The Astrophysical Journal, 636:400–405, 2006 January 1

SN 2005cg: EXPLOSION PHYSICS AND CIRCUMSTELLAR INTERACTION OF A NORMAL TYPE Ia SUPERNOVA IN A LOW-LUMINOSITY HOST[1]

Robert Quimby,[2] Peter Höflich,[2,3] Sheila J. Kannappan,[2] Eli Rykoff,[4] Wiphu Rujopakarn,[4]
Carl W. Akerlof,[4] Christopher L. Gerardy,[5] and J. Craig Wheeler[2]
Received 2005 July 1; accepted 2005 September 9

ABSTRACT

We present the spectral evolution, light curve, and corresponding interpretation for the "normal-bright" Type Ia supernova 2005cg discovered by ROTSE-IIIc. The host is a low-luminosity ($M_r = -16.75$) blue galaxy with strong indications of active star formation and an environment similar to that expected for SNe Ia at high redshifts. Early-time ($t \sim -10$ days) optical spectra obtained with the HET reveal an asymmetric, triangular-shaped Si II absorption feature at about 6100 Å with a sharp transition to the continuum at a blueshift of about 24,000 km s^{-1}. By 4 days before maximum, the Si II absorption feature becomes symmetric with smoothly curved sides. Similar Si II profile evolution has previously been observed in other supernovae and is predicted by some explosion models, but its significance has not been fully recognized. Although the spectra predicted by pure deflagration and delayed detonation models are similar near maximum light, they predict qualitatively different chemical abundances in the outer layers and thus give qualitatively different spectra at the earliest phases. The Si line observed in SN 2005cg at early times requires the presence of burning products at high velocities, and the triangular shape is likely to be formed in an extended region of slowly declining Si abundance that characterizes delayed detonation models. The spectra show a high-velocity Ca II IR feature that coincides in velocity space with the Si II cutoff. This supports the interpretation that the Ca II is formed when the outer layers of the SN ejecta sweep up about 5×10^{-3} $M_\odot$ of material within the progenitor system. We compare our results with other "Branch-normal" SNe Ia with early-time spectra, namely, SN 2003du, 1999ee, and 1994D. Although the expansion velocities based on their Si II absorption minima differ, all show triangular-shaped profiles and velocity cutoffs between 23,000 and 25,000 km s^{-1}, which are consistent with the Doppler shifts of their respective high-velocity Ca II IR features. SN 1990N–like objects, however, showed distinctly different behavior, which may suggest separate progenitor subclasses.

Subject heading: supernovae: individual (SN 2005cg)

Online material: color figures

1. INTRODUCTION

Type Ia supernovae (SNe Ia) are important phenomena in shaping the metal-enrichment history of the universe, excellent tools for probing its expansion history (Riess et al. 1998; Perlmutter et al. 1999), and they provide a unique laboratory to study combustion physics, hydrodynamics, and nuclear and atomic processes. SN 2005cg can shed light on a number of questions involving the physics of supernovae and their use in cosmology. The host is a low-luminosity galaxy, raising the possibility of low metallicity for the SN progenitor, and the galaxy colors suggest a substantial population of young stars. Line profiles of Si II constrain the chemical structure of the outer layers and provide a test for nuclear-burning models.

The most favored models for SNe Ia involve a white dwarf (WD) near the Chandrasekhar mass that accretes matter from a binary companion and eventually results in a thermonuclear explosion. One of the key questions of physics is how the burning front propagates: does it remain a subsonic deflagration front or turn into a weak detonation as in the so-called delayed detonation (DD) models? A key difference between these possibilities is the velocity range of the explosion products. In deflagration models the outer layers of the envelope expand with velocities close to the sound speed (Höflich & Khokhlov 1996) and, by causality, the subsonic deflagration cannot keep up. Thus, the outer layers remain unburned C/O. In contrast, nearly the entire WD undergoes burning in DD models, at least for normal-bright SNe Ia. The structures of the classical deflagration model W7 and DD models are very similar inside the region of incomplete Si burning where the spectra at maximum light are formed, but they are very different in the outer layers responsible for line formation at very early times. For recent reviews on SNe Ia, see Branch (1998) and Höflich (2006).

