SN 2003du: Signatures of the Circumstellar Environment in a Normal Type Ia Supernova?

Christopher L. Gerardy, Peter Höflich, Robert Quimby, Lifan Wang, J. Craig Wheeler, Robert A. Fesen, G. H. Marion, Ken’ichi Nomoto, and Bradley E. Schaefer

ABSTRACT

We present observations of the Type Ia supernova 2003du obtained with the Hobby∗Eberly Telescope (HET) and report the detection of an unusual, high-velocity component in the Ca II infrared triplet near 8000Å, similar to features previously observed in SN 2000cx and SN 2001el. This feature exhibits a large expansion velocity (∼18,000 km s⁻¹) which is nearly constant between −7 and +2 days relative to maximum light, and disappears shortly thereafter. Other than this feature, the spectral evolution and light curve resemble those of a normal SN Ia.

We consider a possible origin for this high-velocity Ca II line in the context of a self-consistent spherical delayed-detonation model for the supernova. We find that the Ca II feature can be caused by a dense shell formed when circumstellar material of solar abundance is overrun by the rapidly expanding outermost layers of the SN ejecta. Model calculations show that the optical and infrared spectra are remarkably unaffected by the circumstellar interaction and the resulting shell. In particular, no hydrogen lines are detectable in either absorption or emission after the phase of dynamic interaction. The only qualitatively different features in the model spectra are the strong, high velocity feature in the Ca II IR-triplet around 8,000Å, and a somewhat weaker O I feature near 7,300Å. The extent and time evolution of the Doppler shift in these features provides an estimate for the amount of accumulated matter and an indication of the mixing in the dense shell. For sufficiently large masses of circumstellar material, a cut-off of the blue wings of strong, un-blended lines (particularly the Si II feature at about 6,000Å) may also be observable.

We apply these diagnostic tools to SN 2003du and infer that about 2 × 10⁻² M⊙ of solar abundance material may have accumulated in a circumstellar shell prior to the observations. Furthermore, in this interpretation, the early light curve data imply that the circumstellar material was originally very close to the progenitor system, perhaps from an accretion disk, Roche lobe or common envelope. Because of the observed confinement of Ca II in velocity space and the lack of ongoing interaction inferred from the light curve, the matter cannot be placed in the outer layers of the exploding white dwarf star or related to a recent period of high mass loss in the progenitor system prior to the explosion. We note that the signatures of circumstellar interaction could be rather common in SNe Ia and may have eluded discovery because, historically, optical spectra did not often extend significantly beyond 7000Å.

Subject headings: supernovae - circumstellar environment - progenitor systems

1W. J. McDonald Postdoctoral Fellow, McDonald Observatory, University of Texas at Austin, Austin, TX 78712
2Department of Astronomy, University of Texas at Austin, Austin, TX 78712
3Lawrence Berkeley Laboratory 50-232, 1 Cyclotron Road, Berkeley, CA 94720
4Department of Physics & Astronomy, Dartmouth College, 6127 Wilder Laboratory, Hanover, NH 03755
5Department of Astronomy, University of Tokyo, Bunkyo-ku, Tokyo 113-0033, Japan
6Department of Physics and Astronomy, Louisiana State University, Baton Rouge, LA 70803
1. Introduction

There is general agreement that Type Ia Supernovae (SNe Ia) result from some process involving the combustion of a degenerate C/O white dwarf (WD) (Hoyle & Fowler 1960). Within this general picture, two classes of models are most likely: (1) An explosion of a C/O-WD with a mass close to the Chandrasekhar limit ($M_{\text{Ch}}$), which accretes matter through Roche-lobe overflow from an evolved companion star (Whelan & Iben 1973). In this case, the explosion is triggered by compressional heating near the WD center. Alternatively, (2) the SN could be an explosion of a rotating configuration formed from the merging of two low-mass WDs, after the loss of angular momentum due to gravitational radiation (Webbink 1984; Iben & Tutukov 1984; Paczynski 1985). Candidate progenitor systems have been observed for both scenarios: WD binary systems with the correct period to merge in a Hubble time and an appropriate total mass (Maxted, March & North 2000); and supersoft X-ray sources (Greiner, Hasinger & Kahabka 1991; Van den Heuvel et al. 1992; Rappaport et al. 1994; Kahabka & van den Heuvel 1997) showing accretion onto the WD from an evolved companion. However, there are still open questions about the details of both the merging and accretion processes (e.g., nomoto82, benz90, piersanti00, nomoto00, nomoto03).

From the observed spectral and light curve properties, the first scenario appears to be the most likely candidate for the majority of normal SNe Ia. In particular, delayed detonation (DD) models (Khokhlov 1991; Woosley & Weaver 1994; Yamaoka et al. 1992) have been found to reproduce the majority of the observed optical/infrared light curves (LC) and spectra of SNe Ia reasonably well (Höflich 1995a; Höflich & Khokhlov 1996; Fisher et al. 1998; Wheeler et al. 1998; Leutz et al. 2001; Höflich et al. 2002). In the DD scenario, a slow deflagration front turns into a detonation. We note, however, that detailed analyses of the observed spectra and light curves indicate that mergers may still contribute to the supernova population (Höflich & Khokhlov 1996; Hatano et al. 2000). For recent reviews see Branch (1999); Hillebrandt & Niemeyer (2000); Höflich et al. (2003).

In both of these scenarios, a certain amount of loosely bound material associated with the mass transfer is likely to remain in the system at the time of the explosion. In the binary mass transfer scenario, the donor star itself may be the source of such material. Based on hydrodynamic calculations, Marietta, Burrows, & Fryxell (2000) found that the SN ejecta wraps around the donor star and, depending on the donor’s evolutionary phase, may strip off up to several tenths of a solar mass of H/He rich gas. As a result, H or He might be observed with expansion velocities of a few hundred km s$^{-1}$, but to-date, no convincing evidence for this kind of stripped material has been observed.

Alternatively in the case of mergers, the exploding star is expected to be surrounded by debris from the merging process which will not undergo thermonuclear burning (e.g., benz90. Khokhlov, Müller, & Höflich (1993) showed that the interaction of the supernova with this material may lead to a shell structure in the ejecta, and the observable consequences for the SN light curve and spectra have been studied subsequently (Höflich & Khokhlov 1996). Although a few events (e.g., SN 1990N; Höflich & Khokhlov 1996) show some evidence for this kind of structure, a strong case for such a shell has yet to be found.

