Spectropolarimetry of the Peculiar Type Ia Supernova 2005hk

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ABSTRACT. We present Keck spectropolarimetry of the unusual Type Ia supernova (SN Ia) 2005hk several days before maximum light. An analysis of the high signal-to-noise ratio total-flux spectrum shows the object’s extreme similarity to the peculiar SN 2002cx. SN 2005hk has an optical spectrum dominated by Fe iii lines and only weak lines of intermediate-mass elements, unlike a normal SN Ia at this epoch. The photospheric velocity measured from the minima of strong absorption lines is very low for an SN Ia (∼6000 km s⁻¹), solidifying the connection to SN 2002cx. The spectrum-synthesis code SYNOW was used to identify the presence of iron-peak elements, intermediate-mass elements, and possibly unburned carbon at similar velocities in the outer ejecta of SN 2005hk. Many weak spectral features remain unidentified. The spectropolarimetry shows a low level of continuum polarization (∼0.4%) after correction for the interstellar component, and only a weak Fe iii line feature is detected. The level of continuum polarization is normal for an SN Ia, implying that the unusual features of SN 2005hk cannot be readily explained by large asymmetries.

1. INTRODUCTION

Supernovae of Type Ia (SNe Ia) represent the thermonuclear explosion of carbon-oxygen white dwarfs, probably as they approach the Chandrasekhar mass in a binary system. Despite the importance of SNe Ia as sites of iron-peak nucleosynthesis and their utility as cosmological standard candles, the actual progenitor systems and details of the explosion mechanism are still unknown; see Hillebrandt & Niemeyer (2000) for a recent review of theoretical models and problems associated with them.

What is clear from an observational point of view is that most SNe Ia fall on a sequence between the peculiar SN 1991bg–like objects at one end and the peculiar SN 1991T–like objects at the other (Branch et al. 1993). The photometric sequence between these two endpoints (Phillips 1993) is paralleled by a spectroscopic sequence (Nugent et al. 1995). SN 1991bg (Filippenko et al. 1992b) was faint and red, had a rapidly declining light curve, and showed prominent lines of Ti ii in its spectrum at maximum light, while SN 1991T (Filippenko et al. 1992a; Phillips et al. 1992) was bright and blue, had a slowly declining light curve, and showed prominent Fe iii lines in its spectrum. Nugent et al. (1995) explained the variation in normal SNe Ia between these two extrema as primarily a temperature effect, driven by the amount of radioactive 56Ni formed in the explosion. Most objects are normal, but estimates of the peculiarity rate vary from 11% to 36% (Branch et al. 1993; Li et al. 2001a), depending on the definition of “peculiar.”

In recent years, some variants from this simple prescription for SN Ia diversity have been found (Li et al. 2001b, 2003; Garavini et al. 2005), including the intriguing object SN 2002cx. Li et al. (2003) showed that SN 2002cx had Fe iii lines in its pre–maximum-light spectrum like SN 1991T, a low total luminosity comparable to SN 1991bg, the lowest photospheric velocities ever measured in an SN Ia at maximum light, an almost normal B-band light curve but a bizarre plateau-like light curve in R and I, peculiar color evolution, and unusually rapid spectral evolution. They concluded that no existing theoretical model could match the combination of features that SN 2002cx exhibited. Jha et al. (2006) showed that the peculiarities persisted to very late times. The spectrum of SN 2002cx nearly 300 days after explosion was dominated by a forest of narrow permitted Fe ii lines, each with a velocity width of ∼700 km s⁻¹. They also reported the detection of low-velocity intermediate-mass elements and possibly O i, with important consequences for SN Ia explosion models. In addition, Jha et al. (2006) presented spectra of several similar objects, including SN 2005hk, showing that SN 2002cx was not unique and therefore that a new subclass of SNe Ia had been overlooked until recently.

In this paper, we present Keck spectropolarimetric data of SN 2005hk, a peculiar SN Ia very similar to SN 2002cx, and an analysis of the total-flux spectrum. Full light curves and a spectral sequence will be presented elsewhere (M. M. Phillips et al. 2006, in preparation).

2. OBSERVATIONS

SN 2005hk in UGC 272 was discovered by J. Burket and W. Li (see Quimby et al. 2005) at an unfiltered magnitude of...
~17.5 on 2005 October 30.25 (UT dates are used throughout this paper) by the Lick Observatory Supernova Search with the 0.76 m Katzman Automatic Imaging Telescope (Li et al. 2000; Filippenko et al. 2001; Filippenko 2005). An independent discovery on 2005 October 28 was reported by the Sloan Digital Sky Survey II team, who measured a g magnitude of 18.8, 2 days after a nondetection (no upper limit was reported; Bar- entine et al. 2005). The host galaxy was observed as part of the Sloan Digital Sky Survey (SDSS J002749.73−011200.0; Adelman-McCarthy et al. 2006), and a redshift of $z = 0.0131 \pm 0.0002$ was measured. We have adopted this redshift and removed it in all plots in this paper.

Serdue et al. (2005) obtained an optical spectrum of SN 2005hk at Lick Observatory on November 2, which showed the object to be an SN Ia with prominent absorption lines of Fe iii, similar to the peculiar object SN 1991T. The low photospheric conditions and faint apparent magnitude led Jha et al. (2006) to classify SN 2005hk as a member of an emerging subclass of SN 2002cx–like SNe Ia.