High-velocity Ca II (Ca II HV) has been found to be a common feature in SNe Ia (e.g., SN 1994D: Hatano et al. 1999, Fisher 2000; SN 1999ee: Mazzali et al. 2005b; SN 2000cx: Li et al. 2001, Thomas et al. 2004; SN 2001el: Wang et al. 2003; SN 2003du: Gerardy et al. 2004). Wang et al. (2003) showed that this feature in SN 2001el was kinematically distinct from the photospheric Ca II IR triplet and suggested that it could be a consequence of nuclear burning in the WD (perhaps during the deflagration to detonation transition), which causes the ejection of a high-velocity, Ca-rich filament, or that it might be attributed to the surrounding accretion disk, which may have undergone nuclear burning to increase the Ca abundance. Gerardy et al. (2004) studied the formation of the Ca II HV feature based on detailed non–local thermodynamic equilibrium (NLTE) models that included interaction with circumstellar material (CSM). They showed that the Ca II HV feature and its evolution with time could be understood in the framework of the interaction of the ejecta with

[1] Based on observations obtained with the Hobby-Eberly Telescope, which is a joint project of the University of Texas at Austin, Pennsylvania State University, Stanford University, Ludwig-Maximilians-Universität München, and Georg-August-Universität Göttingen.
[2] Department of Astronomy, University of Texas, Austin, TX 78712.
[3] McDonald Observatory, University of Texas, Austin, TX 78712.
[4] Randall Laboratory, University of Michigan, Ann Arbor, MI 48104-1120.
[5] Astrophysics Group, Blackett Laboratory, Imperial College, London SW7 2AZ, UK.

a circumstellar shell of solar composition. They predicted a corresponding blue cutoff in the Si II absorption feature that should be visible at early times.

In this paper we discuss SN 2005cg, a normal SN Ia discovered by the wide-field Robotic Optical Transient Search Experiment-III (ROTSE-III) sky patrol search (Rykoff et al. 2005). In § 2 we give the early broadband ROTSE-IIIc light curve and spectral evolution recorded by the Hobby-Eberly Telescope (HET). We discuss constraints on explosion models from the Si II line profile in § 3 and give an interpretation of the Ca II HV feature in § 4. In § 5 we discuss properties of the host galaxy and its implications for the progenitor. In § 6 SN 2005cg is put into context with other SNe Ia. Conclusions and a discussion are presented in § 7.

2. OBSERVATIONS

SN 2005cg was discovered on UT 2005 June 1 at about 18.0 mag using the 0.45 m ROTSE-IIIc telescope at the High-Energy Stereoscopic Systems (HESS) site in Namibia (Rykoff 2005). The supernova is located at $\alpha = 21^{\rm h}10^{\rm m}50\overset{\rm s}{.}42$, $\delta = +00^\circ12'07\overset{''}{.}6$. Daily follow-up observations with ROTSE-IIIc since discovery give the unfiltered broadband light curve shown in Figure 1. We processed the data with a customized version of the DAOPHOT point-spread function (PSF) fitting package (Stetson 1987) ported to IDL by Landsman (1989). The magnitude zero point for each image was calculated from the median offset of fiducial reference stars to the Sloan Digital Sky Survey (SDSS) r-band values (Abazajian et al. 2005). To determine the date of maximum light, we fit the SN Ia R-band template of Knop et al. (2003) to our data, where the phases are relative to the B-band maximum. The best fit puts the maximum on June 13.4 with a formal error of ± 0.1 days and shows that SN 2005cg is a normal SN Ia.

We obtained a low-resolution ($R \sim 300$) optical spectrum using the Marcario Low Resolution Spectrograph (LRS; Hill et al. 1998) on the HET (Ramsey et al. 1998) on 2005 June 3, which showed SN 2005cg to be a Type Ia supernova (Quimby 2005). The effective wavelength range is 4100–7800 Å for these data and for a second HET LRS spectrum taken on 2005 June 4; at longer wavelengths order-overlap begins to contaminate the spectrum. For subsequent spectral observations we used an OG515 blocking filter, giving an effective coverage of 5150–10000 Å. We used the standard star Wolf 1346 (Massey et al. 1988; Massey & Gronwall 1990), observed with both setups on 2005 June 4, to perform relative spectrophotometric calibration and to correct for telluric absorption. The spectral evolution of SN 2005cg is presented in Figure 2.

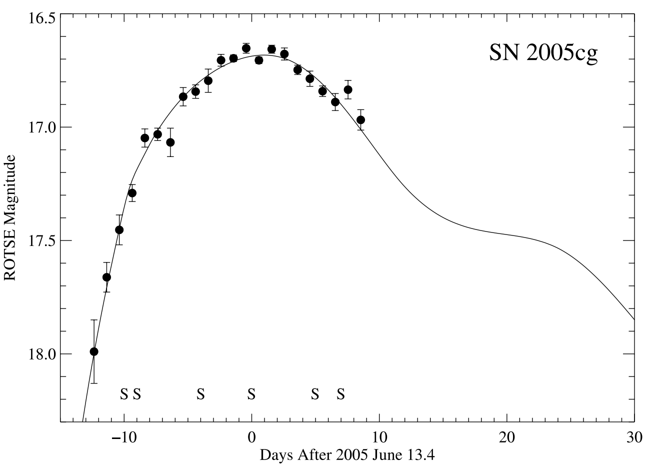

FIG. 1.—ROTSE-IIIc unfiltered light curve of SN 2005cg (magnitudes calibrated against the Sloan r band). The curve is the fitted R-band template from Knop et al. (2003) dilated in time by $(1+z)/s$, where $s = 1.07 \pm 0.02$ is the stretch parameter. Spectral epochs are marked with "S."

