ULTRAVIOLET ABSORPTION LINES FROM HIGH-VELOCITY GAS IN THE VELA SUPERNOVA REMNANT: NEW INSIGHTS FROM SPACE TELESCOPE IMAGING SPECTROGRAPH ECHELLE OBSERVATIONS OF HD 72089

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ABSTRACT

The star HD 72089 is located behind the Vela supernova remnant and shows a complex array of high- and low-velocity interstellar absorption features arising from shocked clouds. A spectrum of this star was recorded over the wavelength range 1196.4–1397.2 Å at a resolving power of λ/Δλ = 110,000 and a signal-to-noise ratio of 32 by the Space Telescope Imaging Spectrograph on the Hubble Space Telescope. We have identified seven narrow components of C i and have measured their relative populations in excited fine-structure levels. Broader features at heliocentric velocities ranging from −70 to 130 km s−1 are seen in C ii, N i, O i, Si ii, S ii, and Ni ii. In the high-velocity components, the unusually low abundances of N i and O i, relative to S ii and Si ii, suggest that these elements may be preferentially ionized to higher stages by radiation from hot gas immediately behind the shock fronts.

Subject headings: ISM: abundances — ISM: individual (Vela supernova remnant) — ISM: kinematics and dynamics — shock waves — stars: individual (HD 72089) — supernova remnants

1. INTRODUCTION

The large number of bright, early-type stars in or behind the Vela supernova remnant (SNR) makes this remnant especially well suited for the study of high-velocity absorption features from shocked gases. An especially interesting example is the star HD 72089, discovered by Jenkins, Wallerstein, & Silk (1984) to have at least six distinct velocity components in Ca ii. Hubble Space Telescope (HST) observations of HD 72089 using the G160M grating on the Goddard High-Resolution Spectrograph (GRS; λ/Δλ ≈ 20,000) revealed the presence of high-velocity C i features with extraordinarily strong absorption coming from excited fine-structure levels, which indicates that the gas is strongly compressed (Jenkins & Wallerstein 1995, hereafter JW95). In their study of gas-phase element abundances in the halo of the Galaxy, Jenkins & Wallerstein (1996, hereafter JW96) used the pattern of element abundances in the high-velocity components toward HD 72089, discovered by Jenkins, Wallerstein, & Silk (1984) to have at least six distinct velocity components in

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2. DATA

HD 72089 is a star with V = 8 and the spectral classification B5 II–III (Houck 1978) that is about 1.7 kpc away from us, located behind the western edge of the Vela SNR. We present in this Letter observations of this star taken on 1997 May 30 at 0022–0354 UT12 to demonstrate the performance of the high-resolution UV echelle spectrograph (E140H mode) on STIS with the 0′2 × 0′09 entrance aperture.

Photoevents registered by the MAMA detector were recorded in the time-tag mode. We created a 2048 × 2048 HiRes image (two samples per MAMA pixel) with corrections for the position of each time-tagged count to compensate for (1) the orbital Doppler motion (amplitude = 10 HiRes pixels) and (2) the motion caused by thermal distortions (0.2 HiRes pixels hr−1, measured from the slow drift of the spectral lines in the data). Our spectra were taken from simple, unweighted extractions with background levels defined by the bottoms of obviously saturated lines. In cases in which lines of interest appeared twice in adjacent orders, the overlapping coverages were co-added.

The wavelength scale was computed with a prelaunch dispersion relation corrected for a zero-point wavelength shift computed from a wavelength calibration observation taken with the data. The precision of this scale is shown by the excellent agreement for the derived wavelengths of narrow features seen in two different orders. Also, the velocities of our C i components agree to within 2 km s−1 (rms error) with those of Na i observed by Danks & Sembach (1995).

Except in the vicinity of the strong stellar Lyα line, our derived spectrum has a signal-to-noise ratio of about 32. From

12 Archive exposure index numbers O4001P9M, PDM, and PHM, with integration times of 1420, 2560, and 2560 s, respectively.
a narrow line of CI (not discussed here), we estimate that the instrumental profile is Gaussian with an FWHM equal to \( \lambda / 1.1 \times 10^6 \). In this latter, we focus principally on the absorption lines of CI (§ 3) with their noteworthy levels of fine-structure excitation, and in § 4 we report on some key elements that show up in ionization stages that are favored in normal H I regions.