We observed SN 2005hk on 2005 November 5.4 using the Low Resolution Imaging Spectrometer (LRIS; Oke et al. 1995) on the Keck I 10 m telescope in spectropolarimetry mode (LRISp). We obtained a total exposure time of 5677 s in the four wave-plate positions ($\theta = 0^\circ$, $45^\circ$, $22.5^\circ$, $67.5^\circ$). The unusual total exposure time was due to poor guiding during the first exposure of the set, which required us to abort and restart the wave-plate rotation sequence. After the end of the sequence, a short (200 s) exposure in the second wave-plate position ($\theta = 45^\circ$) was taken to complement the aborted first exposure. These two shortened exposures did not substantially change the polarimetry if they were included in the reductions, so we have used them in the analysis below.

Our instrumental setup employed both the blue and red sides of LRISp, with the D560 dichroic splitting the incoming light beam. The combination of the 600/5000 grism on the blue side and the 400/8500 grating on the red allowed us to cover a wavelength range of 3170–9240 Å. The 1.75 wide slit gave spectral resolutions of 6 and 9 Å on the blue and red halves of the spectrum, respectively. Conditions were good and the seeing was about $0.9$ during the SN 2005hk observations.

Basic two-dimensional image processing was accomplished using IRAF, along with optimal extraction and wavelength calibration of the one-dimensional spectra. Our own IDL procedures (Matheson et al. 2000) were used to flux-calibrate the spectra and correct for telluric absorption. The starting air mass was low (1.07), but it climbed to 1.2 by the end of observations. The slit was oriented at a position angle (P.A.) of $130^\circ$ to minimize contamination from the host galaxy in background regions along the slit. The parallactic angle over the course of the observations varied from 10$^\circ$ to 50$^\circ$, so differential light loss due to atmospheric dispersion (Filippenko 1982) is visible in the individual spectra of the polarimetric sequence. We assumed the first complete observation had the correct spectral shape, as it was taken at the lowest air mass and the P.A. was closest to parallactic. The spectral shape of the combined flux spectrum was corrected to that of the first observation by means of a low-order spline fit to the ratio of the two.

The spectropolarimetric reductions followed the basic procedure of Miller et al. (1988), as implemented by Leonard et al. (2001). The polarimetric standard star HD 204827 (Schmidt et al. 1992) was observed to determine the P.A. offset of the instrument from the sky reference frame. The blue (red) side flux-weighted average polarization angle over the wavelength range 3980–4920 Å (5890–7270 Å) was set to the cataloged value of 58$^\circ$2 (59$^\circ$1) for the $B$ ($R$) band. The derived offsets agreed to within $0.5$ with observations of the polarization standard HD 19820 (Schmidt et al. 1992). Two null standards, BD +32 3739 and HD 57702 (Schmidt et al. 1992; Mathewson & Ford 1970), were also observed and showed polarizations of $\pm 0.08\%$.

3. RESULTS

3.1. Total-Flux Spectrum

A by-product of the long exposure times necessary for spectropolarimetry is the high signal-to-noise ratio total-flux spectrum. In Figure 1 the spectrum of SN 2005hk is compared to early-time optical spectra of several other SNe Ia. The SN 2002cx spectrum is from 4 days before maximum light in the $B$ band (Li et al. 2003), about the same as this observation of SN 2005hk (W. Li 2006, private communication; M. M. Phillips et al. 2006, in preparation), and appears very similar.

The most prominent features in the spectra of both objects are absorptions due to Fe iii $\lambda \lambda 4404, 5129$. These Fe iii lines are one of the distinguishing characteristics of the peculiar SN 1991T–like class of objects, which are represented in Figure 1 by both the prototype, SN 1991T (Filippenko et al. 1992a), and the well-observed SN 1997br (Li et al. 1999). One distinction is that the Fe iii absorption minima in SN 2002cx and SN 2005hk are observed to fall near 4320 and 5030 Å, implying unusually low expansion velocities ($\sim 6000$ km s$^{-1}$) for these SNe Ia near maximum light (Li et al. 2003; Branch et al. 2004).

Normal SNe Ia at this epoch also have prominent spectral features due to intermediate-mass elements (Si ii, Ca ii, S ii, etc.), as marked in Figure 1 next to the spectrum of SN 1994D (Filippenko 1997). These features are much weaker in the other objects, but are clearly stronger in SN 2005hk than in SN 1991T. They are also stronger in this spectrum of SN 2005hk than in the Lick spectrum from 3 days earlier presented by Jha

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3 See http://www2.keck.hawaii.edu/instr/lris/manuals/polarization/pol_v3.ps for the online polarimeter manual by M. Cohen (1996).

4 IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.
Fig. 1.—Flux spectrum of SN 2005hk compared to the similar objects SN 2002cx (2002 May 17; Li et al. 2003), SN 1997br (1997 April 16; Li et al. 1999), and SN 1991T (1991 April 19; Filippenko et al. 1992a). Also plotted is a representative normal SN Ia, SN 1994D (1994 March 17; Filippenko 1997). Narrow nebular emission lines from a superposed H II region have been clipped from the SN 2002cx spectrum. Numbers in parentheses are dates relative to B-band maximum. The strong Fe III absorption lines are clearly more blueshifted in SN 1991T and SN 1997br than in SN 2005hk. Some strong absorption lines due to intermediate-mass elements (S II, S I, and Ca II) are marked on the SN 1994D spectrum, but they are weak or absent in the other four objects. For complete line identifications, see Fig. 2.

