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## EARLY- AND LATE-TIME OBSERVATIONS OF SN 2008ha: ADDITIONAL CONSTRAINTS FOR THE PROGENITOR AND EXPLOSION

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### ABSTRACT

We present a new maximum-light optical spectrum of the extremely low luminosity and exceptionally low-energy Type Ia supernova (SN Ia) 2008ha, obtained one week before the earliest published spectrum. Previous observations of SN 2008ha were unable to distinguish between a massive star and white dwarf (WD) origin for the SN. The new maximum-light spectrum, obtained one week before the earliest previously published spectrum, unambiguously shows features corresponding to intermediate mass elements, including silicon, sulfur, and carbon. Although strong silicon features are seen in some core-collapse SNe, sulfur features, which are a signature of carbon/oxygen burning, have always been observed to be weak in such events. It is therefore likely that SN 2008ha was the result of a thermonuclear explosion of a carbon–oxygen WD. Carbon features at maximum light show that unburned material is present to significant depths in the SN ejecta, strengthening the case that SN 2008ha was a failed deflagration. We also present late-time imaging and spectroscopy that are consistent with this scenario.

*Key words:* supernovae: general – supernovae: individual (SN 2008ha)

### 1. INTRODUCTION

Supernova (SN) 2008ha has the lowest peak luminosity and ejecta velocity of any SN Ia yet observed (Foley et al. 2009; Valenti et al. 2009, hereafter Paper I and V09, respectively). It peaked at  $M_V = -14.2$  mag, had an ejecta velocity a week after maximum of  $\sim 2000$  km s<sup>-1</sup>, and had a rise time of  $\sim 10$  days; these values are  $\sim 5$  mag fainter, 8000 km s<sup>-1</sup> slower, and 10 days shorter than that of normal SNe Ia, respectively. Together, these observations indicate a very low kinetic energy of  $\sim 2 \times 10^{48}$  erg and an ejecta mass of 0.15  $M_\odot$  (Paper I).

Although SN 2008ha resembles SN 2002cx, the prototype of a class of peculiar SNe Ia with lower than normal luminosity and ejecta velocity (see Jha et al. 2006 for a review of the class), the similar energetics and spectra of SN 2008ha and some peculiar core-collapse SNe led V09 to suggest that the progenitor of SN 2008ha was a massive star. In Paper I, we considered several progenitor and explosion models: (1) the collapse of a massive star to a black hole with most of the star “falling back,” (2) a runaway nuclear reaction caused by electron capture on a white dwarf (WD), (3) the failed deflagration of a WD, and (4) nuclear burning of a massive He shell on the surface of a WD in an AM CVn system (a “SN.Ia;” Bildsten et al. 2007).

Delicate balancing of the energetics and the detection of a SN 2002cx-like object in an S0 galaxy makes the fallback model unfavorable for SN 2008ha and the class, respectively. The electron-capture scenario predicts complete burning to <sup>56</sup>Ni with no intermediate-mass elements (IMEs). The observations of SN 2008ha and other members of the SN 2002cx-like class are all consistent with a deflagration (with SN 2008ha being a failed deflagration; Paper I). The SN.Ia model fits SN 2008ha, but cannot currently reproduce the luminosity required for other members of the class.

Nucleosynthetic models provides additional information to distinguish between these models. Explosive C/O burning

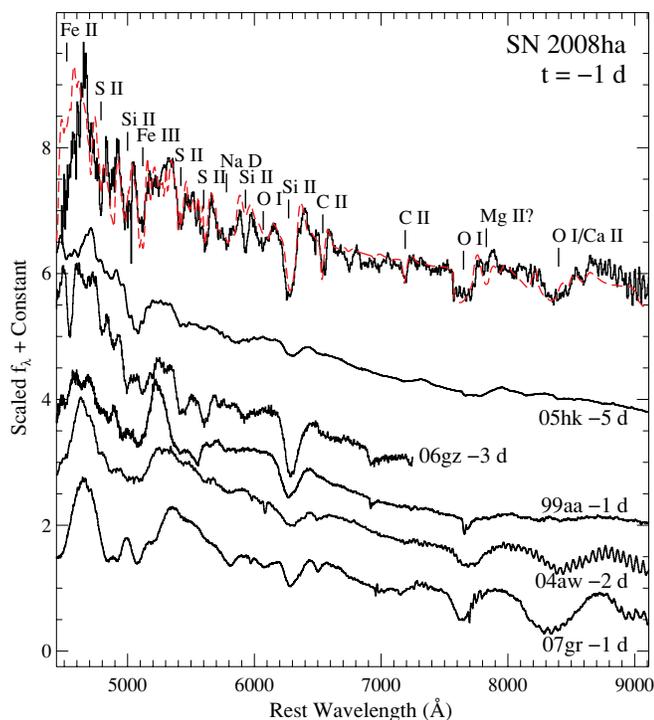
produces a significant amount of S while He burning produces more Ca (see Perets et al. 2009 for a recent examination of explosions with different fractions of each process). Furthermore, it is expected that S is contained in the inner layers of a core-collapse explosion, while it is predominantly in the outer layers of a thermonuclear explosion (e.g., Thielemann et al. 1991). V09 argued that the lack of S in their first spectrum was most consistent with a massive star origin. A strong detection of S at early times would give support for C/O burning and a WD progenitor.