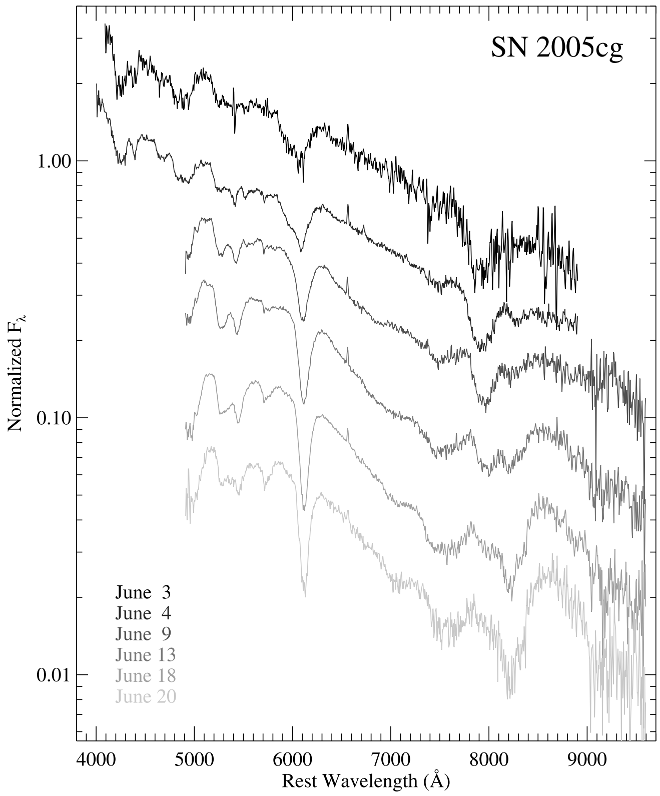

FIG. 2.—HET LRS spectral evolution of SN 2005cg from −10 to +7 days, relative to the derived June 13 maximum. The spectra were normalized between 6900 and 7100 Å and shifted by factors of 2 for clarity. [*See the electronic edition of the Journal for a color version of this figure.*]

The host galaxy of SN 2005cg was observed prior to the explosion by the SDSS and designated SDSS J211050.45+001206.7 (Abazajian et al. 2005). The host has a g-magnitude of 19.719 ± 0.021 and a Petrosian radius of $1\overset{''}{.}991$. Identifying narrow emission features in the HET spectra at 6768, 5013, and 5165 Å as Hα, Hβ, and [O III] λ5007, respectively, we derive a redshift of $z = 0.0313 \pm 0.0010$.

3. THE Si II LINE PROFILES

The first two spectra of SN 2005cg, obtained about 9 and 10 days before maximum, respectively, reveal an asymmetric triangular-shaped Si II absorption profile characterized by an approximately linear (in log flux) slope of the line wings and an extended blue wing. There is also a sharp break in slope or "cutoff" between the blue wing of the Si II line and the continuum. In subsequent spectra (4 days before maximum and later) the profile becomes more curved and symmetric. Although this time dependence has been observed previously (see § 6) and indeed is predicted by DD models (Hoflich et al. 1995), the implications have mostly been ignored. In SN 2005cg, the blue wing of the Si II in the two earliest spectra extends out to 24,000–25,000 km s^{-1}; this requires a significant Si abundance in the outermost layers. Thus, the Si abundance must not decline too rapidly with radius and hence velocity. The DD models depicted in Figure 3 naturally give an extended distribution of Si and line profiles that approximate the early observations. For

