DISCOVERY OF VARIABILITY OF THE PROGENITOR OF SN 2011dh IN M 51 USING THE LARGE BINOCULAR TELESCOPE

D. M. Szczyniecki, J. R. Gerke, C. S. Kochanek, and K. Z. Stanek

1 Department of Astronomy, The Ohio State University, 140 West 18th Avenue, Columbus, OH 43210, USA; szczyniecki@astronomy.ohio-state.edu, gerke@astronomy.ohio-state.edu, ckochanek@astronomy.ohio-state.edu, kstanek@astronomy.ohio-state.edu
2 Center for Cosmology and AstroParticle Physics, The Ohio State University, 191 West Woodruff Avenue, Columbus, OH 43210, USA

Received 2011 October 12; accepted 2011 December 10; published 2012 February 10

ABSTRACT

We show that the candidate progenitor of the core-collapse SN 2011dh in M 51 (8 Mpc away) was fading by 0.039 ± 0.006 mag yr⁻¹ during the 3 years prior to the supernova, and that this level of variability is moderately unusual for other similar stars in M 51. While there are uncertainties about whether the true progenitor was a blue companion to this candidate, the result illustrates that there are no technical challenges to obtaining fairly high precision light curves of supernova-progenitor systems using ground-based observations of nearby (<10 Mpc) galaxies with wide-field cameras on 8 m class telescopes. While other sources of variability may dominate, it is even possible to reach into the range of evolution rates required by the quasi-static evolution of the stellar envelope. For M 81, where we have many more epochs and a slightly longer time baseline, our formal 3σ sensitivity to slow changes is presently 3 mmag yr⁻¹ for an $M_V \lesssim −8$ mag star. In short, there is no observational barrier to determining whether the variability properties of stars in their last phases of evolution (post-carbon ignition) are different from earlier phases.

Key words: supernovae: general – supernovae: individual: SN 2011dh

Online-only material: color figure

1. INTRODUCTION

The last few years have seen steady progress in the identification of the progenitors of core-collapse supernovae (ccSNe; see the review by Smartt 2009). The progenitors of Type IIP SNe are red supergiants, although there is some evidence that the most massive progenitors are less massive than the expected upper mass of red supergiants at the end of their lives (Kochanek et al. 2008; Smartt et al. 2009, but see Walmswell & Eldridge 2011). The progenitors of two Type Ib SNe have been identified, a (probably) mass transfer binary system in SN 1993J (Aldering et al. 1994) and the progenitor of SN 2011dh (Maund et al. 2011; Van Dyk et al. 2011). In two cases, SN 2005gl (Gal-Yam & Leonard 2009) and SN 1961V (Kochanek et al. 2011; Smith et al. 2011), the progenitor properties may be consistent with those of massive, luminous blue variables. The dust-enshrouded progenitors of the Type IIn SN 2008S (Prieto et al. 2008a) and the 2008 NGC 300 transient (Thompson et al. 2011) were identified only in the mid-infrared. No progenitors of Type Ibc SNe have been identified, and this will likely remain challenging due to their lower rates, large expected bolometric corrections, and the ease with which a binary companion can be optically brighter (Kochanek 2009). Still, progenitor studies are now well established.

The next frontier is the variability of progenitors. Very little is known observationally about the variability of these stars shortly before explosion. The progenitor of the Type Ipec SN 1987A varied by less than a few tenths of a magnitude during its last century (see Plotkin & Clayton 2004 and references therein), while the progenitor of the Type Ib SN 1993J varied by less than 0.2 mag over a 6 month period 9 years before explosion (Cohen et al. 1995). The progenitor of the Type IIP SN 2008cn was probably variable at a level of ~0.2 mag and the sparse light curve is potentially interpretable as an eclipsing binary (Elias-Rosa et al. 2009). The progenitor of the Type Ib SN 2006jc showed an outburst 2 years before explosion (Pastorello et al. 2007). SN 1961V also had an outburst prior to explosion if it is interpreted as an SN (Kochanek et al. 2011; Smith et al. 2011). In several transients, variability was either observed (SN 2010da, Laskar et al. 2010) or well constrained (SN 2008S, Prieto et al. 2008a; NGC 300-OT, Thompson et al. 2009) in a dusty stellar wind rather than directly in the star. More generally, outbursts in the last ~century before explosion may be required to explain the post-explosion evolution of many Type IIn SNe (e.g., Fox et al. 2011). In short, data are available for very few SNe, and when they exist they are generally too sparse to interpret.