We used the parameterized supernova spectrum-synthesis code SYNOW (Fisher et al. 1997; Fisher 1999) to investigate the SN 2005hk spectrum more quantitatively. SYNOW uses several simplifying assumptions for computational ease, such as spherical symmetry, a blackbody-emitting photosphere, and a resonance-scattering line source function in the Sobolev approximation. Each ionic species is assumed to have an optical depth that declines exponentially with velocity above some photospheric velocity \( v_{\text{ph}} \), with an \( e \)-folding scale \( v_e \) and level populations in local thermodynamic equilibrium (LTE) at some excitation temperature \( T_{\text{exc}} \). The strength of SYNOW is that of a fast line-identification tool, rather than ejecta abundance determinations or detailed spectral modeling of the full SN spectrum.

In the top panel of Figure 2 we present a fit using seven ions that we believe are present in SN 2005hk with high confidence. The photospheric velocity used in the fit was 5000 km s\(^{-1}\), and the ions were assumed to have \( v_e = 2000 \) km s\(^{-1}\), with no maximum velocity imposed. (However, O I and Mg II are mildly detached, \( v_{\text{ph}} = 6000 \) km s\(^{-1}\).) The low-ionization species (Ca II, Mg II, S II, Si II, and O I) were fit using an excitation temperature of 10,000 K, while a higher \( T_{\text{exc}} \) of 15,000 K was used for the doubly ionized species (Fe III and Si III). The higher value of \( T_{\text{exc}} \) was necessary to match the strength of the Fe III feature near 5900 Å. This synthetic spectrum fails to fit some of the features of SN 2005hk, particularly at bluer wavelengths, so we generated a second fit with four additional ions (Ti II, Ni II, Co II, and C III), whose presence we regard as possible, but not definite. This second synthetic spectrum is shown in the bottom panel of Figure 2. The additional ions are responsible for spectral features at desirable wavelengths, as well as a decrease in the amount of near-ultraviolet (UV) flux, as discussed below. A list of reference lines used in the fit and their optical depth can be found in Table 1.

Branch et al. (2004) presented a SYNOW analysis of the SN 2002cx spectra. Of most relevance to us as a basis for comparison is the earliest spectrum they analyzed, from 1 day before maximum light. The best fit for SN 2002cx has \( v_{\text{ph}} = \)
Fig. 2.—SYNOW fits (dashed lines) to the flux spectrum of SN 2005hk (solid line). The fit presented in the top panel has seven ions we believe are present with high confidence. The fit shown in the bottom panel is the same as that in the top, but with four additional species whose presence is less certain (Co ii, Ni ii, Ti ii, and C iii). The flux scale is linear and approximates $f_n$ with an arbitrary tilt applied to better show spectral features, and the wavelength scale is logarithmic to better show relative velocity widths of spectral features. The primary species responsible for spectral features are marked. See the text and Table 1 for SYNOW fit parameters.

7000 km s$^{-1}$ and $v_p = 1000$ km s$^{-1}$. While the derived parameters imply a somewhat higher photospheric velocity in SN 2002cx, $v_p$ and $v_e$ are covariant and the two spectra show very similar absorption minima, except that in direct comparison it is evident that the minimum of the Si ii $\lambda 6355$ line is at a lower velocity in SN 2005hk. The SN 2002cx SYNOW fit used six species (Si ii, Si iii, S ii, Ca ii, Ti ii, and Fe iii), all of which are present in our SN 2005hk fit. The presence of Ti ii is not certain in either fit, but Ti ii $\lambda 3760$ matches the absorption seen near 3680 Å in both objects. Branch et al. (2004) observed that this SN 2002cx fit could provide an adequate model for the SN 1991T–like object SN 1997br (Li et al. 1999) if the photospheric velocity were increased, indicating the kinship between these two classes of supernovae.

The SN 2005hk fit has five species not used for SN 2002cx. Two of the ions, O i and Mg ii, have their strongest effects on the spectrum between 7500 and 9500 Å, so they could not have been detected at early times in SN 2002cx because the available spectra do not extend as far to the infrared (IR). The Mg ii $\lambda 4481$ line also makes a contribution in the blue, but it could have been overlooked in SN 2002cx. We also note that the Mg ii and O i lines in the red part of the spectrum are stronger than the neighboring Ca IR triplet, which is opposite of most SNe Ia (Filippenko 1997). By comparison, the early spectra of SN 1991T are rather featureless at these wavelengths. Oxygen and magnesium are both products of incomplete carbon burning, so their presence could be a diagnostic of the explosion process. We cannot be certain that the difference here between SN 2005hk and SN 1991T is solely due to differing composition as opposed to greater velocity smearing or higher temperatures and ionization levels, but more detailed study is warranted.

In addition, Ni ii and Co ii are used in the second SYNOW fit shown in Figure 2, but were not used in the SN 2002cx fit. Their presence helps to fit features in the UV that were not included in the spectral range of the early SN 2002cx spectra. In particular, the flux minimum near 3300 Å is rather interesting. SN 1991T showed a deep absorption trough near 3200 Å that was interpreted by Filippenko et al. (1992a) to be the signature of Co ii and hence of complete silicon burning in the outer envelope of that object. Jeffery et al. (1992) showed that while iron-peak elements are responsible for the UV opacity in SNe Ia, an atmosphere consisting solely of iron would have a flux peak here, while nickel and cobalt produce a minimum. The more detailed models of Mazzali et al. (1995) confirmed and extended this result. By varying the composition of the atmosphere, they found that deflagration products (taken from the popular W7 model of Nomoto et al. [1984]) were inadequate to fit the depth of this feature in SN 1991T at early times and that a substantial amount of $^{56}$Ni and its decay products was necessary. SYNOW is the wrong tool to use to determine abundances in SN 2005hk, but the identification of Ni ii and Co ii in this spectrum is suggestive of the presence of completely burned material in the outer layers of SN 2005hk.

