SPECTRAL SIGNATURES OF GRAVITATIONALLY CONFINED THERMONUCLEAR SUPERNova EXPLOSIONS

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ABSTRACT

We consider some of the spectral and polarimetric signatures of the gravitationally confined detonation scenario for Type Ia supernova explosions. In this model, material produced by an off-center deflagration (which itself fails to produce the explosion) forms a metal-rich atmosphere above the white dwarf surface. Using hydrodynamical simulations, we show that this atmosphere is compressed and accelerated during the subsequent interaction with the supernova ejecta. This leads ultimately to the formation of a high-velocity pancake of metal-rich material that is geometrically detached from the bulk of the ejecta. When observed at the epochs near maximum light, this absorbing pancake produces a highly blueshifted and polarized calcium IR triplet absorption feature similar to that observed in several Type Ia supernovae. We discuss the orientation effects present in our model and contrast them to those expected in other supernova explosion models. We propose that a large sample of spectropolarimetric observations can be used to critically evaluate the different theoretical scenarios.

Subject headings: hydrodynamics — polarization — supernovae: general

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1. INTRODUCTION

After decades of study, the mechanism of the explosion of a white dwarf in a Type Ia supernova (SN Ia) remains uncertain (Hillebrandt & Niemeyer 2000). Several of the proposed theoretical models (Arnett 1969; Khokhlov 2001; Reinecke et al. 2002) have failed to produce objects with the energetics and chemical composition compatible with observations (Höflich et al. 2002). These two characteristics are best captured by the so-called delayed-detonation models (Khokhlov 1991; Gamezo et al. 2004; Plewa et al. 2004). In such models, a mild ignition occurs near the center of the accreting, massive white dwarf and sparks a deflagration (subsonic flame). During the subsequent evolution, a deflagration to detonation (supersonic re-active wave) transition (DDT) takes place.

Despite the promise of the DDT models, it remains unclear how a transition to detonation occurs—in all standard DDT models calculated so far, the detonation was triggered artificially. However, Plewa et al. (2004) have proposed a gravitationally confined detonation (GCD) model in which a detonation naturally follows a slightly off-center ignition. In this scenario, the deflagration takes the form of a single bubble, buoyantly rising to the stellar surface. At the bubble’s breakout, the surface layers of the star are laterally accelerated and begin sweeping across the stellar surface, converging opposite the breakout point. The subsequent compression of the colliding streams and thermalization of the kinetic energy triggers a detonation. The authors speculate that, as in the standard DDT case, the detonation will consume the remaining fuel, producing an energetic explosion with chemically stratified ejecta. The stability of the GCD is currently the subject of more detailed numerical study.

One of the most striking properties of the GCD model is that the products of the deflagration are brought to the surface of the white dwarf prior to detonation. This material constitutes a small fraction of the stellar mass and is rich in metals. This compositional “pollution” of the outer stellar layers is reminiscent of a peculiar feature noticed in the spectra of some SNe Ia. In a handful of objects, observers have identified a highly blueshifted Ca II IR triplet absorption (Hatano et al. 1999; Li et al. 2001; Wang et al. 2003; Gerardy et al. 2004), indicating absorbing material moving at velocities ~20,000 km s\(^{-1}\), much higher than that characteristic of other spectral lines. Given that velocity is proportional to radius in expanding SN atmospheres, the high-velocity (HV) calcium absorption indicates a component of absorbing material geometrically detached from the bulk of the ejecta. Spectropolarimetry of SN 2001el further showed that the HV absorption was highly polarized, indicating that the absorbing material was distributed aspherically with perhaps a clump-like geometry (Wang et al. 2003; Kasen et al. 2003).

In this Letter, we demonstrate that the ejecta structure characteristic of the GCD scenario can naturally explain observations of the peculiar HV calcium absorption feature in SNe Ia.

2. METHODS

We studied the postdetonation evolution of the GCD model using a simplified numerical setup in which spherical SN ejecta runs into an aspherical metal-rich atmosphere. For the SN ejecta structure, we used the W7 model (Nomoto et al. 1984) with an initial radius of 3 × 10\(^3\) cm. Around the ejecta, we placed an ellipsoidal metal-rich extended atmosphere representing the bubble of burned material expelled during the GCD breakout. The composition of this material was taken to be the oxygen-burned composition 4 from Table 3 of Khokhlov et al. (1993), which consists of 57% silicon, 27% sulfur, 7.1% iron, 2.7% calcium, and small amounts of other elements. The extended atmosphere had an axis ratio of 1.2, had a semimajor axis length of 6 × 10\(^4\) cm, and was centered at 3 × 10\(^8\) cm. The density of the atmosphere decreased exponentially with a scale length of 3 × 10\(^8\) cm. The atmosphere was uniformly expanding.