Indeed, a number of possible signatures of interaction with a circumstellar environment have been studied, including X-rays (Schlegel & Petre 1993; Schlegel 1995), radio (Boffi & Branch 1995) and, most often, narrow absorption and emission lines due to H I, He I, and He II lines (Chugai 1986; Livne, Tuchman, & Wheeler 1992; Branch et al. 1995). Despite these efforts, most SNe Ia show no observational evidence for any of these indicators and, in the few cases with possible detections, serious doubts remain (Cumming et al. 1996). The most comprehensive search for H I emission lines been done for SN 1994D by Cumming et al. (1996) who found an upper limit for the progenitor mass loss of $1 \times 10^{-5} M_{\odot}$.

Thus, despite significant progress in our understanding of Type Ia supernovae, we still have few observational constraints on the progenitor environment, or the type of the donor star in the accreting WD scenario, nor has there been much observed evidence for interaction of circumstellar material with the expanding supernova shell. Likewise, little is known about the variety of the progenitor systems Wheeler (1991).

However, the recent discovery of strong hydro-
gen lines in SN 2002ic (Hamuy et al. 2003) has drawn new interest in this subject, and emphasized the importance detecting circumstellar material as a tool for understanding the progenitor system. Whereas most of the optical spectrum of SN 2003ic closely resembles that of a normal SN Ia, the H lines show characteristics very similar to those seen in SNe II: namely both broad and narrow components. Significantly more than $0.1M_\odot$ of H-rich material is required to explain the features in SN 2003ic, with the H-rich gas at distances between $10^{16} - 10^{17}$ cm. This matter might be attributed to a short period of high mass loss in a binary system or during a planetary nebula phase several thousand years before the explosion (Hamuy et al. 2003; Wang et al. 2003b; Livio & Riess 2003).

In this work, we revisit the question of circumstellar interaction in SNe Ia in the context of a high-velocity component of the Ca II infrared triplet feature. A strong, high-velocity Ca II component was observed in SN 2001el, an otherwise normal SN Ia (Krisciunas et al. 2003), and also in the unusual SN 2000cx (Li et al. 2001). In SN 2001el, this high-velocity Ca II feature was well separated in velocity space from the rest of the Ca II feature, and was strongly polarized (Wang et al. 2003a). Wang et al. (2003; see also Kasen et al. 2003) suggest that this feature in SN 2001el 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. Alternatively, they suggest that it might be attributed to the surrounding accretion disk perhaps having undergone nuclear burning to increase the Ca abundance.

We note that observations of some other SNe Ia have also shown a much weaker high-velocity component of the Ca II IR triplet (e. g. SN 1994D), which may be understood as a transient ionization effect when Ca III recombines to Ca II (Höflich, Wheeler, & Thielemann 1998). However, given the steep density gradient expected in the outer regions of the SN ejecta, it would be difficult to create a high-velocity Ca II feature as strong as those seen in SN 2000cx, and SN 2001el.

Here, we present observations of the Type Ia SN 2003du which shows a strong high-velocity Ca II feature similar to those seen in SN 2000cx and SN 2001el. Through a quantitative study of the formation of this IR Ca II feature and related spectral properties, we examine a variation on the “accretion-disk” scenario of Wang et al. (2003a). In particular, we consider the case of solar abundance circumstellar material, rather than Ca-enriched gas. In § 2, we discuss the observations and data reduction. In § 3, we use detailed models for the explosion, light curves and spectra to study the signatures of the accumulation of hydrogen-rich matter by a SNe Ia. We then develop these signatures as diagnostic tools for probing the circumstellar environment of SNe Ia. In § 4, these tools are applied to the observations of SN 2003du, and we show that the spectral features are consistent with a H-rich shell formed by the interaction with matter related to the mass transfer in the progenitor system. Finally, in § 5 we discuss the results in the general context and address the limits of our study.

### 2. Observations and Data Reduction

SN 2003du was discovered in UGC 9391 by LOTSS (Schwartz & Holvorcem 2003) on 22 April 2003 (all dates are UT) at about 15.9m. It was classified as Type Ia by Kotak & Meikle (2003) on 24 April 2003 and resembled SN 2002bo about two weeks before maximum light.

We obtained low-resolution (R ≈ 300) optical spectra of SN 2003du using the Marcario Low Resolution Spectrograph (LRS) on the Hobby*Eberly Telescope (HET). For each epoch, two different setups were used giving effective wavelength ranges of 4100–7800 Å and 5151–10 000 Å. The data for each setup were reduced separately using standard IRAF routines, and then flux-matched in the overlapping region and combined to create a single 4100–10 000 Å spectrum for each night. Relative spectrophotometric calibration was accomplished by observing standards from Massey et al. (1988), Massey & Gronwall (1990), and Oke (1990). We are not able to obtain accurate absolute fluxes with LRS due to the time-variable effective aperture of the HET, and so the absolute flux levels of these spectra are only approximate.

In addition to the HET spectroscopic observations, we also imaged SN 2003du with the 0.45 m robotic ROTSE IIIb telescope (Akerlof et al. 2003) to obtain an unfiltered broad-band light-curve.
ROTSE IIIb observed SN 2003du at roughly 1 hour intervals during each night when conditions were safe to open the telescope enclosure, although some data taken through very thick cloud cover were later discarded. The data were processed using the ROTSE automated reduction pipeline software, which delivers magnitudes for every source identified, relative to the red magnitudes of USNO A2.0 stars in the field. The pipeline photometry typically show a scatter of about 0.1 – 0.2 mag for all well-detected sources. These data have been acquired during the commissioning phase of ROTSE and test images suggests that the reduced CCD frames are significantly more accurate than the results of the current ROTSE pipeline. We are currently developing a more accurate pipeline for ROTSE observations of supernovae, as well as making observations to determine the ROTSE IIIb color response and the transformations needed to compare ROTSE magnitudes to standard BVRI photometry. For this work, we simply averaged the output of the existing pipeline for each night and the resulting light curve is presented in Figure 1. The arrows indicate the timing of the HET observations, as well as the timing of one epoch, near maximum-light, of UBVRi observations obtained using the 0.8 m telescope at McDonald Observatory.

The observed spectroscopic evolution of SN 2003du is presented in Figure 2. These spectra exhibit a high-velocity component in the Ca II feature near 8000 Å (Fig. 3). The Doppler shift of this feature (≈ 18,000 km s⁻¹) remains well above the photospheric velocity (≈ 11,000 km s⁻¹) until the feature fades shortly after maximum light. Note that although the centroid of the absorption feature shifts somewhat to the red as it evolves, this is due to the blue side fading earlier than the red, rather than a shift of the entire feature. The high-velocity absorption remains constrained in velocity space, and in particular, the red edge of the absorption remains constant at about -13,000 km s⁻¹. In all other respects, the observed spectral evolution closely resembles that of a normal Type Ia supernova such as SN 1994D (Branch, Romanishin, & Baron 1996; Branch 1999) The near-maximum UBVRi colors (Table 1) of SN 2003du are also consistent with the expected colors of a normal SN Ia (Phillips et al. 1999).