The presence or absence of carbon in the spectrum is par-

| Parameter | C iii | O i | Mg ii | Si ii | Si iii | S ii | Ca ii | Ti ii | Fe iii | Co ii | Ni ii |
|-----------|-------|-----|-------|-------|--------|------|-------|-------|--------|-------|-------|
| $\lambda_{\text{cen}}$ (Å) | 4647  | 7773 | 4481  | 6347  | 4553   | 5454 | 3934  | 4550  | 4420   | 4161  | 4067  |
| $\tau$     | 0.3   | 0.08 | 0.35  | 0.2   | 0.25   | 0.8  | 0.04  | 0.7   | 0.2    | 0.1   |
particularly interesting because of the implications for modeling the explosion of SN 2005hk. Some three-dimensional simulations of SN Ia deflagrations have shown that a significant amount (~40%) of the carbon and oxygen remains after explosion (Travaglio et al. 2004). One potential explanation for both the low luminosities and low expansion velocities of SNe 2002cx and 2005hk is that the explosions were very inefficient and an anomalously large amount of fuel was left unburned. At the conditions expected in an early-time SN Ia atmosphere, C \( \alpha \) through C \( \beta \) are the relevant ionization stages of carbon (Hatano et al. 1999). Features attributed to C \( \alpha \) \( \lambda 6580 \) and C \( \alpha \) \( \lambda 7235 \) have been identified in the premaximum spectra of several normal SNe Ia (e.g., SN 1998aq: Branch et al. 2003), and C \( \alpha \) has been identified in the near-IR spectra of the peculiar low-luminosity SN 1999by (Höflich et al. 2002), although Marion et al. (2006) placed strict upper limits on the presence of C \( \alpha \) in the premaximum near-IR spectra of three normal SNe Ia. Unfortunately, our spectra do not extend far enough to the near-IR to test for the presence of C \( \alpha \) lines.

In the SYNOW fit presented in the bottom panel of Figure 2, we have included C \( \beta \) because an absorption near 4564 \( \AA \) is consistent with the strongest optical line of C \( \beta \), the triplet at \( \lambda 4647 \), blueshifted by the photospheric velocity. A similar feature was tentatively identified as C \( \beta \) in an early spectrum of SN 1999aa by Garavini et al. (2004). We regard this detection as possible because we cannot claim an identification based on a single spectral feature to be unambiguous, especially given the many as-yet-unidentified lines. The SYNOW fit shown in Figure 2 does show an additional C \( \beta \) feature just outside of our wavelength range at 9300 \( \AA \), which might be observable in other spectra or other SN 2002cx–like objects.

SN 2005hk has a weak emission feature at 7250 \( \AA \) with a corresponding P Cygni absorption at 7100 \( \AA \) that seems promising for C \( \beta \) \( \lambda 7235 \), but attempts to fit it using SYNOW failed. The SYNOW fits to \( \lambda 7235 \) overpredict absorption due to \( \lambda 6580 \). The observed spectrum does have an absorption feature at the appropriate wavelength, but it is much too weak to match the model. LTE models generically predict that \( \lambda 6580 \) should be stronger than \( \lambda 7235 \) because the lower levels of \( \lambda 7235 \) are the upper levels for \( \lambda 6580 \). Likewise, the synthetic spectra with C \( \alpha \) predict an absorption due to the \( \lambda 4745 \) multiplet that falls on an observed emission feature at 4662 \( \AA \). The two longer wavelength features are either not due to C \( \beta \) or they are far out of LTE, but in any case we cannot identify C \( \beta \) with certainty. Jeffery et al. (1992) encountered similar difficulties with the identification of C \( \beta \) in the early spectra of the more normal SN Ia 1990N (but see Mazzali 2001). The wavelength coincidence of features in the observed spectrum with the strongest expected lines of C \( \beta \) and C \( \beta \) is suggestive, but we cannot claim a firm detection of any form of carbon at this time.

One last unusual aspect of the SN 2005hk spectrum is the presence of many low-amplitude, high-frequency spectral features, particularly at wavelengths less than ~6000 \( \AA \). See Figure 3 for a closer look at some of these features, which have amplitudes of a few percent of the continuum over scales of 20–30 \( \AA \). Despite the 11 species present in the synthetic spectrum, it does not reproduce this small-scale structure. Branch et al. (2004) noted the existence of many weak features in the premaximum spectra of SN 2002cx. They were also unable to fit these features with SYNOW and speculated that either non-LTE level populations enhanced otherwise weak lines or clumpy velocity structure in the ejecta might be responsible. The SN 2005hk spectrum shows many of the same features, plus others visible due to its higher signal-to-noise ratio, making clumps at SN 2002cx–specific velocities seem less likely. In addition, if the ejecta were strongly clumped, we might expect to see some polarimetric signature, as in SN 2004dt (Wang et al. 2004; see below). We do not at this time have solid identifications for these features, but their confinement to wavelengths blueward of 6000 \( \AA \) suggests an origin in iron-peak elements. It is conceivable that many of them are also present in other SNe Ia, but are blended together in objects with higher expansion velocities.