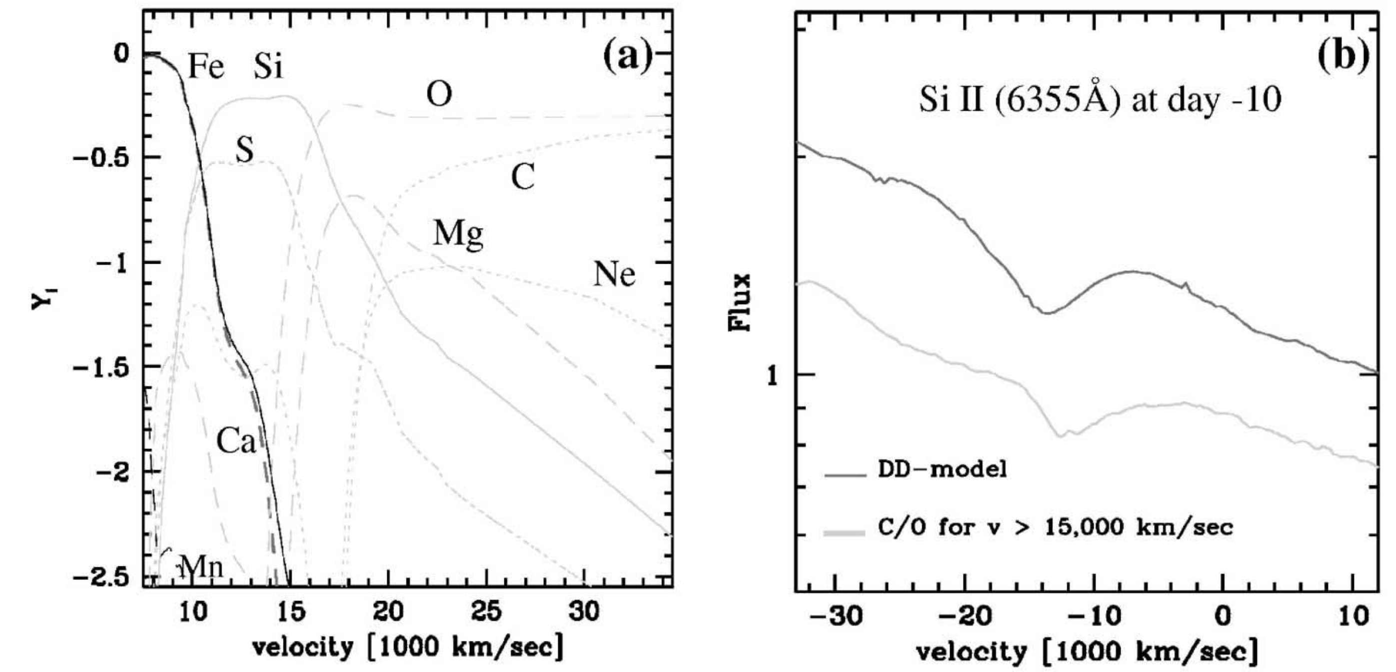

Fig. 3.—(*a*) Abundance structure of the delayed detonation model 5*p*0*z*22.25 for a normal-bright SNe Ia (Höflich et al. 2002). (*b*) Early-time model spectra of the Si II λ6355 line at about 8.5 days after the explosion. Between 11,000 and 15,000 km s^{-1}, products of explosive O burning have almost constant abundance ratios, because the isotopic distribution is given by quasi-nuclear equilibrium within the Si group. Layers with $v > 15{,}000$ km s^{-1} undergo explosive carbon burning, but about 10% and 1% of Si is freshly synthesized up to velocities of 19,000 and 28,000 km s^{-1}, respectively. In the early DD model spectra (*top line*), the Si II absorption feature shows a triangular shape with an extended blue wing and a small blend due to Fe II at about 26,000 km s^{-1}. For comparison, we also present a spectrum (*bottom line*) assuming unburned C/O matter for $v > 15{,}000$ km s^{-1}, similar to W7 (see text). [*See the electronic edition of the Journal for a color version of this figure.*]

comparison, we also give the line profile assuming that no burning took place above velocities of 15,000 km s^{-1}, corresponding to the deflagration model W7 (Nomoto et al. 1984); this profile lacks the extended blue Si wing. Outward mixing of Si has been suggested as a means to provide higher velocity Si II (Harkness 1986). In principle, mixing properties of deflagration models may be tuned to reproduce chemical profiles similar to DD models; however, the composition of high-velocity mixed matter would consist of explosive oxygen-burning products, namely Si and S, and lack explosive carbon-burning products, such as Mg. Typically, SNe Ia show strong Mg II lines in the near-IR at high velocities that require a Mg abundance of a few percent, consistent with layers undergoing explosive carbon burning (e.g., Bowers et al. 1997; Wheeler et al. 1998; Höflich et al. 2002; Marion et al. 2003).

In models, the triangular shape of the Si II profile requires the line formation to take place in a region of Si concentration that declines faster with distance than the density slope. The profile is linear in log flux if the abundance logarithm declines linearly with velocity, and its extent in velocity space is linked to the abundance if the effective optical depth is small. At very early times, when the effective optical depth is large close to the absorption trough, the linear profile would be to the blue of a "round absorption core." At later times the highest velocity material has thinned; thus, the model spectra show deeper layers of the explosion and probe a more restricted region of velocity space due to the more shallow velocity gradient. During these phases, the classic "6150" Si II profile is seen with a gentle roll-over on the blue wing as it meets with the continuum.

