AN EXTREMELY BRIGHT ECHO ASSOCIATED WITH SN 2002hh

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ABSTRACT

We present new, very late time optical photometry and spectroscopy of the interesting Type II-P supernova SN 2002hh, in NGC 6946. Gemini/GMOS-N has been used to acquire visible spectra at six epochs between 2004 August and 2006 July, following the evolution of the SN from age 661 to 1358 days. Few optical spectra of Type II supernovae with ages greater than 1 yr exist. In addition, g', r', and i' images were acquired at all six epochs. The spectral and photometric evolution of SN 2002hh has been very unusual. Measures of the brightness of this SN, both in the R and I bands, as well as in the $H\alpha$ emission flux, show no significant fading over an interval of nearly 2 years. The most straightforward explanation for this behavior is that the light being measured comes not only from the SN itself but also from an echo off nearby dust. Echoes have been detected previously around several SNe, but these echoes, at their brightest, were $\sim$8 mag below the maximum brightness of the SN. At $V \sim 21$ mag, the putative echo dominates the light of SN 2002hh and is only $\sim$4 mag below the outburst's peak brightness. There is an estimated 6 mag of total extinction in V toward SN 2002hh. The proposed explanation of a differential echo/SN absorption is inconsistent with the observed $BVRI$ colors.

Subject headings: dust, extinction — scattering — supernovae: general

1. INTRODUCTION

The condensation of dust in supernova (SN) ejecta is not well constrained by observations, since the detection of newly formed dust in young SNe in nearby galaxies has been extremely rare. Signatures of condensing dust can be observed in nearby Type II SNe approximately 1–2 yr after core collapse. There are three strong indications of the formation of dust: (1) a sudden decrease in continuum brightness in the visible due to increased dust extinction, (2) an accompanying development of an infrared excess arising from dust grains absorbing higher energy photons and reemitting them in the infrared, and (3) the development of asymmetric, blueshifted emission-line profiles (e.g., Sugerman et al. 2006). This combination of observable effects can be best explained by dust forming within the expanding ejecta and preferentially extinguishing emission from the far-side (hence redshifted) gas, which also results in a shift of the centroid of the emission-line profiles to the blue, optical dimming, and mid-infrared brightening (Lucy et al. 1989, 1991). Asymmetric emission-line profiles have been seen in SNe 1987A, 1998S, 1999em, 2003gd, and possibly 2004et (e.g., Danziger et al. 1991; Gerardy et al. 2000; Elmhamdi et al. 2003; Pozzo et al. 2004; Sugerman et al. 2006; Sahu et al. 2006). In the sample of seven supernovae with such spectra, dust appears to have formed in the ejecta of at least five. Even within this small sample the dust formation times range from near 300 days to 550 days.

SN 2002hh was discovered in NGC 6946 on 2002 October 31 (Li 2002). With the subsequent discovery of SN 2004et, there have now been eight SNe discovered in NGC 6946 in less than a century. A spectrum of SN 2002hh, obtained on 2002 November 2, showed a broad but very low contrast $H\alpha$ emission and absorption features with a very red, nearly featureless continuum, indicating a very young Type II SN (Filippenko et al. 2002). Optical imaging shows extensive dust obscuration in this region of NGC 6946 and Meikle et al. (2002) estimate a total absorption of $A_V \sim 6.1$ mag toward SN 2002hh of which about 1 mag is Galactic foreground obscuration. This estimate was made by comparing the observed $J - K_s$ color to template IR light curves (Mattila & Meikle 2001) and is supported by the strong interstellar Na I D absorption seen in the spectrum (Filippenko et al. 2002). CO emission was seen in K-band spectra of SN 2002hh in the first 6 months after outburst (Pozzo et al. 2004). The light curve of SN 2002hh shows it to be a Type II-P, where the SN remains at or near maximum brightness for $\sim$3 months after the explosion (Pozzo et al. 2006).

Thermal emission from dust in or near SN 2002hh was detected at mid-infrared wavelengths from 590 to 994 days by the *Spitzer Space Telescope* and confirmed by higher angular resolution Gemini/Michelle observations (Barlow et al. 2005; Meikle et al. 2006). An optically thick dust shell has been inferred, having a mass of 0.04–0.15 $M_\odot$ and suggesting a massive M supergiant or luminous blue variable precursor. The inner radius of the shell is estimated to be $\sim$1 × 10^{17} to $\sim$1 × 10^{18} cm (Barlow et al. 2005; Meikle et al. 2006). The highest velocity gas from the SN 2002hh explosion will not reach this circumstellar dust for approximately 28 yr (Meikle et al. 2006). Barlow et al. (2005) could not rule out the formation of new dust in the ejecta of SN 2002hh, since any mid-infrared emission from new dust would be swamped by emission from the existing circumstellar dust, which would occupy a far larger solid angle.

Pozzo et al. (2006) first suggested the existence of an IR echo in the *JHK* bands around SN 2002hh at early epochs up to 314 days. Meikle et al. (2006) found that the mid-IR flux declined by about 10% from 590 to 994 days. They suggested that most of the mid-IR

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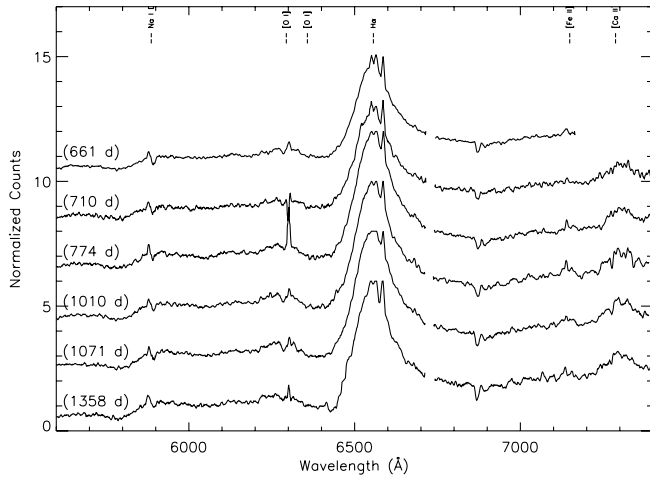[7] Department of Physics, UMBC, 1000 Hilltop Circle, Baltimore, MD 21250; sbank1@umbc.edu.

