FAR ULTRAVIOLET SPECTROSCOPIC EXPLORER OBSERVATIONS OF A SUPERNOVA REMNANT IN THE LINE OF SIGHT TO HD 5980 IN THE SMALL MAGELLANIC CLOUD

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ABSTRACT

We report a detection of far-ultraviolet absorption from the supernova remnant SNR 0057−7226 in the Small Magellanic Cloud (SMC). The absorption is seen in the Far Ultraviolet Spectroscopic Explorer (FUSE) spectrum of the luminous blue variable/Wolf-Rayet star HD 5980. Absorption from O iv λ1032 and C iii λ977 is seen at a velocity of 300 km s⁻¹ with respect to the Galactic absorption lines, 170 km s⁻¹ with respect to the SMC absorption. The O vi λ1038 line is contaminated by H₂ absorption but is present. These lines are not seen in the FUSE spectrum of Sk 80, only ~1' (~17 pc) away from HD 5980. No blueshifted O vi λ1032 absorption from the SNR is seen in the FUSE spectrum. The O vi λ1032 line in the SNR is well described by a Gaussian with FWHM = 75 km s⁻¹. We find log N(O vi) = 14.33–14.43, which is roughly 50% of the rest of the O vi column in the SMC (excluding the SNR) and greater than the O vi column in the Milky Way halo along this sight line. The N(C iv)/N(O vi) ratio for the SNR absorption is in the range of 0.12–0.17, similar to the value seen in the Milky Way disk and lower than the halo value, supporting models in which SNRs produce the highly ionized gas close to the plane of the Galaxy, while other mechanisms occur in the halo. The N(C iv)/N(O vi) ratio is also lower than the SMC ratio along this sight line, suggesting that other mechanisms contribute to the creation of the global hot ionized medium in the SMC. The O vi, C iv, and Si iv apparent column density profiles suggest the presence of a multiphase shell followed by a region of higher temperature gas.

Subject headings: stars: individual (HD 5980) — supernova remnants — ultraviolet: ISM

1. INTRODUCTION

Supernovae are thought to be one of the main sources of the hot coronal gas in the interstellar medium (ISM; McKee & Ostriker 1977; Sembach, Savage, & Tripp 1997). There have been few absorption-line observations of the hot gas in individual supernova remnants (SNRs), however, so global descriptions of the ISM have been forced to rely on models of evolving SNRs to reproduce the characteristics observed in absorption-line studies of the Galactic disk and halo (Slavin & Cox 1992, 1993; Shull & Slavin 1994; Shelton 1998). In particular, the O vi λ1032, 1038 lines are very important probes of collisionally ionized gas near \(3 \times 10^3\) K. While several SNRs have been observed in O vi emission (Blair et al. 2000; Sankrit et al. 2001), few have been studied in O vi absorption. Jenkins, Wallerstein, & Silk (1976) detected O vi absorption in the Vela SNR with the Copernicus satellite, but since then the opportunities to observe the spectral region containing the O vi lines have been limited. With the launch of the Far Ultraviolet Spectroscopic Explorer (FUSE; Moos et al. 2000), this spectral window has been reopened.

HD 5980 (Sk 78, AV 229; \(l = 302°07, b = -44°95\)) is a luminous blue variable/Wolf-Rayet star on the edge of the H ii region NGC 346 (N66) in the Small Magellanic Cloud (SMC). De Boer & Savage (1980) first noticed an absorption system at \(V_{\text{LSR}} = 300\) km s⁻¹ arising in a highly ionized cloud in International Ultraviolet Explorer spectra of this star. Fitzpatrick & Savage (1983) suggested that the cloud might be an SNR moving toward HD 5980 at ~150 km s⁻¹. This interpretation was confirmed by a radio detection of an SNR in N66, SNR 0057−7226 (Ye, Turtle, & Kennicutt 1991), coinciding with the X-ray source IKT 18 (Inoue, Koyama, & Tanaka 1983; Wang & Wu 1992). High-velocity HÎ emission was also seen at this position by Chu & Kennicutt (1988).

Koenigsberger et al. (2001) observed HD 5980 with the Space Telescope Imaging Spectrograph (STIS) on the Hubble Space Telescope. They detected the SNR in ultraviolet absorption lines and were able to separate the absorption into two components at \(V_{\odot} = 312\) and \(343\) km s⁻¹ (\(V_{\text{LSR}} = 300\) and \(331\) km s⁻¹) in some of the lines. They also detected excess absorption at \(V_{\odot} = 33\) and \(64\) km s⁻¹ (\(V_{\text{LSR}} = 21\) and \(52\) km s⁻¹), suggesting that the high-velocity gas is located on the far side of an expanding structure. The STIS spectrum contains absorption features of N v and C iv, which probe gas at \(~2 \times 10^5\) and \(~1 \times 10^5\) K, respectively. In this Letter, we present FUSE data on even hotter gas in SNR 0057−7226.

