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PROBING THE INTERSTELLAR MEDIUM ALONG THE LINES OF SIGHT TO SUPERNOVAE SN 1994D AND SN 1994I[1]

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ABSTRACT

We present high-resolution ($\sim$8 km s^{-1}) echelle observations of SN 1994D and 1994I covering the optical Na D interstellar absorption lines and the region around Hα. The high-quality spectra reveal a complex pattern of Na D absorption systems along the path to both supernovae. The velocity systems can be identified with contributions from the Galactic disk, the host galaxy of each supernova, and absorbing material having "anomalous" velocities inconsistent with simple rotation within our Galaxy or the respective host galaxies.

The anomalous velocity gas along the line of sight to SN 1994D may be intergalactic in origin and is infalling toward NGC 4526, the Virgo cluster host galaxy of SN 1994D. We consider several hypotheses for the anomalous velocity systems seen toward SN 1994I. The most likely explanation is that they are optical counterparts of "high-velocity clouds," normally studied in 21 cm emission, associated with either the Galactic halo or the halo of the host galaxy NGC 5194 (M51). These metal-bearing, low-column density clouds may be much more common than previously thought. At least some metal-line QSO absorption systems may be associated with high-velocity clouds in the halos of intervening galaxies.

We use the derived Na column densities to estimate the extinction of the two supernovae. For SN 1994D, we obtain $A_V = 0.08^{+0.08}_{-0.04}$ mag, consistent with independent estimates based on considerations of the supernova colors near maximum brightness. Several complications conspire to make the extinction estimate for SN 1994I very uncertain. Our best estimate yields $A_V = 3.1^{+3.1}_{-1.5}$ mag, although there are reasons to believe that the true extinction is $\lesssim$1.4 mag.

Finally, we note that no narrow Hα emission or absorption is detected to 2 σ equivalent width limits of 3 mÅ in the spectrum of SN 1994D, a Type Ia supernova. Unfortunately, this observation does not provide very significant constraints on models of the progenitor; SN 1994D was observed $\sim$3 weeks after maximum brightness, by which time little if any Hα would be expected even if circumstellar hydrogen were present.

Subject headings: galaxies: individual (NGC 4526, NGC 5194) — ISM: abundances — supernovae: individual (SN 1994D, SN 1994I)

1. INTRODUCTION

Supernovae in external galaxies provide useful beacons with which to investigate the interstellar medium (ISM) along their lines of sight, allowing us to probe the kinematics and composition of the gas and dust in the Galaxy, in intergalactic space, and in the host galaxies of the supernovae themselves. The lack of many narrow features in the spectra of supernovae, coupled with their high luminosity (especially near maximum brightness in their light curves), make them ideally suited as background "continuum" sources onto which interstellar absorption lines may be imprinted. Together with a few suitable active galactic nuclei (e.g., West et al. 1985; Morton & Blades 1986), this technique has been applied to a handful of supernovae (D'Odorico, Pettini, & Ponz 1985; Rich 1987; Vidal-Madjar et al. 1987; D'Odorico et al. 1989; Steidel, Rich, & McCarthy 1990; Meyer & Roth 1991; Bowen et al. 1994).

The availability of two recently discovered, nearby supernovae, the Type Ia SN 1994D in NGC 4526 (Treffers et al. 1994) and the Type Ic SN 1994I in NGC 5194 = M51 (Phillips 1994; Clocchiatti et al. 1994; Wheeler et al. 1994), offered a ripe opportunity to further pursue such investigations. Here we report on high-resolution optical spectra of these objects. Both targets were relatively bright at the time of our observations, allowing us to attain high signal-to-noise ratios (S/N). We derive extinction estimates based on interstellar absorption lines of the Na D doublet, discuss the implication of these measurements for the dust composition and metallicity of the ISM in the host galaxies, and investigate the nature of the kinematic features detected. Gas with anomalous velocities observed toward SN 1994I may lend insight into the origin of QSO metal-line absorption systems.

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2. OBSERVATIONS AND DATA REDUCTION

The data were obtained on 1994 April 14 UT using the HIRES echelle spectrometer (Vogt 1992, 1994) with the W. M. Keck 10 m telescope on Mauna Kea, Hawaii. SN 1994D was at $V \approx 13.3$ mag, $\sim$23 days after maximum brightness ($V_{max} \approx$ 11.8 mag; Richmond et al. 1994), and SN 1994I was comparably bright, $V \approx 13.4$ mag roughly 5 days after maximum ($V_{max} \approx 12.8$ mag; Filippenko et al. 1995).

Since the CCD employed (Tektronics 2048 × 2048 square pixels, pixel size 24 μm) only covers a portion of the full spectral range, we carefully selected the echelle and cross disperser grating angles to position the spectral features of interest on the CCD. This was achieved using the "HIRES Spectral Format Simulator" (Vogt 1994) prior to the observing run. The setup chosen for these observations spanned the region 4240–6720 Å in 31 spectral orders; small gaps in the coverage were present for $\lambda \gtrsim 5100$ Å. A KV408 order blocking filter was used to cut off second-order blue light. As we were mainly interested in detecting the Na D doublet (D2 = 5889.950 Å, D1 = 5895.924 Å), we ensured that these lines fell on a cosmetically clean portion of the chip. Unfortunately, it was impractical to include the Ca II H and K lines in our observing program. We chose the "C5" slit decker to prevent overlapping orders as well as to provide adequate sky background, yielding a slit with dimensions 1″.15 × 7″ and a spectral resolution of $R = 38{,}000$. (The comparison lamp emission lines near Na D had an average full width at half-maximum [FWHM] of 0.16 Å, or ~7.9 km s^{-1}.) We binned the chip 1 × 2 (spectral × spatial dimension) in order to decrease the effective readout noise; each binned pixel then subtended ~0″.41 on the sky, with a readout noise of ~5 electrons. Bias frames were taken at the beginning and end of the night to confirm the stability of the chip, and we verified that the dark current was negligible.

SN 1994D and SN 1994I were exposed for a total of 1800 and 1200 s, respectively, the exposure time being divided into two integrations per supernova in order to facilitate rejection of cosmic rays during the data reduction (see below). To enable identification and removal of telluric lines in the spectra of the program objects, we also observed the sdF5 star HD 84937 (Oke & Gunn 1983), whose spectrum has relatively few features. Since neither an image rotator nor an atmospheric dispersion compensator are currently available on HIRES, some light losses probably resulted from atmospheric dispersion because the position angle of the slit was generally not at the parallactic angle (Filippenko 1982); however, this effect should not be too severe, given that the objects were observed at relatively low air masses (~1.4–1.5 for SN 1994D, ~1.35–1.4 for SN 1994I). The sky was photometric during the entire night, but the seeing was ~1″.2–1″.3, worse than usual on Mauna Kea.