3. HIGH-EXCITATION CI

In the interstellar medium (ISM), the excited \( ^3P_1 \) and \( ^5P_2 \) fine-structure levels (denoted CI* and CI**) in the ground state of CI can be populated by collisions with neutral hydrogen atoms, electrons, and protons (Bahcall & Wolf 1968; Jenkins & Shaya 1979; Keenan 1989; Roueff & Le Bourlot 1990). In a previous HST study of HD 72089, JW95 measured remarkably strong CI* and CI** lines in the component at \( v = 121 \) km s\(^{-1}\). The large implied gas pressure suggested that this CI absorption arises in compressed gas following a shock inside a cloud that had been hit by the supernova blast wave. Our new STIS observations of HD 72089 have substantially improved resolution and provide an opportunity to verify and refine the results of JW95.

We analyzed CI multiplets near 1277, 1280, and 1329 Å using a component-fitting technique (Spitzer & Fitzpatrick 1993; Fitzpatrick & Spitzer 1997) that minimizes the \( \chi^2 \) between the fit and the data to determine the set of velocity centroids, \( b \)-values, and column densities, assuming that the original intensities were convolved with an instrumental line spread function consisting of a Gaussian function with FWHM = 4 HiRes pixels. A comparison of the derived fits with the recorded spectra near the 1277 and 1329 Å CI absorption complexes is shown in Figure 1. The parameters for the seven individual absorption components are given in Table 1. The associated \( \sigma \) errors include the effects of random photon noise, residual fixed pattern noise, and uncertainties in determining the continuum. Since we relied on empirically derived backgrounds, there may be additional systematic errors at about the 5% level. Such errors, however, will tend to shift all of the CI, CI*, and CI** column densities in a given multiplet in the same direction and thus will not significantly affect the derived population ratios, \( f_i \) and \( f_z \), listed in the last two columns of the table. Figure 1 indicates that many lines are free from blending, and consequently the component parameters are well constrained by the data.

At sufficiently high densities in a warm gas, the level populations approach their relative statistical weights, i.e., 1:3:5, so that \( f_i \rightarrow 0.33 \) and \( f_z \rightarrow 0.56 \). We confirm the determination by JW95 that this condition is found for the component at the highest velocity (our component 7). We find that some components at low and intermediate velocities (components 2, 4, and 6) have values of \( f_i \) and \( f_z \) that must arise from blends of unresolved components, each with differing degrees of CI excitation caused by very different pressures or levels of ionization.\(^{13} \) This conclusion is supported by the slightly larger \( b \) values of these components. Finally, component 3 has an unusually low excitation level. Gas within this region would have a pressure of \( \rho/k \approx 1300 \) cm\(^{-3}\) K if \( T = 300 \) K (and electron and proton densities are low enough to be neglected), but \( \rho/k \) could be as large as 7400 cm\(^{-3}\) K at the upper limit for

\[^{13}\text{See § IVa of Jenkins & Shaya (1979) for a simple geometrical method of interpreting possible combinations of absorbing regions that blend together and produce measured} (f_i, f_z) \text{ that are inconsistent with a single source region.}\"

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**Fig. 1.—Absorption profiles in the heliocentric velocity frame of the (top) CI 1277 and (bottom) CI 1329 multiplets. The profile fits based on the component parameters in Table 1 are overplotted on the data, and the velocities of the seven components in the various CI, CI*, and CI** lines in these multiplets are indicated. The CI multiplet near 1280 Å was also fitted but is not shown here.**

**4. SELECTED ATOMS AND IONS**

The general character of the velocity components for ionization stages of elements that have an ionization potential greater than 13.6 eV is very different from the narrow components seen in CI. CI emphasizes mostly regions that have large internal densities, while lines from such species as CI II, N I, O I, Si II, S II, and Ni II are likely to arise from a much broader range of conditions in generally lower density clouds. It is no surprise that the latter group displays lines that have a broad velocity extent with virtually no evidence for narrow, unresolved substructures (see below). For this reason, we choose to analyze the features in the context of their apparent optical depths, \( \tau_\alpha \), as a function of radial velocity \( v \) (Savage & Sembach 1991; Jenkins 1996), a concept that is more general than component fitting. For the line complexes of N I, O I, Si II, and S II, the saturation at low velocities was too large to allow any column density determinations (see Fig. 2). The lines of CI II and CI** near 1335 Å were hopelessly saturated at all velocities.