To provide further constraint on the color evolution, we convolved the reduced HET spectra with the BVRI filter functions of Bessel (1990) to obtain effective photometry for each of the HET observations. Zero-points for the effective photometry were obtained by convolving the same filter functions with the synthetic spectrum of Vega presented by Castelli & Kurucz (1994). While the absolute fluxing of the HET data is poor, the relative spectrophotometry is accurate and thus the derived colors are still meaningful. (Note that for the B-band we performed the convolution over only part of the Bessel bandpass, since the data cut off below 4200 Å. For this reason, the HET (B – V) colors are somewhat less accurate than the (V – R) and (R – I) colors.) The resulting colors are presented in Table 1, along with the real UBVRi colors measured on 07 May 2003. Comparison of the HET derived colors on 06 May and 08 May with the UBVRi measurements suggest that the HET derived colors are probably accurate to about 0.1 mag. When compared to the Riess, Press, & Kirshner (1996) templates, the observed SN 2003du colors lie within the “1-σ” region for normal SNe Ia.

3. Model Calculations

To examine the effects of interaction with circumstellar material, we begin with a 1-D delayed detonation model for the supernova. The chemical and density structure of the outer regions of the SN ejecta are modified to model the hydrodynamic effect of the circumstellar interaction. The result is then input into a radiation transport code to calculate synthetic lightcurves and spectra.

3.1. Delayed-Detonation SN model

Our study is based on the delayed detonation scenario (Khokhlov 1991) because it has been found to reproduce the optical and infrared light curves and spectra of typical SNe Ia reasonably well (?, e. g.)h95,hk96,mugen97,fisher98,wheeler98,lentz01,h02. It also provides a natural explanation for the brightness decline relation (Phillips 1993; Hamuy et al. 1996a,b) as a consequence of opacity effects in combination with nearly constant explosion energies for SNe Ia (Höflich et al. 1996; Maeda et al. 2003).

Hydrodynamic explosions, light curves, and synthetic spectra are all calculated self-consistently
using only physically motivated connections between the different calculations. Given an initial structure for the progenitor and a description of the nuclear burning front, the light curves and spectra are calculated directly from the explosion model without any additional tunable parameters. This methodology forges a strong link between the physical processes being modeled and the predicted observables. As a result, comparing the model results with observations can provide a great deal of insight, at the expense of having to perform rather more difficult calculations.

For this study, a single SN model was chosen, which roughly matches the observed properties of normal Type Ia supernovae. However, no attempt has been made to fine-tune the SN model to “fit” the observations of SN 2003du. The details of the numerical methods and the resulting SN model used for these calculations are presented in Appendix A.

3.2. Circumstellar Interaction Model

We consider the case of homologously expanding SN envelope running into a stationary circumstellar medium of solar-abundance gas. We model the region of circumstellar interaction in a manner similar to Chevalier (1982) and the density profiles of the interaction region are based on his self-similar solution. The collision of the SN ejecta and environment sets up a forward- and reverse-shock structure, separated by a contact discontinuity at a distance \( R_c \). This produces a high-density region with shocked ejecta and swept up matter, subsequently referred to as the shell, and a low-density precursor region of ambient gas. The inner edge of the shell is given by the location \( R_{sh} \) of the reverse, adiabatic shock. Because the shock front is Rayleigh-Taylor unstable (Chevalier 1982; Dwarkadas & Chevalier 1998) we assume that the reverse shocked region consists of a mixture of SN and circumstellar matter.

For the calculation of synthetic spectra we assume that the circumstellar matter originates close to the supernova and has been overrun by the SN ejecta well before the observations. As a consequence, the structure of the interaction region undergoes free homologous expansion and our configuration will not exhibit emission from the forward shock. Furthermore, at the time of the observations expansion and radiative cooling have erased the thermal signature from the shock interaction itself. The temperature structure of the expanding shell is calculated by taking into account radiative processes, gamma-ray heating, and adiabatic cooling. As a consequence, the interaction will not significantly contribute to the luminosity if the interaction takes place early on, i.e. at distances small compared to the SN photosphere at the time of the observation. (As we discuss below, the light-curve of SN 2003du indeed suggests that any strong circumstellar interaction occurred before its discovery around two weeks before maximum light.)

We note that this model makes certain implicit simplifying assumptions, such as spherical symmetry, power law density profiles for the ejecta and the surrounding medium, and pure adiabatic shocks. However, the qualitative results are relatively robust. While deviations away from these assumptions will tend to change the quantitative details of the resulting shell structure somewhat, the models are sufficient for the qualitative and order-of-magnitude quantitative analysis presented here.

3.3. Results

3.3.1. General Considerations

The basic result of the interaction is the accumulation of circumstellar matter (of mass \( M_{acc} \)) in a shell (of mass \( M_{sh} \)). As the highest velocity ejecta runs into the reverse shock, it is decelerated down to the shell velocity \( v_{sh} \). Some of the basic quantities of the shell are shown in Figure 5. Both the shell velocity and the total amount of kinetic energy converted by the interaction depend on \( M_{acc} \). Typically, the shell consists of about 1/3 accumulated solar-abundance circumstellar matter and 2/3 SN ejecta with a composition depending on the shock velocity (Compare Figs. 4 & 5).

For a given SN explosion model, the relation between the shell mass and its velocity is fixed. Within the delayed-detonation scenario, the energy generation is nearly independent of changes in the explosion model because for \( M_{Ch} \) models, the mass and density structure of the SN envelope hardly changes, although the chemistry of the outer envelope is different (Höflich et al. 2002). Conversely, only part of the C/O WD is burned in a pure deflagration scenario, reducing the ki-
netic energy of the ejecta. As a consequence, we expect lower shell velocities for those models.

As example cases, we consider shells which are produced by running into (case I) a stellar wind with a velocity $v_{RSG}$, (case II) a combination of a nearby mass and a stellar wind, or (case III) a constant density environment. For the first two cases, the mass accumulated in the shell at time $t$ can be obtained by scaling the relation for a constant mass loss rate

$$M_{acc}(t) = M_{acc}(t = 0) + M_{sh}(t,v_{RSG}) \times t$$

where $v_{sh}$, $v_{RSG}$ and $M$ are the shell velocity, the wind velocity of the progenitor system and the mass loss rate, respectively. For an environment of constant particle density $N$ (case III), we have

$$M_{acc} = \frac{4\pi}{3N_{av}} \mu_e N R_c^3$$

where $\mu_e$ and $N_{av}$ are the mean molecule mass and Avogadro's number, respectively.