4. EVIDENCE FOR CSM INTERACTION

The early spectra of SN 2005cg show strong absorption around 7900 Å, which we attribute to high-velocity Ca II (8498, 8542, and 8662 Å). This feature is common to most, if not all, SNe Ia observed before maximum light in the appropriate wavelength range (Mazzali et al. 2005a). Gerardy et al. (2004) credit this absorption to a surrounding ($<6\times10^{14}$ cm) region of hydrogen-rich material, possibly from an accretion disk, Roche lobe, or common envelope, swept up by the outer layers of the SN ejecta. Based on the early light curve of SN 2003du, Gerardy et al. (2004) rule out a stellar wind as a possible origin for this hydrogen-rich material. For SN 2001el, Mattila et al. (2005) find a lack of Hα emission in the early-time spectra and thus rule out a dense continuous wind outside a few $\times 10^{15}$ cm. Both papers suggest that the circumstellar matter is located within the progenitor system.

Since burning a given mass of C/O to Si or to heavier elements releases roughly the same amount of energy, the velocity of the outer layers of the SN ejecta will remain approximately constant for a variety of explosion models provided the Chandrasekhar-mass WD is completely burned. Following Gerardy et al. (2004), we can therefore determine the mass of CSM swept into the shell simply by requiring momentum conservation. With this and a polytropic density gradient for the WD, we can then find $M_{\rm CSM}$ by measuring the shell velocity from the Ca II HV line profile. Figure 4 shows the Si II and Ca II line profiles from the June 4 spectrum of SN 2005cg plotted in velocity space relative to 6355 and 8567 Å, respectively. These wavelengths represent the average of the doublet and triplet lines, respectively, weighted by their *gf*-values. The shell velocity is $\sim$23,000 km s^{-1}, measured from the minimum of the Ca II HV, giving $(5-7)\times10^{-3}\,M_{\odot}$ of the CSM accumulated in the shell.

The Si II absorption profile can be understood in the framework of DD models (see § 3), but, neglecting CSM interaction, the wings are expected to extend to $\approx$30,000 km s^{-1} (Fig. 3). With an interacting shell, the outer SN ejecta are slowed down.

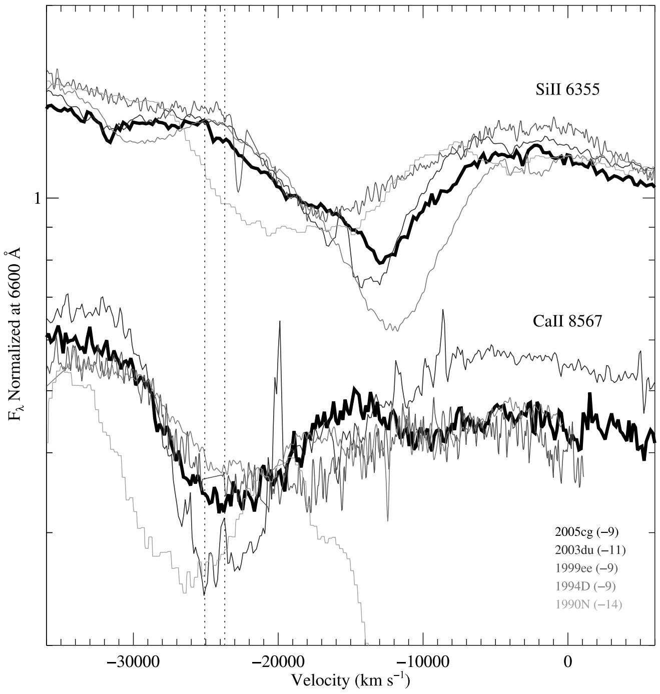

FIG. 4.—Si II and Ca II line velocities for normal-bright SNe Ia at early epochs. The vertical dotted lines mark the range of Si II cutoff velocities and are seen to align with the blue edge of the Ca II HV absorption minima, as expected for an optically thin shell. [*See the electronic edition of the Journal for a color version of this figure.*]

For SN 2005cg, the blue wing of the absorption terminates abruptly at $\sim$24,000 km s^{-1} (Fig. 4). We interpret this cutoff as a truncation in the velocity distribution created when the outer ejecta layers are decelerated as they interact with the CSM.

The changing optical depth of the thinning shell will move the apparent Ca II HV minimum to the red with time. Even so, the coincidence of the Si cutoff with the blue edge of the Ca II HV minimum seen in Figure 4 supports the interpretation that the Si cutoff is caused by the CSM shell. We note that there is a slight dip in the Si II line profile near the cutoff velocity. While this may simply be due to Fe II absorption, it is possible that this is a signature of the Si produced in the outer layers of the explosion piling up in the shell.