To within the noise fluctuations, the high-velocity components of the weakest lines of N I, Si II, and Si II** yield values of apparent column density, \( N_\lambda (v) = 3.768 \times 10^{14} \tau_\alpha (v) / (f_k) \) cm\(^{-2}\) (km s\(^{-1}\))\(^{-1}\), that are consistent with those from the strongest lines. The lines for these three species cover ranges of \( f_k \) that differ by factors of 3, 3, and 10, respectively. Unfortunately, the strong line of Si II at 1260.422 Å has very
serious interference from the line of Fe II at 1260.533 Å, so we cannot compare it with the weaker feature at 1304.370 Å. The good agreements indicate that the derived $\tau_0(v)$ values are not underestimated because of the presence of saturated substructures that are not resolved by the instrument (and this probably applies to many species other than N i, S ii, and Si ii*). Thus, it is not necessary to invoke the special correction procedure outlined by Jenkins (1996), and henceforth we will replace $N_0(v)$ with $\bar{N}(v)$, the true column density per unit velocity.

The lowest five panels in Figure 2 show log $\bar{N}(v)$ for S ii, Si ii, Ni ii, N i, and O i, with the ordering of these species being based on an apparent decrease in general abundances below their cosmic abundances (Anders & Grevesse 1989; Grevesse & Noels 1993; but see § 5), assuming that sulfur is undepleted (Fitzpatrick & Spitzer 1997). The magnitudes of these deficiencies for the most negative and the most positive velocity peaks are listed in the second column of Table 2. For

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**TABLE 1**

PROFILE-FITTING RESULTS: COMPONENT VELOCITIES, DOPPLER PARAMETERS, AND COLUMN DENSITIES FOR C i, C i*, AND C ii**

| Component Number | $v_0$ (km s$^{-1}$) | $b_0$ (km s$^{-1}$) | log N(C i) | log N(C i*) | log N(C ii*) | $f_i^a$ | $f_i^b$ |
|------------------|---------------------|---------------------|-------------|-------------|-------------|--------|--------|
| 1                | $3.2 \pm 0.1$       | $1.6 \pm 0.3$       | $12.84 \pm 0.02$ | $12.29 \pm 0.08$ | $<11.7^d$ | $0.22$ | $<0.054$ |
| 2                | $6.5 \pm 0.2$       | $6.3 \pm 0.7$       | $12.96 \pm 0.02$ | $13.06 \pm 0.02$ | $12.92 \pm 0.02$ | $0.39$ | $0.29$ |
| 3                | $16.7 \pm 0.1$      | $2.2 \pm 0.4$       | $12.78 \pm 0.02$ | $11.54 \pm 0.41$ | $11.6^e$ | $0.05$ | $<0.059$ |
| 4                | $26.2 \pm 0.1$      | $5.3 \pm 0.6$       | $13.11 \pm 0.02$ | $12.85 \pm 0.03$ | $12.60 \pm 0.04$ | $0.29$ | $0.17$ |
| 5                | $35.4 \pm 0.1$      | $3.2 \pm 0.2$       | $12.94 \pm 0.02$ | $12.97 \pm 0.01$ | $12.59 \pm 0.03$ | $0.43$ | $0.18$ |
| 6                | $90.5 \pm 0.2$      | $5.0 \pm 0.7$       | $13.28 \pm 0.06$ | $12.50 \pm 0.04$ | $12.72 \pm 0.02$ | $0.29$ | $0.49$ |
| 7                | $120.9 \pm 0.1$     | $2.9 \pm 0.2$       | $12.36 \pm 0.03$ | $12.79 \pm 0.02$ | $13.00 \pm 0.01$ | $0.34$ | $0.54$ |