2. OBSERVATIONS AND DATA REDUCTION

HD 5980 was observed by FUSE on 2000 July 2. The data are archived in the Multi-Mission Archive at the Space Telescope Science Institute as data sets P1030101–P1030104. Spectra were taken through the large (LWRS, \(\sim 30°\)) apertures. Four individual exposures were combined for a total integration time of 5734 s. A spectrum of Sk 80 (AV 232), an O7 Iaf+ star (Walborn 1977), which lies close to HD 5980 on the sky, and which we use as a comparison star (data set P10302), was observed on the same day as HD 5980 and reduced in the same manner.

The FUSE instrument consists of four channels, two optimized for short ultraviolet wavelengths (SiC1 and SiC2: 905–1100 Å) and two optimized for longer UV wavelengths (LiF1 and LiF2: 1000–1187 Å). The O vi lines are covered by all four channels, but the effective area is largest for data recorded in LiF2. The C iii line is covered by the SiC channels. We require that any absorption feature be present in two channels to be considered real.

The raw data were reduced using the standard FUSE cali-
the nominal resolution of the data is the spectrum near the lines of interest. The vertical dashed lines are, from left to right, the Milky Way at 0 km s\(^{-1}\), the SMC at \(\sim130\) km s\(^{-1}\), and SNR 0057–7226 at \(\sim300\) km s\(^{-1}\). All three components of O\(\text{vi}\) at \(\lambda1037.62\) absorption are blended with other lines, and the Milky Way and SMC components of C\(\text{miii}\) at \(\lambda977.02\) absorption are heavily saturated.

The calibration pipeline (CALFUSE v1.8.7) available at Johns Hopkins University. The velocity zero point was set by shifting the Milky Way component of the H\(_2\) and low-ionization lines to 0 km s\(^{-1}\), based on the results of Mallouris et al. (2001). The spectra were binned by 3 pixels (\(\sim6\) km s\(^{-1}\) near O\(\text{vi}\)), and the nominal resolution of the data is \(\sim20\) km s\(^{-1}\) (FWHM). The relative wavelength solution is accurate to \(\sim6\) km s\(^{-1}\) on average. The signal-to-noise ratio in the binned data is \(\sim50\) near the O\(\text{vi}\) lines. The continuum levels were chosen by fitting low-order (<6) Legendre polynomials to line-free regions of the spectrum near the lines of interest.

3. RESULTS

Figure 1 shows the observed absorption profiles of O\(\text{vi}\) and C\(\text{miii}\) in the spectra of HD 5980 and Sk 80. The two stars are separated by \(\sim1\)' or \(\sim17\) pc, assuming a distance of 59 kpc to the SMC (Mathewson, Ford, & Viswanathan 1986). Absorption features of O\(\text{vi}\) at \(\lambda1032\) and C\(\text{miii}\) at \(\lambda977\) are detected at 300 km s\(^{-1}\) in the FUSE spectrum of HD 5980, but no similar features are seen in the Sk 80 spectrum. The edge of the radio SNR extends very close to the projected position of Sk 80 (Ye et al. 1991). Either the 300 km s\(^{-1}\) absorbing region does not extend as far as Sk 80, or Sk 80 is in front of the absorbing gas. Absorption from hot gas in the Milky Way and the SMC is also seen in the spectra of both stars and will be the subject of a future paper. The O\(\text{vi}\) at \(\lambda1038\) line at 300 km s\(^{-1}\) is contaminated by two H\(_2\) lines, \(P(1)\) \(5–0\) and \(R(2)\) \(5–0\), but it is clearly much stronger in the HD 5980 spectrum than in Sk 80.

The Milky Way and SMC O\(\text{vi}\) at \(\lambda1032\) profiles in the HD 5980 and Sk 80 spectra look very similar. Figure 2 shows an overlay of the two spectra as well as the HD 5980 spectrum divided by the spectrum of Sk 80 (the stellar continua near O\(\text{vi}\) at \(\lambda1038\) and C\(\text{miii}\) at \(\lambda977\) did not match as well). The Milky Way and SMC components divide out almost completely. The 300 km s\(^{-1}\) absorption toward HD 5980 remains and is well described by a Gaussian with an FWHM of 75 km s\(^{-1}\). This corresponds to a temperature of \(\sim2 \times 10^6\) K if the line is broadened solely by thermal motions. We do not see any absorption from the approaching side of the SNR in the divided spectrum, identified in the STIS spectrum by Koenigsberger et al. (2001).