3.2. Spectropolarimetry

3.2.1. Correction for ISP

Before analyzing the polarimetry, we must correct the observations for the effects of interstellar polarization (ISP), both in our own Galaxy and in UGC 272. The expected Galactic contribution to the ISP is low, as the Galactic latitude is high (\( \sim 63^\circ 5 \)) and the dust maps of Schlegel et al. (1998) predict a Galactic reddening, \( E(B - V) \), of only 0.023 mag. The polarization efficiency \( \rho_{\text{MAX}}/E(B - V) \) of Galactic dust has been found to be typically 3% mag\(^{-1}\), with a maximum value of 9% mag\(^{-1}\) (Serkowski et al. 1975). We observed two stars, HD
2158 and HD 2636, to act as probes of the actual Galactic ISP. Following the prescription of Tran (1995), both stars are within 0.6 of SN 2005hk and have spectroscopic parallaxes that place them more than 150 pc above the Galactic plane and thus sample almost all of the Galactic dust column along that line of sight. According to the discussion above, we expect a polarization of about 0.07%, with a maximum of 0.2%. The actual debiased, flux-weighted V-band polarizations we measure for HD 2158 and HD 2636 are 0.14% at $\theta = 131^\circ \pm 2^\circ$ and 0.25% at $\theta = 130^\circ \pm 1^\circ$, respectively.

Lacking a reason to prefer one star over the other, we averaged the two together to form our estimate of the Galactic contribution to the ISP, and smoothed versions of $q$ and $u$ were subtracted from the observations of the supernova. This non-parametric procedure was followed because at this low polarization level we must allow for the potential effects of instrumental polarization that might cause the polarization to not follow the standard wavelength dependence of Serkowski et al. (1975). The null standards, as noted above, had measured polarizations below 0.08%, but we have seen instrumental polarization artifacts at the 0.1% level with LRISp in the past, particularly on the blue side of the spectrograph (Leonard et al. 2002). The probe stars were observed immediately after SN 2005hk and with the slit at the same position angle, and thus should have similar amounts of instrumental polarization, if any. Any uncertainties in the removal of Galactic ISP are folded into the estimation of the host-galaxy contribution to ISP below.

It is instructive at this point to examine the location of the SN 2005hk spectropolarimetric data points in the $q$-$u$ plane, as shown in Figure 4. The data have been binned up to 100 Å per point for clarity, and noisy data at the ends of the spectrum are not plotted in this figure. The first important fact is that the overall polarization is low, less than 0.5%. The second is that the points do not lie randomly in the plane. The distribution of points is elongated in a direction that does not intersect or point to the origin. This clearly means that host ISP cannot be the sole source of polarization in SN 2005hk (Howell et al. 2001; Leonard et al. 2002). The effect of vector subtraction of a small value of ISP is similar to changing the origin of the $q$-$u$ plane, as the wavelength dependence of ISP is not strong (Serkowski et al. 1975). Furthermore, the data points at shorter wavelengths are systematically located below those at longer ones, indicating a gradient in polarization percentage in this object.

The contribution of dust in the host galaxy of SN 2005hk, UGC 272, to the total ISP is harder to determine than that of our Galaxy. The magnitude of the expected polarization can be estimated as above from the reddening, and the reddening in turn can be estimated from the interstellar Na I D $\lambda\lambda$5890, 5896 absorption lines. Absorption due to Na I D can be seen in Figure 3 at the redshift of UGC 272, with an equivalent width (EW) of $\sim$0.35 Å. Barbon et al. (1990) found a crude relationship between the reddening and the total equivalent width of Na I D absorption, $E(B-V) = 0.25$ mag Å$^{-1}$ $\times$ EW(Na I D). This, combined with the Serkowski et al. (1975) relationship for polarization efficiency, yields an estimate for the typical expected host ISP of 0.26%.

Munari & Zwitter (1997) have also derived a relationship for the reddening as a function of the EW of the D1 component of Na I absorption, but the two components of the host Na I D absorption are not resolved in our spectrum. The sight lines in the Munari & Zwitter (1997) study showed a variation in the ratio of EWs for Na I D1 : D2 of 1.1 : 1 to 2 : 1. Using these values as a bracket for the true value, the range of expected polarizations is 0.18%–0.24% for the Munari & Zwitter (1997) relationship, consistent with that predicted using the Barbon et al. (1990) relationship. The dotted circle shown in Figure 4 has a radius of 0.26% to show the magnitude of the expected host ISP relative to the data, although dust with maximal polarization efficiency could show 3 times as much polarization.

The Na I D methods described above can only estimate the
magnitude of host ISP, but not the direction. Fortunately, we can use the SN 2005hk polarimetry itself to estimate the host ISP. The optical spectrum of an SN Ia at blue wavelengths is expected to have almost no continuum polarization on theoretical grounds. Opacity due to many overlapping spectral features from iron-peak elements should act to depolarize the continuum, even if the continuum is intrinsically polarized by electron scattering in an aspherical atmosphere (Howell et al. 2001). Different authors in the literature have chosen different methods to take advantage of this assumption. Howell et al. (2001) used an ISP that made the polarization at the (arbitrary) blue end of their spectra almost zero. Wang et al. (2004) and Leonard et al. (2005) used the polarization at specific wavelengths of blue (λ < 5000 Å) emission features to define an ISP under the assumption that the observed polarization of these emission features is entirely due to ISP. We adopt a spectral window of 4000–4200 Å in the SN rest frame to measure our host ISP. The exact endpoints of this window are arbitrary, but this region was chosen to avoid the strong Ca II and Fe III absorption lines at nearby wavelengths that could potentially show polarization features. Our measured value for (qISP, uISP) of (0.009%, −0.272%) has a formal uncertainty of 0.018% in each Stokes parameter. This point is marked by a square in Figure 4 and is consistent with our expectations from the reddening arguments above. We have adopted a Serkowski et al. (1975) law with Rv = 3.1 to subtract this ISP on the assumption that dust in UGC 272 resembles Galactic dust.