Theoretically, all SN progenitors are variable because their envelopes are evolving on a thermal timescale in response to the rapid changes in the core luminosity. In the standard lore, this quasi-equilibrium evolution is too small to be observable. Rough estimates can be extracted from some tabulated evolution models, and typical rates in the optical are 0.1–1.0 mmag yr⁻¹ (Schaller et al. 1992; Heger et al. 2000; Heger & Langer 2000), but none of these studies was really intended for studies of the surface evolution during the last century. While these rates are small, it is certainly possible to achieve the necessary photon counting statistics to detect 1 mmag yr⁻¹ changes in progenitors for nearby (<10 Mpc) galaxies (see the discussion in Section 3).

It is likely in most cases that other sources of variability will dominate and mask the slow evolution of the envelope. Many massive stars vary either regularly or irregularly, although good statistics for the evolved stars likely to be SN progenitors seem to be lacking. The nature of the variability is closely related to the stellar type (e.g., Szczyniecki et al. 2010), but not as yet in a manner that is a better diagnostic of the star than its location in a color–magnitude diagram except in the limit of helioseismology. There are theoretical arguments that the pulsational properties of red supergiants change with the onset of carbon burning (Heger et al. 1997), but this has not been developed to the point of providing any observational guidance. Similarly, Arnett
et al. (2011) show that in three dimensions the nuclear burning fronts of stars in these late phases can be very dynamic, which could drive surface effects. Thus, it is likely that the progenitors are variable, particularly the red supergiants, but it is unknown whether the variability properties of SN progenitors show any recognizable difference from stars that have not commenced carbon burning.

Another source of variability comes from shells of material ejected during outbursts either as observed for SN 2006jc (Pastorello et al. 2007) or inferred from the post-SN evolution (e.g., Fox et al. 2011). Ejected material has observable effects on the light curve of the progenitor if dust forms in the ejected material. As a dusty shell expands, its optical depth drops as \( \tau \propto 1/r^2 \propto 1/t^2 \) and the star becomes steadily brighter and bluer, as is observed for sources such as \( \eta \) Carinae (see the review by Humphreys & Davidson 1994). Observing these changes, as well as the associated mid-IR emission, constrains the time of the eruption if unobserved and the amount of material ejected.

Finally, close binary stars can show ellipsoidal variations from a relatively broad range of viewing angles and eclipses from a narrow range. For example, the progenitor of SN 1993J had a roughly 15% probability of producing visible eclipses based on the binary evolution models of Stancliffe & Eldridge (2009). It would, however, require extraordinarily good luck to find a supernova progenitor in an eclipsing binary since a more typical probability is 5% for a 100% binary fraction, and for the distance limits we are considering (<10 Mpc) the SN rate is only \( \sim 1 \text{yr}^{-1} \). In most cases it will likely be easier to identify candidate binary companions once the SN has faded (see Kochanek 2009).

With wide-field cameras on 8.5 m class telescopes it is now possible to begin exploring these problems in nearby (<10 Mpc) galaxies. While crowding means that the Hubble Space Telescope (HST) is generally needed to provide absolute photometry, difference imaging methods make it relatively easy to monitor individual stars from the ground because luminous variable stars are relatively rare and hence not crowded. This is illustrated in Gerke et al. (2011), where we identified over 100 Cepheids in M 81 using the Large Binocular Cameras (LBC; Giallongo et al. 2008) on the twin 8.5 m Large Binocular Telescope (LBT). The shortest period Cepheids in Gerke et al. (2011), at \( P = 10 \) days, have masses of order \( M \approx 6 M_\odot \) (e.g., Bono et al. 2000) that are well below the mass limit for SN progenitors. We are presently monitoring 25 nearby galaxies in the \( UBV \) bands using the LBT/LBC, sparsely monitoring most and more intensively monitoring a few. By rotating the galaxies through the intensive monitoring list we gradually build a picture of both long- and short-term variability. In addition to the search for variable stars, the data also enable two more speculative projects. The first is to set limits on the existence and rate of failed supernovae, massive stars forming black holes without a dramatic external signature (Kochanek et al. 2008). Based on the best current statistics for star formation and supernova rates, these could represent up to half of all stellar deaths (Horiuchi et al. 2011).