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Fig. 1.—Hydrodynamical simulation of the model SN ejecta interacting with the extended atmosphere. Panels a–c show the density in log scale; panel d depicts the magnitude of the velocity. The density scale is shown by the color bar in panel c, while the velocity scale is shown by the color bar in panel d. The black contour line corresponds to a calcium number abundance of 0.01. (a) Density distribution at the beginning of the simulation ($t = 0$ s). (b) Density distribution at $t = 0.3$ s. Notice the remarkable deformation of the calcium-rich material in the upper part of the computational domain. (c) Density distribution at the final time ($t = 1.24$ s). Notice that the calcium-rich region has been strongly compressed into a pancake-like structure. (d) Velocity magnitude at the final time. The calcium-rich absorber is seen moving at velocity $\sim 21,000$ km s$^{-1}$ with a substantial velocity gradient across the structure.

The major difference is the final velocity of the calcium-rich material exceeding $1\%$. In particular, the contour in the top portion of the image marks calcium produced in the deflagration; the inner calcium-rich ring is that of the W7 nucleosynthesis. The overall hydrodynamic evolution in our model is best described as ejecta impacting a stratified atmosphere, with shock-related effects playing a minor role. In Figure 1b ($t = 0.3$ s), a mostly spherical expansion of the SN shock can be seen in the lower part of the computational domain. In the upper part of the domain, the ejecta impacts and deforms the extended atmosphere. By $t = 1.24$ s (Fig. 1c), that impact has led to the compression of the calcium-rich material into a pancake-like structure of radius $\sim 30,000$ km, located near $z \approx 2 \times 10^8$ cm. By that time, the ambient medium surrounding the atmosphere has been completely overrun by the forward SN shock. The reverse shock can be seen as the highly contrasted spherical structure starting at $(r, z) = (0, -2.6 \times 10^8)$ cm.

Beginning at $t \approx 1$, the overall expansion becomes increasingly homologous, and we stop our calculation at $t = 1.24$ s. Figure 1d shows the total velocity in the upper portion of the computational domain at the final time. The calcium-rich pancake structure shows a significant velocity gradient across its body ($\Delta v/c \approx 0.02$). The central region of the pancake ($r = 0$) moves with velocity spanning $17,000-24,000$ km s$^{-1}$, while near the outer rim the velocity is higher ($22,000-28,000$ km s$^{-1}$).

In the case of more massive atmospheres, the overall evolution and resulting morphology are similar to the case described above. The major difference is the final velocity of the calcium-rich pancake. For a model with $m_{\text{atm}} = 0.016 M_\odot$, the inner part of the pancake moves with velocities $14,000-20,000$ km s$^{-1}$, while the outer edge moves at $21,000-26,000$ km s$^{-1}$. For an even
more massive atmosphere ($m_{\text{ini}} = 0.08 M_\odot$), the velocities are still lower, increasing from 10,000–12,000 km s$^{-1}$ to 17,000–21,000 km s$^{-1}$ across the pancake. In this case, the calcium-rich pancake almost overlays the region of intermediate-mass elements in the W7 ejecta.

The synthetic spectrum of the model at a time when the SN is near maximum light has been obtained after homologously expanding the ejecta to 20 days (Fig. 2, lower panel). Given the enhanced abundance of intermediate-mass elements and relatively low temperature ($T \approx 5500$ K), the pancake is opaque in the Ca II IR triplet lines. For a viewing angle, $\theta$, in which the observer looks directly down on the pancake ($\theta = 0^\circ$), the pancake obscures the SN photosphere, creating a broad and highly blueshifted HV calcium absorption feature near 8000 A. The HV feature seen in the model compares well to that observed in SN 2001el (Wang et al. 2003), shown in the top panel of Figure 2. For larger viewing angles, the pancake obscures less (or none) of the photosphere, and the HV feature is weaker or absent in the model spectrum. This orientation effect may explain why in some SNe, such as SN 1994D (Patat et al. 1996), an HV calcium feature at maximum light is seen only weakly or not at all.

The spherical geometry of the calcium-rich pancake also leads to significant polarization over the HV calcium feature (Fig. 3). Light in the SN ejecta becomes polarized by electron scattering. By convention, a positive (negative) polarization level signifies polarization aligned parallel (perpendicular) to the symmetry axis. The black lines show the polarization level, while the gray lines show the corresponding (arbitrarily scaled) flux spectrum. The insets illustrate how the HV calcium line polarization is caused by the partial obscuration of the SN photosphere (light blue disk) by the calcium-rich pancake (dark blue object). [See the electronic edition of the Journal for a color version of this figure.]

45$^\circ$, the model closely reproduces the HV line polarization peak observed in SN 2001el (Wang et al. 2003). For larger $\theta$, vertically polarized light from the side edges of the photosphere dominates, and the line polarization changes sign (Fig. 3c). For $\theta \approx 110^\circ$, the pancake no longer obscures the photosphere and leaves no obvious signature in either the flux or the polarization spectrum (Fig. 3d).