Data reduction followed standard procedures in IRAF.[4] After trimming excess pixels and removing the bias level of the chip, pixel-to-pixel gain variations in the two-dimensional spectra were removed through division by a spectrum of an internal quartz lamp obtained close in time to the program object exposure. The spectral orders of the quartz exposure were first normalized by fitting a low-order polynomial along the dispersion. Despite the relatively short exposure times, cosmic rays contaminated a significant number of pixels. We successfully removed the cosmic rays with an algorithm which replaced each corrupted pixel in one exposure by the corresponding, uncorrupted pixel in the redundant exposure. One-dimensional spectra of each order were extracted by summing five pixels (effective aperture 1″.15 × 2″.05) centered on a polynomial fit to the centroid of the light distribution along the dispersion; an average of the median values on either side of the extraction window represented the background level. We calibrated the wavelength scale using exposures of thorium and argon hollow cathode comparison lamps. A third-order polynomial fit to the lines identified in the list given by Willmarth (1987) yielded a wavelength solution with a dispersion of ≈0.003 Å (1 σ), or 0.15 km s^{-1} at the wavelength of Na D. Finally, the spectra were normalized to unity by fitting a low-order spline function to the continuum.

[4] IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

3. RESULTS

3.1. *The Na D Absorption Systems*

The final, calibrated spectra of the region encompassing the Na D doublet for SN 1994D and SN 1994I are shown in Figures 1*a* and 1*b*, respectively. The two exposures have been summed, and, for the purposes of the display, each pixel has been binned to a constant resolution of 0.08 Å The wavelengths have been converted to the heliocentric frame, after removing the Earth's motion (−9.99 km s^{-1} for SN 1994D and −9.27 km s^{-1} for SN 1994I). In each panel, the data for the supernova are shown as a histogram in the solid line, while the theoretical line profiles (discussed below) used to fit the data are shown as a dashed line. Individual velocity systems (see Table 1) are labeled by tick marks near the bottom of each panel. To illustrate that spectral features of interest are not severely contaminated by telluric lines, mainly attributable to H_2O in the Na D region, we plotted the spectrum of the standard star, HD 84937, at the top of each panel as a solid curve. Known telluric features (Sembach, Danks, & Savage 1993; Lallemet et al. 1993) in this spectral region are marked above the standard star spectrum to guide the eye. The quality of the spectra is quite high: the approximate S/N per pixel of the continuum in the region shown ranges from 90 to 100 for SN 1994D and from 80 to 100 for SN 1994I. The equivalent width detection limit of each component of the Na D doublet is ~3 mÅ (2 σ).

The absorption spectra of both supernovae, in particular SN 1994I, are very complex, each containing multiple velocity systems heavily blended together. Moreover, some of the velocity systems of the main blend in SN 1994I (systems 6–14) are clearly optically thick, as the ratio of the D2 to D1 lines approaches unity. To measure the column densities of Na I of the various systems, we fit the data (unbinned) with theoretical Voigt profiles (see Carswell et al. 1991 for details). Briefly, for each velocity system, a model absorption profile is computed for an initial set of values of the column density, N(Na I), heliocentric velocity, v_h, and Doppler parameter, b $(=2^{1/2}\,\sigma)$. After convolving with the instrumental profile, which is assumed to be a Gaussian having a FWHM equal to that measured for the comparison lamp emission lines, the model profile is compared with the observed profile. Minimization of the χ^2 of the fit yields the optimal values of N(Na I), v_h, and b for each velocity system, as listed in Table 1. To check the results of the profile fitting, we confirmed for SN 1994D that the classical doublet-ratio method (Spitzer 1968), which uses the measured equivalent widths of the doublet to determine column densities, gave essentially identical results under the assumption that the distribution of velocities of the absorbing material is Gaussian in shape. Most of the absorption systems of SN 1994I were not amenable to this comparison, since the doublet-ratio method does not give reliable results for log N(Na I) $\gtrsim$ 13.3 (Strömgren 1948).

We applied several constraints to the fitting procedure to facilitate the profile fitting. First, we fit a minimum number of velocity systems to blends by selecting only those which were at least partially resolved. Second, in cases where the choice for the b value was ambiguous, we chose the largest value which was consistent with the data; an upper limit on b corresponds to a lower limit on the derived values of the column density (Nachman & Hobbs 1973). Finally, we initially fit that component of the Na D doublet which we deemed to be more reliable. In the case of SN 1994D, whose lines are all unsatu-