Fig. 1.—New Gemini/GMOS spectra of SN 2002hh from day 661 to day 1358. For display purposes, the narrow emission lines from NGC 6946 have been truncated.

flux may have come from dust in the star formation region associated with the SN 2002hh precursor. They found no evidence for new dust condensing in the ejecta, nor did they attribute the bulk of the emission to heated circumstellar material. The small declining component of the IR flux is attributed to an IR echo. An echo around SN 2002hh has been confirmed in the optical by B. E. K. Sugerman et al. (2007, in preparation), who have found a small but well-resolved circular scattered-light echo in visible light roughly $0.18''$ in diameter at the astrometric position of the supernova. In this paper we present a series of new, late-time optical spectra and photometry of the Type II-P SN 2002hh that were obtained to look for evidence of dust formation in its ejecta.

2. OBSERVATIONS

Spectroscopy was obtained using the Gemini North telescope and the GMOS-N instrument during semesters 2004B, 2005B, and 2006A. Three spectra of duration 900 s each were obtained on 2004 August 20. These were obtained in long-slit mode with a slit orientation of $190°$ in order to make use of a bright guide star. A $0.75''$ slit width was used for the observations with the B600-G5303 grating in first order. The central wavelengths of the spectra were 5720, 5700, and 5680 Å, respectively, to ensure that the two gaps between GMOS-N's three CCD chips could be bridged. A 2×2 binning of the CCD pixels in the low gain setting was employed.

Two additional epochs for SN 2002hh in 2004 were obtained using Director's Discretionary (DD) time. On 2004 October 8, three spectra, each of 720 s duration, were obtained with a setup identical to that described above. The observations had central

wavelengths of 5970, 5950, and 5930 Å, respectively. These longer central wavelengths were selected in order that the [Ca II] $\lambda\lambda7291$, 7324 lines would be recorded. A second set of spectra were obtained on 2004 December 11 UT. Each had a duration of 720 s and had central wavelengths of 5970, 5950, and 5930 Å, respectively.

Two epochs of spectra were obtained in 2005. The configuration of GMOS-N was identical to that above. The first epoch was obtained on 2005 August 4. Each exposure had a duration of 900 s to reduce the effect of fading of the SN on the signal-to-noise ratio of the spectra and had central wavelengths of 5970, 5950, and 5990 Å, respectively. The second epoch was obtained on 2005 October 4, and each spectrum then also had an exposure of 900 s. The central wavelengths were 5970, 5950, and 5990 Å, respectively.

The final epoch of spectra reported in this paper were obtained under an identical GMOS-N configuration on 2006 July 18. Each had a duration of 900 s and had central wavelengths of 5970, 5950, and 5990 Å, respectively.

All spectra had adjacent GCal flat exposures taken prior to changes to new central wavelengths. CuAr spectra used to calibrate the pixel-to-wavelength transformation were obtained during daytime. A single set of bias frames was used to reduce all of the spectra. The spectra from each individual night were averaged and normalized.

Spectra were reduced using IRAF version 2.12.2a and version 1.8 of the IRAF external package `gemini`. The usual pattern of reduction tasks `gbias`, `gsflat`, `gsreduce`, `gswavelength`, `gstransform`, `gsskysub`, and `gsextract` was employed. Sky subtraction regions were identified by eye and usually incorporated about 50 pixels on either side of the SN spectrum itself. Observations were not fluxed due to the lack of photometric conditions on several of the nights and also due to the primary goal of recording line profile variations. The radial velocity of NGC 6946 is $+48$ km s^{-1}. Emission lines from incompletely subtracted H II regions in the SN 2002hh spectra allow us to register the supernova to the local standard of rest in the galaxy. The spectra are shown in Figure 1 and are summarized in Table 1. (The spectra in Fig. 1 have not been dereddened.) We adopt 2002 October 29 as the explosion epoch (Pozzo et al. 2006).

The position of the peak of the Hα emission line is poorly determined due to the contamination of the $\lambda\lambda6548$–6584 [N II] doublet and the $\lambda6563$ Hα line from the H II region. To gauge the change in line position and symmetry, we instead measured the wavelength at which the ascending and descending portions of the line profile reached 50% of their peak values. Prior to making this measurement, a linear continuum slope correction was applied based on the average intensity levels in the $\lambda\lambda6240$–6260 and 6940–6960 regions of the spectra. The intensity of the Hα line changes rapidly through the 50% points, ensuring precise estimates

TABLE 1
HALF-INTENSITY Hα WAVELENGTHS AND PHOTOMETRY FOR SN 2002hh

Observation Date (UT)	Age (days)	50% Hα λ_{asc} (Å)	50% Hα λ_{des} (Å)	R[a] (mag)	I[a] (mag)
2004 Aug 20	661	6499.9	6618.8	19.87	18.98
2004 Oct 8	710	6497.2	6620.8	19.91	19.01
2004 Dec 11	774	6499.6	6625.5	19.97	19.13
2005 Aug 4	1010	6498.9	6619.6	20.15	19.35
2005 Oct 4	1071	6500.2	6623.2	20.15	19.40
2006 Jul 18	1358	6497.9	6621.1	...	19.60

[a] The R and I magnitudes were converted from the observed g', r', and i' instrumental magnitudes. See text.
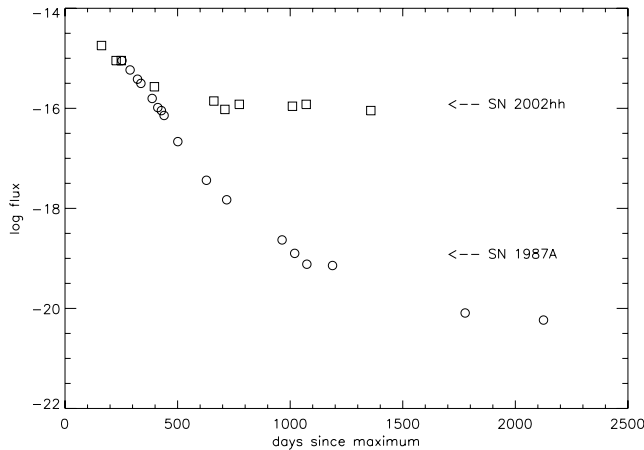
Fig. 2.—Measures of the peak counts in Hα in SN 1987A (*circles*) and SN 2002hh (*squares*) plotted against time since maximum light.