The second speculative goal is to study the variability of SN progenitors. Unfortunately, the first SN in our sample, SN 2009dh in NGC 3627 (Monard 2009), occurred when we had almost no data and it also lay behind a dust lane in the wings of an unobscured bright star (see Elias-Rosa et al. 2011). We obtained no interesting limits on the variability of the progenitor, although we should be able to obtain \( UBV \) photometry of the progenitor once the SN has faded. The second SN in our sample is SN 2011dh in M 51 (Griga et al. 2011). A candidate progenitor for SN 2011dh was rapidly identified by several groups (Maund et al. 2011; Van Dyk et al. 2011). The object is relatively yellow (\( T \sim 6000 \text{K} \)) which is further supported by age dating of the stellar population associated with the SN (Murphy et al. 2011) and there are suggestions that the spectral energy distribution (SED) may represent a composite of two, presumably binary, stars. Furthermore, Prieto & Hornoch (2011), Arcavi et al. (2011), and Soderberg et al. (2011) argue that the star which exploded must be a more compact, blue star based on the rapid evolution of the early-time light curve and spectroscopy. This would be consistent with the presence of H\( \alpha \) emission in pre-explosion HST images (Szczygielet al. 2011). Since truly yellow stars are rare, the color could be due to blending light from a blue and a red star, as was found for SN 1993J (Aldering et al. 1994) and suggested for SN 2008cn (Elias-Rosa et al. 2009). This is difficult to reconcile with the available SED, so the unusual temperature could also be an additional indicator of binarity (e.g., Prieto et al. 2008b).

As discussed in Kochanek (2009), we expect 50%–80% of SNe to occur in stellar binaries, and it is relatively easy for the cooler star to dominate the optical emission. Combined with the Type IIb spectroscopic type, the system seems very similar to the binary progenitor of SN 1993J. While we have yet to carry out the intensive monitoring phase for periodic variables in M 51, we have 5/4 epochs of \( UBV/R \) data spread over 3 years and came close to observing the star just before it exploded since the next run started on 2011 June 2 with M 51 as a high-priority target. The candidate progenitor is well detected in all epochs and variable. We will simply refer to this star as the progenitor to avoid constant use of the clumsy phrase “candidate progenitor,” but the ultimate interpretation of its variability clearly depends on resolving this ambiguity. In Section 2 we describe the data and our variability analysis based on difference imaging. In Section 3 we discuss some of the implications. We adopt a distance to M 51 of 8.3 Mpc (Poznanski et al. 2009) and a foreground Galactic extinction of 0.035 mag (Schlegel et al. 1998).

### 2. DATA AND RESULTS

We observed M 51 with the LBT/LBC before the SN explosion on 2008 March 9, 2009 January 28, 2010 March 19, 2011 February 11, and 2011 April 29, and after the explosion on 2011 June 5 and 9. The LBC-Red camera was not available for the 2011 February 11 epoch. Table 1 summarizes the observations. The LBC cameras have a pixel scale of 0.224, and the galaxy was placed on the central chip 2 of each camera. The images were bias-corrected and flat fielded using sky flats following standard procedures using IRAF mscred tasks. Figure 1 shows the \( UBV \) reference images as compared to the archival HST

| Date       | LBC Red  | LBC Blue |
|------------|----------|----------|
| 2008 Mar 9 | 6 × 300  | 2, 2, 2 × 300 |
| 2009 Jan 28| 8 × 200  | 3, 2, 3 × 200 |
| 2010 Mar 19| 14 × 200 | 3, 6, 5 × 200 |
| 2011 Feb 11| 9 × 200  | 3, 3, 3 × 200 |
| 2011 Apr 29| 9 × 200  | 3, 3, 3 × 200 |
| 2011 Jun 5 | 9 × 200  | 3, 3, 3 × 200 |
| 2011 Jun 9 | 9 × 200  | 3, 3, 3 × 200 |

Note. Exposure times are in seconds.
images of the region. The star is clearly visible, but blended with the blue star O.5 to the northeast. The progenitor dominates the BVR fluxes (based on the HST images, it represents 65%, 76%, and 87% of the B, V, and I fluxes, respectively), while the U-band flux is dominated by the blue star and we see a corresponding shift in the location of the peak.

We analyzed the images using the ISIS difference imaging package (Alard & Lupton 1998; Alard 2000) with a modified star matching procedure based on SExtractor (Bertin & Arnouts 1996) that performs more reliably in our fields. The earlier LBC data had some significant rotations and translations relative to the nominal field centers, and we discovered that the standard ISIS interpolation routine mishandles interpolation in this circumstance. Once identified, the problem was corrected by modifying the ISIS spline2.c routine to correctly identify the target column associated with each row. We interpolated the individual sub-images to an R-band reference frame using a second-order polynomial for the coordinate transformation constructed from 100 to 300 stars with typical rms residuals in the stellar matches of less than 0.1 pixels. A reference image was constructed for each band from 6 to 10 of the sub-images obtained prior to the SN. We carried out the difference imaging both on the individual sub-frames and by combining the interpolated sub-frames and then difference imaging the combined images.