For this discussion, we consider H-rich shells produced by the accumulation of $M_{acc}(t = 20d) = 2, \times 10^{-2}M_\odot$. The properties of the system are $\dot{M} = 2, \times 10^{-4}M_\odot$ yr$^{-1}$ and $v_{RSG} = 10$ km s$^{-1}$ (case I), $\dot{M} = 1, \times 10^{-5}M_\odot$ yr$^{-1}$ plus an early accumulation of $1.98 \times 10^{-2}M_\odot$ (case II), and a constant particle density $N = 1.2 \times 10^6$ g cm$^{-3}$ (case III).

3.3.2. Conversion of Kinetic Energy

In the upper right of Figure 5, we plot the rate of kinetic energy conversion in the shock. Though some of this energy will go into turbulent motion, and ionization of the gas, a significant fraction will likely be emitted as X-Ray/UV/optical radiation (Fransson, Lunquist & Chevalier 1996). Thus, we expect significant modification of the light curves for case I and III, and even case II unless the wind component is very small.

For SNe Ia that exhibit essentially normal light curves (such as SN2003du), we can therefore rule out that any accumulated matter originates from mass loss over an extended period of time or from a constant density environment. In our light curve (Fig. 1), we do not see any significant additional energy input 60 days after the explosion (about 40 days after maximum) which limits $\dot{M}$ to $\leq 1, \times 10^{-5}M_\odot$ yr$^{-1}$. We note that this limit is consistent with upper limits for the mass loss in SN 1994D by Cumming et al. (1996) based on the lack of observed $H_\alpha$ emission. Moreover, late time light curves of typical SNe Ia do not show evidence for any additional energy source even after several years (7, e. g.)wells94,schmidt94.

3.3.3. Spectral Signatures

In light of this constraint, we consider shells that are formed early on in absence of continuous mass loss (case II with $\dot{M} = 0$). Such a shell might originate, for example, from an accretion disk, the Roche-lobe of a companion donor star or a common envelope of the progenitor system. To construct the density structure of the expanding shell, we assume the ejecta freely expand out to $10^{13}$ cm before running into circumstellar matter of constant density with a thickness of $R_C - R_{sh}$. To construct the shell, we assume power law densities for the outer SN ejecta ($p_{SN} \propto r^{-n}$), with $n$ given by the explosion model (close to $n \approx 7$; see Fig. 4).

Detailed spectra have been calculated for shell masses of 0, 2, and $5 \times 10^{-2}M_\odot$ for several epochs. For illustration, optical and near IR spectra are shown in Figure 6 for day 15 (about 3 days before maximum light in $V$). We chose this epoch as a reference because the high-velocity Ca II feature is well developed (the photosphere is far inside the shell region) and, moreover, the transient high-velocity feature due to the recombination of Ca III to Ca II is at its most pronounced (Höflich, Wheeler, & Thielemann 1998) which also allows us to discuss this potential complication.

Overall, the model spectra with the three different shell masses are remarkably similar, although large electron cross sections and backscattering cause some “smearing out” of the line features in the higher shell mass models. This insensitivity of the overall spectrum to the shell mass is a result of the large distance between the shell and the line forming region. Nearly all of the spectral features are formed in regions well inside the shell, and are therefore largely unaffected by the interaction.

In most optical and IR features, the main difference is the outer cutoff at the blue edge of strong lines which is caused by the deceleration of the high-velocity ejecta by the reverse shock (see Fig.
7). Still, for the most part, the shell has little effect on the spectra beyond quantitative changes at the level of the intrinsic variability in normal SNe Ia. Even shells with about $5 \times 10^{-2} M_\odot$ might elude discovery.

However, there are two features that exhibit qualitative rather than quantitative changes with increasing shell mass. In the presence of a shell, high-velocity components appear in the Ca II IR triplet at about 8000 Å and in a feature between 7300 and 7500 Å due to a blend of O I/Mg II line feature due to an O I blend (7775, 7774 & 7772 Å) between 7300 and 7400 Å for shells with $M_{\text{acc}} = 2 \times 10^{-2} M_\odot$, and $5 \times 10^{-2} M_\odot$ the high-velocity Ca II Doppler shift corresponds to about 19,000 km s$^{-1}$ and 14,000 km s$^{-1}$, respectively. Furthermore, unlike the ionization effect discussed above, the Doppler shift stays nearly constant when the mass of the shell is not significantly changing.

Note that a slight shift in the centroid of the absorption is to be expected. Since the shell is also undergoing free homologous expansion, the outer regions of the shell will undergo geometric dilution faster than the inner edge. As a result, we may expect to see the feature fade faster at the blue, high-velocity end than the red end, shifting the feature’s centroid to the red.

3.3.4. High-Velocity Ca II IR Triplet Feature

If caused by shell formed via circumstellar interaction, the high-velocity component of Ca II (combined with an accurate model for the underlying supernova) can provide a measure for the mass of the the accumulated matter $M_{\text{acc}}$ if a series of spectra are available.

First, however, we discuss a potential complication for such a measurement. As we noted in the introduction observations of some SNe Ia show a much weaker, high-velocity component of Ca II IR triplet, (e.g. SN 1994D). In such cases, the high-velocity Ca II feature can also be interpreted as a transient ionization effect as Ca III recombines to Ca II (Höflich 1995a; Höflich, Wheeler, & Thielemann 1998; Lentz et al. 2001). During this recombination phase, models for normal SNe Ia show an outer and inner region of Ca II separated by Ca III. Recombination from Ca III to Ca II occurs around maximum light and the Doppler shift of the high-velocity absorption component recedes rapidly and merges with the photospheric Ca II feature. Because of the steeply declining density gradient in the ejecta, the high-velocity component formed in this way is rather weak, only about 20% relative to the continuum in our model. These effects can be seen in the reference model without the circumstellar envelope (see Fig. 8).

In the models which include the circumstellar interaction, a rather strong high-velocity Ca II component appears, with a Doppler shift corresponding to the expansion velocity of the shell (Fig. 5) rather than the photospheric velocity. In combination with explosion models (but actually relatively model independent in a delayed-detonation scenario), this provides a good measure for the shell mass. For example, with $M_{\text{acc}} = 2 \times 10^{-2} M_\odot$, and $5 \times 10^{-2} M_\odot$ the high-velocity Ca II Doppler shift corresponds to about 19,000 km s$^{-1}$ and 14,000 km s$^{-1}$, respectively. Furthermore, unlike the ionization effect discussed above, the Doppler shift stays nearly constant when the mass of the shell is not significantly changing.