3. DISCUSSION

3.1. *Spectra*

Pozzo et al. (2006) observed SN 2002hh in the optical and near-IR from day 3 to 397. Optical spectra, including Hα and [O I] $\lambda\lambda$6300, 6364, were obtained at seven epochs. Pozzo et al. commented that, in general, the spectra of SN 2002hh resemble those of SN 1987A at similar epochs. In particular, SN 1987A and SN 2002hh both showed P Cygni profiles in Hα and Na I D at early times (Phillips & Williams 1991). The biggest difference between the SN 2002hh and SN 1987A was the strength of the [Ca II] $\lambda\lambda$7291, 7323 and the Ca II near-infrared triplet, which was much stronger in SN 1987A (Pozzo et al. 2006). Their last spectrum, obtained on day 397, shows no evidence for a developing asymmetry due to dust forming in the ejecta.

Figure 1 shows the new spectra obtained at an additional six epochs, which extend the spectral coverage to day 1358. None of the new spectra reveal an asymmetry in Hα similar to that which developed in SN 1987A around day 526 and which is believed to have indicated dust formation (see Fig. 7 of Phillips & Williams 1991). The Hα profile in SN 2002hh never completely lost its P Cygni shape, having a broader red wing than a blue wing (Duschinger et al. 1995). Not only is there no development of a blue asymmetry, but also the FWHM of Hα has increased in the day 661–1358 spectra compared to the last epoch of Pozzo et al. (2006) at day 397 without any statistically significant shift in line centroid. No increase in the opacity in the red wing of the line is seen in SN 2002hh. In fact, the red and blue wings both become broader between day 397 and 661. No such broadening of Hα was seen in SN 1987A (Phillips & Williams 1991). As seen in Table 1, the half-power points of Hα show no sensible evolution of either position over the course of the observations reported here.

The fact that the Hα emission-line profile has not developed a blue asymmetry but rather has retained its P Cygni shape and broadened since day 397 may be due to the presence of an echo around SN 2002hh. It is possible that dust formation in 2002hh is perhaps hidden or its interpretation confounded by scattered light from an echo resulting in a systematic error in the estimated age of the spectral features in the optical (Meikle et al. 2006). However, Pozzo et al. (2006) note that the spectrum of SN 2002hh obtained on day 397 has developed a strong blue continuum, indicating that the echo may have been affecting the light from SN 2002hh even at this early epoch.

Since SN 2002hh is a Type II-P, it stayed near maximum brightness for ∼3 months. Although there is a gap in the photometry of SN 2002hh from day 43 to 166, its light-curve behavior was consistent with both SN 1987A and SN 1999em (Pozzo et al. 2006). Any SN light echo pulse width will be quite broad, since it will contain an integral of the SN light over the first 3 months. Van Dyk et al. (2006) estimated a pulse width of ∼43 days in the B band and ∼138 days in the R band for the Type II-P SN 2003gd. The pulse width of SN 2002hh is likely to be on the same order as the length of the plateau phase of the light curve, ∼100 days. The echo spectrum seen at late times would have been an average of the SN spectrum over this period. Pozzo et al. (2006) reported spectra from SN 2002hh at days 4, 8, and 44. At day 44, the lines in the SN spectrum had already taken on the P Cygni profile shape that was seen all the way out to day 1358.

The late-time Gemini/GMOS spectra do resemble the Pozzo et al. (2006) day 44 spectrum of SN 2002hh. The day 44 spectrum and the new late-time (day 661–1358) spectra presented here are all broader than the last Pozzo et al. epoch at day 397. The Hα emission profiles from the six Gemini/GMOS epochs spanning over

for the ascending and descending half-peak wavelengths. In Table 1 we list, from left to right, the UT observation date, the age of the supernova, the wavelength at which the ascending portion of the Hα line reached 50% of its peak value, and the corresponding position on the descending wing. The uncertainty in these wavelengths is ±2 Å, based on the repeatability of the number for each of the three or four spectra obtained on a given observation date.

On each of the six epochs described above, SN 2002hh was also observed in imaging mode with GMOS-N in the g', r', and i' bands. Exposure times were 60 s. The instrumental g', r', and i' magnitudes were converted to standard Johnson-Cousins R and I magnitudes using the photometric sequence from Table 1 of Pozzo et al. (2006). The standard stars that fell on the central chip of GMOS-N (the chip on which SN 2002hh was imaged) were used for this purpose.

A simultaneous least-squares solution involving common color terms but floating zero points for each night was used to transform the instrumental g', r', and i' ALLFRAME magnitudes to the V, R, and I sequence from Pozzo et al. (2006). The uncertainties in the V, R, and I transformations thus derived were 0.033, 0.014, and 0.010 mag, respectively. All transformations were confirmed to be linear, with the bulk of the higher uncertainty in the V transformation being due to the residuals of two stars of intermediate color, 13 and 14.

The transformations were then inverted to allow the estimation of the V, R, and I magnitudes from the instrumental g', r', and i' magnitudes. The derived transformations are

$$V = 0.7111g' - 0.0829r' + 0.3728i' + \text{zero point},$$

$$R = 0.0000g' + 0.7540r + 0.2264i' + \text{zero point},$$

$$I = 0.0000g' - 0.2786r' + 1.2531i' + \text{zero point}.$$

We were not able to provide V magnitudes for SN 2002hh because the supernova light was too confused with other nearby sources of similar brightness in every image taken in the g' bandpass. On 2006 July 18, SN 2002hh could not be measured accurately in the r'-band image for similar reasons, but if it is assumed that the color of the SN was similar to that of the Pozzo standard number 5, then $I = 19.60$ mag. (The small coefficient of the r' magnitude in the transformation to I makes the transformation reasonably robust to reasonable values for the color.) The measured R and I magnitudes of SN 2002hh for the six epochs are listed in Table 1 and plotted in Figure 2.