Koenigsberger et al. (2001) detected two redshifted components associated with the SNR in low ions: a strong component at \(V_{\text{LSR}} = 300\) km s\(^{-1}\) and a weaker component at \(V_{\text{LSR}} = 331\) km s\(^{-1}\). The absorption in the FUSE spectrum is located at \(V_{\text{LSR}} \sim 300\) km s\(^{-1}\), corresponding to the strong component. We do not detect the \(V_{\text{LSR}} = 331\) km s\(^{-1}\) component in C\(\text{miii}\) or O\(\text{vi}\). The absorption lines from this component seen by Koenigsberger et al. (2001) were very weak, so this component may be blended with the main absorption system at 300 km s\(^{-1}\) in the FUSE data. Fitzpatrick & Savage (1983) detected a weak component at 325 km s\(^{-1}\), which, if present in the FUSE data, would be blended with the broad 300 km s\(^{-1}\) component.

Table 1 lists the measured equivalent widths and column densities for the O\(\text{vi}\) and C\(\text{miii}\) lines and upper limits on S\(\text{vi}\) and Fe\(\text{ii}\). No O\(\text{i}\) or H\(_2\) absorption is seen at 300 km s\(^{-1}\). The S\(\text{miii}\) and S\(\text{iv}\) lines in the FUSE bandpass are blended with other absorption lines, so we cannot determine whether any high-velocity absorption is present. Column densities were calculated by integrating the apparent column density per unit velocity over the velocity range given, an approach that is valid...
if the intrinsic line width is comparable to or broader than the instrumental line spread function (LSF; Savage & Sembach 1991). At temperatures of $3 \times 10^5$ K, where the abundance of O vi peaks in collisional ionization equilibrium (Sutherland & Dopita 1993), the line width from thermal broadening ($\approx 30$ km s$^{-1}$) is larger than the FUSE LSF width ($\approx 20$ km s$^{-1}$), so the condition is most likely satisfied. The C iii abundance peaks at a lower temperature ($T \sim 7 \times 10^4$ K), and it is possible that unresolved saturated absorption exists. In this case, the measured column density of C iii is a lower limit to the true value. The uncertainty estimates in Table 1 include statistical noise fluctuations and modest continuum placement uncertainty.

(Sembach & Savage 1992). For the very faint N v line, continuum placement may dominate the uncertainty, so its effects were evaluated by varying the continuum fit.

We have reanalyzed the STIS data taken with the E140M grating from Koenigsberger et al. (2001) so that the equivalent widths could be measured over the same velocity ranges used for the FUSE data. These values are also given in Table 1 (lines with $\lambda > 1200 \, \AA$ were measured from STIS data). We also measured the O vi equivalent width and column density toward HD 5890 using the spectrum that had been divided by the Sk 80 spectrum. Using the divided spectrum, we place an upper limit (3 $\sigma$) of $\log N$(O vi) $\leq 13.43$ on the approaching side, $\sim 11\%$ of the column density of the receding side.

### 4. Discussion

Models of evolving SNRs (Slavin & Cox 1992, 1993; Shetton 1998) predict the production of O vi in gas heated to $T > 10^5$ K by shocks. The existence of O vi in the SNR requires shock speeds of at least $\sim 160$–$170$ km s$^{-1}$ (Hartigan, Raymond, & Hartmann 1987). If the absorption seen in the FUSE spectrum traces only the receding side of the shell, and the systemic velocity of the SNR is $176$ km s$^{-1}$ (Hartigan, Raymond, & Hartmann 1987), then the expansion velocity is at least $124$ km s$^{-1}$ and may be higher if the sight line is offset from the center of the remnant. Chu & Kennicutt (1988) detected H$\alpha$ emission separated from the SMC emission by $170$ km s$^{-1}$, so shock velocities this high certainly seem plausible. Assuming that $N$(O vi)/$N$(O) $\leq 0.2$ (Sutherland & Dopita 1993), and using log [O/H] = $-3.85$ for NGC 346 (Peimbert, Peimbert, & Ruiz 2000), we find that $N$(H$^+$) $\geq 8.1 \times 10^{18}$ cm$^{-2}$. The $3 \sigma$ upper limit on O i from the STIS spectrum is $N$(O i) $\leq 3.0 \times 10^{17}$ cm$^{-2}$, which corresponds to $N$(H$^+$) $\leq 2.1 \times 10^{17}$ cm$^{-2}$, so H$^+$/H$^+$ $\geq 38$. Koenigsberger et al. (2001) estimated $N$(H) $= (4.3–12.0) \times 10^{18}$ cm$^{-2}$ in the shell, close to our estimated value of $N$(H$^+$), so most of the gas in the shell may be ionized if the H$^+$ and H$^+$ are coplanar.