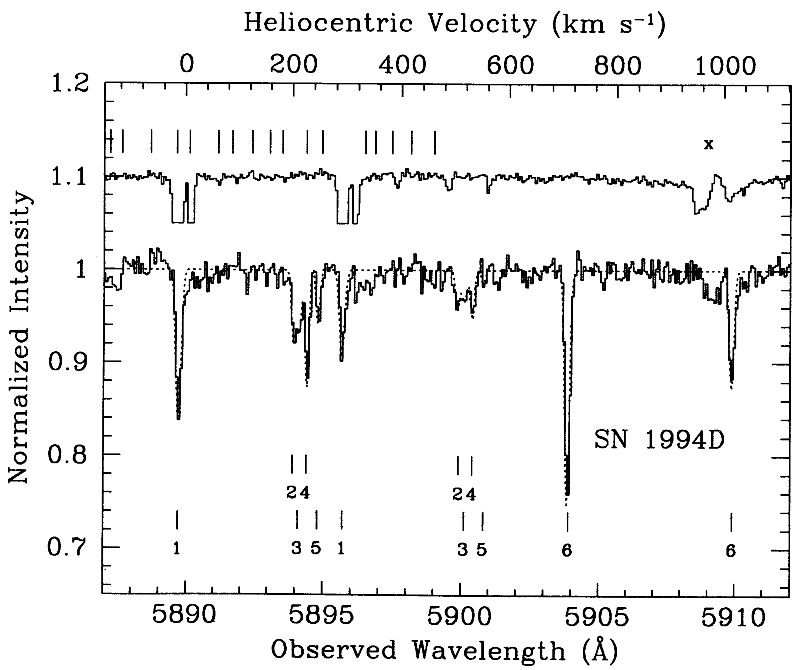

FIG. 1*a*

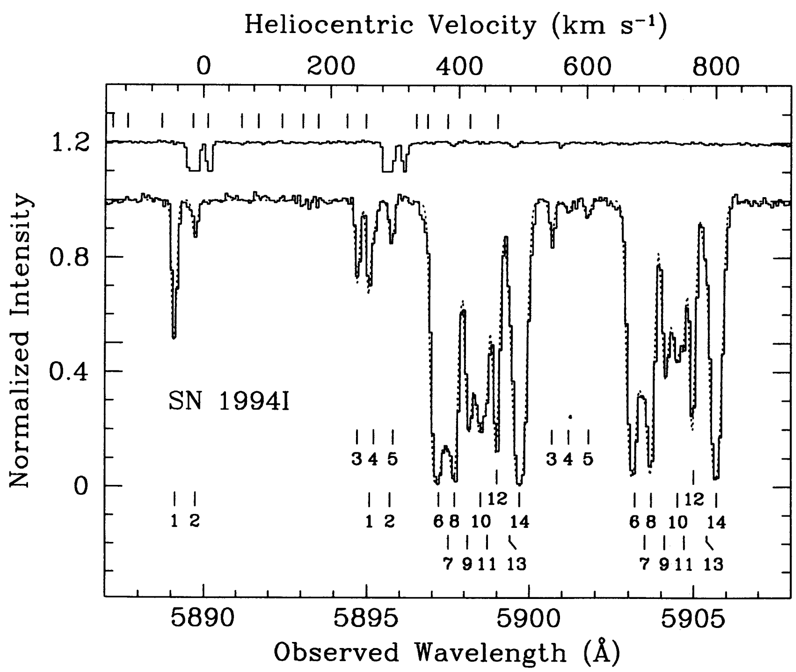

FIG. 1*b*

FIG. 1.—(*a*) Calibrated spectrum of SN 1994D encompassing the Na D region. The ordinate shows the normalized intensity in arbitrary units, the bottom abscissa the wavelength corrected to the heliocentric frame, and the top abscissa the corresponding heliocentric velocity. The D2 component (5889.950 Å) was used to set the velocity scale to zero. For the purposes of the display, the data have been binned to a resolution of 0.08 Å ($\sim$4 km s^{-1}) per pixel. The data for the supernova are shown as a histogram in the solid line, with the model profiles for the absorption systems superposed as a dashed line. The various velocity systems are identified with tick marks near the bottom of the panel. To illustrate that contamination by telluric lines is negligible, we also show the spèctrum of the standard star, HD 84937, at the top of the panel. The interstellar Na D lines in the HD 84937 spectrum have been clipped for clarity. The positions of known telluric features are identified by tick marks. Note that the dip slightly redward of the D1 component of system 6 for SN 1994D and the broad feature blueward of it ($\sim$5909 Å) are caused by a defect on the CCD, as they also appear in the HD 84937 spectrum (slightly shifted due to the different location of the star on the chip). Velocity system 1 is Galactic in origin, systems 2–5 are due to the disk of NGC 4526, and system 6 may be intergalactic gas infalling toward NGC 4526 (see § 3.1 for details). Note that the systemic velocity of NGC 4526 is 448 km s^{-1}. (*b*). Calibrated spectrum of SN 1994I encompassing the Na D region. Labels and convention are the same as in panel (*a*). Systems 1 and 2 originate from the Galactic disk, systems 3–5 are most likely high-velocity clouds from the Galactic halo, and systems 6–14 arise from NGC 5194 (see § 3.1 for details). Note that the systemic velocity of NGC 5194 is 463 km s^{-1}.

TABLE 1

MEASUREMENTS OF THE Na D INTERSTELLAR ABSORPTION LINES

System Number	W_λ(D2) (mÅ)	W_λ(D1) (mÅ)	v_h (km s^{-1})	b (km s^{-1})	log N(Na I) (cm^{-2})	log N(H) (cm^{-2})	A_V (mag)
			SN 1994D				
1............	40±2	24±2	-11.4±0.3	4.9±0.6	11.3±0.1	19.61±0.3	0.021
2............	51±1[a]	27±1[a]	203.3±1.2	2.1±1.0	10.9±0.1	19.22±0.3	0.009
3............			213.8±1.5	4.5±1.0	10.9±0.1	19.22±0.3	0.009
4............			228.1±0.3	0.9±0.8	11.2±0.1	19.51±0.3	0.017
5............	10±1	6±3	248.2±0.6	1.9±1.0	10.8±0.1	19.13±0.3	0.007
6............	56±1	31±2	709.0±0.3	3.8±0.3	11.5±0.1	19.79±0.3	0.032
Galactic (1)					11.3±0.1	19.61±0.3	0.021
NGC 4526 (2-6)					11.8±0.2	20.09±0.7	0.065
Total					11.9±0.2	20.18±0.7	0.079
			SN 1994I				
1............	91±1	54±3	-42.9±0.3	1.4±0.4	12.4±0.4	20.66±0.5	0.24
2............	19±2	16±3	-10.8±0.6	2.7±1.2	11.1±0.1	19.41±0.3	0.01
3............	51±1	28±1	243.1±0.6	1.1±0.4	11.5±0.2	19.79±0.4	0.03
4............	21±3	8±2	268.6±1.2	2.5±1.0	10.9±0.1	19.22±0.3	0.009
5............	14±3	16±1	297.7±0.9	2.0±1.0	11.1±0.1	19.41±0.3	0.01
6............	2265±10[b]	1830±10[b]	367.2±0.3	6.8±0.3	13.1±0.1	19.42±0.3[c]	0.01
7............			383.4±0.9	2.6±0.3	12.4±0.1	20.66±0.3	0.24
8............			395.1±0.3	2.4±0.3	15.1±0.1	21.42±0.3[c]	1.38
9............			418.2±0.3	5.6±0.2	12.4±0.1	20.66±0.3	0.24
10...........			435.6±0.3	8.1±0.4	12.4±0.1	20.66±0.3	0.24
11...........			447.3±1.0	1.8±1.0	12.1±0.1	20.38±0.3	0.13
12...........			460.5±0.3	1.6±0.3	14.6±0.1	20.92±0.3[c]	0.44
13...........			478.5±1.0	2.5±1.0	11.4±0.1	19.70±0.3	0.03
14...........			497.4±0.3	7.5±0.6	13.1±0.1	19.42±0.3[c]	0.01
Galactic (1-2)					12.4±0.4	20.68±0.6	0.25
Halo (3-5)					11.7±0.2	20.02±0.6	0.05
NGC 5194 (6-14)					15.2±0.3	21.71±0.9	2.76
Total					15.2±0.6	21.76±1.2	3.06

[a] Sum of systems 2–4, which are blended together.

[b] Sum of systems 6–14, which are blended together.

[c] N(H) calculated assumig N(Na I) $\approx$ N(Na), a cosmic abundance for Na of 1.9×10^{-6} relative to H, and a depletion of a factor of 4 for Na (see text for details).

rated, we chose the stronger of the two components (D2) because it has a higher S/N. For SN 1994I, we adopted the same strategy for the unsaturated lines, except for instances where the D2 component was blended with another feature, in which case the D1 component was chosen instead. For the nearly saturated complex of lines, the D1 components are more reliable than those of D2, since the former are weaker. In all cases, we repeated the fits using the second doublet component, fixing the value of b to that derived from the initial fit while varying N(Na I) and v_h, in order to verify the robustness of the final solution.