700 days are almost identical and show no significant profile evolution with time as seen in Figure 1. We find that the extrema of the Hα wings indicate an expansion velocity between 11,000 and 13,000 km s^{-1} for our observed epochs, where the uncertainty is dominated by the assumption of the continuum locations. The FWHM of all six epochs are ∼5600 km s^{-1}. This is significantly broader than the profiles from days 162 to 397, which have FWHM of ∼4500 km s^{-1} (Pozzo et al. 2006). No spectra were taken between days 44 and 162, but the day 44 spectrum was in the middle of the time period of the light pulse, which we believe is being scattered toward us in the echo. These late-time Hα profiles, broader than the previously observed epoch (day 397), support the interpretation that the late-time spectrum is dominated by the echo.

To investigate the contribution from the echo, the counts from SN 2002hh in the Hα emission-line profiles were examined. In Figure 2, the peak counts in Hα in the Gemini/GMOS spectra from all six epochs are plotted together, scaled to their exposure times, along with the epochs observed by Pozzo et al. (2006). The spectra could not be fluxed, since no standards were observed, but they were acquired with the same slit and the same setup and at similar air masses during each observation. The counts should be roughly representative of the relative fluxes, taking into account the uncertainties (∼30%) introduced by differences in seeing and transparency. In particular, the lowest count rates were associated with the worst seeing, which occurred on days 710 and 1358. This comparison in Figure 2 shows that there is no evidence for significant fading of the peak flux in Hα over the period from day 661 to 1358. We also plot the evolution of SN 1987A's scaled peak Hα flux (Caldwell et al. 1993; the SUSPECT supernova spectrum database) in Figure 2. If SN 2002hh had faded in a manner similar to SN 1987A, then from day 397 (Pozzo et al. 2006) to day 1358, Hα should have faded by a factor of ∼10^4. However, SN 2002hh's Hα flux drops by only a factor of 2 from 397 to 1358. Since SN 2002hh is a Type II SN, its massive precursor star likely was located in a star formation region with significant Hα flux. We have decomposed the narrow H ii region emission lines and compared their flux to the broad SN Hα emission. On day 661, the narrow emission lines made up only 16% of the flux. So most of the flux is from the SN, which is distinguished in any case by its very broad Hα emission up to day 1358. The fact that the broad Hα emission profile can be seen and measured even at day 1358 means that we are still measuring SN 2002hh without significant contamination from other sources.

3.2. Photometry

The latest published V-band photometry of SN 2002hh, reported by Pozzo et al. (2006), was on day 269—too early to expect to see evidence of fading due to dust formation in the ejecta and also before the echo became noticeable in the optical. Pozzo et al. (2006) detected a $K - L'$ excess that developed in the photometry of SN 2002hh between days 200 and 314. This may indicate the presence of an infrared echo, presumably produced by early-time heating of the circumstellar dust by the SN. Meikle et al. (2006) found no evidence for new dust condensing in the ejecta and suggested that most of the mid-infrared flux may have come from dust in the star formation region associated with SN 2002hh's precursor. They also found that the mid-infrared flux declined by about 10% from day 590 to 994. The small declining component of the infrared flux was attributed to an infrared echo.

The brightness of the echo at optical wavelengths was highly unexpected; the late-time observed brightness of SN 2002hh in the V band was only 4 mag fainter than the light-curve peak of

$V = 17.2$ mag (Pozzo et al. 2006; B. E. K. Sugerman et al. 2007, in preparation). The photometry is also consistent with the lack of fading seen in the Hα emission shown in Figure 2. Typically, one would expect a light echo to appear fainter than the SN maximum by 8 mag or more (Patat 2005).

The fading of SN 2002hh, from its maximum brightness of $R \sim 15.5$ mag and $I \sim 14.3$ mag leveled off around $R \sim 20$ mag and $I \sim 19$ mag sometime between day 269, the last Pozzo et al. (2006) data point, and day 661, the first data point obtained here. This behavior is very different from the SN 1987A light curve that is scaled and plotted for comparison in Figure 3. If SN 2002hh had behaved like SN 1987A, it would have been about 3−4 mag fainter in the R and I bands than observed on day 661. SN 2002hh seems to have faded slowly from $I \sim 19.0$ to 19.6 mag between days 661 and 1358. By day 1358, SN 2002hh was ∼9 mag too bright at I when compared to SN 1987A.

Observations of SN 2002hh in the optical were made with the High-Resolution Camera (HRC) of the Advanced Camera for Surveys (ACS) aboard the *Hubble Space Telescope* (*HST*) on 2005 September 17, 2006 April 23, and 2006 November 18, respectively, that is, on days 1054, 1272, and 1481 after maximum. As will be fully presented in B. E. K. Sugerman et al. (2007, in preparation), these observations reveal a small but well-resolved circular scattered-light echo roughly 0.18″ in diameter at the astrometric position of the supernova. At an estimated distance of 5.9 Mpc, this implies that the scattering dust is roughly 12 lt-yr in front of the SN. The integrated fluxes in F435W, F606W, and F814W from the first epoch roughly convert to Johnson-Cousins B, V, and I magnitudes of 24.3, 21.4, and 19.5 mag, respectively (Sirianni et al. 2005). The V-band brightness decreased by only a few hundredths of a magnitude in the subsequent two epochs. These measurements are fully consistent with ours and show that SN 2002hh had still faded by only ∼4 mag at V from its maximum brightness by day 1481.

By day 661, a typical Type II-P SN with no echo will have faded ∼7.5 mag below its maximum brightness. Normally, an optically thin dust echo will grow brighter as the optical depth of the dust increases (Patat 2005). Patat's sheet model ($R = 200$, $\Delta R = 50$), assuming dust with $\tau = 0.03$, will produce an echo with a brightness ∼11.75 mag below the SN maximum, while dust with $\tau = 2.5$ will produce an echo with a brightness only ∼6.75 mag below the SN maximum. If multiple scattering is taken into account, as it must be when $\tau > 1$, then $\tau = 2.5$ will produce an echo with a brightness ∼9.25 mag below the SN maximum or 3 mag fainter than in the single-scattering model.