Figure 2 shows the light curves with the magnitude at the epoch of highest brightness normalized to zero. In R band, the flux is dominated by the progenitor, and over the last 3 years it faded by roughly 0.13 mag at a rate of 0.039 ± 0.006 mag yr⁻¹. Note that for this light curve we constructed several stacked images for each epoch rather than combining all the data into a single image. The results for the separate images at each epoch are mutually consistent. The B and V light curves show an initial rise and then a fall, although an increasing fraction of the light comes from the contaminating blue star at shorter wavelengths (24% at V and 35% at B). The U-band light curve shows no convincing variability and is primarily emission from the contaminating star. The dotted line marks the date of the SN explosion.

(A color version of this figure is available in the online journal.)
V-, and R-band data were calibrated using a limited number (14) of Sloan Digital Sky Survey (SDSS DR7) stars found on chip 2 (unfortunately, the standards used by Pastorello et al. (2009) are all saturated in the LBT BVR images). We transformed their magnitudes from the ugriz to UBVR$_{c}$ system using Jordi et al. (2006). After eliminating stars with uncertainties larger than 0.3 mag, we were left with only 7, 5, and 8 stars in $B$, $V$, and $R$, respectively, leading to calibration uncertainties of 0.230, 0.095, and 0.081 mag. These absolute calibrations are relatively unimportant for our present discussion. We then constructed light curves from the difference images for all the sources in the LBT DAOPHOT catalogs. Figure 3 shows the variance $\sigma_R$ of these ~27,000 $R$-band light curves as a function of the $R$-band magnitude. The overall trend with magnitude simply represents photon-counting statistics and we have made no major effort to clean the variability catalog of artifacts. Since ISIS tends to underestimate the uncertainties in light curves, we used Figure 3 to rescale its error estimates. Given that most sources are not variable, the light-curve uncertainties should match the median variance seen in Figure 3 (heavy line), and this requires scaling the ISIS light-curve uncertainties upwards by a factor of three. We use these rescaled uncertainties in Figure 2. The final light curve of the SN progenitor is presented in Table 2. The individual uncertainties are correct for the light curve, but there are additional global uncertainties from setting the magnitude of the source in the reference image and the zero point. The uncertainties on the light curves do not include the uncertainties in the magnitude of the star on the reference image. The DAOPHOT uncertainties in the reference image magnitude are 0.03 in $U$, 0.05 in $B$, 0.04 in $V$, and 0.03 in $R$, and the magnitude calibration uncertainties are 0.10 in $U$, 0.23 in $B$, 0.09 in $V$, and 0.08 in $R$.

![Figure 3](http://cas.sdss.org/dr7/en/tools/search/sql.asp)

**Figure 3.** Variable sources in M 51. The points show the variance $\sigma_R$ in the $R$-band light curves of ~27,000 sources as a function of the $R$-band magnitude. The heavy line is the median of the $\sigma_R$ distribution within 0.5 mag wide magnitude bins, while the two thin lines symmetrically enclose 68% of the objects around the median, representing an equivalent of one standard deviation in this non-Gaussian distribution of $\sigma_R$. The properties of the SN 2011dh progenitor are marked with an open circle and we see that it lies just inside the upper thin line, almost falling into the group of 16% most variable objects. We have not carefully inspected this sample for false sources of variability, so the significance of the progenitor variability is underestimated. The general trend simply represents the scaling of photon counting uncertainties with flux ($\sigma_R \propto R/5$).

### Table 2

| Date         | HJD-2450000 (days) | $U$ (mag) | $\sigma_U$ (mag) | $B$ (mag) | $\sigma_B$ (mag) | $V$ (mag) | $\sigma_V$ (mag) | $R$ (mag) | $\sigma_R$ (mag) |
|--------------|-------------------|-----------|------------------|-----------|------------------|-----------|------------------|-----------|------------------|
| 2008 Mar 9   | 54534.5           | 21.80     | 0.05             | 21.91     | 0.02             | 21.27     | 0.02             | 21.32     | 0.02             |
| 2009 Jan 28  | 54859.4           | 21.78     | 0.05             | 21.81     | 0.02             | 21.23     | 0.03             | 21.35     | 0.02             |
| 2010 Mar 19  | 55274.5           | 21.72     | 0.04             | 21.86     | 0.02             | 21.30     | 0.02             | 21.37     | 0.02             |
| 2011 Feb 11  | 55603.5           | 21.74     | 0.03             | 21.89     | 0.01             | 21.30     | 0.01             | 21.37     | 0.02             |
| 2011 Apr 29  | 55680.4           | 21.77     | 0.04             | 21.92     | 0.01             | 21.34     | 0.02             | 21.45     | 0.02             |

*Notes.* The uncertainties on the light curves do not include the uncertainties in the magnitude of the star on the reference image. The DAOPHOT uncertainties in the reference image magnitude are 0.03 in $U$, 0.05 in $B$, 0.04 in $V$, and 0.03 in $R$, and the magnitude calibration uncertainties are 0.10 in $U$, 0.23 in $B$, 0.09 in $V$, and 0.08 in $R$.