5. HOST GALAXY AND PROGENITOR CONSTRAINTS

The host of SN 2005cg is a low-mass dwarf galaxy in a filament or merging group environment (Fig. 5), which raises some interesting questions about SNe Ia progenitors and the properties of high-z SNe Ia. Using the calibrations of Kannappan (2004 and references therein), the host galaxy has $u - r$ color 1.27, luminosity $M_r = -16.75$, half-light radius $r_{50}^r \sim 0.6$ kpc, stellar mass $\sim 4 \times 10^8\ M_\odot$, and atomic gas–to–stellar mass ratio $\sim$1:1 (with a factor of 2–3 uncertainty on the latter two). From the Tully-Fisher relation in r, the galaxy's internal velocity is $\gtrsim$50 km s^{-1}, implying a binding energy high enough to avoid gas blow-away (Mac Low & Ferrara 1999). Nearby analogs with similar colors, masses, and environments display knotty, irregular morphology or postinteraction distortions (based on the Nearby Field Galaxy Survey [NFGS]: Jansen et al. 2000; environments computed following Grogin & Geller 1998). Among analogs with similarly compact radii, most systems have blue-centered color gradients and strong star formation [EW(Hα) $\sim$ 25–200], suggesting starburst activity. Gas metallicities are subsolar [$\log(\mathrm{O/H}) + 12 = 8.5$–$8.8$], and 21 cm data yield high gas–to–stellar mass ratios $\sim$0.5–1. We infer that the dwarf host of SN 2005cg is likely to have many similarities to high-z SN hosts: low mass, high gas content, strong star formation, low metallicity, and perhaps environmental perturbations.

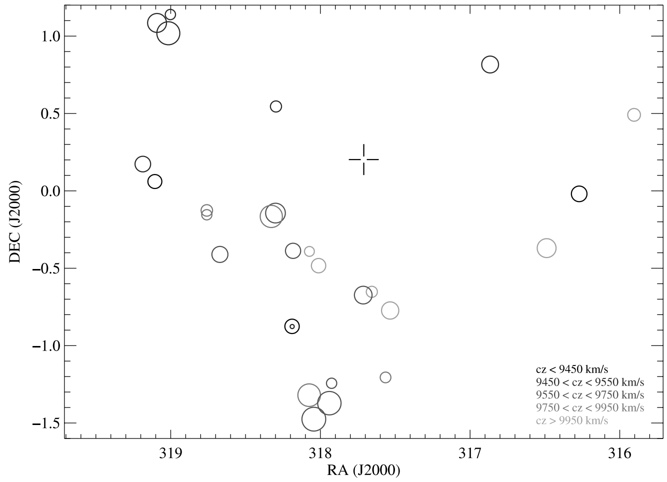

FIG. 5.—Galaxies within $\pm$1000 km s^{-1} of the SN 2005cg host galaxy (*cross*). One degree is $\sim$2.5 Mpc at this distance. No close companion with measured redshift is known, but the global environment is overdense. The elongated structure and low-velocity dispersion ($\sim$285 km s^{-1}) of the galaxy distribution imply a filament or merging group environment rather than a cluster. Visual inspection of galaxy morphologies confirms a field mix of early and late types. The size of the circles represents their relative absolute magnitudes, while the shade indicates the redshift. [*See the electronic edition of the Journal for a color version of this figure.*]

While we cannot directly constrain the age of the SN progenitor, a young progenitor is an intriguing possibility (Oemler & Tinsley 1979). The *ugriz* photometry of the host galaxy suggests at least two stellar populations, with fits to the models of Bruzual & Charlot (2003) generally favoring a 10%–20% young, solar metallicity population (25–100 Myr) mixed with a larger, intermediate-age metal-poor population (640–900 Myr). However, an underlying 2.5–5 Gyr population is not ruled out. In fact, most resolved studies of nearby dwarf galaxies have found traces of ancient stellar populations (e.g., Grebel & Gallagher 2004), consistent with a long and bursty star formation history. For the above-mentioned analogs of our SN host, nominal gas consumption timescales range from 2–13 Gyr, but continuing gas accretion is likely.

6. SN 2005cg IN CONTEXT WITH OTHER SNe Ia

A search through the SUSPECT[6] spectral archive reveals that the triangular Si II and the Ca II HV features are common to other normal SNe Ia around 10 days before maximum light. Included in Figure 4 are SN 2003du at −11 days (Anupama et al. 2005), SN 1999ee at −9 days (Hamuy et al. 2002), and SN 1994D at −9 days (Patat et al. 1996). As with SN 2005cg, all show a remarkably similar blue Si II wing up to $\sim$24,000 km s^{-1} with corresponding Ca II HV. Within our interpretation, the triangular Si II profiles suggest that all these SNe originate from similar explosion conditions. This conclusion is also supported by the recent analysis of photospheric expansion velocities ($v_{\rm ph}$) of Benetti et al. (2005). However, this does not mean that all normal-bright SNe Ia are the same. In our sample, SN 1990N at −14 days shows rather "round" Si II profiles (Leibundgut et al. 1991). Moreover, SN 1990N shows very high but rapidly declining $v_{\rm ph}$ up to a few days before maximum light, followed by

[6] See http://bruford.nhn.ou.edu/~suspect/index1.html.

an almost constant v_{ph} (Benetti et al. 2005). Both behaviors may be understood in the framework of models that produce shell-like structures as expected in mergers or pulsating DD models (Khokhlov et al. 1993; Höflich & Khokhlov 1996).

