INTERSTELLAR SODIUM AND CALCIUM ABSORPTION TOWARD SN 2011dh IN M51

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ABSTRACT

We present high-resolution echelle observations of SN 2011dh, which exploded in the nearby, nearly face-on spiral galaxy M51. Our data, acquired on three nights when the supernova was near maximum brightness, reveal multiple absorption components in Na i D and Ca ii H and K, which we identify with gaseous material in the Galactic disk or low halo and in the disk and halo of M51. The M51 components span a velocity range of over 140 km s\(^{-1}\), extending well beyond the range exhibited by H\(\alpha\) emission at the position of the supernova. Since none of the prominent Na i or Ca ii components appear to coincide with the peak in H\(\alpha\) emission, the supernova may lie just in front of the bulk of the H\(\alpha\) disk. The Na i/Ca ii ratios for the components with the most extreme positive and negative velocities relative to the disk are \(\sim\)1.0, similar to those for more quiescent components, suggesting that the absorption originates in relatively cool gas. Production scenarios involving a galactic fountain and/or tidal interactions between M51 and its companion would be consistent with these results. The overall weakness of Na i D absorption in the direction of SN 2011dh confirms a low foreground and host galaxy extinction for the supernova.

Key words: galaxies: individual (NGC 5194) – galaxies: ISM – ISM: abundances – ISM: atoms – supernovae: individual (SN 2011dh)

Online-only material: color figure

1. INTRODUCTION

Bright supernovae (SNe) occurring in external galaxies afford a unique opportunity to probe the structure of interstellar gas in the Galactic halo as well as in the supernova host galaxy through high-resolution, absorption-line spectroscopy. In recent decades, a number of supernovae have been used in this manner, providing insights into the characteristics of gaseous material in nearby galaxies, in the intergalactic medium, and in Galactic high-velocity clouds, or HVCs (e.g., Jenkins et al. 1984; D’Odorico et al. 1989; Steidel et al. 1990; Meyer & Roth 1991; Bowen et al. 1994, 2000; Vladilo et al. 1994; Ho & Filippenko 1995; King et al. 1995).

The recent discovery of the Type IIb SN 2011dh in M51 (Arcavi et al. 2011; see also Griga et al. 2011; Silverman et al. 2011), which reached a maximum brightness of \(V \approx 12.5\), presented us with the chance to acquire high-resolution spectra to search for interstellar absorption lines in the direction of the supernova. This particular supernova is significant in that it is the third such object to be detected in M51 (the Whirlpool Galaxy; NGC 5194) within the past 20 years, following the discoveries of SN 2005cs (a Type IIP) and SN 1994I (a Type Ic). Ho & Filippenko (1995) obtained high-resolution observations of SN 1994I, finding numerous strong absorption components of Na i D associated with interstellar gas in M51, along with components of more moderate strength, some identified with the disk of our Galaxy and others likely identified as HVCs belonging to either our Galaxy or M51.

In this Letter, we report on high-resolution observations of Na i D and Ca ii H and K absorption along the line of sight to SN 2011dh, which exploded at an apparent position 2\(\alpha\) E and 1.5\(\alpha\) S of the nucleus of M51 (Van Dyk et al. 2011). This corresponds to a projected distance of 6.1 kpc, assuming the distance to M51 is 8.0 Mpc (as listed in the NASA/IPAC Extragalactic Database\(^1\)). The positions of SN 2011dh and SN 1994I (which was located 0.3 or 0.7 kpc from the nucleus) are separated by only 2.3\(\alpha\) on the sky. Thus, by comparing our results with those of Ho & Filippenko (1995), we are able to simultaneously probe small-scale structure in the Galactic disk and halo and galactic-scale structure in the interstellar medium (ISM) of M51.

