FAR-ULTRAVIOLET OBSERVATIONS OF THE NORTH ECLIPTIC POLE WITH SPEAR
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ABSTRACT

We present SPEAR/FIMS far-ultraviolet observations near the north ecliptic pole. This area, at \( b \sim 30^\circ \) and with intermediate HI column, seems to be a fairly typical line of sight that is representative of general processes in the diffuse interstellar medium. We detect a surprising number of emission lines of many elements at various ionization states, representing gas phases from the warm neutral medium to the hot ionized medium. We also detect fluorescence bands of \( \text{H}_2 \), which may be due to the ubiquitous diffuse \( \text{H}_2 \) previously observed in absorption.

Subject headings: ISM: general — ISM: lines and bands — ultraviolet: ISM

1. INTRODUCTION

The north ecliptic pole (NEP) is a region of the sky with no obviously unusual features. Many prior space missions (Einstein, ROSAT, COBE, IRAS, etc.) have conducted deep surveys of this region. Several ground-based surveys have also concentrated on this region as a complement to the space-based surveys (Labov et al. 1989; Elvis et al. 1994). Its location at moderate Galactic latitude \(( b = +29^\circ)\) places it clear of the bright stars of the Galactic plane. In this region, the Galactic \( N(\text{HI}) \) varies from about \( 2 \times 10^{20} \) to \( 8 \times 10^{20} \) \( \text{cm}^{-2} \), which corresponds to a dust opacity of \( \tau_{\text{dust}} = 0.6 \sim 2.3 \) at 1032 Å (Sasseen et al. 2002) or \( \tau_{\text{dust}} = 0.3 \sim 1.4 \) at 1550 Å (Savage & Mathis 1979).

The Spectroscopy of Plasma Evolution from Astrophysical Radiation (SPEAR) instrument, designed for observing emission lines from the diffuse interstellar medium (ISM), was launched in late 2003. SPEAR is a dual-channel far-ultraviolet (FUV) imaging spectrograph ("Short" wavelength channel [S] \( 900 \sim 1150 \) Å, “Long” wavelength channel [L] \( 1350 \sim 1750 \) Å) with \( \Delta \lambda \sim 550 \), with a large field of view (S, \( 40'' \times 46'' \); L, \( 74'' \times 43'' \) imaged at 10'' resolution. (See Edelstein et al. [2006a, 2006b] for an overview of the instrument, mission, and data analyses.) SPEAR sky survey observations consist of sweeps at constant ecliptic longitude from the NEP to the south ecliptic pole through the antisolar point. The duration of each sweep varies between 900 and 1500 s. Each survey scan includes the region near the north and south ecliptic poles, resulting in large exposure times in these regions. We report on deep SPEAR observations of FUV emission spectra from a 15'' radius region centered on the NEP.

2. OBSERVATIONS AND DATA REDUCTION

The NEP data analyzed here include sky survey and pointed observations that occurred between 2003 November 8 and 2004 November 10. To remove times of high background and bright stars from the data set, we have excluded times during which the count rate exceeded 100 s^{-1} (in comparison, a typical photon count rate is \( \approx 20 \text{ s}^{-1} \)). Because stars transit the instrument slit in \( \sim 5 \) s during survey sweeps, this results in minimal loss of observing time. The area of sky lost because of a star is similar to the instrument imaging resolution across the slit width (\( \sim 10'' \times 5'' \); see Edelstein et al. [2006a] for a description of the data reduction pipeline).

To further remove stellar contamination from our data set, we excluded locally intense spatial bins (\( \sim 30\% \) of the viewed area), defined to have \( \geq 3 \) times the median count rate. This level corresponds to a slope change in the histogram of the logarithmic count rate, indicative of a difference in distribution of scattered versus direct starlight. Inclusion of unresolved starlight should not be a factor other than to raise emission-line determination errors. To obtain the highest sensitivity possible, we have binned the entire data set into a single spectrum including a total of \( 3.5 \times 10^5 \) counts over an effective full-slit exposure of 13.5 ks.

3. SPECTRAL MODELING

The raw SPEAR spectrum is composed of many components: detector background, dust-scattered stellar continuum, direct and instrumentally scattered airglow, and interstellar atomic and molecular emission. To model a spectrum, we simultaneously fit all the components to the observed spectrum.

The spectral shape is distorted by the detector electronics and by the data processing pipeline. These distortions appear as fluctuations in a flat-field image. Any broadband component used in our model spectrum must be multiplied by this non-linearity function. (Korpe1a et al. 2003; Rhee et al. 2002).

Both the S and L channels are affected by instrumental background due to cosmic rays, radioactive decay within the detector, and thermal charged particles entering the instrument. These sources of background are relatively uniform across the face of the detectors. Although the charged-particle rate can change with time and orbital position, the positional distribution of these background events is dominated by static fields within the instrument and is relatively constant. A sum of many shutter-closed dark exposures multiplied by a rate factor can be used to model this contribution to the spectrum.