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**TABLE 2**

OBSERVED AND CALCULATED DEFICIENCIES

| SPECIES | log $(A/S)/n_i$ | log $(A/S)_{obs}$ | log $T$ (FROM EQ. [2]) |
|---------|-----------------|-------------------|------------------------|
| N i ($\sim$58) | $-1.72$ | $-2.04^c$ | $-2.39$ |
| N i (121) | $-0.87$ | $-0.93^e$ | $-1.17$ |
| O i ($\sim$58) | $-1.14^c$ | $-1.35$ | $-2.01$ |
| O i (121) | $-0.90$ | $-0.42$ | $-0.87$ |
| Al ii ($\sim$58) | $-0.58^d$ | $-0.07^b$ | $-0.18$ |
| Al ii (121) | $-0.66^d$ | $e$ | $-0.03$ |
| Si ii ($\sim$58) | $-0.36$ | $e$ | $-0.03$ |
| Si ii (121) | $-0.21$ | $e$ | $0.00$ |
| S ii ($\sim$58) | $0.00$ | $-0.12^c$ | $-0.24$ |
| S ii (121) | $0.00$ | $e$ | $-0.04$ |
| Fe ii ($\sim$58) | $-0.82^d$ | $e$ | $-0.75$ |
| Fe ii (121) | $-0.35^d$ | $e$ | $-0.02$ |
| Ni ii ($\sim$58) | $e$ | $-0.74$ |
| Ni ii (121) | $-0.51$ | $e$ | $-0.03$ |

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* Numbers in parentheses identify velocity components: “≈58” applies to $\bar{N}(v)$ (for the second column) over the heliocentric velocity range $-70$ to $-45$ km s$^{-1}$, where eq. (1) gives $n_i = 4.6$ and $5.3$ cm$^{-3}$ for log $T = 2.7$ and 3.4, respectively, and “≈121” applies to the range 112–130 km s$^{-1}$ ($n_i = 35$ and 39 cm$^{-3}$).

* Numbers neglect charge exchange reactions with H because the fitting formulae for cross sections are not valid for $T < 10^4$ K, but judging from the small effect at $10^4$ K, the omission of these reactions is probably not important.

* May include some contamination from the 1301.874 A feature of P i at low velocities.

* Column density from JW96, compared with S ii measured in this investigation.

* Since log $R > -0.1$ at $T = 10^4$ K, the same probably applies here, even though we cannot include charge exchange reactions.

* Charge exchange reactions have a big effect at $T = 10^4$ K; thus, we have no confidence in quoting a number that neglects charge exchange at lower values of $T$.

* Some Ni ii is present, but the absorption feature is too weak to measure.

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**Fig. 2.—Plots of log $\bar{N}(v)$ for five species, as labeled (lower panels), and the relationship log $[\text{N}/\text{Si}^{\prime}\text{H}]$ (top panels)—an indicator of the local electron density, $n_i$ (see eq. [1]). The dashed lines (drawn at an arbitrary level for S ii) represent levels that are consistent with the elements’ cosmic abundance relative to S, i.e., the fact that the peaks of some species (e.g., N i and O i) are substantially displaced downward from the dashed lines relative to their counterparts for S ii indicates that these elements are less abundant than expected, relative to S. Transition $f$-values were taken from Morton (1991), except for Si ii (Spitzer & Fitzpatrick 1993) and Si ii* (Luo, Pradhan, & Shull 1988).**
some species, there are velocity regions in which the features are either lost in the noise or badly saturated. We have omitted these parts of the tracings from the figure. Absorption by low-
velocity P ii λ1301.874 could be adding to the right-hand side of the O i peak centered at −60 km s$^{-1}$. The plotted lines consist of a superposition of three determinations (often overlapping)—a middle line that represents our best estimate for log $N$(i) that is flanked by ones that represent the extremes that could be caused by worst combinations of systematic errors (1σ) in either the zero intensity level or the placement of the continuum level (errors caused by noise are not included, as one can estimate these from the size of the random wiggles in the tracings).