2. OBSERVATIONS AND DATA REDUCTION

Our data were acquired with the Astrophysical Research Consortium (ARC) 3.5 m telescope at Apache Point Observatory (APO), using the echelle spectrograph, which provides complete wavelength coverage in the range 3800–10200 Å with a resolving power of \(R \approx 31,500\) (\(\Delta \lambda \approx 9.5 \text{ km s}^{-1}\)). Three 30 minute exposures of SN 2011dh were obtained on 2011 June 9, one on 2011 June 13, and three more on 2011 June 20 (all dates are given in UT), during which time the supernova increased from \(V \approx 13.2\) to \(V \approx 12.6\). Evidently, our observations on June 20 were made shortly before maximum brightness. The bright, nearby star \(\eta\) UMa (B3 V; \(V = 1.85\)) was also observed on June 9 and 20 to aid in the removal of telluric absorption lines in the spectrum of SN 2011dh.

The raw exposures were reduced using a semi-automated pipeline reduction procedure, which employs standard IRAF routines for bias correction, cosmic-ray removal, scattered-light subtraction, one-dimensional spectral extraction, flat-fielding, and wavelength calibration. The reduction procedure is based on the IRAF Data Reduction Guide for the ARC Echelle Spectrograph written by J. Thorburn.\(^2\) Atmospheric absorption lines were removed from individual, calibrated exposures of SN 2011dh with the IRAF taskTelluric using \(\eta\) UMa as the telluric standard. This procedure accounts for differences in airmass as well as in the abundances of telluric species between the standard spectrum and the exposure being corrected (see Figure 1 for a demonstration of the effectiveness of the telluric line removal procedure in the vicinity of Na i D). The corrected spectra were

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\(^1\) http://ned.ipac.caltech.edu/

\(^2\) http://www.apo.nmsu.edu/arc35m/instruments/ARCES/
then shifted to the reference frame of the local standard of rest (LSR) and the individual exposures were co-added to produce a final, high signal-to-noise ratio (S/N) spectrum of SN 2011dh. The S/N ranges from $\sim$110 near 5900 Å to $\sim$40 near 3900 Å.

The only interstellar absorption features positively identified in our final spectrum of SN 2011dh are those of the Na I D ($\lambda$5895; $\lambda$5889) and Ca II H ($\lambda$3968) and K ($\lambda$3933) doublets. The overlapping echelle orders containing these lines were combined to improve the S/N and the resulting spectra were normalized to the relatively featureless continuum. As seen in Figure 2, we detect Na I and Ca II absorption both from the Milky Way (near $V_{LSR} = 0$ km s$^{-1}$) and from M51 (near the M51 systemic velocity of $V_{LSR} = 468$ km s$^{-1}$; Walter et al. 2008, applying a heliocentric-to-LSR velocity correction of 12 km s$^{-1}$). Given the overall weakness of these features, it is not surprising that other optical absorption lines, such as K i $\lambda$7698, Ca i $\lambda$4226, CH $^+$ $\lambda$4232, and CH $\lambda$4300, are not detected. However, we are unable to search for K i $\lambda$7698 absorption at the redshift of M51 due to the presence of strong night sky emission lines at the same wavelengths.

Before analyzing the final combined spectrum of SN 2011dh, we compared the nightly co-added spectra from June 9 and 20—the two nights on which we have the best S/N due to our having obtained multiple exposures—in order to search for variations in the absorption profiles. A variable component might be expected if the absorption originates in circumstellar material associated with the progenitor of SN 2011dh, which gets swept up in the supernova blast wave. Upon careful inspection, we find no evidence for significant variation in any of the Na I or Ca II components. Thus, the results of this Letter are based solely on the analysis of the combined spectrum.

### 3. ANALYSIS

The interstellar Na I and Ca II absorption profiles toward SN 2011dh were analyzed by means of the profile fitting routine ISMOD (Y. Sheffer, unpublished), which fits multiple Voigt components to the observed spectrum, convolving the intrinsic line profile with an instrumental profile, assumed to be Gaussian in shape. Using a simple rms-minimizing technique, ISMOD determines best-fit values for the velocity, $b$-value, and column density of each component. Since the absorption features are relatively weak, line saturation is not a major concern for these data. Only the Na I component near $V_{LSR} = -30$ km s$^{-1}$, which presumably arises from gas within the Milky Way, shows significant optical depth at line center. For this component, the ratio of the Na I D$_2$ to D$_1$ equivalent widths is 1.2 (as opposed to 2.0 in the optically thin case) and implies a Doppler width of $b = 2.1 \pm 0.2$ km s$^{-1}$. In order to derive an accurate column density for this mildly saturated component, the $b$-value was held fixed at 2.1 km s$^{-1}$ in the profile fit for both the D$_2$ and D$_1$ lines.

