and 1.4 M$_\odot$ of ejecta mass. SN 2009ku is marked with the blue circle.

formed to determine M_V at peak. We assume that there is negligible host-galaxy extinction, which is supported by the relatively blue colors of SN 2009ku. Regardless, SN 2009ku must have been at least as bright as our value of $M_V = -18.4$ mag at peak. There is no clear correlation between $\Delta m_{15}(R)$ and M_V for SN 2002cx-like objects, even when restricting to the sample of McClelland et al. (2010). The five objects with published values (including SN 2009ku) have a large range in M_V. Although most SN 2002cx-like objects have similar decline rates in R, SN 2008ha is significantly faster than the other objects.

There is a correlation between decline rate and ejecta velocity; however, SN 2008ha is an outlier. Using Arnett's Law (Arnett 1982), we can derive a relationship between ejecta velocity and $\Delta m_{15}(R)$ (if we assume that the R band is representative of the light-curve shape of the bolometric light curve) that depends on ejecta mass. By assuming that a typical SN Ia has 1.4 M$_\odot$ of ejecta, we obtain curves of constant ejecta mass which we present in the upper-left panel of Figure 3. All SNe except for SN 2008ha are consistent with $1.0 - 1.4$ M$_\odot$ of ejecta.

Stretching the gri light curves of SN 2005hk to match those of SN 2009ku before peak, we derive a rise time of 18.2 ± 3.0 days. Correcting the gri peak magnitudes of SN 2009ku with the gri bolometric corrections from SN 2005hk, we find that SN 2009ku had a peak bolometric luminosity of $(6.4 \pm 1.6) \times 10^{42}$ ergs sec^{-1}. Applying Arnett's Law (Arnett 1982) to the rise time and peak luminosity of SN 2009ku, we find that SN 2009ku had a ^{56}Ni mass of 0.3 ± 0.1 M$_\odot$. This is larger than that found for SN 2005hk (0.22 M$_\odot$; Phillips et al. 2007) but

less than typical SN Ia explosions ($\sim 0.4 - 0.9$ M$_\odot$; e.g., Stritzinger et al. 2006).

Finally, there does appear to be a relationship between peak luminosity and ejecta velocity, *except for SN 2009ku*, which has a much lower velocity than its peak luminosity suggests (or has a much higher peak luminosity than its velocity suggests) and is a significant outlier.

4. DISCUSSION AND CONCLUSIONS

PS1 is expected to discover several dozen SN 2002cx-like objects per year in the Medium-Deep Survey alone (S. Rodney, private comm.). SN 2009ku is the first of this class to be discovered (and spectroscopically confirmed) by PS1. SN 2009ku is also the most distant member of the class (400 Mpc; followed by SN 2007qd at 175 Mpc). Although the early survey PS1 data had a gap in the post-maximum light curve, measurements from additional telescopes were able to partially fill this gap.

SN 2009ku peaked at $M_V = -18.4$ mag, which is fainter than typical SNe Ia, but also slightly brighter than SNe 2002cx and 2005hk at peak (Li et al. 2003; Phillips et al. 2007). SN 2009ku declined very slowly in *gri* relative to other SN 2002cx-like objects, with $\Delta m_{15}(r) = 0.32 \pm 0.05$ mag. Despite the relatively high peak luminosity and slow decline, SN 2009ku had spectra that are most similar to the very low-luminosity and fast-declining SN 2008ha (Foley et al. 2009; Valenti et al. 2009; Foley et al. 2010a), including a very low ejecta velocity ($v \lesssim 2000$ km s^{-1}).

Although the spectra of SNe 2008ha and 2009ku are similar, SN 2009ku had a stronger Si II $\lambda 6355$ feature and weaker [Ca II] $\lambda\lambda 7291, 7324$ and Ca II NIR triplet features. Although these differences may be related to ionization or opacity effects, another possibility is that the burning products of the explosion produced a different ratio of Si to Ca in the two explosions. This could be explained by different degrees of both He and C/O burning (e.g., Perets et al. 2009), or simply by a different efficiency for the burning in both explosions. Disen-

tangling these effects are beyond the scope of this study, but may provide additional insight into the explosions of these objects. Indeed, this may be the key difference between two very spectroscopically similar SNe that differ by a factor of ~ 40 in peak luminosity.

McClelland et al. (2010) suggested that there was a relationship between light-curve shape, peak luminosity, and ejecta velocity for SN 2002cx-like objects, including SN 2008ha. Their sample does show a relationship between ejecta velocity and peak luminosity; however, SN 2009ku is a clear outlier to this relationship. The class of SN 2002cx-like objects appear to be quite heterogeneous, with SNe 2008ha and 2009ku providing examples for the diversity.

With PS1, we expect to discover enough SN 2002cx-like objects to map the parameter space of the class. Additionally, by probing parameter space neglected until recently, PS1 will continue to find rare and interesting objects. SN 2009ku is an example of the diverse transient phenomena that PS1 will discover. In the coming years, our understanding of this class and other exotic transients will be greatly improved by PS1 and eventually LSST.

Facilities: PS1(GPC1), Gemini:South(GMOS), Magellan:Clay(MagE), NOT(ALFOSC)

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