The SN 2008ha spectra presented in Paper I and V09 spanned the phases of 6.5–68.1 days past maximum light in the *B* band (2008 November 12.7 UT; Paper I; UT dates will be used throughout this Letter). Here we present two spectra which extend this range in both directions, with phases of  $-1$  and 231 days relative to *B* maximum. We also present late-time photometry which constrains the amount of generated <sup>56</sup>Ni. These observations, including the detection of strong S lines in the maximum-light spectrum, further constrain the possible progenitor and explosion models for SN 2008ha, and highly favor a WD progenitor.

### 2. OBSERVATIONS AND DATA REDUCTION

We have obtained two new spectra of SN 2008ha. The early-time spectrum was obtained on 2008 November 11 (one day before *B* maximum) with the Hobby–Eberly Telescope using the Low Resolution Spectrograph (Hill et al. 1998). The spectrum is the combination of four 450 s exposures. The late-time spectrum was obtained on 2009 July 1/2 (231 days after *B* maximum) with Gemini-North using GMOS in nod and shuffle (N&S) mode (Hook et al. 2004). The GMOS spectrum is the combination of six 1280 s (after accounting for nod time) exposures, producing 12 spectra with effective exposure times of 640 s and a total exposure time of 7680 s. The GMOS spectra were obtained with three slightly different central wavelengths to compensate for chip gaps. Five of the six exposures were obtained on July 1, with the remaining exposure obtained on July 2.

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**Figure 1.** Optical spectrum of SN 2008ha at  $t = -1$  days relative to  $B$  maximum (solid black line) and a SYNOW model fit (red dashed line). The spectrum is dominated by IMEs. Spectra of SNe 1999aa, 2004aw, 2005hk, 2006gz, and 2007gr are shown for comparison (each shifted by selected amounts to give the best match to the ejecta velocity of SN 2008ha).

Standard CCD processing and spectrum extraction were accomplished with IRAF.<sup>6</sup> The GMOS data were reduced using the Gemini IRAF N&S package. 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. We employed our own IDL routines to flux calibrate the data and remove telluric lines using the well-exposed continua of spectrophotometric standards (Wade & Horne 1988; Foley et al. 2003, 2006).

Two epochs of  $r$ -band images were obtained on 2009 June 23 and 2009 July 1/2 with LDSS3<sup>7</sup> on the Magellan Clay telescope and with GMOS on the Gemini-North telescope, respectively. These images were reduced using standard techniques. The flux of the SN was determined by fitting a PSF profile in the flattened images using the DoPHOT photometry package (Schechter et al. 1993). Since all of our images presumably have some SN flux, difference imaging is not yet possible. The presence of an underlying H II region causes our flux measurements to be upper limits to the true SN flux. We convert the  $r$ -band instrumental magnitudes into  $R$ -band magnitudes using the  $R$ -band catalog magnitudes of local standard stars (Paper I). No instrumental color corrections were applied.

### 3. SPECTRAL ANALYSIS

#### 3.1. Maximum-light Spectrum

The maximum-light spectrum (shown in Figure 1) consists almost exclusively of IMEs with low ejecta velocities. The

minima of the Si II  $\lambda 6355$  and O I  $\lambda 7774$  features are blueshifted by  $\sim 3700$  and  $5100 \text{ km s}^{-1}$ , respectively. The Si II feature was much weaker a week later (the first spectrum from Paper I) and could not be directly measured, but the characteristic photospheric velocity of  $\sim 2000 \text{ km s}^{-1}$  for the day 6 spectrum is approximately half that of Si II in the maximum-light spectrum. Similarly, the O I velocity is 2.5 times larger at maximum brightness than it is at  $t = 6$  days.