3.3.5. High-Velocity O I Feature

The other qualitative difference in the models which include interaction is the appearance of a line feature due to an O I blend (7775, 7774 & 7772 Å) between 7300 and 7400 Å for shells with $M_{\text{acc}} = 2$ and $5 \times 10^{-2} M_\odot$, respectively. This feature shows the same Doppler shift and evolution with time as the Ca II feature (i.e. related to the dynamics of the shell and not the photosphere). However, unlike the Ca feature, the oxygen is not primordial but produced during explosion. Burned matter contributes about 2/3 of the shell mass (see Figs. 4 & 5). Solar abundances of oxygen do not provide sufficient optical depth in the shell to cause a strong feature. The appearance of this feature would imply that a significant amount of burnt SN ejecta has piled up in the dense shell.

3.3.6. Hydrogen, Helium, & Carbon

It is worth mentioning what the models do not predict, but we might have expected to see from a shell formed by the interaction of an exploding SNe Ia and hydrogen-rich matter: namely hydrogen, helium and carbon lines. About 20% of the shell consists of hydrogen. Nonetheless, the model spectra do not exhibit any significant Balmer or Paschen lines, even for $M_{\text{acc}}$ of $5 \times 10^{-2} M_\odot$.

In the absence of heating by an ongoing inter-
action between SN and its environment, the temperature in the shell is low ($T \approx 4500$ to $5000$ K). At these temperatures, excitation of metal lines is strongly favored over hydrogen, due to the much lower excitation energies. For example, $10.2$ eV for H I vs. $2.22$ eV ($1D \rightarrow 1S$), $9.0$ eV ($3P \rightarrow 3S$), $1.57$ eV ($5S \rightarrow 5P$) for the singlet, triplet, and quintet state of Calcium and, $1.9$ eV needed for collisional coupling between the singlet and triplet state). The optical depth of the shell is small for $\gamma$ rays ($\lesssim 0.01$ in all cases), keeping the non-thermal excitation of hydrogen low, and thus the hydrogen is mainly neutral. Since most H I atoms are in the ground state, the optical depth of the shell is very small for Balmer and Paschen lines and no absorption features can be seen.

Moreover, in the presence of heavy elements, strong charge exchange reactions between hydrogen and metals (with a lower ionization potential) are the preferred path for H recombination rather than the radiative process. As a result, we do not see any significant emission component due to hydrogen. These same arguments hold even more true for He I. Note that while strong charge exchange reactions are expected to suppress H and He features, they are not really needed because, even without microscopic mixing, detection of the broad, weak H emission features ($\approx 1$ to $2\%$ of continuum in case II) would hardly be possible.

On the other hand, because carbon and oxygen have excitation energies and line cross sections closer to those of Ca, we could expect strong C I features due to transitions at $9405$ Å, and $10691$ Å as was observed in the subluminous SN 1999by (Höflich et al. 2002). In normal-bright delayed detonation models, the corresponding lines do not show up strongly because nearly the entire WD is incinerated, leaving little carbon in the ejecta. However, in alternative scenarios for SNe Ia such as deflagration and merger models, more than $0.1 M_{\odot}$ of the WD remains unburned. For example, in the W7 model (Nomoto, Thielemann, & Yokoi 1984), about $0.17 M_{\odot}$ does not undergo nuclear burning and, as a consequence, approximately equal amounts of O and C would be seen in the shell.

If our data showed a clear detection of the high-velocity O I feature, then the lack of any strong observed carbon features in SN 2003du would strongly argue against such a scenario. As it stands, however, the ionization state of the ejecta in the shell is not strongly constrained by our observations of SN 2003du (see below), and thus the interpretation of the lack of C I features is strongly model dependent.

### 4. Comparison with Observations

It is beyond the scope of this paper to present a detailed comparison between theory of the explosion and observations as done for SN 1994D (Höflich 1995a) or SN 1999by (Höflich et al. 2002). This would require high quality light curves to determine the interstellar reddening and global properties, and also good spectroscopic time coverage, including post maximum spectra to decipher the structure of the inner parts of the envelope. A detailed analysis would involve fine tuning of the free model parameters, namely the initial progenitor, properties of the burning front and the central density of the exploding WD. Such an analysis will be the subject of a future paper when the relevant data become available.

Instead, the goal here is simply to compare the model predictions with the observations of SN 2003du, determine whether such a scenario might plausibly reproduce the observed phenomenon, and then discuss the implied shell properties. As an example, in Figure 9, the observed and theoretical spectra have been plotted at about $3$ days before maximum light (corresponding to the May 03 data). The continuum slope of the model roughly matches the spectrum and the Doppler shifts of lines generally agree to within about $\approx 1000$ km$^{-1}$. (Note that the vertical offset in the red is an artifact due to a poor match between the calibration of the two spectroscopic setups on May 03.) Thus our model, although not tuned in any manner, is a decent match for SN 2003du.

In Figure 10, a comparison of the IR Ca II triplet is given for about $\approx 3$ days. The strength and Doppler shift of the high-velocity component of the Ca II is roughly consistent with $M_{\mathrm{acc}} \approx 2 \times 10^{-2} M_{\odot}$. Note that the observed line profile is broader than the model profile; an indication that the absorbing material is somewhat less confined than in the model. As in the observations, the model predicts that the high-velocity Ca II starts to become weak around maximum light, and dis-
appears a few days later. The highest mass model can clearly be ruled out, as the high-velocity feature in this model is essentially completely blended with the photospheric absorption, and does not appear as a well separated feature at all.

The model without a shell does exhibit a high-velocity component to the Ca II feature, but it is significantly too weak, (at least with this SN model) to account for the observed high-velocity feature. Furthermore, as was discussed in the previous section, a feature due to the ionization effect exhibits an entirely different evolution than is seen in SN 2003du. As the SN ejecta expands and cools, the inner and outer regions of the Ca III region begin to recombine to Ca II. Thus the observed high-velocity feature would shift steadily to the red, eventually merging with the photospheric line.

In contrast, the observed evolution of the high-velocity feature more closely resembles the expected evolution for a shell that is fixed in velocity space. The line centroid shifts slightly to the red as the feature ages, but the absorption never moves beyond its upper or lower boundaries. In the shell model, the slight shift of the minimum in the high-velocity component occurs because the inner layers of the shell contribute more to the opacity as it expands homologously, and also because the absorption depression is formed on the steep blue edge of the main component of Ca II, which gains considerable strength during the observations. Note that the observed red edge of the high-velocity feature, corresponding to the inner edge of the shell, remains constant, consistent with the notion that the kinematics of the shell are unchanged, and only the relative density of the inner and outer regions of this finite shell are evolving.