The heavy line is the median of the $\sigma_R$ distribution within 0.5 mag wide magnitude bins, while the two thin lines symmetrically enclose 68% of the objects around the median, representing an equivalent of one standard deviation in this non-Gaussian distribution of $\sigma_R$. The properties of the SN 2011dh progenitor are marked with an open circle and we see that it lies just inside the upper thin line, almost falling into the group of 16% most variable objects. We have not carefully inspected this sample for false sources of variability, so the significance of the progenitor variability is underestimated. The general trend simply represents the scaling of photon counting uncertainties with flux ($\sigma_R \propto R/5$).

We can construct a better comparison sample by searching for “true” analogs to the progenitor in the $B$, $V$, and $I$ catalogs obtained from the HST images (constructed with DAOPHOT). We matched the magnitudes $m_{i,j}$ of each potential analog to the typical star, with 93% of the stars having smaller slopes in absolute value. However, note that simply comparing to stars of similar $R$-band magnitude averages over stars of many types, and there are probably many false outliers in the distribution because we have not inspected all the light curves of these objects for artifacts.

We matched the magnitudes $m_{i,j}$ of each potential analog to the typical star, with 93% of the stars having smaller slopes in absolute value. However, note that simply comparing to stars of similar $R$-band magnitude averages over stars of many types, and there are probably many false outliers in the distribution because we have not inspected all the light curves of these objects for artifacts.

We can construct a better comparison sample by searching for “true” analogs to the progenitor in the $B$, $V$, and $I$ catalogs obtained from the HST images (constructed with DAOPHOT). We matched the magnitudes $m_{i,j}$ of each potential analog to the typical star, with 93% of the stars having smaller slopes in absolute value. However, note that simply comparing to stars of similar $R$-band magnitude averages over stars of many types, and there are probably many false outliers in the distribution because we have not inspected all the light curves of these objects for artifacts.
Figure 4. Variability statistics of M 51 stars. The scatter diagram shows the distribution of objects in light-curve slope $s$ and rms residual $\sigma$ for the progenitor (large circle), for 3800 stars within 1 $R$ mag of the progenitor (small points) and for 77 analog stars of similar luminosity and spectral energy distribution (crosses). The dashed lines mark the values observed for the progenitor for both signs of the slope. The panels to the side show projected histograms of the comparison stars, where the histogram for the small sample of analogs has been multiplied by 10. While the rms variability of the progenitor is typical of either sample, stars fading as rapidly as the progenitor are relatively rare.

those of the progenitor $m_{p,i}$,

\[
\chi^2 = \sum_{i=R,V,I} (m_{p,i} - m_{a,i} - \Delta M - R_i \Delta E)^2 \sigma_0^{-2},
\]

allowing for a difference in luminosity $|\Delta M| < 0.5$ mag and extinction $|\Delta E| < 0.1$ and accepting those with $\chi^2 < 4$ for a fixed $\sigma_0 = 0.1$ mag. This identified 235 such stars, of which 77 lay outside the masked regions of the $R$-band LBT image. Many of the potential analogs lie in the central regions of M 51, which are saturated in our $R$-band images, while the remainder trace the spiral arms. We visually examined the analogs to detect any potential artifacts. Figure 4 also shows the variability properties of these analog stars (black crosses), and the slope of the progenitor is still unusually large, with only 5% (four objects) of the analogs showing larger absolute slopes.

3. DISCUSSION

Our primary result is that with only 4/5 epochs of ground-based data there is no difficulty in detecting low-level variability in a supernova-progenitor candidate at a distance of almost 10 Mpc. In the $R$ band we find a relatively steady decline of $s = 0.039 \pm 0.006$ mag yr$^{-1}$ over a three year baseline with rms residuals of only 0.02 mag. With so few epochs so sparsely spaced, we cannot interpret this light curve physically as it is practically impossible to distinguish between the possible explanations as to the nature of the variability. The uncertainty about the true identity of the progenitor further complicates the interpretation in any case. As noted by Kochanek (2009), 50%–80% of ccSNe should be in stellar binaries at the time of explosion. Furthermore, if the binary consists of a blue, hot star and a red (in this case yellow) cool star and the blue star explodes, it will not be uncommon for the visual emission from the progenitor to be dominated by the red companion rather than the star which exploded. This issue will be resolved as the direct emission from the SN fades, although we should note that the system most advanced as a possible analog, SN 1993J, produces so much emission from the expanding shock moving through the circumstellar medium that the binary companion only became observable a decade later (see Maund et al. 2004).