Figure 3 compares the O vi apparent column density profile with those of C iv, Si iv, Si iii, and Si ii convolved with a $15$ km s$^{-1}$ FWHM Gaussian to approximate the FUSE resolution. The red sides of the profiles of the high ions have similar shapes, while on the blue side the higher ions extend over progressively larger velocity ranges, so that in terms of $V_{\text{blue}}$, the velocity of the blue edge of the profile,
ionization structure is a multiphase shell of swept-up ISM material dominated by hot gas. A possible interpretation of this of absorption by lower ionization lines, suggests that this motions contribute to the line broadening.

\[ \text{O}^\text{iv} \text{ high side of the ISM average of Sembach et al.} \]

\[ \text{C}^\text{iv} \]

\[ \text{Si}^\text{iv} \]

\[ \text{V}^\text{!} \]

\[ \text{absorption at 250 km s}^{-1} \].

\[ \text{Near 300 km s}^{-1} \].

\[ \text{The} \text{C}^\text{iv} \text{IV has a distinct tail of absorption to negative relative velocities that extends almost as far as the O} \text{IV absorption. Near 300 km s}^{-1}, \text{the O} \text{IV/C} \text{IV ratio implies temperatures} \sim (2.0-2.5) \times 10^4 \text{K}, \text{while the C} \text{IV/Si} \text{IV ratio suggests} T \lesssim 10^5 \text{K if the gas is in ionization equilibrium (Sutherland & Dopita 1993). There appears to be gas at several different temperatures at this velocity, a conclusion supported by the presence of Si ii, Si iii, and Si iv. The C} \text{IV and O} \text{IV absorption at 250 km s}^{-1}, \text{along with the absence of absorption by lower ionization lines, suggests that this material is dominated by hot gas. A possible interpretation of this ionization structure is a multiphase shell of swept-up ISM moving at the highest velocity (300 km s}^{-1}, \text{with the cavity behind it filled with hot gas. The C} \text{IV/Si} \text{IV ratio is} \sim 5 \text{in the shell, similar to that seen in the old SNR Radio Loop IV, and on the high side of the ISM average of 3.8} \pm 1.9 \text{ (Sembach et al. 1997). The line ratios imply temperatures lower than that indicated by the O} \text{IV line width, suggesting that nonthermal motions contribute to the line broadening.} \]

Table 2 lists the observed \( N(\text{C} \text{IV})/N(\text{O} \text{IV}) \) and \( N(\text{C} \text{IV})/N(\text{N} \text{V}) \) ratios for SNR 0057--7226, for the SMC and Milky Way along this sight line, and the general disk and halo values. Also listed are the predictions of models of different mechanisms for producing high ions. The observed \( N(\text{C} \text{IV})/N(\text{O} \text{IV}) \) ratio in SNR 0057--7226 agrees well with the predicted ranges of models of evolving SNRs. The observed value of \( N(\text{C} \text{IV})/N(\text{O} \text{IV}) \) for SNR 0057--7226 is close to the Milky Way disk value and very different from the halo value. The \( N(\text{C} \text{IV})/N(\text{N} \text{V}) \) ratio in the SNR also agrees with the disk value. While there may be a metallicity effect on the observed ratios, the observed values for SNR 0057--7226 lend support to models of hot gas production (Shull & Slavin 1994) in which supernovae are largely responsible for the highly ionized gas in the Galactic disk, while different processes such as turbulent mixing layers (Slavin, Shull, & Begelman 1993) and radiatively cooling fountain gas (Shapiro & Benjammon 1991) are responsible for the hot gas in the upper halo. The observed SNR ratios are also quite different from the general SMC ratios along this sight line, suggesting that mechanisms other than evolving SNRs, such as those listed in Table 2, contribute to the extended hot gas in the SMC.

The column density of O iv in the SNR is \( \sim 40\% - 65\% \) of the O iv column in the SMC component (excluding the SNR). Thus, only three such SNRs would be needed to explain all of the O iv in the SMC in this direction. Since this sight line is in the star-forming region NGC 346, it is quite plausible that multiple SNRs may exist along this sight line. The column density of O iv in the SNR is greater than that in the entire Galactic component in this direction. If SNR 0057--7226 is representative of SNRs in general, then they may be able to account for much of the O iv observed in the ISM of the Milky Way.

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