Such kinematic stability implies that the shell is in free expansion and most of the shell must have been accumulated prior to the first spectroscopic observations. This implies a strict upper limit for the distance between the circumstellar material and the WD progenitor of \( D_{\text{matter}} \leq v_{\text{shell}} \times t \approx 1.5 \times 10^{15} \text{cm} \). This puts some constraints on the origin of the material, which might originate from an accretion disk around the white dwarf, mass filling the Roche lobe of the donor star, a common envelope in which the WD is embedded, or, perhaps, a period of very high mass loss immediately prior to the explosion. The last is rather unlikely, as the period of mass loss must be shorter than 50 years prior to the explosion, even if we assume a wind of 10 km s\(^{-1}\) which is at the low end for red supergiant winds. Moreover, the interaction with such a wind would convert bulk flow kinetic energy at a rate of \( 2 \times 10^{44} \text{ erg s}^{-1} \) (Fig. 5), a significant fraction of which should be visible as additional luminosity, but we see no evidence for any significant excess in the observed light curve.

An even tighter limit comes from the early light curve. SN 2003du was discovered on April 22, (about 4 days after the explosion, in the timeline of the model explosion), at about 2.5" below maximum light which is typical for normal SNe Ia (e. g. Phillips et al. 1999). This leads to an estimate for \( D_{\text{matter}} \leq v_{\text{shell}} \times t \leq 6 \times 10^{15} \text{cm} \). The kinetic energy conversion is proportional to the mass accumulation rate in the shell. To produce the same shell by interaction with a stellar wind would either result in very unrealistic luminosities early on, or the deposited energy has to go into expansion work rather than luminosity.

Indeed, the lack of any observed interaction in the light curve argues that the bulk of the interaction likely occurred close to the progenitor system, so that adiabatic expansion of the freely expanding shell dissipated most of the shock energy. These constraints tend to argue that the circumstellar material is most likely directly related to the progenitor system as in the accretion disk or Roche lobe scenarios.

Note that for small \( D_{\text{matter}} \), a shell may not stay as confined as assumed in our models since there will have been more time for internal dynamics to “smear-out” the sharp edges of the shell. Such an effect would tend to broaden the shell features. Indeed, the observed high-velocity Ca feature is somewhat broader than the model prediction. Note that if the “shell” were significantly non-spherical (as in the case of an accretion disk, for example) the kinematics would also likely be significantly affected.

On the other hand, because of the observed confinement of Ca II in velocity space, the matter cannot be attributed to the outer layers of the WD itself. Redistribution of energy during the hydrodynamical phase would have produced a smooth velocity profile very similar to the freely expanding ejecta (Fig. 4). Since no dense shell would
be formed in the outer layers, any material from
the surface of the WD would have a very low op-
tical depth and the observed spectrum would look
essentially identical to a normal SN Ia.

5. Final Discussions and Conclusions

In this paper, we have presented a series of
optical spectra and broad band photometry of
SN 2003du obtained with the Hobby∗Eberly Tele-
scope and the ROTSE IIIb telescope, respectively.
Overall, the spectral evolution and the light curve
resemble that of a normal bright SNe Ia, except for
a significant, high velocity component to the Ca
II IR triplet. This high-velocity component exhibits
an expansion velocity of about 18,000 km s\(^{-1}\) in-
stead of the significantly smaller velocity measured
in the other photospheric lines. We suggest that
the high-velocity Ca feature near 8000 Å may be
the spectroscopic signature of a shell formed by
the interaction of the supernova ejecta with the
circumstellar environment.

Based on detailed calculations for the explosion,
light curves and spectra, the observable effects of
such a shell have been examined and diagnostic
tools developed. The model shells are formed by
interaction between SN ejecta and circumstellar
material of solar abundance. The circumstellar
material has been overtaken by the expanding en-
velope prior to the time of the observations with
little or no significant ongoing interaction. The
high-velocity component of the IR triplet of Ca II
can be understood within this framework as being
cau sed by solar abundance material piled up in
the dense shell behind the shock. This material is
likely mixed via Rayleigh-Taylor instabilities with
the reverse-shocked outer layers of the SN ejecta.
We find that the optical and IR spectra are little
affected by a shell with an accumulated mass of
up to a few hundredths of a solar mass. Hydro-
gen and Helium lines are strongly suppressed due
to the low temperatures in the shells and charge
exchange with heavy elements being the preferred
method of hydrogen recombination.

The main signatures of the shell in the model
spectra are a high-velocity Ca II component of
the IR triplet, and a weaker O I line near 7300
to 7400 Å. Although similar in nature, these fea-
tures probe different physics. The Doppler shift of
the high-velocity component of Ca II is a sensitive
measure of the amount of accumulated matter in
the circumstellar shock, whereas the Doppler shift
of the O I can be used as consistency check and,
more importantly, as a test for mixing of shell and
envelope material. Unlike the Ca II feature, the
O I feature is only formed with oxygen abundances
which exceed the solar value by about 2 orders of
magnitude.

Related to the interaction process and the de-
celeration of high-velocity ejecta is the conversion
of kinetic energy. Assuming reasonable factors of
efficiency for the conversion to photons, the lack
of evidence for any additional associated luminos-
ity strongly argues in favor of a very low density
environment for SNe Ia (outside of the immediate
vicinity of the progenitor system) and provides ad-
ditional constraints for the origin of any circum-
stellar material.

In light of these results, the interpretation of the
high-velocity Ca II IR feature seen in SN 2001el
should also be revisited. Our results here sug-
gest that calcium enrichment may not be required
to reproduce the effect seen in SN 2001el. The
stronger Ca II feature and the observed polariza-
tion provide somewhat stronger constraints, how-
ever, and will require a more detailed calculation
which is beyond the scope of this work.

For SN 2003du, we find that the observations
can be understood as a result of a shell formed
by the accretion of about 2 × 10\(^{-2}\)M\(_\odot\) of matter
with solar composition. The observations are con-
sistent with the picture that the shell consists of
a mixture of accreted and envelope matter. The
early light curve data strongly suggest that the
matter originates from close to or within the pro-
genitor system, as an accretion disk, the Roche
lobe of the companion, or a common envelope.
An episode of strong mass loss would require un-
realistically short durations, very high mass loss
rates and probably very high luminosities early
on. Thus, the circumstellar phenomena we suggest
here for SN2003du are unlike those for SN 2003ci
which require a large H mass at large distances
(≈ 10\(^{16}\)...17 cm; Wang et al. 2003b).

In summary, moderate mass shells of around
10\(^{-2}\)M\(_\odot\) show no significant signatures in the opti-
cal and NIR except the high-velocity Ca II feature
near 8000 Å and the O I feature at about 7300 Å.
In the past, both could easily elude detection be-
cause observations often did not extend far enough
to the red, and even when they did, the increasing noise longwards of 7000 Å and contamination by atmospheric absorption bands confuse the issue. SN 2003du may not, in fact, be all that unusual an event. Other SNe Ia (SN 2002cx, SN 2001el) have shown similar Ca II features, and a systematic search for this phenomenon in SNe Ia may provide significant constraints on the environment and progenitor systems of these objects.