The identification of IMEs is confirmed by fitting the spectrum with the SN spectrum-synthesis code SYNOW (Fisher et al. 1997). Although SYNOW has a simple, parametric approach to creating synthetic spectra, it is a powerful tool to aid line identifications (see Paper I for details). In the early-time spectrum, SYNOW unambiguously identifies the presence of O, Na, Si, S, Ca, and Fe, all common features in maximum-light SN Ia spectra, as well C, which is rarely seen. Although strong Si II is the hallmark feature of SNe Ia, there are examples of SNe Ic with strong Si features (Taubenberger et al. 2006; Valenti et al. 2008); however, those objects did not have strong S II features.

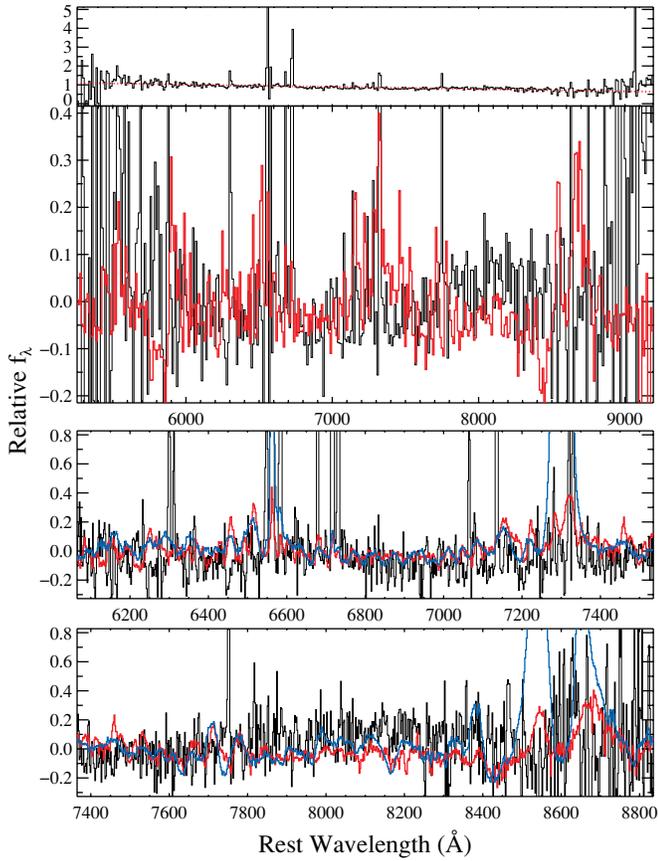
The SYNOW fit of SN 2008ha is similar to those of the  $-1$  and  $-5$  days spectra of SNe 2002cx (Branch et al. 2004) and 2005hk (a SN 2002cx-like object; Chornock et al. 2006), respectively. The differences are primarily a lower expansion velocity and the presence of C II for SN 2008ha (Chornock et al. 2006 did fit the SN 2005hk spectrum with C III, but the identification was ambiguous). SN 2008ha appears to have weaker Fe lines than the other objects, signaling a lower  $^{56}\text{Ni}$  yield relative to that of IMEs.

We compare the maximum-light spectra of SN 2008ha to SNe Ia and SNe Ic finding that SN 2008ha most closely resembles a SN Ia. Our comparison spectra (see Figure 1) include SN 2005hk, a SN Ia similar to SN 2002cx (Phillips et al. 2007), SN 1999aa, a slightly over-luminous SN Ia (Garavini et al. 2004), SN 2006gz, a luminous SN Ia with C features in its pre-maximum spectra (Hicken et al. 2007), SN 2004aw, a SN Ic that was originally classified as a SN Ia (its true nature was only realized with nebular spectra; Taubenberger et al. 2006), and SN 2007gr, a well-observed SN Ic with a spectrum somewhat similar to SN 2004aw (Valenti et al. 2008). The maximum-light spectrum of SN 2008ha is generally similar to all five comparison spectra after correcting for velocity differences. But the SNe Ic have weaker Si II than that seen in SN 2008ha and lack obvious S II lines. The SNe Ia (and particularly SN 2006gz) have spectra that are more similar to the spectrum of SN 2008ha, strengthening the classification of SN Ia for SN 2008ha; however, the spectra still have differences, and it is difficult to definitively place SN 2008ha in this class.