The spectrum of SN 1994D contains at least six velocity systems, all of which are rather weak (Table 1). Because of its low heliocentric velocity ($v_h \approx -11$ km s^{-1}), system 1 most likely originates in the Galaxy. Systems 2–5, with $v_h \approx 200$–250 km s^{-1}, probably arise from the disk NGC 4526, an S0 galaxy with a prominent dust lane. The apparent position of the supernova (9″ W, 7″ N of the nucleus) appears to coincide with the *front* side of the disk. Given that the inclination of NGC 4526 is $\sim 77°$ (calculated using the formula given in Aaronson, Mould, & Huchra 1980 for an axial ratio of 0.33, as listed in de Vaucouleurs et al. 1991 [hereafter RC3]), and its major axis lies along position angle 113° (RC3), we find that SN 1994D is ~ 1.4 kpc from the nucleus, assuming that it indeed lies in the disk and adopting a distance of 16.8 Mpc (Tully 1988). The rotational velocity of NGC 4526, as measured through the 21 cm line, is 255 km s^{-1} (RC3). Subtracting the corresponding radial velocity component (~ 240 km s^{-1}) from the systemic velocity of NGC 4526 ($v_h \approx 448$ km s^{-1}; RC3), therefore, naturally accounts for the observed velocities of systems 2–5. The velocity of system 6 ($v_h \approx 709$ km s^{-1}) seems anomalously large if it belongs to NGC 4526. Since the expected velocities near the position of the supernova should be in the range of 200–250 km s^{-1} (as for systems 2–5), the velocity of system 6 deviates from this by 450–500 km s^{-1}.

Multiple velocity systems are also present in the spectrum of SN 1994I, although the equivalent widths of the absorption lines are much larger than in SN 1994D. Systems originating from three different volumes of absorbing material along the pathlength can be identified. The two low-velocity systems ($v_h \approx -43$ and -11 km s^{-1}) are probably Galactic, while the heavily blended complex of at least nine systems (6–14) with $v_h \approx 370$–500 km s^{-1} undoubtedly is associated with NGC 5194, whose systemic velocity is 463 km s^{-1} (RC3). If the detected narrow Hα emission line (§ 3.3) originates from the site of the supernova, its observed velocity ($v_h \approx 496$ km s^{-1}) suggests that all but one (system 14) of the velocity systems must be moving *away* from the supernova ($\Delta v \approx 20$–130 km s^{-1}) and *toward* the observer. We consider it highly unlikely that these velocities are produced by SN 1994I itself. With an ionization potential of only 5.1 eV, Na I would be completely ionized in the vicinity of the explosion. Perhaps these velocities stem from an outflow related to the active nucleus present in NGC 5194 (§ 4.3). Interestingly, there are three additional weak systems present (3–5) with intermediate velocities ($v_h \approx$ 243, 269, and 298 km s^{-1}) which do not seem to belong either to the disk of the Galaxy or to NGC 5194. The nature of these systems with apparently anomalous velocities is discussed below (§ 4.2).

3.2. *Column Density and Extinction Estimates*

The column densities of Na I, N(Na I), derived through profile fitting (§ 3.1) can be translated into total hydrogen column densities, $N(\mathrm{H}) = N(\mathrm{H\ I}) + 2N(\mathrm{H_2})$, by adopting the correlation between these two quantities established for Galactic stars. Early studies (Hobbs 1974, 1976) reported that $N(\mathrm{Na\ I}) \propto N(\mathrm{H})^{\gamma}$, with $\gamma \approx 2$. On the other hand, inclusion of additional measurements, particularly those which sampled regions having much lower column densities, revealed that the relation between N(Na I) and N(H) is actually *linear* instead of quadratic in form. A fit to all the available data yielded log $N(\mathrm{Na\ I}) = 1.04 \pm 0.08 \log N(\mathrm{H}) - 9.09$ (Ferlet, Vidal-Madjar, & Gry 1985), with a 1 σ scatter of $\sim \pm 0.3$ dex. As Ferlet et al. (see also Federman 1981) note, however, the slope of the relation appears to deviate from unity for high column densities; above $N(\mathrm{H}) \approx 10^{21}$ cm^{-2} (corresponding to $N[\mathrm{Na\ I}] = 5.6 \times 10^{12}$ cm^{-2}), the slope steepens to $\gamma \approx 2$, the exact value being very uncertain because there are no data points with $N(\mathrm{Na\ I}) > 10^{14}$ cm^{-2}. This behavior can be easily understood by considering the ionization balance of Na as a function of density. As shown explicitly by Ferlet et al. (1985), the dominant ionization stage of Na switches from primary Na II in a diffuse medium to an ever increasing concentration of Na I as self-shielding of the UV radiation field by dust and molecular hydrogen becomes more effective at higher densities. The observed threshold of $N(\mathrm{H}) \approx 10^{21}$ cm^{-2} roughly coincides with the onset of molecular hydrogen formation. The net effect is to boost the abundance of Na I, although to our knowledge a detailed quantitative calculation has not yet been performed.

We used the fit of Ferlet et al. (1985) to derive N(H) from our N(Na I) measurements, applying it only to systems with $N(\mathrm{Na\ I}) < 5.6 \times 10^{12}$ cm^{-2}, where the fit is valid. Several systems from the disk of NGC 5194 (systems 6, 8, 12, and 14) have values of N(Na I) which fall on the nonlinear part of the N(Na I)–N(H) diagram. To obtain a crude estimate of N(H) for these systems, we made the following simple assumptions: (1) *all* of the Na is neutral, (2) the cosmic abundance of Na is $\sim 1.9 \times 10^{-6}$ relative to H (Ross & Aller 1976), and (3) the depletion of Na in the gas phase is a factor of 4 and roughly independent of density, consistent with the measurements of Phillips, Pettini, & Gondhalekar (1984). Cohen (1973), on the other hand, found that the Na D equivalent widths toward stars in dark clouds are very small and concluded that Na must be heavily depleted in dense environments, perhaps by as much as a factor of 10. It is difficult to reconcile this result with those of Ferlet et al. (1985) and Phillips et al. (1984) without additional observations. Bearing in mind that the depletion of Na may be incorrect, we list N(H) for all the systems in Table 1.

