The Astrophysical Journal, 558:L35–L38, 2001 September 1
© 2001. The American Astronomical Society. All rights reserved. Printed in U.S.A.

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

Charles G. Hoopes, Kenneth R. Sembach, J. Christopher Howk, and William P. Blair
Department of Physics and Astronomy, Johns Hopkins University, 3400 North Charles Street, Baltimore, MD 21218;
choopes@pha.jhu.edu, sembach@pha.jhu.edu, howk@pha.jhu.edu, wpb@pha.jhu.edu
Received 2001 June 29; accepted 2001 July 27; published 2001 August 3

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 VI 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 H_2 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 λλ1032, 1038 lines are very important probes of collisionally ionized gas near 3×10^5 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; $l = 302.^{\circ}07$, $b = -44.^{\circ}95$) 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 $V_{LSR} = 300$ 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 Hα 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} ($V_{LSR} = 300$ and 331 km s^{-1}) in some of the lines. They also detected excess absorption at $V_{\odot} = 33$ and 64 km s^{-1} ($V_{LSR} = 21$ 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 $\sim 2 \times 10^5$ and $\sim 1 \times 10^5$ 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, 30″ × 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 LiF1. It is the primary source of data considered here, although all the results were verified in LiF2 data. 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-

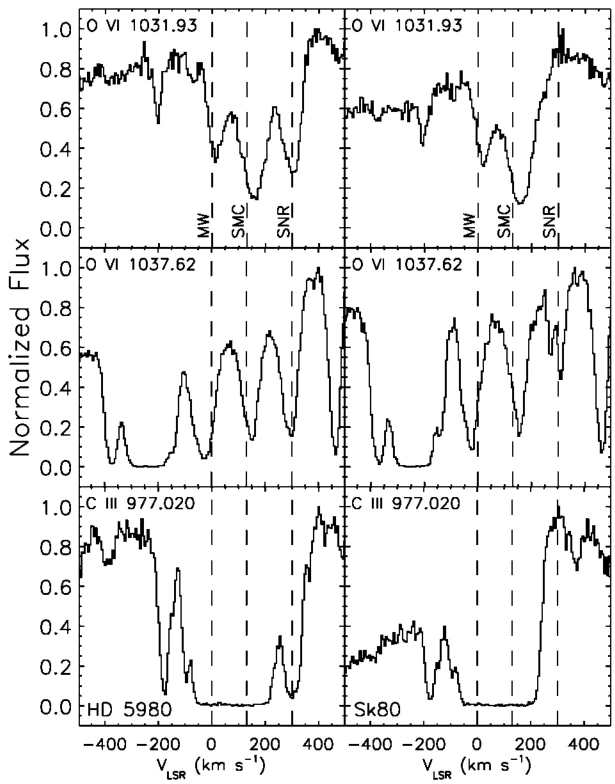

FIG. 1.—Observed line profiles for selected interstellar lines in the spectrum of HD 5980 and Sk 80. The spectra have been normalized by dividing by the maximum flux value in the velocity range plotted. The velocities indicated by the vertical dashed lines are, from left to right, the Milky Way at 0 km s^{-1}, the SMC at ∼130 km s^{-1}, and SNR 0057−7226 at ∼300 km s^{-1}. All three components of O VI λ1037.62 absorption are blended with other lines, and the Milky Way and SMC components of C III λ977.02 absorption are heavily saturated.

bration 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 (∼6 km s^{-1} near O VI), and the nominal resolution of the data is ∼20 km s^{-1} (FWHM). The relative wavelength solution is accurate to ∼6 km s^{-1} on average. The signal-to-noise ratio in the binned data is ∼50 near the O 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 VI and C III in the spectra of HD 5980 and Sk 80. The two stars are separated by ∼1′, or ∼17 pc, assuming a distance of 59 kpc to the SMC (Mathewson, Ford, & Visvanathan 1986). Absorption features of O VI λ1032 and C III λ977 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 VI λ1038 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.