The spectrum of SN 2008ha unambiguously contains the signature of C in its ejecta, showing strong absorption corresponding to C II  $\lambda 6580$  and C II  $\lambda 7234$ . Carbon lines have been seen in the spectra of some SNe Ia (e.g., Hicken et al. 2007) and in some SNe Ic (e.g., Valenti et al. 2008). Although it is rare for SNe Ia to show strong C absorption near maximum light, there is an example in the small sample (Yamanaka et al. 2009). It is worth noting that there are also SNe Ic with C features at this phase. If SN 2008ha was the result of a WD explosion, a significant amount of C extends further into the ejecta than most SNe Ia. If the progenitor of SN 2008ha was a massive star, then the strong C lines at maximum light may indicate a large C layer or significant mixing in the progenitor.

<sup>6</sup> IRAF: the Image Reduction and Analysis Facility is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc. under cooperative agreement with the National Science Foundation.

<sup>7</sup> <http://www.lco.cl/telescopes-information/magellan/instruments-1/ldss-3/>



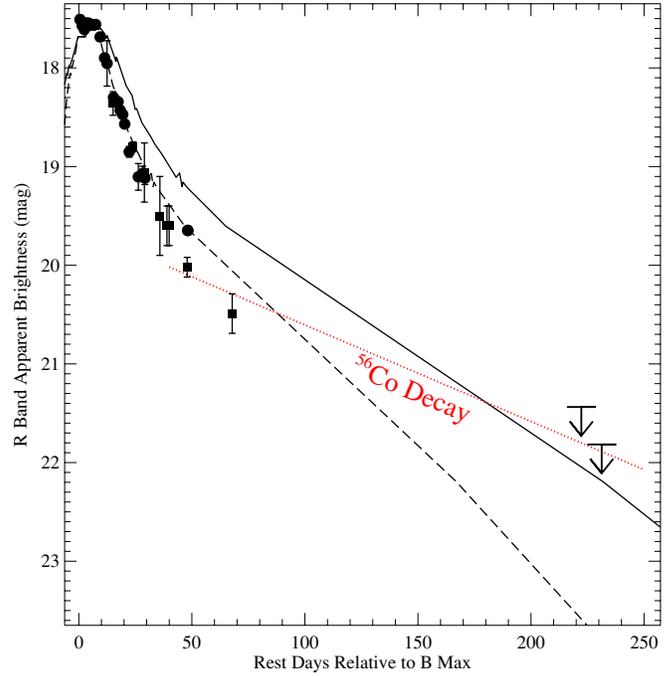
**Figure 2.** Top panel: the extracted 231-day optical spectrum of SN 2008ha (solid black line), which is contaminated by an underlying H II region. A linear fit to the continuum is also shown (red dotted line). Second panel: the continuum-subtracted spectra of SNe 2008ha (black line) and 2002cx ( $t = 227$  days; red line; Jha et al. 2006). Bottom panels: the continuum-subtracted spectrum of SN 2008ha from above is reproduced on an enlarged scale with finer resolution. The red and blue lines are the continuum-subtracted day 227 spectrum of SN 2002cx and day 62 spectrum of SN 2008ha (Paper I).

### 3.2. Late-time Spectrum

The late-time ( $t = 231$  days) spectrum of SN 2008ha is shown in Figure 2 along with the day 227 spectrum of SN 2002cx. We compensate for the contamination of an underlying H II region by subtracting a linear continuum fit from each SN spectrum and compare the residual spectra.

The lower panels of Figure 2 present the continuum-subtracted spectrum of SN 2008ha on an expanded wavelength scale. The low signal-to-noise ratio (S/N) of the spectrum prevents us from detecting any individual feature in a SN 2002cx-like spectrum other than possibly [Ca II]  $\lambda\lambda 7291, 7324$  or the Ca II NIR triplet (8498, 8542, and 8662 Å). The late-time spectrum of SN 2008ha exhibits no obvious emission from [O I] (which is expected for SNe Ic and predicted for deflagration models; Gamezo et al. 2003), [Ca II], or Ca II. In fact, there appears to be absorption at the position that we would expect Ca II emission. As the observations were performed in N&S mode, there was no local background subtraction performed, and these features are not an artifact of having SN light in a background region. This wavelength range has significant night-sky emission, and imperfect skyline subtraction may cause such features. Regardless, there are no definitive detections of strong, broad features corresponding to Ca II.