Our analysis of Ca II absorption toward SN 2011dh rests mostly on the Ca II K line, because the weaker H components are strongly affected by noise in the spectrum. We initially fit the Na I D and Ca II K profiles by focusing on the prominent components seen in both species. Ultimately, we were required to include additional components to account for the extra Ca II absorption surrounding the main Galactic component and to fill in gaps between the stronger Na I and Ca II components associated with M51. To aid in the process of decomposing the blended profiles, the $b$-values were constrained to fall within certain limits consistent with ultra-high-resolution surveys of the Galactic ISM (e.g., Welty et al. 1994, 1996). We note, however, that $b$-values derived in this study are more appropriately referred to as "effective" $b$-values since at our resolution ($\Delta v \sim 9.5$ km s$^{-1}$) unresolved substructure almost certainly exists in the data. The results of fitting the Ca II K line were then applied to Ca II H to check for consistency, holding the relative velocities, $b$-values, and fractional column densities fixed.

Table 1 presents the Na I and Ca II equivalent widths (and 1σ uncertainties) derived from our profile fits to these lines (see Figure 2). In Table 2, we give the fitted column density and $b$-value of each Na I D and Ca II K component along with the mean LSR velocity. In most cases, the uncertainties in $N$ reflect the uncertainties in $W_{\lambda}$, which are based on the rms deviations in the continuum and the widths (FWHM) of the absorption features. These uncertainties effectively include both photon noise and errors in continuum placement. For the Na I
Figure 2. Normalized high-resolution spectra of SN 2011dh in the vicinity of the Na I D and Ca II H and K lines. Synthetic absorption profiles (red curves) are shown superimposed onto the observed spectra (black lines). Dotted features denote overlap in the Na I D lines. Tick marks indicate the positions of the fitted components. Vertical dotted lines mark the local rest velocity of the Galaxy ($v_{LSR} = 0$ km s$^{-1}$) and the systemic velocity of M51 ($v_{LSR} = 468$ km s$^{-1}$). (A color version of this figure is available in the online journal.)