5. IONIZATION BY RADIATION FROM SHOCKS

The strong deficiencies of N and O shown in Table 2 are inconsistent with previous findings for the general ISM that indicate that these two elements are only mildly depleted (Hibbert, Dufton, & Keenan 1985; Cardelli, Savage, & Ebbets 1991; Cardelli et al. 1991; Meyer et al. 1994). One possible interpretation of this phenomenon is that ionizing radiation from nearby shock fronts moves the atoms to higher, unseen stages of ionization. To investigate the plausibility of this idea for these two species and others, we performed a simple exercise. For representative values of $N$(Si ii)/$N$(Si iii) of 10$^{-2}$ and 10$^{-1.5}$ for the components centered at −58 and 121 km s$^{-1}$, respectively, we used the collision cross section and radiative decay rate of the upper fine-structure level given by Keenan et al. (1985) to obtain the electron density as a function of temperature,

$$n_e \equiv \frac{8.97T^{0.5}N(\text{Si i})N(\text{Si ii})}{\exp(-413K/T) - 0.5N(\text{Si i})/N(\text{Si ii})}. \quad (1)$$

We then used the 13–54 eV ionizing radiation field of Shull & McKee (1979) for a shock with a velocity of $v_s = 100$ km s$^{-1}$ and a preshock density of $n_i = 10$ cm$^{-3}$ (see JW95) and evaluated the ionization equilibrium between the visible stages in Table 2 (denoted with a subscript 1) and the next two higher ionization states (subscripts 2 and 3) to obtain the ratio

$$R \equiv \frac{n_i}{n_i + n_2 + n_3} = \left\{ \frac{(\Gamma_1 + \delta_1 n_2)\Gamma_2 + \alpha_2 n_2 + \delta_2 n_3}{(\alpha_1 n_2 + \delta_1 n_3)(\alpha_2 n_2 + \delta_2 n_3)} \right\}^{-1}. \quad (2)$$

with $n_i = n_i^2\alpha_{i=2,3}/\Gamma_i$. $\Gamma_1$ and $\Gamma_2$ are the photoionization rates out of the two lower stages, using cross sections calculated from the analytic approximations of Verner et al. (1996; and Verner & Yakovlev 1995 for Ni). The recombination coefficients $\alpha_1$ and $\alpha_2$ were evaluated from the parameters for the fitting equations given by Shull & Van Steenberg (1982; and Aldrovandi & Péquignon 1974 for Al). Values for the charge exchange rates $\delta_1$ (X$_1 +$ H $\rightarrow$ X$_2 +$ H$^+$) and $\delta_2$ (X$_2 +$ H $\rightarrow$ X$_1 +$ H$^+$) were derived from the fits given by Kingdon & Ferland (1996). Unfortunately, for all elements except oxygen, these charge exchange fits are valid only for $T > 10^4$ K. We neglected any possible self-absorption of the ionizing radiation by neutral hydrogen, and we did not include charge exchange with He. At log $T \approx 2$, only the lower of the two Si ii$^+$/Si ii cases has an acceptable solution in equation (1) (given $n_i = 80$ cm$^{-3}$), and values of log $R$ were about equal to 0 for all species except for N i, where log $R = −0.32$. Values of log $R$ at two representative higher temperatures are given in the third and fourth columns of Table 2. At temperatures much above those given in the table, collisional ionization becomes important. Postshock gases that are cooling radiatively through temperatures of order 10$^4$ K can likewise exhibit depressions of O i and N i (Trapero et al. 1996; Benjamin & Shapiro 1997).

The results shown in Table 2 indicate that the apparent deficiencies of O and N in the high-velocity components might be due to ionization by radiation from the associated immediate postshock gas and/or nearby shocks. They also indicate that measurements of Fe ii and Ni ii in such components could, to a lesser extent, be underrepresenting the true gas-phase abundances of these elements when the electron densities are low. Measurements of Al iii, Si iii, and S iii would still yield reliable abundances, and thus the observed 0.6 dex deficiency of Al iii indicates that this element may still be locked up in the remnants of the dust grains that survive the passage of a shock (note that JW96 saw very low amounts of Al iii at high velocity).

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