In L, the largest broadband spectral component is dust-scattered stellar continuum. We model the input spectrum to the dust scattering process as a sum of spectra for upper main-sequence (UMS) stars. Each spectrum is weighted by using a power-law UMS luminosity function \( (dN/dM_\star \propto M_\star^{-1}) \), where \( M_\star \) is the absolute magnitude and \( dN/dM_\star \) is the volume density of stars per unit magnitude) and a dilution factor that depends on the weighted mean distance of the stars. The spectral sum is multiplied by a dust opacity scaled to a variable \( N(\text{HI}) \) and
by a dust albedo function (Draine 2003) with a variable total dust surface area. The best fits for this function typically occur very near to the measured UMS luminosity function, with $\alpha \sim 0.2$ (Reed 2001). Because the stellar features in this spectrum cannot be directly measured, there may be some bias in our measurements of the overlying resonance lines (C iv $\lambda\lambda$1548, 1551, O vi $\lambda\lambda$1032, 1038, Si iv $\lambda\lambda$1394, 1403, etc.), on the order of $\sim$1000 photons s$^{-1}$ cm$^{-2}$ sr$^{-1}$ (line intensity units, LU). We include this effect in our error analysis. Our best-fit continuum, which could include unresolved stars, is $300^{+30}_{-10}$ photons s$^{-1}$ cm$^{-2}$ sr$^{-1}$ (continuum intensity units, CU) in L. In S, because of its lower sensitivity and higher non-astrophysical background, we are only able to place a statistical upper limit of 1200 CU. However, given the wavelength dependence of the dust albedo, we expect that the true astrophysical continuum in S is no higher than in L.

We first attempted to fit atomic line emission by using linear combinations of collisional ionization equilibrium (CIE) plasma models with a limited abundance gradient versus T. We attribute this method’s lack of success to photoexcitation of resonance lines, non-CIE effects, and abundance variations that are not T-related. To fit the line emission, we have instead fitted the spectrum of each species separately with a per-species intensity parameter. When CHIANTI parameters are not involved with a T-related Gaussian to model the instrument spectral resolution. We use the atomic parameters of CHIANTI (Young et al. 2003) to determine the spectrum of the species versus T. This spectrum is then normalized and multiplied by the intensity parameter. When CHIANTI parameters are not available for a species, we use a spectrum calculated using the NIST Atomic Spectra Database.

We then consider the effects of self-absorption of spectral resonance lines. In the case of highly ionized species, we assume that all lines are optically thin. We also assume this to be the case for species that would be completely photoionized in the warm neutral medium (WNM) (ionization potential IP $< 13.6$ eV). For species that are likely to be abundant in the WNM and warm ionized medium (WIM), IP $\approx 13.6$ eV, we assume that resonance lines are optically thick ($\tau > 10$) and that the distances to the illuminating stars are large compared with the $\tau = 1$ surface. In cases where the ground state is split, absorbed resonance-line photons will be converted to the excited state, greatly changing the relative contributions in the multiplet. We model this by attenuating the ground-state transition by a large factor. We will develop a more accurate way of treating these optical depth effects in future work.

4. DISCUSSION

The spectrum of the bright Lyman series geocoronal emission, easily visible in Figure 1, can be modeled using a temperature and total line flux. The largest S-channel broadband component is scattered geocoronal Ly$\alpha$ (1216 Å) emission. This line occurs in the bandpass gap between S and L. The L channel is immune to Ly$\alpha$ contamination because it includes a CaF$_2$ filter that is very nearly opaque to Ly$\alpha$ radiation. We fit the S scattering with two components, an exponential scatter proportional to $\exp(-\lambda \lambda - \lambda_{\alpha}/\alpha)$ with $\alpha \approx 200$ Å, and an isotropic component. The scattering, summed over the entire spectrum, is $\sim 0.08\%$ of a $\sim 5000$ ryd Ly$\beta$ incident flux. Because the Ly$\alpha$ transition is optically thick, and because the scattering fractions are independent parameters, we fix the estimated incident Ly$\alpha$ flux at 1100 times the Ly$\beta$ flux, which helps the solution to converge. While the fractional scatter and exponential width of these components are free parameters in our spectral model, the values we obtain vary little from one data set to the next.