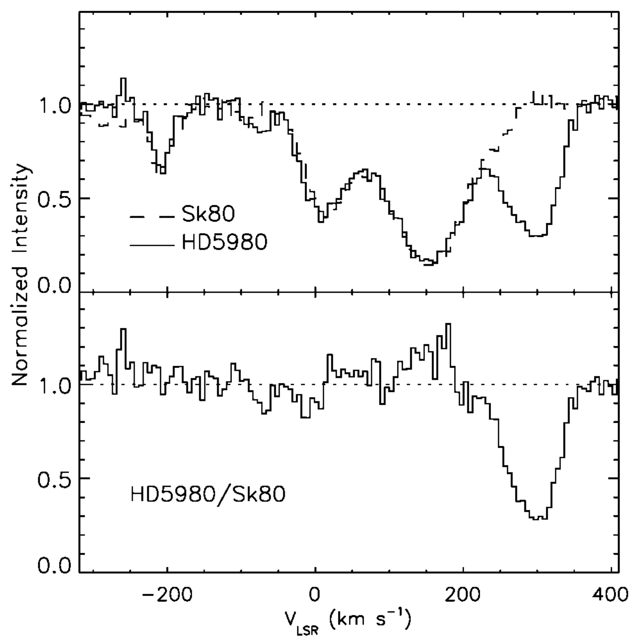

FIG. 2.—O VI λ1032 line in the spectra of HD 5980 and Sk 80. The top panel shows the two continuum-normalized spectra, with HD 5980 as the solid line and Sk 80 as the dashed line. The bottom panel shows the HD 5980 spectrum after dividing it by the Sk 80 spectrum.

The Milky Way and SMC O VI λ1032 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 VI λ1038 and C III λ977 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 $\sim 2 \times 10^6$ 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 $V_{LSR} = 300$ km s^{-1} and a weaker component at $V_{LSR} = 331$ km s^{-1}. The absorption in the *FUSE* spectrum is located at $V_{LSR} \sim 300$ km s^{-1}, corresponding to the strong component. We do not detect the $V_{LSR} = 331$ km s^{-1} component in C III or O 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 VI and C III lines and upper limits on S VI and Fe II. No O I or H_2 absorption is seen at 300 km s^{-1}. The S III and S 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

TABLE 1
LINE STRENGTHS AND COLUMN DENSITIES

Line	log $f\lambda$[a]	Velocity Range (km s^{-1})	W_λ[b] (mÅ)	log N[b] (cm^{-2})
O VI λ1031.93	2.14	230–350	206 ± 12	14.41 ± 0.02
O VI λ1031.93[c]	2.14	230–350	191 ± 8	14.36 ± 0.03
O VI λ1031.93[c,d]	2.14	0–150	<34	<13.43
C III λ977.02	2.87	260–360	251 ± 5	13.97 ± 0.04
S VI λ933.38	2.61	260–360	<23	<12.83
Fe II λ1144.94	2.08	260–360	<14	<13.03
Fe III λ1122.52	1.95	260–360	<30	<13.53
C IV λ1548.20	2.47	230–350	112 ± 8	13.53 ± 0.03
C IV λ1550.77	2.17	230–350	57 ± 5	13.49 ± 0.04
N V λ1242.80	1.99	230–350	12 ± 4	13.03 ± 0.12
O I λ1302.17	1.80	230–350	<24	<13.48

[a] The f-values are from Morton 1991 except for Fe II, which is from Howk et al. 2000.
[b] The uncertainties given are 1 σ estimates, and limits are 3 σ estimates.
[c] These quantities were measured on the HD 5980 spectrum after dividing by the Sk 80 spectrum.
[d] This is the limit on absorption from the approaching side of the SNR.

if the intrinsic line width is comparable to or broader than the instrumental line spread function (LSF; Savage & Sembach 1991). At temperatures of 3×10^5 K, where the abundance of O VI peaks in collisional ionization equilibrium (Sutherland & Dopita 1993), the line width from thermal broadening (≈30 km s^{-1}) is larger than the *FUSE* LSF width (≈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 $\lambda > 1200$ Å 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 σ) of log N(O VI) ≤ 13.43 on the approaching side, ~11% of the column density of the receding side.