Finally, we have also to mention the limits of this work. To begin with, this work is not an attempt to reach a definitive conclusion as to the nature of the high-velocity Ca absorption, as not all potential diagnostic tools have been applied to SN 2003du and alternative explanations may still be open. Rather we have shown that interaction with solar abundance circumstellar material is a plausible explanation for this phenomenon. In examining the implications for such an interpretation, we have developed observational tools which could be used to probe the circumstellar environment. However, these tools still need significant refinement. In particular, our study has only covered a small parameter space and, for the most part, has been limited to the case without ongoing interaction. For the formation of the shell, we assumed adiabatic shocks. Depending on the origin of the accreted matter, some of the shell material may be accumulated before the phase of homologous expansion has been established for the SN ejecta, and the shell structure might therefore be modified. The larger width of the high-velocity Ca II component of SN 2003du (compared to the models) may already be an indicator for such an effect.

Also, we did not take into account the likely 3-D nature of either the SN ejecta or the circumstellar material. Indeed, the polarization measurements for SN 2002el (Wang et al. 2003a) indicate that the Ca II (and thus, in this interpretation, the shell) is not spherical but may be toroidal, or a large scale filament with a significant scale height which selectively blocks light from the underlying photosphere and causes polarization (Höflich 1995a; Höflich et al. 2002; Kasen et al. 2003). Moreover, the polarization confirms that the high-velocity Ca II in SN 2001el is related to a region morphologically separated from the overall SN ejecta. Aside from the line polarization, the 3-D nature of the absorbing gas will also affect the implied mass of circumstellar material. The high velocity component of the IR Ca II measures a column depth along the line of sight and the actual mass may be lower by a factor of a few depending on the covering factor of the absorbing material. We do not expect a large correction factor because these strong high-velocity features to not appear to be uncommon (SN 2003du, SN 2002cx, SN 2001el) although the present data base is too small for meaningful statistics.

To address these questions, detailed 3D calculations for the interaction of ejecta and environment should be performed similar to those for the interaction of the donor star by Marietta, Burrows, & Fryxell (2000) Upcoming systematic surveys of supernovae at moderate red shifts will provide the large samples needed to study the systematic properties of the progenitor systems. These same surveys are expected to provide spectra earlier than -7 days as in our study of SN2003du Such data will provide even tighter limits on the origin of the H-rich layers, and call for the use of the entire sample of diagnostic tools described above.

We would like to thank the staff of the Hobby∗Eberly Telescope and McDonald Observatory for their support. The Hobby∗Eberly Telescope is operated by McDonald Observatory on behalf of The University of Texas at Austin, the Pennsylvania State University, Stanford University, Ludwig-Maximilians-Universität München, and Georg-August-Universität Göttingen. The Marcario Low Resolution Spectrograph is a joint project of the Hobby-Eberly Telescope partnership and the Instituto de Astronomía de la Universidad Nacional Autónoma de México. We would like to acknowledge Carl Akerlof, Don Smith, Eli Rykoff, and the members of the ROTSE collaboration for their enormous (and continuing) work on the design, construction, and implementation of the ROTSE telescopes and software. Finally we would like to thank E. Robinson for helpful discussion.

This research is supported, in part, by NASA grant NAG 5-7937 (PH) and NSF grant AST0098644 (JCW).
A. Details of the SN Model

A.1. Numerical Methods

Our calculations take into account detailed hydrodynamics, nuclear networks, radiation transport for low and high energy photons, opacities and include solvers to calculate the atomic level populations in full (albeit simplified) NLTE for both light curves and synthetic spectra utilizing accelerated Lambda Iteration and level merging as commonly used in stellar atmospheres (\cite{hilier03,hugeny03,werner03}. These computational tools have been used to carry out several previous analyses of SN Ia \cite{h95,h02}. For more details, see H"oflich (2003a,b), and references therein.

Spectra are computed using the chemical, density, and luminosity structure as well as the \(\gamma\)-ray deposition resulting from the light curve code. For the detailed atomic models, typically between 27 and 137 bound levels are taken into account for the main ionization stages. For each of these detailed atomic models, neighboring ionization stages have been approximated by simplified atomic models restricted to just LTE levels with a few NLTE levels. The energy levels and cross sections for bound-bound transitions are taken from Kurucz (1993) starting at the ground state. Here, we use H I (14/31/91), He I (15/28/46), C I (27/123/242), C II (23/31/57), O I (43/129/431), O II (28/43/75), Mg II (20/60/153), Si II (35/212/506), Ca II (41/195/742), Ti II (62/75/592), Fe II (137/3120/7293), Co II (84/1355/5396), and Ni II (71/865/3064), where the first, second and third numbers in brackets denote the number of levels, the number of bound-bound transitions, and the number of discrete lines for the radiation transport. The third number is larger than the second because nearby levels within multiplets have been merged for the rates. In addition, 404508 LTE-lines are taken into account using an equivalent-two level approach.

For calculating detailed spectra, the explosion models have been remapped from 912 to about 200 radial grid points for the atmospheres with the zones concentrated in the line forming region. \(7.4 \times 10^4\) frequency points have been used, oversampling the synthetic spectra. In an expanding atmosphere, the frequency and velocity space are coupled and thus the effective resolution of the spectra is about 1000. The noise in the spectra (see Fig. 7) below this effective resolution is a direct result of the oversampling in the frequency space and can be used as an estimate for the internal numerical accuracy.

A.2. SN Model Results

The structure of the initial model of the C/O white dwarf is based on a star with 5 solar masses at the main sequence and solar metallicity which, at the end of its evolution, has lost all of its H and He-rich layers. By accretion, its core has grown close to the Chandrasekhar limit. At the time of the explosion of the WD, the central density is \(2.0 \times 10^9\) g cm\(^{-3}\) and its mass is close to \(1.37 M_\odot\). The deflagration-detonation transition density \(\rho_{tr}\) is \(2.5 \times 10^7\) g cm\(^{-3}\). During the explosion, about \(0.6 M_\odot\) of radioactive \(^{56}\)Ni are produced. The density and chemical structure are shown in Figure 4. The maximum brightness in \(V\), the \((B-V)\) color near maximum, the rise time to maximum light, and decline ratio in \(V\) over 15 days are \(-19.29 m\), \(-0.02 m\), and \(1.0 m\), respectively; typical for normal SNe Ia. Further details for this reference model, including the progenitor evolution, explosion, and light curves can be found in Dominguez, H"oflich & Straniero (2001) and H"oflich et al. (2002), where it is named 5p0222.25.
REFERENCES