Table 2

| Comp. No. | $v_{LSR}$ (km s$^{-1}$) | Na I D$_2$ | Ca II K |
|-----------|-------------------------|------------|---------|
|           | $b$ (km s$^{-1}$)       | $b$ (km s$^{-1}$) | $b$ (km s$^{-1}$) | $b$ (km s$^{-1}$) | $b$ (km s$^{-1}$) | $b$ (km s$^{-1}$) | $b$ (km s$^{-1}$) | $b$ (km s$^{-1}$) |
| Milky Way | Na I D$_1$ | Na I D$_1$ | Na I D$_1$ | Ca II K | Na I D$_1$ | Na I D$_1$ | Na I D$_1$ | Na I D$_1$ | Na I D$_1$ | Na I D$_1$ |
| 1         | -61.9 ± 1.5            | ...        | ...        | ...        | < 10.4     | 3.8        | 11.31 ± 0.08 | 11.72 ± 0.04 | 5.7 ± 1.0 |
| 2         | -49.0 ± 1.5            | ...        | ...        | ...        | < 10.4     | 3.8        | 11.61 ± 0.04 | 11.50 ± 0.06 | < 0.1    |
| 3         | -29.6 ± 0.2            | 2.1        | 12.48 ± 0.14 | 2.1        | 12.48 ± 0.07 | 12.48 ± 0.06 | 3.8        | 11.72 ± 0.04 | 11.72 ± 0.04 | 5.7 ± 1.0 |
| 4         | -12.9 ± 1.5            | ...        | ...        | ...        | < 10.4     | 2.1        | 11.50 ± 0.06 | 11.50 ± 0.06 | < 0.1    |
| 5         | -0.4 ± 1.5             | ...        | ...        | ...        | < 10.4     | 2.1        | 11.55 ± 0.05 | 11.55 ± 0.05 | < 0.1    |
| M51       | 6                      | +445.2 ± 1.5 | 2.6       | 10.85 ± 0.06 | 10.93 ± 0.09 | 10.86 ± 0.05 | ...        | < 11.0     | 11.66 ± 0.04 | 0.7 ± 0.1 |
| 7         | +473.7 ± 1.0           | 2.1        | 11.52 ± 0.02 | 2.6        | 11.57 ± 0.02 | 11.53 ± 0.01 | 2.1        | 11.66 ± 0.04 | 0.7 ± 0.1 |
| 8         | +482.0 ± 0.3           | 0.5        | 10.92 ± 0.06 | 1.3        | 10.90 ± 0.09 | 10.92 ± 0.05 | 3.8        | 11.29 ± 0.08 | 0.4 ± 0.1 |
| 9         | +498.0 ± 1.5           | 0.6        | 10.58 ± 0.10 | 0.5        | 10.72 ± 0.13 | 10.61 ± 0.08 | 3.8        | 11.42 ± 0.07 | 0.2 ± 0.1 |
| 10        | +508.8 ± 2.8           | 2.4        | 11.25 ± 0.02 | 2.6        | 11.27 ± 0.04 | 11.25 ± 0.02 | 3.8        | 11.21 ± 1.0  | 1.1 ± 0.3 |
| 11        | +523.2 ± 5.0           | 2.1        | 10.58 ± 0.10 | 1.4        | 10.48 ± 0.20 | 10.56 ± 0.09 | 1.2        | 11.13 ± 0.11 | 0.3 ± 0.1 |
| 12        | +540.3 ± 0.2           | 2.6        | 11.37 ± 0.02 | 2.6        | 11.34 ± 0.04 | 11.37 ± 0.02 | 1.0        | 11.54 ± 0.06 | 0.7 ± 0.1 |
| 13        | +587.4 ± 0.8           | 1.4        | 11.05 ± 0.04 | 1.9        | 11.16 ± 0.05 | 11.08 ± 0.03 | 2.1        | 11.07 ± 0.12 | 1.0 ± 0.3 |

Notes: Upper limits on column densities for nondetections are 3$\sigma$.

a Mean (and 1$\sigma$ standard deviation) of the velocities found in Na I D$_2$ and Ca II K.

b Weighted mean of the column densities derived from the Na I D$_2$ and D$_1$ lines.

component near $v_{LSR} = -30$ km s$^{-1}$, the column density uncertainties also include the effects of varying the b-value within the range allowed by the errors in the doublet ratio. Final Na I column densities were determined by taking the weighted mean of the column densities derived from the D$_2$ and D$_1$ lines, while for Ca II we simply adopted the more precise results from Ca II K. The agreement with column densities from Ca II H is at the 10% level or better. The last column of Table 2 presents the N(Na I)/N(Ca II) ratio (or limits on the ratio) for each of the Milky Way and M51 components.

We find total Na I D$_2$ and D$_1$ equivalent widths of 180.1 ± 5.0 mA and 106.2 ± 5.1 mA, respectively, for the features associated with M51. These values are in good agreement with those reported by Arcavi et al. (2011), which were obtained from Keck High Resolution Echelle Spectrometer data. As those authors noted, such weak absorption in the Na I D lines indicates...
very little host galaxy extinction in the direction of SN 2011dh, probably less than the Galactic foreground extinction, which corresponds to an interstellar reddening of $E(B - V) = 0.035$ (Schlegel et al. 1998).

4. DISCUSSION

An exciting aspect of this investigation is our ability to compare high-resolution optical spectra of two supernovae from the same external galaxy, allowing us to examine structure in the Galactic disk and halo at small angular scales as well as in the ISM of M51 at scales of several kiloparsecs. A comparison between our NaI D results for SN 2011dh and those of Ho & Filippenko (1995) for SN 1994I reveals both similarities and differences between the two lines of sight, which are separated by only 2.3° on the sky (near Galactic coordinates $l = 105°$, $b = 69°$).