Between  $t = 56$  and 227 days, the velocity width of the [Ca II] feature in SN 2002cx decreased from FWHM  $\approx 2400$  km s $^{-1}$



**Figure 3.** R-band light curve of SN 2008ha. The circles and squares are from Paper I and V09, respectively. The upper limits are from our new photometry. The red dotted line indicates the decay expected from generating  $10^{-3} M_{\odot}$  of  $^{56}\text{Ni}$ . The solid and dashed black lines are the light curve of SN 2005hk (Phillips et al. 2007; Sahu et al. 2008) shifted to match the peak brightness of SN 2008ha. The dashed line has been scaled to match the width of SN 2008ha (see Paper I for details), while the solid line has not been modified.

to  $\sim 900$  km s $^{-1}$ . In the day 62 spectrum of SN 2008ha, [Ca II] had FWHM  $\approx 900$  km s $^{-1}$ . If the width of the feature decreases at the same rate in both objects, we expect the feature to have FWHM  $\approx 350$  km s $^{-1}$  in the late-time spectrum of SN 2008ha. All narrow lines have a similar redshift and velocity width ( $\sim 200$  km s $^{-1}$  FWHM, equivalent to the instrumental resolution). It is possible that the velocity width is below our instrumental resolution, and in that case we could mistake lines from the SN as lines from the H II region (such as [O I]). There are no intermediate-width emission lines (such as H or He) that one would expect if the SN ejecta were interacting with a dense circumstellar medium associated with a massive star progenitor.

The ratio of [N II]  $\lambda 6584$  and H $\alpha$  lines from the H II region is 0.046, corresponding to a metallicity (as determined by the N2 method of Pettini & Pagel 2004) of  $12 + \log(\text{O}/\text{H}) = 8.14 \pm 0.03$  (stat). This is consistent with that of a nearby H II region (Paper I) and indicative of no significant H emission from circumstellar interaction.

## 4. PHOTOMETRIC ANALYSIS

We reproduce the early-time light curves of SN 2008ha from Paper I and V09 in Figure 3 along with our two late-time photometric upper limits. Our late-time imaging resulted in R-band measurements of  $21.43 \pm 0.05$  and  $21.82 \pm 0.05$  mag 222 and 231 days after B maximum, respectively. However, these images have had no template subtraction, so the photometry reflects the brightness of the combination of the SN and the underlying H II region, and therefore, these numbers are upper limits on the brightness of the SN. The differences in two measurements may indicate real fading between the two epochs, but can also be explained as systematic differences in the instrument/filter responses.

Paper I found that the light curves of SNe 2005hk and 2008ha were well matched if the light curve of SN 2005hk was “stretched” by a factor of 0.73. In Figure 3, we compare the *R*-band light curve of SN 2008ha to that of SN 2005hk (Phillips et al. 2007; Sahu et al. 2008) both with and without this stretching. The stretched light curve is a good approximation of the early-time behavior because the spectral energy distributions (SEDs) are similar. But the light curves exhibit different decline rates because the SNe had different opacities, amounts of ejecta/ $^{56}\text{Ni}$ , and kinetic energies. The ejecta of SN 2002cx-like objects appear to be optically thick at very late times (Jha et al. 2006; Sahu et al. 2008), so opacity effects may still dominate at  $t = 250$  days. Regardless, the SN 2005hk light curves should give an indication of the expected decay rate at late times if SN 2008ha evolves in a similar fashion.

If the peak luminosity is powered by  $^{56}\text{Ni}$  decay, then the luminosity at late times should be powered by  $^{56}\text{Co}$  (the decay product of  $^{56}\text{Ni}$ ) decay. The brightness at late times is therefore directly related to the  $^{56}\text{Ni}$  mass. Assuming the relationship between  $^{56}\text{Ni}$  mass and bolometric luminosity (Sutherland & Wheeler 1984), a solar SED for bolometric corrections, and full  $\gamma$ -ray trapping, the late-time photometry places a limit of  $M_{^{56}\text{Ni}} \lesssim 10^{-3} M_{\odot}$  (see Figure 3). This value is also consistent with the brightness of SN 2008ha at  $t \approx 60$  days. Considering the uncertainty of the SED, this is consistent with the estimate from the early-time light curve of  $(3.0 \pm 0.9) \times 10^{-3} M_{\odot}$ .