While the utility of finding that the progenitor is an eclipsing binary is obvious, one could legitimately ask whether detecting other sources of variability has any use. At a very basic level, these stars are different from all other stars in their galaxies. In a Hertzsprung–Russel diagram this is not apparent because there is nothing special about their luminosities and surface temperatures. Variability opens a new window to search for these differences. There may be none, but the default expectation that there are no precursor signals to SNe is essentially based on assuming that the only effect is the quasi-static evolution of the stars and that this is too slow to detect.

How slow is the quasi-static evolution? Figure 5 shows estimates of the rate of evolution for the last century before collapse derived from the models tabulated by Schaller et al. (1992), Heger et al. (2000), and Heger & Langer (2000). The stars are generally becoming slightly fainter and hotter at rates of 0.1–1 mmag yr$^{-1}$. Bear in mind that these models were not intended for this purpose. Based on photon statistics, it is possible to detect such slow rates of change. Given $N$ observations with an 8.5 m telescope, uniformly spaced over time $T$ (in years), with exposure time $t_{exp}$ for each epoch, the 3σ sensitivity to a temporal gradient is

\[
s_3 \simeq \frac{0.040 \text{ mag}}{T} \left( \frac{D}{10 \text{ Mpc}} \right) \left( \frac{(1 + B)k}{N t_{exp}} \right)^{1/2} 10^{-0.2(M_V+8)}
\]
for a star of absolute luminosity $M_V$ at distance $D$ with the background flux in the extraction aperture being $B$ times that of the star. For the $R$-band observations of M 51, we have $T = 3.1$ years, $N = 4$, $N_{\text{exp}} = 8000$ s, $D = 8.3$ Mpc, and $B \simeq 10$, yielding $s_3 \simeq 14$ mmag yr$^{-1}$ for the $M_V \simeq -8$ mag progenitor star. This result does not depend significantly on the adopted SN distance—if we take $D = 7.1$ Mpc (used by Maund et al. 2011) or $D = 7.66$ Mpc (van Dyk et al. 2011), then $s_3 \simeq 12–13$ mmag yr$^{-1}$. The formal estimate from our progenitor light curve is that we reached $s_3 \simeq 18$ mmag yr$^{-1}$, roughly consistent with this estimate but well above even the highest rates shown in Figure 5.

Consider, however, the data we have accumulated on M 81 to study its variable stars (Gerke et al. 2011). With $D = 3.6$ Mpc, $N = 50$, $N_{\text{exp}} = 21540$ s, and $T = 4.1$ years, the nominal $3\sigma$ sensitivity of $s_3 \simeq 3$ mmag yr$^{-1}$ (at $M_V = -8$) is below some of the quasi-static evolution rate predictions. Extending the time baseline to 10 years reaches $s_3 \simeq 1$ mmag yr$^{-1}$, and campaigns with $N = 1000$ and $T = 30$ years yielding $s_3 \simeq 0.1$ mmag yr$^{-1}$ are conceivable. This does assume a fixed instrumental configuration, but a 10 year baseline yielding $s_3 \simeq 1$ mmag yr$^{-1}$ sensitivity is probably achievable. While the gradient seems small, the absolute change is 0.01 mag. Thus, it is possible to obtain the photon statistics needed to probe this phase of stellar evolution, and we know from ground-based millimagnitude photometry of planetary transits (see the review by Winn 2011) and $\sim 10^{-2}$ mmag photometry of transits in space (Borucki et al. 2009) that systematic errors can be controlled well enough to approach the statistical limits. A millimagnitude is not what it used to be.

A few other regimes of stellar evolution, such as the post-helium flash evolution of stars onto the horizontal branch (L. Bildsten 2011, private communication) and some massive stars in the Hertzsprung gap should also be fast enough to observe, albeit not at Mpc distances. We do need theoretical models intended for making estimates of the surface evolution in these last phases, particularly since most studies of stellar evolution literally freeze the envelope for the last phases.

The systematic problem that will most limit measurements of quasi-static evolution is that stars vary on many timescales other than this evolutionary timescale. Variability acts like an added source of noise, essentially adding $B \simeq (A/\sigma_{\text{phot}})^2$ to Equation (2), where $A$ is the amplitude of any unmodeled variability and $\sigma_{\text{phot}}$ is the typical photometric error at any epoch. If other sources of variability dominate, then the question becomes whether the variability of progenitors can be distinguished from that of other stars. With the sparse data we have, we can only consider simple metrics. Here we examined variability in the space of a mean trend and the residuals around it, finding that the progenitor has modestly unusual variability properties. Since there is essentially no theoretical guidance on variability in these late phases, other than the study by Heger et al. (1997) that the oscillation properties change, and we are faced with the additional uncertainties about the nature of the progenitor, it is premature to draw conclusions. We will probably need variability statistics on several progenitors to begin having a clear path for interpreting the results.