As an aside, we note that it is possible to use these polarization measurements as a constraint on the reddening to SN 2005hk. One possible explanation for the low apparent luminosity of SN 2002cx–like objects is extinction, although this is hard to reconcile with the relatively blue early-time B − V color of SN 2002cx (Li et al. 2003). We have adopted a host ISP of 0.272%, which for standard dust polarization efficiencies corresponds to E(B − V) = 0.091 mag. If this is combined with the Galactic contribution and an Rv of 3.1 is adopted, then we estimate a total extinction of Av = 0.35 mag, not nearly enough to conclude SN 2005hk was an SN Ia of intrinsically normal luminosity (M. M. Phillips et al. 2006, in preparation).

3.2.2. SN 2005hk Polarization

The continuum polarization of SNe Ia can be understood as the result of electron scattering in an aspherical supernova atmosphere (Höflich 1991; Jeffery 1991). If the projection of the supernova on the sky were circularly symmetric, the local polarization vectors would cancel each other when averaged over the unresolved object and no polarization would be measured. Therefore, the continuum polarization level represents a meaningful measurement of the asphericity of the supernova. A number of authors have used the spectral region near 7000 Å to define a continuum region in SN 2005hk. The wavelengths were chosen to avoid the O I λ7774 absorption trough. We measure Stokes parameters of (0.124%, 0.088%) for this region prior to ISP subtraction and mark this point with a diamond in Figure 4. After subtraction of our chosen ISP, this continuum region has a polarization angle of 35° at a level of 0.36%, an entirely typical value for a normal SN Ia, as discussed below.

The one-dimensional presentation of spectropolarimetric data is problematic because of the inherent two-dimensional nature of the measured Stokes parameters. In addition, at low polarizations the formal polarization [P = (q2 + u2)1/2] is statistically biased. One solution is to rotate the q−u coordinate system by a convenient amount to new, rotated Stokes parameters (RSP) chosen to align one Stokes parameter (called qRSP here) with the axis of the system. In this new coordinate system, qRSP is an estimator of the total amount of polarization aligned with the axis of symmetry and uRSP can show deviations from a single axis of symmetry in the system.

For SN 2005hk, we have chosen to rotate the Stokes parameters by 35° to align qRSP with our chosen red continuum window of 7000–7500 Å. These new rotated Stokes parameters are presented in Figure 5 and show a continuum polarization rising from zero near 4000 Å (by construction for this choice of ISP) to ~0.4% at 9000 Å. The flatness of the θ-curve and the lack of significant features in uRSP show that a single axis of symmetry dominates the continuum polarization. Note that at very low polarization levels, such as seen at wavelengths less than 5000 Å in our data, the angle of polarization becomes ill-defined. No strong line features are seen in the polarimetry, but there does appear to be a weak polarization modulation at the Fe III λ5129 line. A 0.2% depression in qRSP indicates some depolarization, and a smaller feature in uRSP may indicate a rotation of the axis of symmetry. Other, smaller polarimetric features may also be present, but we caution against overinterpretation of weak (<0.1%) spectropolarimetric features.

4. DISCUSSION

Early attempts to measure broadband polarization of SNe Ia were unsuccessful, both due to the low intrinsic polarization levels and the difficulty of disentangling the effects of ISP, so intrinsic polarization remained undetected until SN 1996X showed marginal evidence at the ~0.3% level (Wang et al. 1997). Since then, intrinsic polarization has been detected in a number of SNe Ia, both in the continuum and in line features (Howell et al. 2001; Kasen et al. 2003; Wang et al. 2003, 2004; Leonard et al. 2005).

There are no published spectropolarimetric data for SN 1991T–like or SN 2002cx–like objects to act as a basis for comparison with SN 2005hk, but there are a few relevant measurements. SN 2004by had an early-time spectrum that showed prominent Fe III lines like SN 1991T (Foley et al. 2004), and Pereyra & Magalhães (2005) obtained a single epoch of R-
band imaging polarimetry 2 weeks after maximum light. They found a polarization of 0.11\% ± 0.02\%, consistent with the polarization of the foreground stars in their field and therefore with low intrinsic supernova polarization. Leonard et al. (2000) reported on maximum-light spectropolarimetry of the unique SN Ia 2000cx, which resembled the SN 1991T–like class of objects (Li et al. 2001b). They found a continuum polarization of ~0.5\%, with a 0.3\% modulation across the Si ii line, but most of the continuum polarization may be due to ISP (D. Leonard 2006, private communication). SNe Ia with normal spectra and luminosities have shown continuum polarizations at the level of ~0.3\% (Wang et al. 1997, 2003; Leonard et al. 2005). Two subluminous SNe Ia, SN 1997dt and SN 1999by (which resembled SN 1991bg), have shown somewhat higher continuum polarizations, up to 0.5\% and 0.8\%, respectively, with the exact values depending on assumptions about ISP and the limited wavelength range of the observations for these two objects (Howell et al. 2001; Leonard et al. 2005).