There has been significant discussion in the literature regarding the nature of the dust along the direct line of sight to SN 2002hh. Pozzo et al. (2006) reconsidered the extinction for SN 2002hh in some detail and concluded that a line-of-sight dust pocket containing atypically small dust grains contributed to a total $A_V = 5.3$ mag as a result of a two-component dust model ($A_V = 3.3$ mag and $R_V = 3.1$ mag plus $A_V = 1.7$ mag and $R_V = 1.1$ mag). It is, a priori, rather unlikely that there is dust in NGC 6946 with $R_V = 1.1$ mag. Another possible explanation is that there is a mismatch between the intrinsic spectral energy distribution (SED) of SN 2002hh and that of SN 1999em, which was used as a lightly reddened template. Wang (2005) alternatively suggested that light scattered from circumstellar dust near the SN will cause apparently small values of R_V. It should be noted that in Wang's model the inner radius of the shell is at 10^{16} cm, whereas Pozzo et al. (2006) suggest that dust within 10^{17} cm of the SN would be evaporated. The apparently low value for R_V could also be caused by combining dust with two different values of R_V (McGough et al.
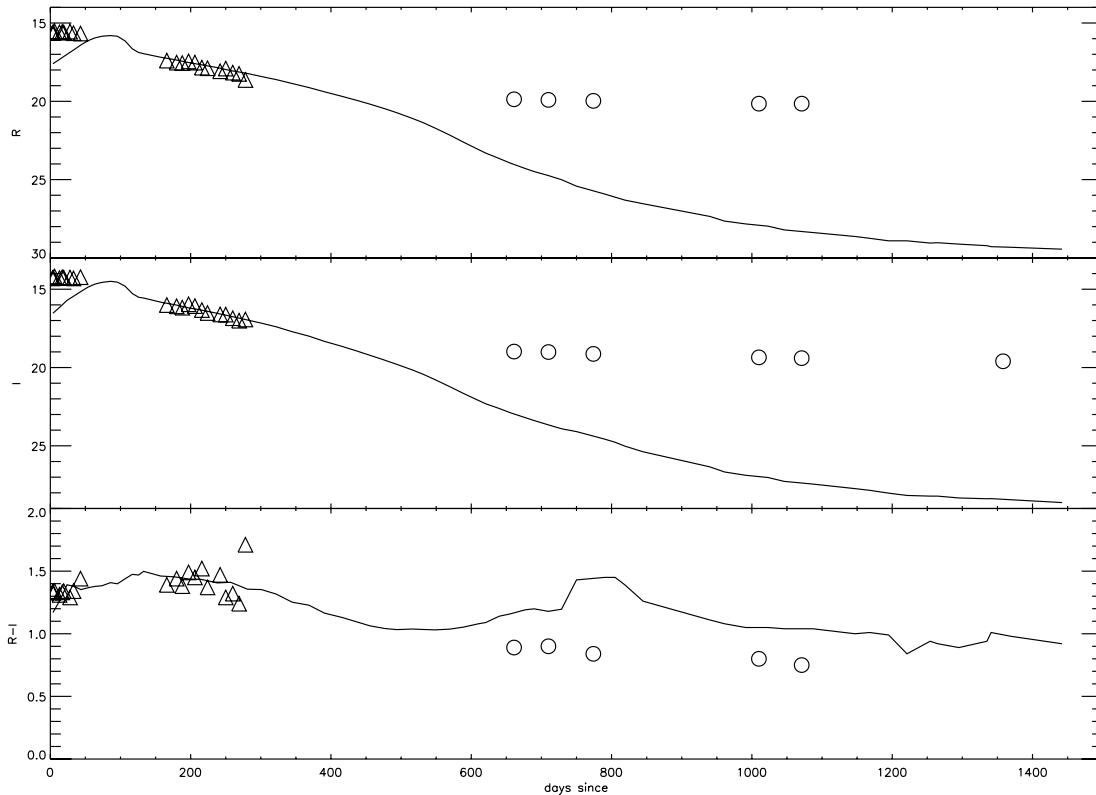
FIG. 3.—Light curve of SN 2002hh plotted against a scaled light curve from SN 1987A (Hamuy & Suntzeff 1990; Walker & Suntzeff 1991; *solid line*). The upper two panels show the observed R and I photometry, while the lower panel show the $R − I$ colors. The SN 1987A $R − I$ colors have been adjusted assuming $A_V = 5$ mag and $R_V = 3.1$. The SN 2002hh photometry is from Pozzo et al. (2006; *triangles*) and from this study (*circles*).

2005). Nevertheless, the possibility of anomalous dust must be seriously considered when modeling the echo in SN 2002hh.

In one possible scenario, the extreme brightness of the SN 2002hh echo can be explained if the optical depth is much greater ($\sim$6 mag) along the line of sight to the SN than in other nearby directions ($\lesssim$1 mag). The SN light from the echo could skirt the large dust optical depth situated directly in front of SN 2002hh and be bright by comparison (see Fig. 1 of Patat et al. 2006.) The observed light curve and spectral evolution could be accounted for by the proposed differential total absorption.

