Binary Paths to Type Ia Supernovae Explosions
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Evidence for Circumstellar Material in Type Ia Supernovae via Sodium Absorption Features

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Abstract. Type Ia supernovae are very good tools for measuring distances on a cosmic scale. The consensus view is that mass transfer onto a white dwarf in a close binary system leads to a thermonuclear explosion, though the nature of the mass donor is still uncertain. In the single-degenerate model it is a main-sequence star or an evolved star. In the double-degenerate model it is another white dwarf. We study the velocity structure of absorbing material along the line of sight to 35 Type Ia supernovae and find a statistical preference for blueshifted structures, likely arising in gas outflows from the supernova progenitor systems, consistent with a single-degenerate progenitor for a substantial fraction of Type Ia supernovae in nearby spiral galaxies.

Keywords. stars: supernovae, circumstellar matter

1. Introduction

Type Ia supernovae (SNe Ia) have large and calibratable luminosities, making them very good tools for measuring distances on a cosmic scale to gauge the geometry and evolution of the Universe (Reiss *et al.* 1998; Perlmutter *et al.* 1999). Understanding the nature of the progenitor system is important, as progenitor evolution or a changing mix of different progenitors may bias cosmological inferences. The consensus view of SNe Ia is that mass transfer onto a massive carbon-oxygen white-dwarf (WD) star in a close binary leads to a thermonuclear explosion, as the mass of the WD approaches the critical Chandrasekhar mass limit (Whelan & Iben 1973). In the single-degenerate (SD) model the mass donor is either a main-sequence star or an evolved subgiant or giant star, whereas in the competing double-degenerate (DD) model it is another WD (Iben & Tutukov 1984).

In the SD scenario, nonaccreted material blown away from the system before the explosion should remain as circumstellar matter (CSM) (Branch *et al.* 1995). Detection of CSM in SNe Ia spectra would lend support to the SD model. Patat *et al.* (2007) reported such a detection on the basis of time-variable Na I D absorption features in optical spectra of SN 2006X. Chugai (2008) suggested that the sodium absorption could not have been caused by CSM due to ionization considerations. Detailed arguments to the contrary have been presented by Simon *et al.* (2009) and Patat *et al.* (2010). Additional detections were reported for three other events: SNe 2007le (Simon *et al.* 2009), 1999cl (Blondin *et al.* 2009), and 2006dd (Stritzinger *et al.* 2010). A single or small number cases can be explained as special cases, therefore, a larger sample is needed.

The results of this study are presented in greater detail in Sternberg *et al.* 2011.

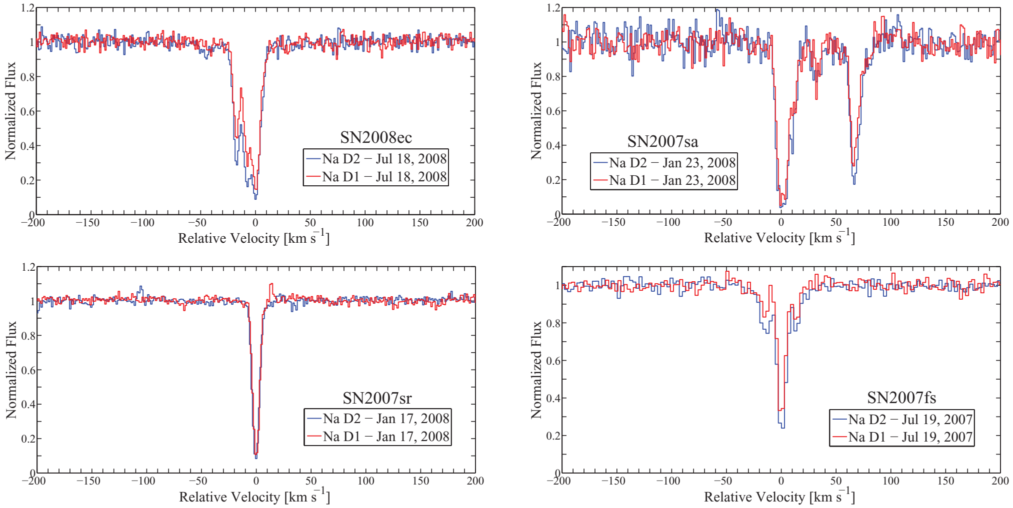

Figure 1. Graphic examples of the three absorption structure classes: Blueshifted (upper left); Redshifted (upper right); Single/Symmetric (lower left/right).