4. DISCUSSION

We have demonstrated that the observations of a peculiar HV calcium feature in SNe Ia are naturally explained within the GCD model. In the model, burned material expelled during the breakout of the deflagrating bubble forms an extended atmosphere above the stellar surface. That atmosphere is subsequently compressed and accelerated during the hydrodynamic interaction with the SN ejecta. This leads to the formation of an HV calcium-rich pancake with a cross section comparable to that of the underlying photosphere. The partial obscuration of the photosphere by the pancake results in an HV calcium absorption feature with significant line polarization.

In our model, the blueshift of the absorption feature depends sensitively on the mass of the expelled material. For the fiducial case studied here ($m_{\text{ini}} = 0.008 M_\odot$), the pancake material spans the velocity range 17,000–24,000 km s$^{-1}$ and is geometrically detached from the bulk of the SN ejecta. This compares well with the velocities inferred from the HV calcium feature of SN 2001el. As the atmosphere mass is increased, the absorbing pancake moves at lower velocity and eventually blends with the region of intermediate-mass elements in the SN ejecta. In such a case, we might expect a very different observable signature, in which the pancake material increases the strength and blueshift of several of the normal SN Ia spectral features. This could provide an orientation-dependent explanation for the unusually high velocities and peculiar velocity evolution of the normal features in some SNe Ia (e.g., SN 1984A [Branch 1987] and SN 2002bo [Benetti et al. 2004]).

The large size of the absorbing pancake results in the distinctive orientation effects present in our model. The strength of the HV flux absorption depends only on the fraction of the...
The recombination of Ca$^{+}$ ionization effect discussed by Gerardy et al. (2004), whereby to separate the signatures of the HV absorber from the “transient relations. Note that multiepoch observations may be necessary to distinguish a much smaller fraction of SNe showing a persistent HV absorber in the GCD model using a rich sample of spectropolarimetric observations. In particular, our model predicts a single absorber in the GCD model using a rich sample of HV absorbers. This case can be distinguished from the case of standard DDT models may in principle produce a number of bubbles of burned material present in the pure deflagration and interaction with a companion star (Marietta et al. 2000; Kasen et al. 2004). Another interesting possibility is to consider the GCD framework with rotation of the progenitor included. In such a case, the trajectory of the buoyantly rising deflagrating bubble is not expected to be aligned with the rotation axis of the progenitor. This lack of correlation follows from the fact that the convective core of the white dwarf is expected to produce ignition seed points in a largely stochastic manner. Such a scenario should be studied in the future by means of integrated multidimensional hydrodynamical simulations.

The presence of an HV calcium absorber can possibly be explained in other explosion scenarios. For example, the large bubbles of burned material present in the pure deflagration and standard DDT models may in principle produce a number of HV absorbers. This case can be distinguished from the case of a single absorber in the GCD model using a rich sample of spectropolarimetric observations. In particular, our model predicts a much smaller fraction of SNe showing a persistent HV calcium feature as well as the aforementioned polarization correlations. Note that multiepoch observations may be necessary to separate the signatures of the HV absorber from the “transient ionization” effect discussed by Gerardy et al. (2004), whereby the recombination of Ca$^{+}$ to Ca$^{2+}$ in the cold outer layers of ejecta may also give rise to a (short-lived) HV IR triplet absorption in the epochs prior to maximum light.

For several SNe Ia, polarization in the continuum has also been detected, indicating a global asymmetry in the bulk of the SN ejecta. In SN 2001el, the continuum polarization angle differed from that of the HV calcium feature, suggesting that the orientation of the HV absorber deviated from that of the ejecta. One possible explanation for this difference is that the ejecta acquired a separate, large-scale asymmetry owing to the interaction with a companion star (Marietta et al. 2000; Kasen et al. 2004). Another interesting possibility is to consider the GCD framework with rotation of the progenitor included. In such a case, the trajectory of the buoyantly rising deflagrating bubble is not expected to be aligned with the rotation axis of the progenitor. This lack of correlation follows from the fact that the convective core of the white dwarf is expected to produce ignition seed points in a largely stochastic manner. Such a scenario should be studied in the future by means of integrated multidimensional hydrodynamical simulations.

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Photosphere obscured by the pancake and hence decreases monotonically with $\theta$. The line polarization, in contrast, is maximal when either a large or a small part of the photosphere is covered. Such behavior could be tested with a large sample of spectropolarimetric observations of SNe Ia; in particular, one could study the correlation between the HV calcium polarization level with the depth of the flux absorption.

Although the HV calcium feature is the most profound signature of the absorbing pancake, the opacity due to numerous iron and titanium lines creates a modest flux depression in the wavelength region 3500–4500 Å. This leads to a variation of the $B$-band magnitude with viewing angle of order 1/10 of a magnitude. As discussed in Branch et al. (2004) and Thomas et al. (2004), the temporal evolution of this opacity should also affect the shape of the SN light curve. Therefore, the presence of the calcium-rich absorber is another intrinsic source of SN Ia photometric diversity, of possible relevance to their cosmological application.