Using the time-integrated spectrum of SN 1999em, reddened, as described by Pozzo et al. (2006) to reproduce the expected light pulse from SN 2002hh, the predicted observed colors for the SN 2002hh echo are $B − V = 2.7$ mag, $V − I = 3.1$ mag, and $R − I = 1.3$ mag. These are consistent with the colors actually observed for SN 2002hh at early epochs (Pozzo et al. 2006).
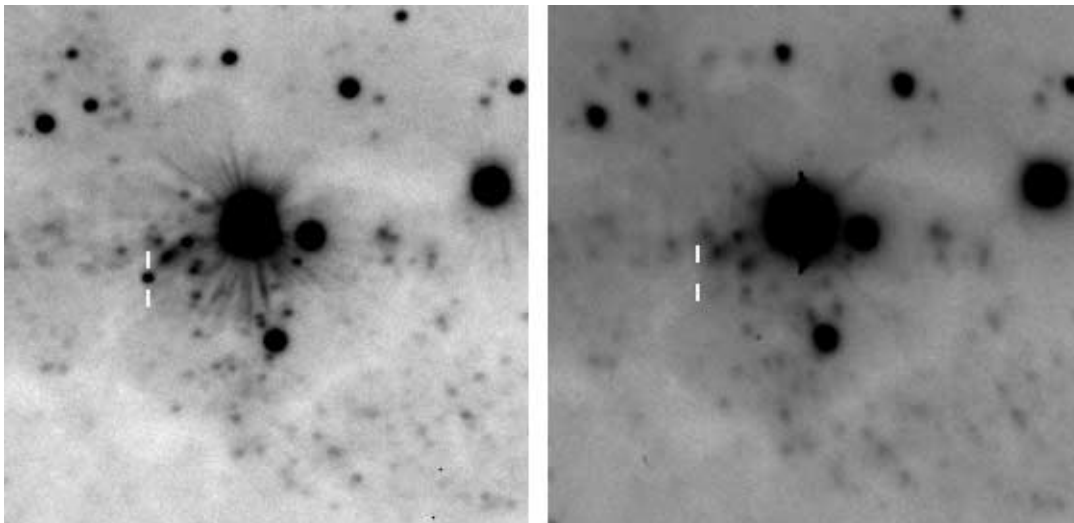

FIG. 4.—*Left*, Gemini/GMOS r' image taken on 2004 August 20; *right*, R-band image taken with the preoutburst CFHT CFH12K image on 2000 September 27. The position of SN 2002hh is marked on both images. The supernova is $R \sim 19.9$ mag on 2004 August 20, and there is an upper limit of $\sim$23.0 mag for any confusing source at the position of SN 2002hh on 2000 September 27. The field is $40'' \times 40''$. North is up, and east is to the left.
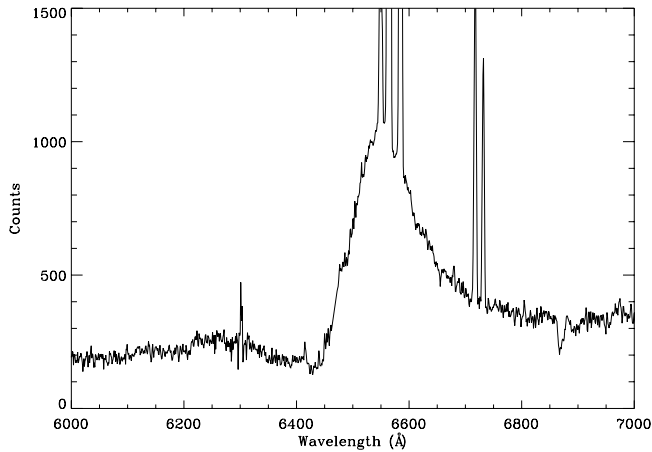
FIG. 5.—Gemini/GMOS spectrum of SN 2002hh taken on 2006 July 18. The plotted spectrum is the average of three individual spectra taken on the same date. The ratios of the peak line emission to the continuum on either side of the Hα line are very similar to those seen in the spectrum taken of SN 2002hh on day 44.

However, at late epochs (>600 days), when the light of SN 2002hh was apparently dominated by the echo light, the colors were $B - V \sim 2.6$ mag, $V - I \sim 1.8$ mag, and $R - I \sim 0.8$ mag. The $V - I$ and $R - I$ colors are significantly bluer than the observed early-time colors of SN 2002hh however, these colors are reasonably consistent with the reddened supernova light scattering from Galactic-type dust with a modest optical depth $A_V \sim 0.5$ (Sugerman 2003). In this scenario, the echo light passes through the same dust that is reddening the directly transmitted light from SN 2002hh and then passes through and is scattered off dust lying nearby, which also adds a small amount of reddening.

No line-of-sight sources that might contaminate the light curve and spectroscopy of SN 2002hh are seen in the shifted and combined sum of three 120 s R-band images (550745o, 550746o, and 550747o) taken on UT 2000 September 27 prior to outburst and shown in Figure 4. The seeing and depth of the combined image is very similar to our Gemini r' images and allows us to constrain the precursor to be fainter than $R = 23.0$ (or 7.5 mag fainter than maximum light). To further clarify the relative strength of the continuum and Hα line at late times, the unfluxed but sky-subtracted Gemini/GMOS spectrum for SN 2002hh is shown in Figure 5. The ratio of the peak Hα to blue-side continuum is 5.0, and the ratio of Hα to red-side continuum is 2.9. These numbers are very

similar to their day 44 counterparts of 4.75 and 2.7 (Pozzo et al. 2006), respectively, and fully consistent with the light echo explanation for the late-time photometry and spectroscopy.

We note that the appearance of a resolved echo clearly indicates the dominance of the echo light above the local background. In an aperture surrounding the echo in F606W, the sky value is 2.4×10^{-3} (counts s^{-1} pixel^{-1} and in F658N it is 7.4×10^{-4} counts s^{-1} pixel^{-1}. This compares to peak values of the echo of 0.73 counts s^{-1} pixel^{-1} in F606W and 9.2×10^{-2} in F658N. In other words, the peak surface brightness of the echo is 300 times brighter than the background in F606W and 125 times brighter in F658N.

While the bluer $V - I$ and $R - I$ colors are consistent with the scenario in which the echo light is significantly less reddened than the direct SN light, the $B - V$ color measured by B. E. K. Sugerman et al. (2007, in preparation) is much too red. SN 2002hh is quite faint in the B band and this measurement has a large uncertainty (>0.5 mag), so the $B - V$ color could be bluer than reported here. If the these colors are based solely on a less reddened path, then the $V - I$ and $R - I$ colors imply that the echo light passes through dust with an A_V that is 2–2.5 mag less than the direct light from the SN. This scenario would serve to explain at least some of the excess late-time brightness of the SN 2002hh echo. For the time being, SN 2002hh is unique—it appears to have the brightest echo yet observed around a SN, by a wide margin.