Both investigations find a strong Galactic NaI component at $v_{LSR} \approx -30$ km s$^{-1}$ (system 1 in the nomenclature of Ho & Filippenko 1995), which likely originates from relatively nearby gas, since there is very little difference in the NaI column density between the two sight lines. The $N$(NaI)/$N$(CaII) ratio for this component ($5.7 \pm 1.0$) is indicative of a high degree of Ca depletion, a characteristic of cool diffuse clouds at relatively low velocities (Siluk & Silk 1974; Hobbs 1983). Indeed, the LSR velocity of the component is consistent with the expected velocity of gas participating in Galactic rotation at $l = 105°$ (e.g., Sembach & Danks 1994). We do not detect the weaker Galactic component at $v_{LSR} \approx 0$ km s$^{-1}$ (system 2 in Ho & Filippenko) in NaI, but do observe this component, and other Galactic components at more negative velocities, in CaII. These additional Galactic components have only upper limits on $N$(NaI)/$N$(CaII)—suggesting low ratios ($<0.1$)—and so presumably trace warmer gas, where Ca depletion is not as severe or where much of the neutral Na has been destroyed through collisional ionization.

Along with absorption components identified as belonging to the Milky Way, we find several components in NaI and CaII toward SN 2011dh with $v_{LSR} \approx 450$--590 km s$^{-1}$. These are almost certainly associated with interstellar gas in M51, as are the much stronger NaI components that Ho & Filippenko (1995) detect in the spectrum of SN 1994I with $v_{LSR} \approx 380$--510 km s$^{-1}$ (their systems 6--14). Since SN 1994I occurred near the nucleus of M51, while SN 2011dh exploded in one of the outer spiral arms (see Figure 1 in Arcavi et al. 2011), the large difference in total NaI column density between the portions of M51 probed by the two lines of sight is understandable. Like many spiral galaxies, the inner region of M51 exhibits only weak Hβ emission (Filippenko 1995), which likely originates from relatively nearby gas, since there is very little difference in the NaI column densities in maps of the ISM of M51 at scales of several kiloparsecs. A comparison between our NaI D results for SN 2011dh and those of Ho & Filippenko (1995) for SN 1994I reveals both similarities and differences between the two lines of sight, which are separated by only 2.3° on the sky (near Galactic coordinates $l = 105°$, $b = 69°$).

The strongest M51 component in our NaI and CaII data for SN 2011dh has a velocity of $v_{LSR} \approx 474$ km s$^{-1}$ (component 7), which is close to the adopted recessional velocity of the galaxy of 468 km s$^{-1}$. At the apparent position of SN 2011dh, however, the velocity exhibited by disk gas should be significantly higher than the systemic velocity due to the inclination of M51 ($i = 42°$; Tamburro et al. 2008). The velocity field (moment 1 map) provided by The H1 Nearby Galaxy Survey (THINGS; Walter et al. 2008) indicates a mean H1 velocity of $v_{LSR} \approx 524$ km s$^{-1}$ at the supernova position. The corresponding H1 emission profile exhibits a single narrow (FWHM $\approx 18$ km s$^{-1}$) peak at this velocity, with no prominent emission at the velocity of component 7 (see Figure 3).

Adopting the mean H1 velocity from THINGS as the local disk velocity at the position of the supernova, the observed absorption from M51 ranges from $v - v_{disk} \approx -79$ km s$^{-1}$ (component 6) to $+63$ km s$^{-1}$ (component 13). The velocity dispersion in NaI is $\sim 39$ km s$^{-1}$, and $\sim 33$ km s$^{-1}$ in CaII. Both are larger than the H1 velocity dispersion, which is $\sim 20$ km s$^{-1}$ at the supernova position (based on the THINGS moment 2 map). The fact that we are detecting more components in NaI and CaII than are detected via H1 emission—and detecting them over a broader range in velocity—is most likely related to the limited sensitivity of the H1 observations. The column density detection limit in THINGS channel maps of M51 is log $N$(H1) $\sim 20.1$ (for a 3σ detection in at least two channels; see Walter et al. 2008). For comparison, the NaI column densities of components 6--13 imply H1 column densities in the range log $N$(H1) $\sim 19.8$--20.2, indicating that much of this H1 would be undetectable. In contrast, the H1 emission actually detected by THINGS at the position of SN 2011dh yields log $N$(H1) $= 20.6 \pm 0.1$. If the supernova were positioned behind this material, we would expect to see NaI absorption with a column density approaching log $N$(NaI) $\sim 12.3$.