Table 1. Results of the sodium absorption structure classification.

Sample	Blueshifted	Redshifted	Single/Symmetric	Total
SNe Ia	12 [16]	5 [6]	5 [6]	22 [28]
CC SNe	4 [8]	3 [5]	2 [3]	9 [16]
MW (SNe)	12 [13]	13 [16]	17 [22]	42 [51]
MW (QSO)	10	13	6	29
MW (QSO+SNe)	22 [23]	26 [29]	23 [28]	71 [80]

2. Methods and Results

We obtained high-resolution single epoch spectra of 35 SNe Ia and 11 core-collapse (CC) SNe using the HIRES and MIKE spectrographs (mounted on the Keck and Magellan telescopes respectively) with spectral resolution ($R = \lambda/\delta\lambda$) of ~50,000 and ~30,000 respectively. In addition we studied previously published high-resolution spectra of 6 SNe Ia and 7 CC SNe. The results of the extended sample (i.e., our observed and the previously published data) are presented in square brackets.

We normalized the spectra in the vicinity of the Na I D lines. We classified the features of objects that exhibited sodium absorption into three classes (see Figure 1 for graphic examples): (i) *Blueshifted*: One strong absorption feature with weaker features at shorter wavelengths with respect to it; (ii) *Redshifted*: One strong absorption feature with weaker features at longer wavelengths with respect to it; (iii) *Single/Symmetric*: A single absorption feature, or several features with both blue and redshifted structures of similar magnitude. Classification results are presented in Table 1. The Galactic absorption samples, MW(SNe) and MW(QSO) are the Galactic absorption exhibited on the line of sight to the SNe in our sample or to QSOs published by Ben Bekhti *et al.* (2008) respectively.

We fit Voigt profiles to the absorption features using VPFIT (developed by R. F. Carswell and available for download from http://www.ast.cam.ac.uk/~rfc/vpfit.html), which calculated the column density of absorbing material, their relative velocities

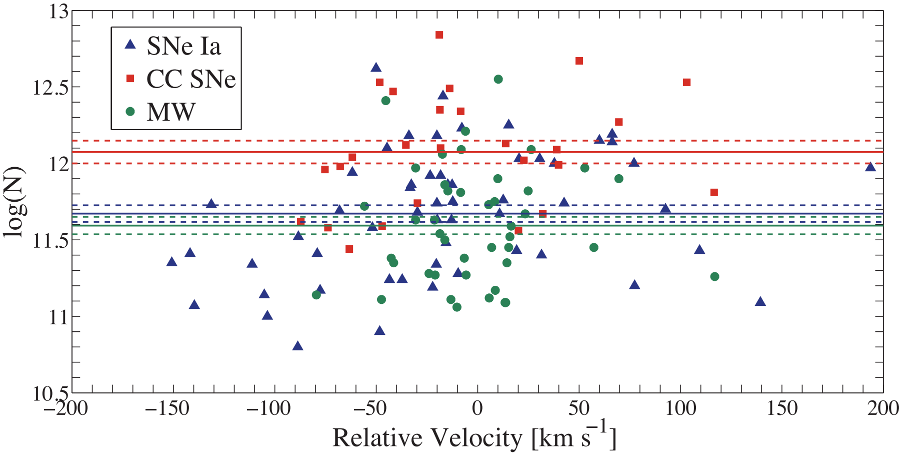

Figure 2. log(N) vs. relative velocity (relative to the zero velocity component) as calculated from the Voigt profile fitting using VPFIT. The horizontal lines mark the mean log(N) of the different samples and the dashed horizontal lines uncertainty in the mean. $<\log(N)>_{\text{SNe Ia}} = 11.67 \pm 0.054$; $<\log(N)>_{\text{CC SNe}} = 12.07 \pm 0.075$; $<\log(N)>_{\text{MW}} = 11.59 \pm 0.058$. Zero velocity components are not plotted.