APPENDIX

TERTIARY STANDARDS FOR NGC 6946

The frequency with which supernovae have appeared in NGC 6946 during the last century suggests that the definition of a local set of faint tertiary standards, suitable for use on large telescopes, would be a worthwhile undertaking. In § 2, we described the determination of the transformations to the V, R, and I system of local photometric standards list by Pozzo et al. (2006) in their Table 1. We defined a set of fainter standards in the following way. Stars selected were present in our output photometry lists in all three filters (g', r', and i') at all six epochs for which the photometric instrumental uncertainties were all less than or equal to 0.03 mag. There were 110 such stars. These are labeled 101–210 so that there is no confusion with the Pozzo et al. numbering scheme.

The instrumental g', r', and i' magnitudes were transformed to the VRI system determined by Pozzo et al. (2006), and the unweighted mean and standard deviation of the six points for each star are listed in Table 2. The uncertainties do not formally include the uncertainties in the transformation—they are the standard deviations for the set of six transformed magnitudes in each filter. The locations of the standard stars are plotted in Figure 6, which is an r' image with an exposure of 60.0 s obtained with GMOS-N on 2004 August 20. North is $10°$ counterclockwise from vertical, and east is $90°$ clockwise from north. The image scale is 0.1454″ per pixel, and the height and width of the image are 149″ and 335″, respectively.