In summary, the magnitude of the continuum polarization in SN 2005hk is entirely consistent with observations of other SNe Ia. Core-collapse supernovae, by contrast, show polarizations of up to a few percent (e.g., Leonard & Filippenko 2005). Current evidence seems to indicate that the core-collapse supernova explosion mechanism is fundamentally aspherical, and objects with lower polarization levels are those with extensive hydrogen envelopes that act to damp and hide asymmetries. The low polarization of thermonuclear supernovae indicates a more nearly spherical explosion mechanism. Whatever unknown mechanisms are generating asphericities in the explosions of normal SNe Ia, such as instabilities in the growth of a deflagration front (e.g., Ghezzi et al. 2004), are probably also responsible in SN 2005hk.

The continuum polarization percentage in some other SNe Ia varies with wavelength. The most striking example is the low-luminosity SN 1999by (Bowyer et al. 2001), whose polarization rises dramatically to the red, as it does to a lesser extent in SN 2005hk. Thomson scattering is independent of wavelength, so the slope in polarization percentage is interpreted as a signature of the depolarizing effect of line opacity, which is stronger at UV and blue wavelengths than in the red (Howell et al. 2001). This result is dependent on the choice of ISP, which has been driven by the expectation of low intrinsic polarization at blue wavelengths. SN 2001el provides a note of caution, as the ISP derived from the polarization of blue emission features at early times (Kasen et al. 2003) does not agree with the polarization at late times (Wang et al. 2003) when the intrinsic polarization should be low. We do not have multiple epochs of polarimetric data on SN 2005hk, so we cannot use the late-time polarization to test our choice of ISP.

A number of SNe Ia have shown definite spectropolarimetric line features, but in SN 2005hk they are weak. The strongest line features (P ≲ 2.5\%) have been seen in those SNe Ia that show high-velocity absorption at early times in the Ca II IR triplet and the Si ii lines. Kasen et al. (2003) showed that partial obscuration of the photosphere by clumps of intermediate-mass elements at high velocity provides an adequate description of the polarimetric data for SN 2001el, perhaps due to a gravitationally confined detonation (Kasen & Plewa 2004). Wang et al. (2004) preferred to explain the strong polarization features of SN 2004dt by clumpy protrusions of silicon into an oxygen-rich layer in the outer SN atmosphere, maybe as a result of turbulent burning processes during the explosion. SN 2005hk does not show high-velocity absorptions and the Si ii and Ca II lines are weak, so these strong polarization modulations are not expected. We can at least conclude that the lack of strong polarization increases in the absorption troughs of SN 2005hk limits the presence of inhomogeneous clumps above the photosphere.
SNe Ia lacking the high-velocity material show much smaller line polarization features, usually at the same level as the continuum polarization or less (Howell et al. 2001; Leonard et al. 2005). Howell et al. (2001) showed that, in general, strong absorption lines in SNe Ia should be associated with polarization minima as most photons have been absorbed and reemitted in the line, destroying the directional information imprinted by electron scattering. The spectral features in SN 2005hk may be just too weak to leave strong polarization signatures. For example, some of the strongest polarization features have been seen in other SNe Ia in the Si ii λ6355 absorption line, but in SN 2005hk the absorption depth is only ~12% of the continuum. In the simple aspherical toy models of Leonard & Filippenko (2001), such a feature would only be expected to result in a polarization feature that was at most ~12% of the continuum polarization level. This model does not take into account optical depth effects, clumping, or multiple overlapping lines, but it may allow us to understand the lack of strong spectropolarimetric line features in SN 2005hk.

For a continuum polarization of 0.4%, this model would predict a polarization modulation in the Si ii line that is undetectable at our current signal-to-noise ratio. The strongest optical lines in SN 2005hk are the blue Fe ii lines, and we do see evidence for depolarization by 0.2% and maybe an angle rotation in λ5129. The polarization signatures in the blue may be expected to be small (in the absence of clumping) if all the weak overlapping iron-peak lines destroy polarization of the pseudocontinuum at blue wavelengths, so the additional opacity of strong lines has little additional depolarizing effect.

Although no preexisting supernova model explains all the peculiarities of SN 2002cx, one new model that does address some of the issues and makes specific polarimetric predictions for both the continuum and lines is the ejecta hole model of Kasen et al. (2004). They followed up on the simulations of Marietta et al. (2000), who determined that the donor star to the exploding white dwarf of an SN Ia could leave a noticeable imprint on the ejecta in the form of a hole. The opening angle of the hole was 30°–40° for main-sequence, subgiant, or red giant donor stars. Kasen et al. (2004) found that sight lines down the hole allow an observer to see more deeply into the ejecta. This has several effects on the observed spectrum, including increasing the prominence of higher ionization species, weakening absorption lines, and lowering the observed photospheric velocity relative to more typical sight lines. These effects seem promising for SNe 2002cx and 2005hk. Unfortunately, they also found that objects viewed down a hole would be somewhat brighter than normal. Kasen et al. avoided this difficulty by proposing that if SN 1991T–like objects are intrinsically normal SNe Ia viewed down a hole, then SN 2002cx–like objects could be the analogs of the subluminous SN 1991bg–like class of objects, but viewed down an ejecta hole. One difficulty with this scenario is that the SN 2002cx–like objects have only been seen in late-type spiral galaxies (Jha et al. 2006), while the SN 1991bg–like objects are more common in early-type galaxies (Howell 2001).