7. DISCUSSION AND CONCLUSIONS

SN 2005cg appears to be a Branch-normal SN Ia in terms of its light curve and spectra. It is therefore remarkable that this normal SN Ia may shed new light on thermonuclear explosions and SN research in general.

Rare for low-*z* SNe Ia, the host is a faint, blue galaxy with strong indications for active star formation and an environment comparable to SNe Ia at high redshifts. Because low-mass galaxies tend to be low in metallicity, SN 2005cg is a good candidate to have a low metallicity or young progenitor. As discussed in § 5, the current results are inconclusive, and we may never know whether SN 2005cg originates from a young or old population. However, after the SN fades, detailed analysis of the host galaxy should allow us to address the question of metallicity. If it is low and homogeneous over the galaxy, SN 2005cg may be the new empirical standard for a low-metallicity SNe Ia.

The second remarkable feature is the method of discovery. SN 2005cg was discovered in a blind, wide-field transient search by ROTSE-III in a galaxy that would not have been targeted in traditional low-redshift searches. Previously, there has been a difference in the way low- and high-redshift SNe are sampled: high-*z* SNe are discovered in blind searches, while low-*z* SNe are found with targeted surveys biased to the larger, more productive host galaxies. Recently, blind wide-field searches have been conducted to discover nearby SNe in a manner consistent with the high-*z* searches (cf. SNFactory in Aldering et al. 2002), netting several SNe Ia in low-luminosity hosts, including SN 1999aw with its exceptionally faint ($M_B \sim -12$) host (Strolger et al. 2002). These SNe Ia in low-luminosity hosts deserve much closer scrutiny.

SN 2005cg draws attention to the importance of line profiles as diagnostic tools. In the early spectra, the Si II λ6355 line rises slowly up from the minimum to the blue edge, where it sharply meets with the continuum between 24,000 and 25,000 km s^{-1}. This characteristic is commensurate with DD models that give a slow decrease in Si II production out to the edge of the WD; however, it is inconsistent with pure deflagration models such as W7 that do not burn the outer layers completely and hence do not predict Si II at velocities above $\sim$14,500 km s^{-1}. In principle, mixing may produce extended Si structures, but this would be inconsistent with Mg II features commonly seen in the IR spectra. SN 2005cg provides additional evidence that we need a detonation phase in SNe Ia explosions.

Another remarkable feature of SN 2005cg is the presence of a high-velocity component in Ca II. This high-velocity feature can be well understood in the framework of an interaction of the rapidly expanding ejecta with H- or He-rich surroundings within the progenitor system (Gerardy et al. 2004). As predicted, the Ca II HV coincides with the high-velocity cutoff in the Si II line. Although this observation supports the model presented by Gerardy et al. (2004), circumstellar interaction is not necessarily a unique interpretation.

Finally, we compared SN 2005cg in the context of other Branch-normal supernovae and found them strikingly homogeneous in appearance both with respect to the triangular Si II profiles and in the high-velocity cutoffs in Si, which are consistent with the Ca II HV features. Combining our sample with that of Gerardy et al. (2004), Doppler shifts indicate CSM shell masses in the range between 5×10^{-3} and 40×10^{-3} $M_{\odot}$. Alternative interpretations of the high-velocity Ca II (see § 1) seem to be less satisfactory. The long-lived nature disfavors interpreting the feature as Ca III recombining to Ca II (Höflich et al. 1998), while the ubiquity disfavors the ejection of a thin Ca-rich filament that would only be observed from restricted angles. Moreover, expanding shells are likely to wrap around narrow filaments, and thus we would not expect the relation between the Si II cutoff and Ca II HV. Nonetheless, Ca II polarization observed in SN 2001el (Wang et al. 2003; Kasen et al. 2003) requires some sort of asymmetry, and consequently the mass estimates for the shell containing the Ca II HV are upper limits, which may need to be reduced by factors of 2–3. Recently, Mazzali et al. (2005a) suggested that the presence of high-velocity Si is evidence for deflagrations, which we find unlikely: Mg II in the IR excludes mixing of a deflagration model (see § 3), and the ubiquity of Si II at high velocities disfavors line-of-sight effects. Moreover, the relation of the Si II cutoff to the Ca II HV points to a common origin.

In our sample of early-time spectra, most of the SNe Ia can be understood within the framework of the same model; however, there is a remarkable exception to the homogeneity with respect to the light curves, early-time spectra, and evolution of the velocities: SN 1990N and the similar event SN 2001el (Mattila et al. 2005). This may be regarded as a hint of distinct SNe Ia subclasses and lend support to earlier suggestions that attributed this division to different progenitors, such as pulsation-delayed detonations or mergers (Höflich & Khokhlov 1996).