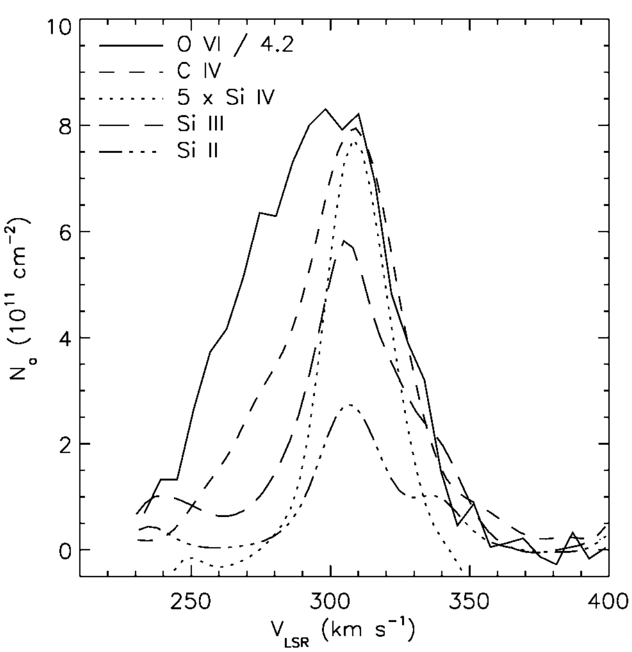

FIG. 3.—Comparison of the O VI λ1031.93, C IV λ1548.20, Si IV λ1393.76, Si III λ1206.50, and Si II λ1260.42 apparent column density profiles. The profiles have been scaled by the factors listed in the upper left corner. The STIS profiles (C IV, Si IV, Si III, and Si II) have been convolved with a Gaussian with FWHM = 15 km s^{-1} to compare with the O VI profile observed by *FUSE*. The Si II and Si III lines are strong and may contain unresolved saturated structure but are shown to demonstrate the velocity structure. The column densities for these lines should be considered lower limits.

4. DISCUSSION

Models of evolving SNRs (Slavin & Cox 1992, 1993; Shelton 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 ~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} (Koenigsberger et al. 2001), 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 Hα 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) ≤ 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 σ upper limit on O I from the STIS spectrum is N(O I) ≤ 3.0×10^{13} cm^{-2}, which corresponds to N(H I) ≤ 2.1×10^{17} cm^{-2}, so $H^+/H^0 \geq 38$. Koenigsberger et al. (2001) estimated N(H) = (4.3–12.0) × 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^0 and H^+ are cospatial.

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_{blue}, the velocity of the blue edge of the profile,

TABLE 2
Column Density Ratios

Location	N(C IV)/N(O VI)	N(C IV)/N(N V)
SNR 0057−7226	0.12–0.17	2.0–4.5
SMC (toward HD 5980)	≥0.71	≥5.1
Milky Way (toward HD 5980)	∼1.3[a]	∼6.8[a]
Milky Way (disk)	0.08–0.26[b]	∼3.8[c]
Milky Way (halo)	0.46–1.91[b]	4.3–7.0[c]
Mixing layer[d]	1.0–3.4	7.8–28
Cooling fountain[e]	0.1–0.5	2.2–6.8
Conductive interface[f]	0.2–0.4	1.8–2.6
SNR models[g]	0.1–0.2	1.9–2.3

[a] C IV and N V from Sembach & Savage 1992.
[b] From Spitzer 1996.
[c] C IV and N V from Savage, Sembach, & Lu 1997.
[d] From Slavin et al. 1993; see Sembach, Savage, & Hurwitz 1999 for details.
[e] From Sembach et al. 1999.
[f] From Borkowski, Balbus, & Fristrom 1990; see Sembach et al. 1999 for details.
[g] From Slavin & Cox 1992; see Sembach et al. 1997 for details.

V_{blue}(O VI) < V_{blue}(C IV) < V_{blue}(Si IV). The C IV has a distinct tail of absorption to negative relative velocities that extends almost as far as the O VI absorption. Near 300 km s^{-1}, the O VI/C IV ratio implies temperatures ∼(2.0–2.5) × 10^5 K, while the C IV/Si IV ratio suggests $T \leq 10^5$ 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 IV and O VI absorption at 250 km s^{-1}, 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}), with the cavity behind it filled with hot gas. The C IV/Si IV ratio is ∼5 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 ± 1.9 (Sembach et al. 1997). The line ratios imply temperatures lower than that indicated by the O VI line width, suggesting that nonthermal motions contribute to the line broadening.