With that in mind, Kasen et al. (2004) made specific spectropolarimetric predictions for the consequences of an ejecta hole. If the system were oriented such that our line of sight were aimed straight down the hole, then the projection onto the sky would be symmetric and very little polarization should be expected. Such an exact alignment would be quite rare, and even small angular offsets from the axis of symmetry should produce measurable effects. They made a sample calculation of a polarization spectrum for a line of sight oriented 20° to the axis of their model hole (opening half-angle of 40°) and found that such an orientation gave very low continuum polarization (~0.1%, reflecting the fact that their model was symmetric apart from the hole) with strong line polarization peaks (~1% level). We measure a somewhat higher continuum polarization and no strong line features, in apparent contradiction to the expectations of this model.

5. CONCLUSIONS

We have presented single-epoch spectropolarimetry of SN 2005hk and an analysis of the high signal-to-noise ratio total-flux spectrum. The flux spectrum is very similar to that of the peculiar SN Ia 2002cx. Both supernovae resemble the class of SN 1991T–like objects near maximum light in that they show prominent lines of Fe ii and only weak lines of intermediate-mass elements such as Si ii and Ca ii that characterize the early spectra of normal SNe Ia (Filippenko 1997). In addition, SN 2005hk shows low expansion velocities of ~6000 km s⁻¹, similar to those of SN 2002cx. Li et al. (2003) found that no existing theoretical model for SNe Ia could reproduce all of the peculiarities of SN 2002cx. Observations of SN 2005hk provide additional constraints for models of this new subclass of SNe Ia.

We have presented a set of line identifications using SYNOW. Our SYNOW fit for SN 2005hk is very similar to a previous analysis of SN 2002cx (Branch et al. 2004), but with five additional ionic species. Four of these are due to our superior wavelength range and do not necessarily indicate spectral differences between the two objects. A detailed analysis of a time series of spectra could also clarify the identification of spectral features attributed to those species whose presence is less certain in our analysis of this individual spectrum. If all of our possible line identifications are correct, then we have identified the signatures of iron-peak elements, intermediate-mass elements, and maybe unburned carbon at similar velocities in the early spectra of SN 2005hk. Our SYNOW-based analysis is unsuitable for determining the actual relative abundances of these three groups of species, but a clear next step for future research is for detailed supernova spectrum synthesis codes to attempt to model the spectrum of SN 2005hk.

Of particular interest is whether normal deflagration products (e.g., Nomoto et al. 1984) can fit the SN 2005hk spectrum for
The short half-life of $^{56}\text{Ni}$ implies that nickel must have been of a detonation (Filippenko et al. 1992a; Mazzali et al. 1995). The supernova, as was interpreted in SN 1991T to be the sign of a detonation (Filippenko et al. 1992a; Mazzali et al. 1995). The short half-life of $^{56}\text{Ni}$ implies that nickel must have been present in larger quantities at earlier times for it to still be seen in the current spectrum, so the signatures of nickel should be looked for in any spectra of SN 2002cx–like objects obtained at very early epochs. A potential consequence is that radioactive material present in the outermost ejecta might not make a large contribution to the luminosity.

One of the most perplexing mysteries of SN 2002cx is how that object could have a spectrum dominated by iron at both early and late times and yet have such a low luminosity and small expansion velocities. The characteristic velocity scale (and hence kinetic energy per unit mass) of SNe Ia near maximum light ($\sim 10,000$ km s$^{-1}$) is set by the energy release of the fusion of carbon and oxygen up to iron-peak or even just intermediate-mass elements. The presence of a large fraction of unburned material that adds inertial mass to the ejecta could solve this puzzle, but evidence of this raw material in the spectra is scarce. One argument against a large amount of unburned material is the rapid spectral evolution seen originally in SN 2002cx, and confirmed in SN 2005hk by the stronger lines of intermediate-mass elements seen in this spectrum compared to the one from 3 days earlier (Jha et al. 2006). This may indicate that the outer ejecta have relatively low mass, although an analysis of the photometry and spectral evolution is needed to confirm this hypothesis.

One line of evidence in favor of unburned material is the possible presence of weak O i lines in the late-time spectra of SN 2002cx. Here we have looked for carbon in the early-time spectrum of SN 2005hk and have obtained some potential evidence for C ii. Features suggestive of C ii are also present, but we were unable to find a good fit, although more detailed handling of non-LTE effects might allow a secure identification to be made. Similar features seen in normal SNe Ia have been identified as C ii in the past (Branch et al. 2003; Garavini et al. 2004). Höflich et al. (2002) were able to show that the peculiar subluminous SN 1999by had unburned material above the photosphere at early times by detecting C i lines in the near-IR. Near-IR spectroscopy of SN 2005hk or another member of the class of SN 2002cx–like objects at early times would be very useful to see if they more closely resemble SN 1999by in this respect or the more normal SN Ia sample of Marion et al. (2006), which lacked the C i lines.

Our spectropolarimetric data for SN 2005hk are perhaps the least unusual aspect of the object. They show a low level of continuum polarization ($\sim 0.4\%$) and evidence for only weak line features. Therefore, the level of asphericity is quite normal for an SN Ia and models for the unusual aspects of the SN 2002cx–like class of objects that invoke large deviations from spherical symmetry can be rejected, such as the ejecta hole model of Kasen et al. (2004). The lack of strong line features in the spectropolarimetry may be related to the weakness of the Si ii and Ca ii lines. If this is correct, SN 1991T–like objects observed in the future may only show weak polarimetric line features, unless clumping in the ejecta is important. Lastly, a full identification of the weak spectral features might provide additional insight into the nature of SN 2005hk.

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