Next, we used the values of N(H) to derive the extinction toward the supernovae. Assuming that the gas-to-dust ratio is invariant, we adopted the relations $N(\mathrm{H}) = 5.9 \times 10^{21}$ $E(B-V)$ cm^{-2} and $A_V = 3.1\ E(B-V)$ (Spitzer 1978). We obtain total visual extinctions (summed over all systems) of $A_V = 0.08^{+0.08}_{-0.04}$ mag and $3.1^{+3.1}_{-1.5}$ mag for SN 1994D and SN 1994I, respectively. Unfortunately, the formal values of A_V listed in Table 1 for each individual system are quite uncertain (to within a factor of ~ 2), since the N(Na I) versus N(H) correlation itself has a scatter of $\sim \pm 0.3$ dex. The extinction for SN 1994I is especially uncertain for other reasons given in § 4.1. Note that the original, quadratic relation between N(Na I) and N(H) as given in Hobbs (1974) formally would have yielded $A_V = 0.4^{+0.4}_{-0.2}$ mag and $A_V = 8.3^{+8.3}_{-4.2}$ mag for SN 1994D and SN 1994I, respectively.

3.3. *Other Spectral Features*

A Type Ia supernova is generally believed to be produced by a carbon-oxygen (C-O) white dwarf which accretes matter from a companion star until its mass gets sufficiently close to the Chandrasekhar limit ($\sim 1.4\ M_{\odot}$) that degenerate carbon burning is initiated near its center (e.g., Nomoto, Thielemann, & Yokoi 1984; Woosley & Weaver 1986; Wheeler & Harkness 1990). In one class of models (Whelan & Iben 1973), the companion is a nondegenerate giant or main-sequence star, and the accreted material is generally rich in hydrogen (although accretion of helium is also possible; Iben & Tutukov 1991). In a separate class of models, the companion star is also a degenerate C-O white dwarf (Yungelson et al. 1994, and references therein); hydrogen should be absent from the system, unless the explosion occurs shortly after the end of the second common-envelope phase.

At this time there are few ways in which to observationally discriminate between the different models. One important approach, however, is to search for transient, narrow Hα absorption or emission in the early-time spectra of Type Ia supernovae. Branch et al. (1983), for example, gave tentative evidence for a weak, short-lived Hα emission line in a spectrum of SN 1981B obtained 6 days after maximum brightness; the feature was not visible 5 days later. A more convincing case is that of SN 1990M, in which an absorption line plausibly identified with Hα was detected in a spectrum obtained 4 days prior to maximum brightness (Polcaro & Viotti 1991). The line was broader than expected (FWHM ≈ 750 km s^{-1}), and it was weaker or absent only 4 days later. In both objects the weakening or disappearance of the feature might be attributed to ejecta overtaking the nearby neutral hydrogen.

Since the S/N and resolution of our spectrum of SN 1994D are very high, we searched for weak Hα near the supernova's systemic velocity. We failed to detect any absorption or emission features in the velocity range between 200 and 250 km s^{-1} (Fig. 2*a*); an upper limit to the equivalent width (W_λ) of Hα is ~ 3 mÅ (2 σ). Unfortunately, this does not provide significant constraints on models of the progenitor; SN 1994D was observed ~ 23 days after maximum brightness, by which time (1) any hydrogen in its immediate vicinity may have been overtaken by the ejecta, and (2) there was no longer a sufficiently intense ultraviolet radiation field exciting or ionizing the hydrogen.

The spectrum of SN 1994I shows Hα in emission, as well as [N II] $\lambda\lambda$6548, 6583 (Fig. 2*b*), close to the systemic velocity of NGC 5194. These are clearly produced by a superposed H II region. The Hα line ($W_\lambda = 200 \pm 10$ mÅ), centered at $v_h \approx 496$ km s^{-1}, has a narrow component which can be represented with a Gaussian with FWHM ≈ 40 km s^{-1}, as well as a broader wing (FWZI ≈ 140 km s^{-1}) which appears to be slightly blueshifted (~ 30 km s^{-1}) with respect to the core of the line. There is an additional weak ($W_\lambda = 11 \pm 1$ mÅ), narrower (FWHM ≈ 20 km s^{-1}) emission line redward of the main Hα line; if identified with Hα, it has $v_h \approx 653$ km s^{-1}. A

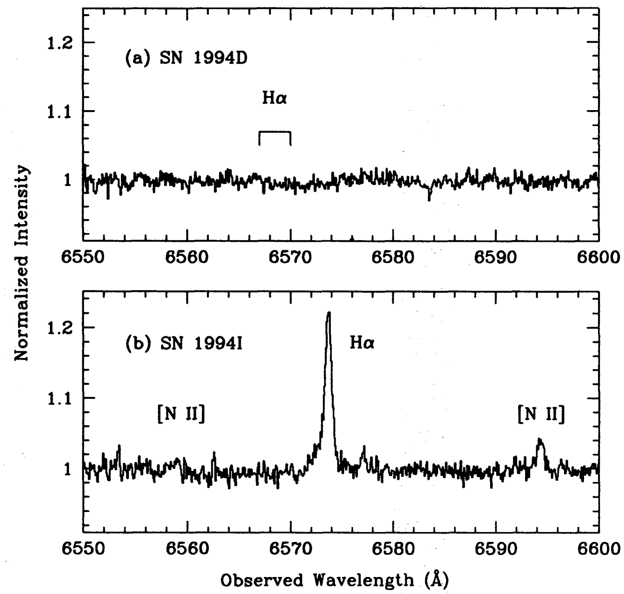

FIG. 2.—Calibrated spectra of SN 1994D and SN 1994I around the Hα region. The ordinate shows the normalized intensity in arbitrary units and the abscissa wavelength corrected to the heliocentric frame. (*a*) The position of the Hα line for the range of systemic velocities expected near the location of the supernova ($v_h \approx$ 200–250 km s^{-1}) is shown. (*b*) Hα and [N II] λλ6548, 6583 emission lines at the position of SN 1994I.

Gaussian with FWHM ≈ 40 km s^{-1} provides an adequate fit to [N II] λ6583 ($W_\lambda = 32 \pm 1$ mÅ); because of the lower S/N of this line, it is not obvious if a broad component analogous to that seen in Hα is present.

We carefully searched the data for other spectral features of interest, but the results were negative. In particular, we looked for evidence of absorption from the strongest diffuse interstellar bands (DIBs; Herbig 1975), whose origin remains enigmatic, and [Fe X] λ6375 emission, which might arise from $T \gtrsim 10^6$ K coronal gas in the Galactic halo (Hobbs 1984). It is somewhat surprising that no DIBs are seen toward NGC 5194, despite the presence of such strong Na D absorption. If one considers, for example, the well-observed DIB at 5780 Å as measured in Galactic stars, fairly well-defined correlations exist between its equivalent width and either N(Na I) or $E(B-V)$ (Herbig 1993). Although the expected feature will be quite smeared out because of the large range in velocities, the above mentioned correlations predict an equivalent width of several hundred mÅ, which would be clearly discernible in our spectra if present. We find no convincing evidence of *any* DIBs near the positions anticipated if the absorption were to have the same velocity range as that encompassing the Na D systems 6–14. Little is known about DIBs in external galaxies; they have been seen only in the Large Magellanic Cloud (Vladilo et al. 1987), in NGC 5128 (D'Odorico et al. 1989), and in NGC 4579 (Steidel et al. 1990). The lack of DIBs in our spectra of SN 1994I may reflect actual differences in the composition of the ISM at the position of NGC 5194 being probed, or it may be a consequence of the kinematics of the gas.