We would like to thank the staff of the Hobby-Eberly Telescope and McDonald Observatory for their support, the HESS site staff, and the ROTSE collaboration. This research is supported, in part, by NASA grant NAG 5-7937 (P. H.) and NSF grants AST 03-07312 (P. H.) and AST 04-06740 (R. Q. and J. C. W.). S. J. K. is supported by an NSF Astronomy and Astrophysics Postdoctoral Fellowship, under award AST 04-01547. C. L. G. is supported through UK PPARC grant PPA/G/S/2003/00040.

REFERENCES

Abazajian, K., et al. 2005, AJ, 129, 1755
Aldering, G., et al. 2002, Proc. SPIE, 4836, 61
Anupama, G. C., Sahu, D. K., & Jose, J. 2005, A&A, 429, 667
Benetti, S., et al. 2005, ApJ, 623, 1011
Bowers, E. J. C., et al. 1997, MNRAS, 290, 663
Branch, D. 1998, ARA&A, 36, 17
Bruzual, G., & Charlot, S. 2003, MNRAS, 344, 1000
Fisher, A. K. 2000, Ph.D. thesis, Univ. Oklahoma
Gerardy, C. L., et al. 2004, ApJ, 607, 391
Grebel, E. K., & Gallagher, J. S. 2004, ApJ, 610, L89
Grogin, N. A., & Geller, M. J. 1998, ApJ, 505, 506
Hamuy, M., et al. 2002, AJ, 124, 417
Harkness, R. 1986, in IAU Colloq. 89, Radiation Hydrodynamics in Stars and Compact Objects, ed. D. Mihalas & K.-H. A. Winkler (Berlin: Springer), 166
Hatano, K., Branch, D., Fisher, A., Baron, E., & Filippenko, A. V. 1999, ApJ, 525, 881
Hill, G. J., et al. 1998, Proc. SPIE, 3355, 375
Höflich, P. 2006, Nucl. Phys. A, in press
Höflich, P., Gerardy, C. L., Fesen, R. A., & Sakai, S. 2002, ApJ, 568, 791
Höflich, P., & Khokhlov, A. 1996, ApJ, 457, 500
Hoflich, P., Khokhlov, A. M., & Wheeler, J. C. 1995, ApJ, 444, 831
Höflich, P., Wheeler, J. C., & Thielemann, F. K. 1998, ApJ, 495, 617
Jansen, R. A., Franx, M., Fabricant, D., & Caldwell, N. 2000, ApJS, 126, 271
Kannappan, S. J. 2004, ApJ, 611, L89

Kasen, D., et al. 2003, ApJ, 593, 788
Khokhlov, A., Mueller, E., & Hoeflich, P. 1993, A&A, 270, 223
Knop, R. A., et al. 2003, ApJ, 598, 102
Landsman, W. B. 1989, BAAS, 21, 784
Leibundgut, B., et al. 1991, ApJ, 371, L23
Li, W., et al. 2001, PASP, 113, 1178
Mac Low, M., & Ferrara, A. 1999, ApJ, 513, 142
Marion, G. H., Höflich, P., Vacca, W. D., & Wheeler, J. C. 2003, ApJ, 591, 316
Massey, P., & Gronwall, C. 1990, ApJ, 358, 344
Massey, P., Strobel, K., Barnes, J. V., & Anderson, E. 1988, ApJ, 328, 315
Mattila, S., Lundqvist, P., Sollerman, J., Kozma, C., Baron, E., Fransson, C., Leibundgut, B., & Nomoto, K. 2005, A&A, 443, 649
Mazzali, P. A., et al. 2005a, ApJ, 623, L37
———. 2005b, MNRAS, 357, 200
Nomoto, K., Thielemann, F.-K., & Yokoi, K. 1984, ApJ, 286, 644
Oemler, A., & Tinsley, B. M. 1979, AJ, 84, 985
Patat, F., et al. 1996, MNRAS, 278, 111
Perlmutter, S., et al. 1999, ApJ, 517, 565
Quimby, R. 2005, IAU Circ., 8537, 2
Ramsey, L. W., et al. 1998, Proc. SPIE, 3352, 34
Riess, A. G., et al. 1998, AJ, 116, 1009
Rykoff, E. 2005, IAU Circ., 8537, 2
Rykoff, E., et al. 2005, ApJ, 631, 1032
Stetson, P. B. 1987, PASP, 99, 191
Strolger, L.-G., et al. 2002, AJ, 124, 2905
Thomas, R. C., et al. 2004, ApJ, 601, 1019
Wang, L., et al. 2003, ApJ, 591, 1110
Wheeler, J. C., Höflich, P., Harkness, R. P., & Spyromilio, J. 1998, ApJ, 496, 908