(relative to the zero velocity component, i.e., the strongest absorption feature), and their Doppler parameter ($b = 2\sigma$). The column densities of the absorbing material of each component as function of their relative velocities are plotted in Figure 2.

3. Discussion and Conclusions

The SN Ia sample displays sodium absorption features with a strong preference for blueshifted structures. It is highly improbable that these features arise from absorption in the ISM. Such absorption should have a uniform distribution, as is seen in the Galactic samples (where the absorbing material is known to be ISM). The probability of the SN Ia distribution being a random draw from a uniform one is low, 2.23% [0.54%]. A K-S test rejects the null hypothesis that the SN Ia and MW samples are from the same parent distribution at a 1% significance level. Lastly, absorption due to ISM should also correlate with host galaxy inclination, a correlation that is not displayed by our sample (see Figure 3).

Galactic winds are thought to occur due to the galactic fountain process (Shapiro & Field 1976; Bregman 1980). Sodium is a good tracer of neutral gas and should be observed mainly in the later stages of the galactic fountain, i.e., when the gas is falling back onto the galactic disk. Thus, we would expect to observe a preference for redshifted features. Galactic outflows are observed mainly in galaxies with star formation rate surface density threshold above 0.1 $M_\odot$ yr^{-1} kpc^{-2} and are rare in local ordinary disk galaxies (Weiner *et al.* 2009, and references therein). The SN Ia blueshifted preference is inconsistent with such outflows.

If most of the SNe Ia in our sample are “prompt” events, they could have exploded inside cavities excavated by stellar winds of massive stars (formed in the same star formation event). Absorption features would be blueshifted as we would be observing the SNe through the expanding shell of these cavities. However, even in spirals, SNe Ia do not follow massive stars as traced by H II regions (James & Aderson 2006), rendering this scenario highly improbable.

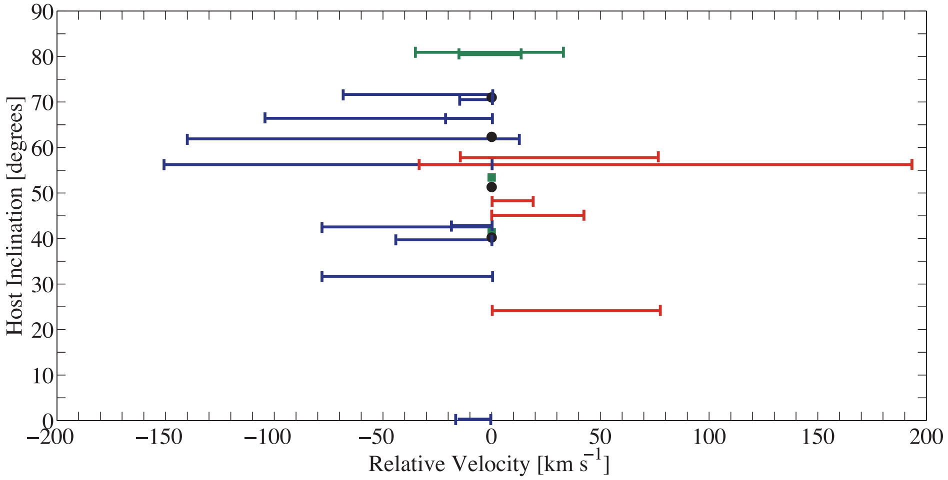

Figure 3. Host inclination vs. relative velocity span of the features in the SN Ia sample.

The sodium absorption features are not consistent with properties of the host galaxies or the environment of the SNe Ia. They are inherent features of the SNe themselves. The absorption features are narrow and relatively slow, inconsistent with properties of SN ejecta, but consistent with absorption arising from material expelled from the progenitor system prior to the SN explosion. i.e., CSM. Our interpretation gains support from a recent study of the symbiotic recurrent novae system RS Ophiuchi showing that a SD system can produce very similar absorption features (Patat *et al.* 2011). Our findings are consistent with a SD progenitor system (Hachisu, Kato, & Nomoto 1999, 2008) for a substantial fraction of SNe Ia in nearby spiral galaxies. Based on the blueshifted preference displayed in our sample a naive lower limit estimate of this fraction (due to a possible viewing angle dependency) is ∼25%.

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