4. DISCUSSION

4.1. *Extinction*

The extinction toward supernovae can be independently estimated by comparing the observed colors with those of unreddened supernovae of the same spectral type, by assuming that the expanding photospheres at early times can be represented as simple blackbodies, and by modeling the light curves or the spectra. Applying the first of these techniques, Richmond et al. (1994) derive an upper limit of $A_V \approx 0.3$ mag for SN 1994D, consistent with our estimates based on the Na D measurements ($A_V = 0.08^{+0.08}_{-0.04}$ mag).

For SN 1994I, various combinations of all three techniques suggest that $A_V \lesssim 1.4$ mag, with a reasonable upper limit being ~2 mag (Schmidt 1994; Höflich 1994; Nomoto et al. 1994; Filippenko et al. 1995). In particular, for $A_V \gtrsim 2$ mag the effective temperature of the photosphere at early times becomes too high for consistency with the observed spectral features. An additional constraint on the extinction of SN 1994I is provided by long-slit, moderate-resolution optical spectra available for the nuclear environment of NGC 5194 (Ho, Filippenko, & Sargent 1995). Although the slit of the observations did not intersect the site of the supernova (14″ E, 12″ S of the nucleus), we have extracted a spectrum of an H II region located at approximately the same galactocentric radius. From the measured Balmer decrement, we estimate that $A_V = 1.9$ mag at the location of the H II region. It is evident from the spectrum that the Balmer emission lines are slightly contaminated by Balmer absorption from the underlying stellar population. Since this contamination affects Hβ more severely than Hα, the ratio Hα/Hβ is likely to be overestimated; the corresponding extinction derived should be considered an upper limit. Although the extinction need not be azimuthally uniform, this value may be representative for the nuclear region. Thus, the nominal extinction provided by the Na D measurements ($A_V = 3.1^{+3.1}_{-1.5}$ mag) is certainly too high, but consistent within the large uncertainty.

Several complications may be affecting our extinction determination for SN 1994I. First, the conversion between N(Na I) and N(H) for the velocity systems that dominate the contribution to the total absorbing column relies on a number of simplifying assumptions which may not be completely valid (§ 3.2). An empirical calibration between N(Na I) and N(H) does not yet exist for regions with high column densities. Second, interpretation of the data may be complicated by metallicity effects. Observations of H II regions in the spiral arms of NGC 5194 (Zaritsky, Elston, & Hill 1990; Díaz et al. 1991) have established that the metallicity in these regions is above solar ($Z/Z_\odot \approx$ 1.5–3) and that, as in many spiral galaxies, the metallicity of the disk of NGC 5194 increases toward smaller radii. SN 1994I is located on a spiral arm, and it is only ~18″ from the nucleus; although to our knowledge there has been no abundance determination for the immediate vicinity of the supernova, the metallicity of its environment is likely to be highly above solar. If the abundance of Na scales with those of O, N, and S (the abundance determination of Díaz et al. rely on optical transitions of these elements), a straightfoward solution to the anomalously high extinction would be to decrease N(Na I) by the same scale factor. The resulting N(H) along the line of sight to SN 1994I would be reduced to (2.3–4.1) × 10^{21} cm^{-2}, corresponding to $A_V \approx$ 1.2–2.1 mag. On the other hand, it is unclear how the dust-to-gas ratio varies with metallicity. There is some indication that in several nearby galaxies (including NGC 5194) the dust-to-gas ratio is correlated with metallicity (Issa, MacLaren, & Wolfendale 1990), but additional data and better statistics are needed to confirm this result. A third complication arises if the column density in the foreground of SN 1994I is *indeed* as high as indicated. As emphasized by Cardelli, Clayton, & Mathis (1989), denser regions of the ISM favor coagulation of grain particles, resulting in modification of the grain size distribution to larger particles, which in turn decreases the total extinction per H nucleus. Although the observational data are scarce, Cardelli et al. find that, for two stars located behind dark couds, $A_V/N(\mathrm{H})$ can be reduced by a factor of ~ 2 relative to the conventional value derived for the diffuse ISM. By comparing the position of SN 1994I with published H I (Rots et al. 1990) and CO (Rand & Kulkarni 1990) aperture synthesis maps of NGC 5194, it appears that the environment of the supernova is very rich in molecular gas, implying that the column densities are quite high. Thus, if our current understanding of grain chemistry is correct, it is plausible that the grains near SN 1994I are skewed toward large sizes. The value of $A_V/N(\mathrm{H})$ adopted in Table 1 would lead to an overestimate of A_V, perhaps by a factor of ~ 2. This would make the resulting value of A_V (~ 1.6 mag) close to those derived by other techniques.

4.2. *High-Velocity Clouds?*

One of the most interesting results of this study is the discovery of absorbing gas having apparently anomalous velocities. Judging from the magnitude of the velocity of system 6 in SN 1994D, we concluded (§ 3.1) that the absorbing gas is unlikely to be physically associated with NGC 4526. The most natural explanation is to assume that the gas has an intergalactic origin, perhaps associated with the intracluster medium of the Virgo cluster, and, since its velocity is positive, it must be *infalling* toward NGC 4526. NGC 4526 does not seem to be closely associated with other neighboring galaxies; thus, it is unlikely that the absorbing gas originates from debris resulting from a tidal interaction.

Because the sight line to SN 1994I is far from the Galactic plane ($l = 104.^\circ87$, $b = +68.^\circ52$), the velocities of systems 3–5 ($v_h = 243$, 269, and 298 km s^{-1}) are inconsistent with those expected from a corotating Galactic halo. We cannot attribute these velocities to disk rotation within NGC 5194, since its disk is nearly face-on. We consider five hypotheses: (1) the gas is associated with, and redshifted with respect to, the Galaxy; (2) the gas is associated with, and redshifted with respect to, NGC 5194; (3) the gas belongs to debris resulting from the interaction between NGC 5194 and its companion, NGC 5195; (4) the gas is intergalactic in origin, not being associated with the Galaxy, NGC 5194, or NGC 5195; and (5) the gas is physically associated with, and accelerated by, the supernova explosion itself.