Table 2 lists the observed N(C IV)/N(O VI) and N(C IV)/N(N 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(C IV)/N(O VI) ratio in SNR 0057−7226 agrees well with the predicted ranges of models of evolving SNRs. The observed value of N(C IV)/N(O VI) for SNR 0057−7226 is close to the Milky Way disk value and very different from the halo value. The N(C IV)/N(N 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 & Benjamin 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 VI in the SNR is ∼40%–65% of the O VI column in the SMC component (excluding the SNR). Thus, only three such SNRs would be needed to explain all of the O VI 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 VI 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 VI observed in the ISM of the Milky Way.

This project benefited from discussions with Charles Danforth. We thank Alex Fullerton and the *FUSE* Hot Star Team for reducing the *FUSE* data. This work is based on data obtained for the Guaranteed Time Team by the NASA-CNES-CSA *FUSE* mission operated by Johns Hopkins University. Financial support has been provided by NASA contract NAS5-32985.

REFERENCES

Blair, W. P., et al. 2000, ApJ, 538, L61
Borkowski, K. J., Balbus, S. A., & Fristrom, C. C. 1990, ApJ, 355, 501
Chu, Y., & Kennicutt, R. C., Jr. 1988, AJ, 95, 1111
de Boer, K. S., & Savage, B. D. 1980, ApJ, 238, 86
Fitzpatrick, E. L., & Savage, B. D. 1983, ApJ, 267, 93
Hartigan, P., Raymond, J., & Hartmann, L. 1987, ApJ, 316, 323
Howk, J. C., Sembach, K. R., Roth, K. C., & Kruk, J. W. 2000, ApJ, 544, 867
Inoue, H., Koyama, K., & Tanaka, Y. 1983, in IAU Symp. 101, Supernova Remnants and Their X-Ray Emission, ed. I. J. Danziger & P. Gorenstein (Dorderecht: Reidel), 237
Jenkins, E. B., Wallerstein, G., & Silk, J. 1976, ApJS, 32, 681
Koenigsberger, G., et al. 2001, AJ, 121, 267
Mallouris, C., et al. 2001, ApJ, in press
Mathewson, D. S., Ford, V. L., & Visvanathan, N. 1986, ApJ, 301, 664
McKee, C. F., & Ostriker, J. P. 1977, ApJ, 218, 148
Moos, H. W., et al. 2000, ApJ, 538, L1
Morton, D. C. 1991, ApJS, 77, 119
Peimbert, M., Peimbert, A., & Ruiz, M. T. 2000, ApJ, 541, 688
Sankrit, R., Shelton, R. L., Blair, W. P., Sembach, K. R., & Jenkins, E. B. 2001, ApJ, 549, 416
Savage, B. D., & Sembach, K. R. 1991, ApJ, 379, 245
Savage, B. D., Sembach, K. R., & Lu, L. 1997, AJ, 113, 2158
Sembach, K. R., & Savage, B. D. 1992, ApJS, 83, 147
Sembach, K. R., Savage, B. D., & Hurwitz, M. 1999, ApJ, 524, 98
Sembach, K. R., Savage, B. D., & Tripp, T. M. 1997, ApJ, 480, 216
Shapiro, P. R., & Benjamin, R. A. 1991, PASP, 103, 923
Shelton, R. L. 1998, ApJ, 504, 785
Shull, J. M., & Slavin, J. D. 1994, ApJ, 427, 784
Slavin, J. D., & Cox, D. P. 1992, ApJ, 392, 131
———. 1993, ApJ, 417, 187
Slavin, J. D., Shull, J. M., & Begelman, M. C. 1993, ApJ, 407, 83
Spitzer, L., Jr. 1996, ApJ, 458, L29
Sutherland, R. S., & Dopita, M. A. 1993, ApJS, 88, 253
Walborn, N. R. 1977, ApJ, 215, 53
Wang, Q., & Wu, X. 1992, ApJS, 78, 391
Ye, T., Turtle, A. J., & Kennicutt, R. C., Jr. 1991, MNRAS, 249, 722