The particular properties of one ambiguous object are not a revolution. But the ability to make the measurements may be revolutionary. Using difference imaging techniques we can measure the variability of any SN progenitor within 10 Mpc from a ground-based 8.5 m telescope at levels that certainly approach and may reach the variability expected from the quasi-static evolution of the stars. Any variability significantly above that level is trivial, and we simply face the quantitative question of whether the variability of post-carbon ignition stars can be distinguished from that of other stars. In other words, we could ask whether the variability properties can be used to point at stars about to explode. The “about to” is likely on the order of the present duration of human civilization (the $10^3–10^4$ years after carbon ignition), but this is still a remarkably narrow window compared to the lifetimes of even massive stars. The important point about our observations of the progenitor of SN 2011dh is that these are now observational questions—we do not know if the answer will be boring or exciting, but we know we can answer the question.

Forty galaxies produce 90% of the local ($<10$ Mpc) ccSNe rate of roughly 1 SN yr$^{-1}$ (see Kochanek et al. 2008). It conservatively requires 4 nights on an 8 m class telescope with a wide-field camera (LBC on LBT, Suprimecam on Subaru, or to a lesser degree, IMACS/Megacam on Magellan) to provide one epoch of data with depth comparable to our present data for all 40 galaxies. Such single-epoch data generally exist but are not very useful because seeing-induced confusion means that photometry of individual stars is essentially impossible at these distances with ground-based optical resolution. Accurate single-epoch fluxes require the high resolution of the HST.
at these distances are not, however, crowded with luminous variable stars even at ground-based resolutions, and, as shown in our study of Cepheids in M 81 (Gerke et al. 2011), variability should be measured from the ground with difference imaging and only the absolute calibrations done from space. Getting to the modest numbers of epochs we use here is relatively easy, roughly 20 nights to obtain 5 epochs for every galaxy. This is approximately where we stand in our LBT survey of 25 of these 40 galaxies—we have a median of 5 epochs. Reaching 30 epochs is expensive, but this is roughly the threshold where one can identify and phase periodic variables like Cepheids and build long-term light curves of fainter transients. At least in our LBT survey, we are initially trying to reach this level for a subset of the galaxies that are interesting for studies of the distance scale (e.g., M 81, NGC 4258, M 101) or where there are interesting, faint transients to be monitored (e.g., SN 2008S in NGC 6946; see Kochanek et al. 2011). Achieving the next level, 100 epochs, probably requires a dedicated imaging telescope like the Large Synoptic Survey Telescope, but only represents 5%–10% of the observing time over a period of 20 years. With this many epochs, most eclipsing binaries will be identified and it should also enable searches for microlensing events.

We thank J. L. Prieto for valuable discussions and help, and T. A. Thompson for comments on the manuscript. We also thank the observers who took the LBT data used in this paper: J. Antognini, D. Atlee, R. Beaton, A. Bedregal, J. Blackburne, R. Beaton, A. Bedregal, J. Blackburne, J. Prieto, G. Privon, K. Rueff, and L. Watson. The authors are supported by NSF grant AST-0908816. Based in part on observations made with the Large Binocular Telescope. The LBT is an international collaboration among institutions in the United States, Italy, and Germany. The LBT Corporation partners are the University of Arizona on behalf of the Arizona university system; the Istituto Nazionale di Astrofisica, Italy; the LBT Beteiligungsgesellschaft, Germany, representing the Max Planck Society, the Astrophysical Institute Potsdam, and Heidelberg University; the Ohio State University; and the Research Corporation, on behalf of the University of Notre Dame, University of Minnesota, and University of Virginia. This work is based in part on observations made with the NASA/ESA Hubble Space Telescope, obtained from the data archive at the Space Telescope Institute. STScI is operated by the association of Universities for Research in Astronomy, Inc. under the NASA contract NAS 5-26555. This research has made use of the NASA/IPAC Extragalactic Database (NED) which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