The first hypothesis is very exciting, as it indicates the possibility that the absorbing clouds are optical counterparts of the well-known, but poorly understood, high-velocity clouds (HVCs) seen in 21 cm H I emission in the Galaxy. (As an operational definition, HVCs have $|v_{\mathrm{LSR}}| \geq 70$ km s^{-1}.) Despite over three decades of intense investigation, the nature of HVCs remains one of the most challenging areas of ISM research; see Wakker (1991) and references therein for a review. Optical and ultraviolet studies toward extragalactic sources and halo stars generally reveal absorbing material with fairly modest velocities ($|v_{\mathrm{LSR}}| \lesssim 100$ km s^{-1}; e.g., Morton & Blades 1986; Bowen 1991; Danly 1989). Velocities typical of the most extreme HVCs known are rare, and the three systems identified in the spectrum SN 1994I add to the small but growing list identified in studies using extragalactic probes. It is of interest to compare our results with those reported in the literature thus far (Table 2). Several points concerning the entries in Table 2 deserve mention. (1) The +208 km s^{-1} system detected toward SN 1987A (Vidal-Madjar et al. 1987) potentially suffers from confusion with gas intrinsic to the Large Magellanic Cloud. On the other hand, a detailed study of a 30′ field surrounding SN 1987A shows that this system is only visible toward the supernova (Molaro et al. 1993), increasing the probability that it in fact may be associated with a Galactic HVC; thus, we included it in Table 2. (2) The velocity field of the absorption associated with SN 1993J is very complex. Bowen et al (1994) suggest that the positive-velocity gas observed may be related to the system of H I streamers associated with the M81/M82 interaction (Yun, Ho, & Lo 1993). The system with $v_{\mathrm{LSR}} = 231$ km s^{-1}, however, appears to be isolated from the remaining systems having positive velocities, and inspection of the channel maps in the vicinity of the supernova does not reveal emission near this velocity (Yun 1994). Thus, it is possible that the absorption system of SN 1993J listed in Table 2 originates from a Galactic HVC, although this interpretation must be regarded with caution in view of the complicated kinematics associated with the tidal streamers (Yun 1994). (3) Although not mentioned by D'Odorico et al. (1989), the systems of SN 1986G ($l \approx 310°$, $b \approx 19°$, $v_{\mathrm{LSR}} \approx 233$ and 254 km s^{-1}) match fairly closely Cloud 219 ($l \approx 310°$, $b \approx 19°$, $v_{\mathrm{LSR}} \approx 200$ km s^{-1}) and possibly Cloud 213 ($l \approx 290°$, $b \approx 18°$, $v_{\mathrm{LSR}} \approx 248$ km s^{-1}) (Wakker & van Woerden 1991).

While half of the detections can be definitively associated with known HVCs, the rest, including the systems toward SN 1994I, do not appear to have obvious 21 cm counterparts in the catalog of Wakker & van Woerden (1991), which is supposed to be fairly complete, especially in the northern sky, down to a sensitivity limit of $\sim 2 \times 10^{18}$ cm^{-2}. These results are not necessarily in conflict; if the H I clouds have angular dimensions much smaller than the size of the telescope beam (half-power beam width $= 35'$ in the case of the Dwingeloo survey), they will be missed because of beam dilution. Indeed, high-resolution synthesis observations of selected HVCs have shown that they exhibit complex fine-scale structure and that only $\sim 30\%$ of the single-dish flux is recovered (Wakker & Schwarz 1991). This raises the important possibility that there may be *many* such HVCs which have been missed by the available H I surveys. As stressed by Meyer & Roth (1991), most optical absorption-line studies lack the sensitivity required to detect the weak features under consideration. Although the compilation of Ca II measurements in Bowen (1991) shows that strong high-velocity features are rare, the situation is much less clear for weak features, especially considering the limited number of observed sight lines.

It is also intriguing to note that, with the exception of one system toward SN 1991T with $v_{\mathrm{LSR}} = -87$ km s^{-1}, the system toward Mrk 205 with $v_{\mathrm{LSR}} = -152$ km s^{-1}, and that of PKS 0837$-$120 with $v_{\mathrm{LSR}} = 105$ km s^{-1}, *all* of the remaining detections have very high velocities ($|v_{\mathrm{LSR}}| \approx 200$–300 km s^{-1}). If we adopt the convention of Wakker (1991), these clouds can be regarded as "very high-velocity clouds." Furthermore, the clouds toward SN 1991T (excluding the one with $v_{\mathrm{LSR}} = -87$ km s^{-1}), SN 1993J, and SN 1994I are unusual in that their velocities are all positive. Although the deep Dwingeloo survey has shown that HVCs with positive velocities do exist, it was found that, relative to the more predominant negative-velocity HVCs, they tend to be fainter, cover less of the sky, and are located mostly in the southern sky. The three aforementioned sight lines with positive-velocity HVCs are all in the northern

TABLE 2

HIGH-VELOCITY CLOUDS TOWARD EXTRAGALACTIC SOURCES

SN	Galaxy	l (deg.)	b (deg.)	v_{LSR}[a] (km s^{-1})	Cloud[b]	Ref.[c]
	NGC 3783	287.46	+22.95	241	Cloud 187	1
	Fairall 9	295.07	−57.83	195	Magellanic Stream	2, 3
	PKS 0837−120	237.18	+17.43	105	HVC 237+17+105	4
	PKS 2155−304	17.73	−52.25	−260	Not detected	5
	Mrk 205	125.45	+41.67	−214	Complex C	6
				−152	Complex C	6
SN 1983N	M83	314.58	+31.97	248	Not detected?	7
SN 1986G	NGC 5128	309.52	+19.42	233	Cloud 213, 219?	8
				254	Cloud 213, 219?	8
SN 1987A	LMC	279.70	−31.94	208	Magellanic Stream	9
SN 1991T	NGC 4527	292.59	+65.18	−87	Not detected	10
				215	Not detected	10
				263	Not detected	10
SN 1993J	M81	142.09	+40.90	231	Not detected	11
SN 1994I	NGC 5194	104.87	+68.52	246	Not detected	12
				272	Not detected	12
				301	Not detected	12

[a] All velocities have been converted to the frame of the local standard of rest (LSR).

[b] The 21 cm HVC with which the optical or UV absorption is associated. With the exception of HVC 237 + 17 + 105, all other designations correspond to the naming scheme described in Wakker & van Woerden (1991). The cloud numbers refer to entries in that catalog.

[c] REFERENCES.—(1) West et al. 1985, (2) Morton & Blades 1986, (3) Songalia 1981, (4) Robertson et al. 1991, (5) Bruhweiler et al. 1993, (6) Bowen & Blades 1993, (7) D'Odorico et al. 1985, (8) D'Odorico et al. 1989, (9) Vidal-Madjar et al. 1987, (10) Meyer & Roth 1991, (11) Bowen et al. 1994, (12) this work.

sky. High-sensitivity, systematic searches toward more extragalactic sight lines might reveal many more such HVCs.