## 5. DISCUSSION AND CONCLUSIONS

The maximum-light spectrum provides key information for understanding the nature of SN 2008ha. The spectrum has strong lines from IMEs, including Si and S. Nucleosynthetic models suggest that strong S features are indicative of C/O burning (e.g., Perets et al. 2009). Furthermore, no core-collapse SN has been observed to have strong S lines at maximum light, and having these features in the maximum-light spectrum indicates that a non-negligible amount of S is in the outer ejecta, suggesting a WD progenitor (e.g., Thielemann et al. 1991). One of the points adduced by V09 in favor of the core-collapse interpretation of this event was the absence of S II and the weak Si II seen in their earliest spectrum, 8 days after maximum brightness. The new data presented here show that S II is present and Si II is significantly stronger than in those data. Although peculiar abundances in the outer layers of a massive star may be the cause of the S lines, the data currently favor the idea of a WD progenitor.

SN 2008ha shares many similarities (luminosity, spectral features, etc.) with SN 2005E, a low-luminosity SN Ib with strong Ca lines at late times (Paper I; Perets et al. 2009). There have been several SN 2005E-like objects discovered, but they exist predominantly in early-type galaxies, in contrast to the primarily late-type hosts of SN 2002cx-like objects (SN 2008ha was discovered in an dwarf irregular galaxy), and suggestive that they have old progenitors. Perets et al. (2009) found that by changing the amount of He and C/O burning, the ratio of S to Ca in the ejecta of a SN can be manipulated. SNe 2005E and 2008ha may have similar progenitors and/or explosion mechanisms. The different host-galaxy populations of these classes may indicate that progenitor age or metallicity has an effect on the resulting explosion, similar to SN 1991T and SN 1991bg-like objects.

To derive the previous estimates of the ejecta mass and kinetic energy, the velocity at 6 days past maximum brightness was extrapolated to the time of maximum assuming a velocity gradient similar to that of a normal SN Ia. With these new data, the extrapolation is not necessary, and the systematic uncertainty

related to these measurements can be reduced. The velocity of the maximum-light spectrum is twice that of the adopted value from Paper I, increasing the kinetic energy and ejecta mass by factors of 8 ( $E \propto v^3$ ) and 2 ( $M \propto v$ ), respectively. We therefore revise our estimates of the kinetic energy to be  $1.8 \times 10^{49}$  erg and  $M_{\text{ej}} = 0.3 M_{\odot}$ . We note that this analysis assumes that the composition and opacity of the ejecta of SN 2008ha are similar to those of a normal SN Ia, which may cause systematic uncertainty of order a factor of 2 (see Paper I for details).

The late-time photometry is consistent with the production of a few times  $10^{-3} M_{\odot}$  of  $^{56}\text{Ni}$ , similar to estimates from the early-time light curve (Paper I; V09). The late-time spectrum shows that there are no extremely strong emission lines from the SN; however, the relatively low S/N spectrum places weak limits on such features.

The strong C lines in the maximum-light spectrum indicate that there is unburned material far into the ejecta, consistent with a deflagration (Gamezo et al. 2003). The low ejecta and  $^{56}\text{Ni}$  mass are consistent with a failed deflagration of a WD that did not disrupt the progenitor (Paper I), but are perhaps also explained by a sub-Chandrasekhar mass or more exotic WD explosion.

Pre-maximum data are critical for understanding the nature of SN 2008ha-like objects. Although our observations are all consistent with a failed deflagration of a WD, we cannot completely rule out other models. If the progenitor of SN 2008ha was a very massive star, one might expect a brightening in X-rays or radio if the progenitor had a wind or pre-explosion outbursts. Future early-time X-ray and radio observations will help constrain the nature of similar events. Eventually, we will detect a SN 2008ha-like object with deep pre-imaging data and either detect or highly constrain the properties of the progenitor.

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*Facilities:* Gemini: Gillett (GMOS), HET(LRS), Magellan:Clay(LDSS3)

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