Bessel, M. S. 1990, PASP, 102, 1181
Chugai, N. N. 1986, SvA, 30, 563
Kotak, R. & Meikle, W. P. S. 2003, IAU Circ. 8122
Kurucz, R. L. 1993, Atomic Data for Opacity Calculations, Cambridge/Center for Astrophysics, CD 1
Schwartz, M. & Holvorcem, P. R. 2003, IAU Circ. 8121


Table 1
SN 2003du Color Evolution

<table>
<thead>
<tr>
<th>Date</th>
<th>(U − B)</th>
<th>(B − V)(^a)</th>
<th>(V − R)</th>
<th>(V − I)</th>
<th>Telescope</th>
</tr>
</thead>
<tbody>
<tr>
<td>01 May</td>
<td>…</td>
<td>−0.10</td>
<td>0.01</td>
<td>−0.16</td>
<td>HET</td>
</tr>
<tr>
<td>02 May</td>
<td>…</td>
<td>−0.02</td>
<td>0.04</td>
<td>−0.07</td>
<td>HET</td>
</tr>
<tr>
<td>06 May</td>
<td>…</td>
<td>−0.12</td>
<td>−0.08</td>
<td>−0.37</td>
<td>HET</td>
</tr>
<tr>
<td>07 May</td>
<td>−0.35 ± 0.06</td>
<td>0.04 ± 0.05</td>
<td>0.03 ± −0.05</td>
<td>−0.39 ± 0.04</td>
<td>0.8 m</td>
</tr>
<tr>
<td>08 May</td>
<td>…</td>
<td>0.00</td>
<td>−0.02</td>
<td>−0.33</td>
<td>HET</td>
</tr>
<tr>
<td>12 May</td>
<td>…</td>
<td>0.19</td>
<td>0.09</td>
<td>−0.14</td>
<td>HET</td>
</tr>
<tr>
<td>30 May</td>
<td>…</td>
<td>0.58</td>
<td>0.11</td>
<td>0.06</td>
<td>HET</td>
</tr>
</tbody>
</table>

\(^a\)For HET data, B-band is cut off at 4200 Å.
Fig. 1.— Unfiltered light curve of SN2003du as obtained by the automatic telescope ROTSE. Dates at which HET spectra and UBVRI colors have been obtained are marked by arrows. From these data, SN2003du could be classified as a normal-bright SNe Ia. Maximum light was at May 06, 2003 with an uncertainty of ±3 days.
Fig. 2.— Spectral evolution of SN2003du between -7 to +5 days relative to maximum light in the ROTSE band. The high velocity component of the Ca II IR-triplet has been marked. The data have been shifted vertically by an arbitrary amount for clarity. The spectra are presented in the rest wavelength of the host galaxy.
Fig. 3.— Spectral evolution of the Ca II IR feature between -5 and +7 days relative to maximum light.
Fig. 4.— Structure of the delayed detonation model. The density (blue, dotted) and velocity (red, solid) are given as a function of the expansion velocity during the phase of homologous expansion (upper plot). The abundances of stable isotopes are given as a function of the expansion velocity (lower plot). In addition, $^{56}\text{Ni}$ is given. The curves with the highest abundance close to the center correspond to $^{54}\text{Fe}$, $^{58}\text{Ni}$ and $^{56}\text{Fe}$. The calculations are based on a delayed detonation model in which a Chandrasekhar mass White Dwarf with central and transition densities of $2 \times 10^9 \text{ g cm}^{-3}$ and $2.5 \times 10^7 \text{ g cm}^{-3}$, respectively. The progenitor WD has been evolved from a star with a main sequence mass of $5M_\odot$ with solar metallicity.
Fig. 5.— Properties of the shell models. For the formation of the shell, we assume adiabatic shocks and complete mixing during the interaction. The total energy gain by the interaction, the mean velocity of the expanding shell, and the ratio between accumulated matter and the total shell mass are given as a function of the accreted matter (above left). Time dependent quantities are given for three cases which all produce a shell of $2 \times 10^{-2} M_\odot$ at day 20. The shell is produced by running into a stellar wind with a velocity of $10 \, \text{km s}^{-1}$ (case I), a combination of a nearby mass and a stellar wind, and an environment with constant density. In the upper right, we give the energy generation rate in comparison with the bolometric LC of the model without interaction. In the lower plots, we give the total mass of the shell and its velocity. For details, see § 3.
Fig. 6.— Influence of an accreted shell on the synthetic spectra (normalized to 7000 Å) between 3,800 and 15,000 Å at −3d relative to $V_{\text{max}}$. Spectra are shown for models without a shell in comparison with H-rich, solar metallicity shells of 2 and $5 \times 10^{-2} M_\odot$. Overall, these shells have little effect on the spectrum although continuum scattering and backheating causes a “smearing-out” of line profiles. The reduced expansion velocity of the outer layers results in a cutoff of the blue wings in the absorption components of strong lines. We plot $F_\lambda \times (\frac{\lambda}{7000 \text{ Å}})^{2.5}$ to show simultaneously both the emission and absorption features in the optical and IR. In the lower plot, we give the radius (normalized to $R_\ast = 10^{15} \text{ cm}$) at which the monochromatic Sobolev optical depth equals 0.1, 1 and 10, respectively, for the model without a shell (black) and $M_{\text{acc}} = 5 \times 10^{-2}$ (blue).
Fig. 7.— Same as Figure 6 with the spectrum enlarged between 5500 and 6740 Å. Changes become significant for a shell mass with $5 \times 10^{-2} M_\odot$ but are marginal for $2 \times 10^{-2} M_\odot$. The main effects of a larger mass are a cutoff of the blue edge of Si and a “smearing” out of features by continuum scattering. No hydrogen lines can be seen (see §3.2.2). Small scale noise below the resolution limit is a measure of the internal accuracy of the models (see §3.1).
Fig. 8.— Same as Figure 6 between 7000 and 8650 Å which is the only region with qualitative changes of individual lines even for the model with $M_H$ of $2 \times 10^{-2} M_\odot$. Features include an OI/MgII blend at 7300 Å and the high velocity Ca II absorption at about 8000 Å.
Fig. 9.— Comparison of theoretical model at day -3 and SN 2003du on May 3rd, roughly three days before maximum light. The observed spectrum has been obtained by combining a blue and red spectrum. The slope change at about 8,000 Å is an artifact related to the normalization of the red and blue data and uncertainties in the instrumental response correction in the overlapping region. Beyond 10,000 Å the spectrum is contaminated by order overlap.
Fig. 10.— Ca II IR feature observed in SN 2003du on May 3rd in comparison with theoretical models. The observation is based on the “red” spectrum only, and avoids most of the calibration error seen in Figure 9. The wiggles in the observations are caused by CCD fringes.