Without knowledge of the distances of the absorbing clouds, it is impossible to distinguish the first hypothesis from the second—that the clouds are HVCs residing in the halo of NGC 5194. If the clouds are associated with NGC 5194, their velocities would imply that they are receding from the galaxy at ~220, 194, and 165 km s^{-1}. The same argument applies to M83, NGC 5128, and M81; the difference between their systemic velocities, which are rather low, and the velocities of the absorbing gas yeilds values which are consistent with those of Galactic HVCs. Until very recently, evidence for HVCs in other galaxies has been scarce. However, sensitive 21 cm observations of face-on spirals reveal that the majority of them do in fact contain gas with velocities similar to those of Galactic HVCs (Schulman, Bregman, & Roberts 1994).

Next, we consider the possibility that the gas originates from tidal debris associated with the NGC 5194/NGC 5195 interaction. Although the velocity field of NGC 5194 is very complex and hard to interpret as a result of the encounter with NGC 5195, examination of high-resolution H I maps (Rots et al. 1990; Tilanus & Allen 1991) indicates no emission with $v_{LSR} \approx 250$–300 km s^{-1} at or near the position of the supernova. Of course, one cannot eliminate the possibility that the H I is below the detection limit of these studies. The three velocity systems have H I column densities ~(2–6) × 10^{19} cm^{-2}, barely above the detection limit of the maps of Rots et al.

The fourth hypothesis, that the gas is an intergalactic cloud, is difficult to test. While examples of intergalactic H I clouds have been reported (e.g., Hart, Davis, & Johnson 1980; Schneider et al. 1983), and, indeed, our observations of SN 1994D suggest that one is associated with NGC 4526, it appears that they are not common in nearby groups of galaxies (Lo & Sargent 1979). If the gas in question does belong to such a cloud, we conclude that it is not primordial in nature.

Finally, the anomalous velocities are probably not produced by SN 1994I itself. As discussed in § 3.1 in connection with the kinematics of the complex containing systems 6–14, Na is unlikely to remain neutral near the supernova. This hypothesis can be directly tested with high-resolution spectra of SN 1994I taken over several epochs; the wavelengths of the absorption lines should not remain constant.

The growing body of evidence that metal-bearing HVCs may be common constituents of the Galactic halo or of the halos of nearby galaxies has important implications for the study of metal absorption lines in QSOs. It has been established that the class of absorption-line systems frequently detected in the Mg II resonance doublet is physically associated with galaxies at intermediate ($z < 1$) redshifts (Wolfe 1990; Steidel 1994). Moreover, the statistics of the distribution of impact parameters of the QSO lines of sight with the images of putative absorbing galaxies can be best explained by assuming that the absorbing gas is distributed in a large, spherical configuration, or "halo" (Steidel 1994). The range of velocities listed in Table 1 agrees well with that observed for the multiple velocity systems in QSO absorbers, which typically span ~200 km s^{-1}. If a similar population of HVCs commonly exists in the halos of other galaxies, as suggested by this study and the observations of Schulman et al. (1994), the halos of intervening galaxies may be responsible for at least some QSO absorption-line systems.

4.3. *Nuclear Outflow in NGC 5194*

We have remarked in § 3.1 that the kinematics of the absorption arising from NGC 5194 are indicative of outflow. The nucleus of NGC 5194 exhibits weak, Seyfert-like activity (Rose & Searle 1982) which is believed to be responsible for the kinematics and excitation of complex emission-line regions observed near the nucleus. Ford et al. (1985) and Cecil (1988) model the bipolar-shaped, off-nuclear emission as outflow emanating from the nucleus. In particular, an "extranuclear cloud" (Cecil 1988) located $\sim 4''$ to the south east of the nucleus appears to be fed by a jet from the nucleus (Crane & van der Hulst 1992) and is observed to be expanding with a velocity of ~ 500 km s^{-1} (Cecil 1988). Although the gas probed by SN 1994I is located considerably farther from the nucleus ($\sim 18''$), it lies close to the axis of the nuclear outflow. Thus, it is conceivable that the velocity structure observed in our spectra is related to the same phenomenon.

5. CONCLUDING REMARKS

High-resolution echelle spectra of SN 1994D and SN 1994I reveal rich systems of interstellar Na D absorption lines originating from several volumes of intervening gas. Along the line of sight to SN 1994D, the absorption systems can be identified with contributions from the Galactic disk, the rotating disk of the host galaxy NGC 4526, and a third unknown source which is unlikely to be physically associated with either of the first two. Judging from the magnitude and direction of its radial velocity, we postulate that the latter might be intergalactic gas, probably associated with the intracluster medium of the Virgo cluster, infalling toward NGC 4526.

In addition to velocity systems arising from the Galaxy, the line of sight to SN 1994I intersects absorbing material which might be associated with a well-known outflow emanating from the active nucleus in NGC 5194. In addition, we identified three systems having velocities incompatible with normal galactic rotation. These absorption systems with apparently anomalous velocities can be most easily explained as optical counterparts of the so-called "high-velocity clouds" (HVCs), physically associated with the halo of either the Galaxy or NGC 5194. We argue that such a population of HVCs may be quite common in the Galactic halo, and that they have previously escaped notice because of sensitivity limitations. Recent observations show that the HVC phenomenon is often found in nearby galaxies. If true, HVCs in the halos of galaxies may be responsible for at least some of the metal-line absorption systems frequently observed in the spectra of QSOs.

No narrow Hα emission or absorption is detected to 2 σ equivalent width limits of 3 mÅ in the spectrum of the Type Ia SN 1994D. Unfortunately, this observation does not provide strong constraints on models of the progenitor.

We model the Na D absorption lines in order to derive column densities and estimates of the extinction toward the two supernovae. For SN 1994D, we obtain $A_V = 0.08^{+0.08}_{-0.04}$ mag, consistent with independent estimates based on the observed colors of the supernova. The estimate for SN 1994I is considerably more uncertain for a number of reasons. With this caveat, our best estimate yields $A_V = 3.1^{+3.1}_{-1.5}$ mag, although there are reasons to believe that the true extinction is $\lesssim 1.4$ mag.

We urge observers in the future to promptly obtain echelle spectra of as many suitably bright supernovae as possible. High S/N data are needed to search for weak features such as the ones identified in this study. In order to derive reliable extinctions from the column densities of optical absorption lines, it would be highly desirable to observe the weaker, usually unsaturated U lines of Na I at $\lambda \approx 3303$ Å. Simultaneous observations of the Ca II H and K lines are also useful, as the $N(\mathrm{Ca}^+)/N(\mathrm{Na}^0)$ ratio is an important diagnostic of the physical conditions and origin of the absorbing material (Routly & Spitzer 1952).

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