Still, the $N$(NaI)/$N$(CaII) ratios exhibited by the M51 components are similar to those seen in disk clouds of the Milky Way (e.g., Sembach & Danks 1994) and in the disks of other external galaxies that have been probed by bright supernovae (e.g., Bowen et al. 2000). The components with higher NaI column densities generally have higher $N$(NaI)/$N$(CaII) ratios, and at least two components have $N$(NaI)/$N$(CaII) $\gtrsim 1$, an indication that the absorption originates in relatively cool gas (see, e.g.,

3 These estimates are based on the roughly quadratic relationship between $N$(NaI) and $N_{H2}$(H) discussed by Welty & Hobbs (2001), and the assumption that virtually all of the hydrogen is in neutral atomic rather than molecular form, as also implied by the NaI column densities. By applying these relationships, we implicitly assume that the metallicity and radiation field in the M51 foreground are similar to typical Galactic values.
Bertin et al. (1993). Interestingly, we find similar ratios (of order unity) in both quiescent gas, with \(|v - v_{\text{disk}}| < 20 \text{ km s}^{-1}\), and higher-velocity clouds, with \(|v - v_{\text{disk}}| \gtrsim 50 \text{ km s}^{-1}\), contrary to expectations based on the Routly–Spitzer effect (Routly & Spitzer 1952). Rather than showing evidence for enhanced grain destruction in high-velocity material, our results indicate that a similar degree of Ca depletion characterizes both quiescent and high-velocity gas in the portion of M51 sampled by this particular line of sight. The higher-velocity material may not have originated very far from the disk, however, since the components have \(|v - v_{\text{disk}}| < 100 \text{ km s}^{-1}\). These velocities are similar to those of intermediate-velocity clouds (IVCs) in the Milky Way, which are usually found within \(-5 \text{ kpc}\) of the Galactic plane (e.g., Wakker et al. 2008).

Typical scenarios invoked to explain the origin of Galactic HVCs and IVCs include a Galactic fountain, tidal stripping from a companion galaxy, and accretion from the intergalactic medium, among others (see Wakker & van Woerden 1997; Richter 2006). Since most of the Galactic IVCs have solar metallicities (Wakker 2001; Richter et al. 2001), their origin can most easily be explained within the context of the Galactic fountain model, in which hot gas is injected into the halo by supernova explosions and then cools and falls back onto the disk. A similar process may be responsible for the relatively cool cloud we find in the direction of SN 2011dh with a high positive velocity, which indicates that it is falling toward the disk of M51. On the other hand, tidal interactions between M51 and its companion (NGC 5195) may have played a role in generating the high-velocity dispersion we observe in Na\(\text{I}\) and Ca\(\text{II}\). Tidal effects may be particularly important for explaining the origin of Na\(\text{I}\) components with high negative velocities, since in the outflow stage of the galactic fountain process the gas is expected to be mostly ionized (Fraternali et al. 2004). Multiple processes may be occurring simultaneously. Indeed, Miller & Bregman (2005) invoke both galactic fountain and tidal stripping scenarios to explain deep Very Large Array observations of M51, which reveal a number of discrete H\(\text{I}\) sources with anomalous velocities.

An interesting result of Ho & Filippenko’s (1995) study of SN 1994I was their detection of Na\(\text{I}\) components at velocities intermediate between those expected for gas associated with the Milky Way and M51 (i.e., \(v_{\text{LSR}} \approx 255–310 \text{ km s}^{-1}\); their systems 3–5). The authors attributed this absorption to HVCs, but could not distinguish between an origin in the Galactic halo or in the halo of M51, since the velocities of the clouds with respect to the overall systemic velocity of the galaxy to which they belong would be similar in either case. We detect no Na\(\text{I}\) or Ca\(\text{II}\) absorption features in this velocity range toward SN 2011dh (just 2′3 away), indicating that if the clouds indeed have a Galactic origin, they exhibit significant structure on small scales.

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