Facilities: LBT, HST

REFERENCES

Alard, C. 2000, A&A, 363
Alard, C., & Lupton, R. H. 1998, ApJ, 503, 525
Aldering, G., Humphreys, R. M., & Richmond, M. 1994, AJ, 107, 662
Arcavi, I., et al. 2011, ApJ, 742, L18
Arnett, W. D., & Meakin, C. 2011, ApJ, 733, 78
Bertin, E., & Arnouts, S. 1996, A&AS, 117, 393
Bono, G., Castellani, V., & Marconi, M. 2000, ApJ, 529, 293
Borucki, W. J., et al. 2009, Science, 325, 709
Cohen, J. G., Darling, J., & Porter, A. 1995, AJ, 110, 308
Elia-Rosa, N., Van Dyk, S. D., Li, W., et al. 2009, ApJ, 706, 1174
Elias-Rosa, N., Van Dyk, S. D., Li, W., et al. 2011, ApJ, 742, 6
Fox, O. D., et al. 2011, ApJ, 741, 7
Gal-Yam, A., & Leonard, D. C. 2009, Nature, 458, 865
Gerke, J. R., Kochanek, C. S., Prieto, J. L., Stanek, K. Z., & Macri, L. M. 2011, ApJ, 743, 176
Giallongo, E., Ragazzoni, R., Grazian, A., et al. 2008, A&A, 482, 349
Griga, T., Marulla, A., Grenier, A., et al. 2011, Central Bureau Electronic Telegrams, 2736, 1
Heger, A., Jeannin, L., Langer, N., & Baraffe, I. 1997, A&AS, 327, 224
Heger, A., & Langer, N. 2000, ApJ, 544, 1016
Heger, A., Langer, N., & Woosley, S. E. 2000, ApJ, 528, 368
Horiuschi, S., Beacom, J. F., Kochanek, C. S., et al. 2011, ApJ, 738, 154
Humphreys, R. M., & Davidson, K. 1994, PASP, 106, 1025
Jordi, K., Grebel, E. K., & Ammon, K. 2006, A&A, 460, 339
Kochanek, C. S. 2009, ApJ, 707, 1578
Kochanek, C. S., Beacom, J. F., Kistler, M. D., et al. 2008, ApJ, 684, 1336
Kochanek, C. S., Szczygieł, D. M., & Stanek, K. Z. 2011, ApJ, 737, 76
Laskar, T., Berger, E., & Chornock, R. 2010, ApJ, 2648, 1
Maund, J. R., Smartt, S. J., Kadri, R. P., Podsiadlowski, P., & Gilmore, G. F. 2004, Nature, 427, 129
Maund, J. R., Takeuchi, T., & Ida, S. 2011, ApJ, 739, 37
Monard, L. A. G. 2009, Cen. Bur. Electron. Telegrams, 1867, 1
Murphy, J. W., Jennings, Z. G., Williams, B., Dalcanton, J. J., & Dolphin, A. 2011, ApJ, 742, 4
Pastorello, A., Smartt, S. J., Mattila, S., et al. 2007, Nature, 447, 829
Pastorello, A., Valenti, S., Zampieri, L., et al. 2009, MNRAS, 394, 2266
Plotkin, R. M., & Clayton, G. C. 2004, J. Am. Assoc. Var. Star Obs., 32, 89
Poznanski, D., Butler, N., Filippenko, A. V., et al. 2009, ApJ, 694, 1067
Prieto, J. L., & Hornoch, K. 2011, Atel, 3433, 1
Prieto, J. L., Kistler, M. D., Thompson, T. A., et al. 2008a, ApJ, 681, 9
Prieto, J. L., Stanek, K. Z., Kochanek, C. S., et al. 2008b, ApJ, 673, 59
Schaller, G., Schaerer, D., Meynet, G., & Maeder, A. 1992, A&AS, 96, 269
Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, ApJ, 500, 525
Smartt, S. J. 2009, ARA&A, 47, 63
Smartt, S. J., Eldridge, J. J., Crockett, R. M., & Maund, J. R. 2009, MNRAS, 395, 1409
Smith, N., Li, W., Silverman, J. M., Ganeshalingam, M., & Filippenko, A. V. 2011, MNRAS, 415, 773
Soderberg, A. M., Margutti, R., Zauderer, B. A., et al. 2011, arXiv:1107.1876
Stancliffe, R. J., & Eldrige, J. J. 2009, MNRAS, 396, 1699
Stetson, P. B. 1987, PASP, 99, 191
Szczygieł, D. M., Khan, R., & Kochanek, C. S. 2011, Atel, 3431, 1
Szczygieł, D. M., Stanek, K. Z., Bonanos, A. Z., et al. 2010, ApJ, 140, 14
Thompson, T. A., Prieto, J. L., Stanek, K. Z., et al. 2009, ApJ, 705, 1364
Van Dyk, S. D., et al. 2011, ApJ, 741, L28
Walmswell, J. J., & Eldrige, J. J. 2011, arXiv:1109.4637
Winn, J. N. 2011, in Exoplanets, ed. S. Seager (Tucson, AZ: Univ. of Arizona Press) (arXiv:1001.2010)