TABLE 2
TERTIARY *VRI* PHOTOMETRIC STANDARDS FOR NGC 6946

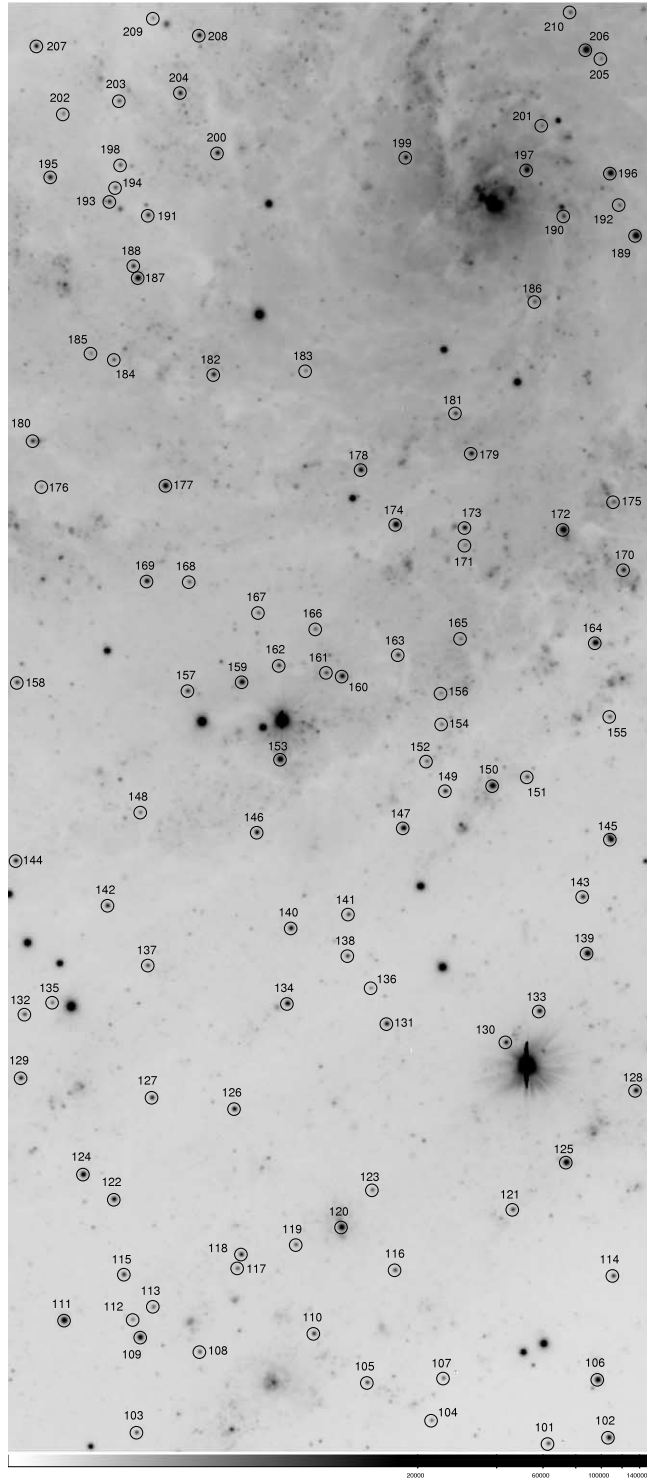| Star	V (mag)	σ_V (mag)	R (mag)	σ_R (mag)	I (mag)	σ_I (mag)	Star	V (mag)	σ_V (mag)	R (mag)	σ_R (mag)	I (mag)	σ_I (mag)
101	20.31	0.03	19.35	0.04	18.42	0.05	156	21.03	0.01	20.43	0.03	20.32	0.03
102	18.71	0.02	18.07	0.02	17.46	0.03	157	19.66	0.02	18.77	0.01	18.01	0.01
103	20.14	0.01	19.23	0.02	17.71	0.02	158	19.54	0.02	18.66	0.00	16.87	0.01
104	20.89	0.03	20.30	0.07	19.65	0.10	159	18.07	0.01	17.43	0.00	16.85	0.00
105	19.95	0.02	19.41	0.02	18.84	0.04	160	18.46	0.01	17.89	0.01	17.33	0.01
106	17.82	0.01	17.37	0.01	16.88	0.02	161	19.98	0.01	19.27	0.01	18.64	0.01
107	20.54	0.03	20.02	0.05	19.46	0.08	162	19.81	0.01	18.74	0.01	17.38	0.00
108	20.11	0.02	19.56	0.01	19.03	0.04	163	19.60	0.02	18.88	0.01	18.21	0.01
109	18.15	0.01	17.42	0.01	16.80	0.01	164	17.87	0.01	17.14	0.01	16.49	0.01
110	19.80	0.01	19.07	0.00	18.40	0.01	165	20.83	0.01	20.18	0.02	19.58	0.02
111	17.38	0.01	16.92	0.01	16.43	0.01	166	20.54	0.01	19.84	0.00	19.20	0.01
112	20.74	0.02	20.39	0.02	20.02	0.03	167	20.69	0.02	19.72	0.01	18.80	0.01
113	20.53	0.01	19.77	0.01	19.10	0.02	168	20.67	0.03	19.59	0.01	18.63	0.01
114	19.86	0.01	19.09	0.02	18.40	0.02	169	18.61	0.00	18.08	0.00	17.54	0.01
115	19.86	0.01	18.83	0.01	17.76	0.01	170	19.11	0.01	18.48	0.01	17.86	0.01
116	20.29	0.00	19.22	0.01	18.09	0.01	171	20.67	0.02	20.30	0.02	19.82	0.03
117	20.53	0.02	19.59	0.01	18.78	0.02	172	17.18	0.01	16.43	0.01	15.80	0.01
118	19.15	0.01	18.63	0.01	18.10	0.01	173	18.76	0.01	18.10	0.01	17.47	0.01
119	20.29	0.01	19.63	0.01	19.06	0.03	174	17.71	0.01	17.02	0.00	16.34	0.01
120	17.43	0.01	16.92	0.01	16.41	0.01	175	20.37	0.03	19.51	0.01	18.76	0.03
121	19.86	0.01	19.14	0.00	18.51	0.01	176	21.36	0.03	20.57	0.01	19.88	0.02
122	18.69	0.01	18.01	0.01	17.40	0.01	177	17.81	0.01	17.29	0.00	16.76	0.00
123	20.48	0.01	19.80	0.00	19.19	0.01	178	18.46	0.01	17.83	0.01	17.23	0.01
124	18.44	0.01	17.48	0.01	16.58	0.01	179	18.84	0.01	18.16	0.01	17.52	0.01
125	17.57	0.01	17.01	0.01	16.47	0.01	180	19.65	0.01	18.87	0.02	18.25	0.01
126	19.00	0.01	18.30	0.01	17.69	0.01	181	19.62	0.01	18.99	0.01	18.39	0.02
127	19.43	0.01	18.69	0.00	18.03	0.01	182	18.96	0.01	18.48	0.01	17.97	0.01
128	18.67	0.01	18.02	0.01	17.43	0.01	183	21.13	0.03	20.32	0.02	19.64	0.01
129	19.50	0.01	18.62	0.01	17.87	0.01	184	20.54	0.04	19.61	0.03	18.81	0.02
130	18.96	0.04	18.41	0.04	17.87	0.02	185	20.66	0.02	20.30	0.03	19.81	0.04
131	19.01	0.01	18.40	0.01	17.85	0.01	186	20.29	0.02	19.31	0.02	17.78	0.02
132	20.31	0.02	19.27	0.01	17.87	0.01	187	17.98	0.01	17.09	0.01	16.30	0.01
133	18.71	0.01	18.23	0.01	17.76	0.01	188	19.80	0.02	18.76	0.01	17.54	0.01
134	18.65	0.01	17.97	0.00	17.35	0.01	189	16.91	0.01	16.34	0.01	15.76	0.01
135	20.77	0.04	19.93	0.03	19.22	0.03	190	19.94	0.02	18.85	0.01	17.75	0.02
136	20.98	0.01	20.33	0.01	19.72	0.02	191	19.49	0.01	18.75	0.01	18.10	0.01
137	20.10	0.01	19.38	0.01	18.77	0.02	192	20.58	0.03	19.59	0.02	18.29	0.02
138	19.75	0.01	19.20	0.01	18.65	0.01	193	19.49	0.01	18.84	0.01	18.22	0.01
139	17.71	0.01	17.15	0.01	16.62	0.01	194	20.24	0.02	19.48	0.01	18.78	0.02
140	18.68	0.01	18.19	0.00	17.70	0.01	195	19.05	0.01	18.31	0.00	17.63	0.01
141	20.21	0.02	19.18	0.01	18.19	0.01	196	17.56	0.01	16.89	0.01	16.28	0.02
142	19.39	0.00	18.76	0.01	18.20	0.00	197	17.99	0.01	17.41	0.01	16.89	0.02
143	19.25	0.01	18.67	0.01	18.09	0.01	198	20.17	0.01	19.53	0.00	18.92	0.02
144	19.17	0.01	18.62	0.00	18.10	0.01	199	19.11	0.01	18.29	0.01	17.57	0.02
145	17.67	0.01	17.16	0.01	16.67	0.01	200	18.80	0.01	18.27	0.01	17.71	0.02
146	18.89	0.01	18.31	0.01	17.75	0.01	201	20.68	0.02	20.08	0.02	19.47	0.06
147	18.31	0.01	17.51	0.01	16.83	0.01	202	20.70	0.02	20.18	0.01	19.64	0.02
148	20.66	0.01	20.08	0.01	19.53	0.01	203	20.20	0.01	19.40	0.01	18.70	0.02
149	19.48	0.00	18.80	0.00	18.19	0.00	204	19.40	0.01	18.50	0.01	17.70	0.02
150	17.53	0.00	16.92	0.01	16.35	0.01	205	21.05	0.05	20.44	0.05	20.03	0.04
151	19.87	0.01	19.25	0.01	18.69	0.00	206	16.98	0.01	16.46	0.01	15.94	0.01
152	20.62	0.04	19.70	0.02	18.84	0.02	207	19.05	0.01	18.40	0.01	17.77	0.02
153	17.44	0.01	16.77	0.00	16.12	0.01	208	18.91	0.01	18.34	0.01	17.76	0.01
154	20.94	0.03	20.08	0.04	19.29	0.05	209	21.21	0.04	20.52	0.03	19.86	0.02
155	20.70	0.01	19.59	0.01	18.54	0.01	210	20.32	0.09	19.36	0.07	18.59	0.06

FIG. 6.—Stars included in Table 2 as tertiary standards.

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