Our model includes spectral features of atmospheric O i, C i, and N i that are much fainter than when seen in daytime observations (e.g., by FUSE, the Far Ultraviolet Spectroscopic Explorer), as SPEAR only observes during orbital eclipse. We detect a spectral feature near 990 Å that is consistent with the O i $\lambda 989$ transition. However, this feature may be blended with N iii $\lambda 990$. If the entirety of the 990 Å feature is due to O i, the lack of detectable O i $\lambda 1356$ emission would indicate $T > 10^{4.6}$ K, which is plausible for interstellar O i. We do detect O i $\lambda 1356$ in data that are not count-rate filtered. The other possibility is that the 990 Å is due to O i at temperatures of a few hundred kelvins, which seems unlikely even for atmospheric O i. The most likely explanation for the lack of any detection of O i emission at $\lambda \neq 990$ Å is that a large portion, if not all, of the 990 Å emission is due to N iii.

We detect relatively strong emission from H$_2$ fluorescence bands even in this region of intermediate N(H i). This is not entirely surprising, since absorption due to H$_2$ is a ubiquitous feature of FUV spectra taken by FUSE (Shull et al. 2000). We fit these features by using interpolation on a sparse grid of H$_2$ models (B. Draine 2004, private communication). Figures 1 and 2 (top) show the best-fit H$_2$ model plotted against the residuals of the spectrum following background, continuum, and scattering subtraction. We detect H$_2$ emission features in both spectral bands. In S, we detect the H$_2$ 965 Å band (to the left of the H i $\lambda 972$ line) and the H$_2$ 986 Å band (to the left of the O i/N iii $\lambda 989$ feature). The H$_2$ 1053 and 1097 Å bands are not detected at any significance. In L, H$_2$ provides contributions throughout the spectrum. We attribute the triple-peaked band structure between 1350 and 1380 Å, the peak near 1440 Å, the broad features at 1520–1530 and 1570–1590 Å, and the peak near 1608 Å to H$_2$. Note that these features are not well fitted by our H$_2$ model. It is not surprising that our
sparse linear model with a single dust absorption column does not fit these data, since the observed emission derives from many lines of sight with varying illumination, gas temperatures, and absorbing columns. In the bottom panels of Figures 1 and 2, we show the residual spectrum following subtraction of the H$_2$ component.

We see intriguing indications of N$_2$ fluorescent emission, most notably the features at 1434, 1445, 1475, and 1660 Å. FUSE has detected absorption due to N$_2$ along some sight lines, albeit at shorter wavelengths (Knauth et al. 2004). We cannot yet discount the possibility that these N$_2$ features are atmospheric, as near the magnetic poles N can be transported to the WNM and WIM, the true Si level of the ground state. The offset between the model feature and the observed line may be due to an uncorrected continuum strength and are expected to be optically thin along this line of sight. However, given the low oscillator strength, we expect these lines to be faint compared with the Si ii and Al ii features.

Emission lines of highly ionized gas expected to be generated in a CIE plasma at temperatures characteristic of the hot interstellar medium (HIM) are shown in Table 1. Of these we detect (>3 $\sigma$) C iii λ977, C iv λλ1548, 1551, Si iv λλ1394, 1403, and O vi λλ1032, 1038. The C iv and Si iv features overlie prominent stellar absorption features that are likely to be present in the dust-scattered stellar radiation. Since the depth of these features is unknown, we set the lower range of our model uncertainty to be the intensity that would be calculated if there were no continuum feature present.

Many of these emission features are resonance lines (R. J. Reynolds 2005, private communication), and because of the substantial interstellar radiation field at these wavelengths, further work will be required to determine whether these lines arise as a result of collisional excitation in the HIM or resonant scattering of the interstellar radiation field. We believe that the short-wavelength lines are less likely to be resonant scatter because the relative intensity of the scattered stellar continuum in the S band is much lower (Korpela et al. 1998).

Our C iv λλ1548, 1551 intensity of 5820 ± 280 LU is marginally higher than values for the diffuse ISM reported by Martin & Bowyer (1990). However, Martin & Bowyer assumed a featureless continuum rather than a continuum with stellar features. If we make the same assumption, our value drops to 4330 ± 210 LU, which is more within the range of values they report.

Our O vi λλ1032, 1038 intensity of 5724 ± 1100 LU is somewhat higher than the typical value measured by FUSE (Shelton 2003). This could be a systematic effect due to the uncertain calibration of the S band. In fact, the ratio of the H$_2$ feature intensities between L and S suggests that we have underestimated the sensitivity of S. Since this is an average over a very large region, it is also possible that the O vi emission is due to several small regions with very high intensity, such as supernova remnants.

The double-peaked feature near 1400 Å is a blend of Si iv λλ1393.8, 1402.8 and O iv] λλ1400.7, 1407.4. The O iv] emission is of great interest because, as a semiforbidden line, it is not strongly affected by the radiation field but is a direct indicator of collisional processes. Assuming a 2:1 ratio for the Si iv doublet components, our model determines the O iv] doublet intensity to be 1980 ± 300 LU and the Si iv doublet intensity to be 1430 ± 160 LU.

### Table 1

| Species | $\lambda$ (Å) | $I_2$ (LU) | Statistical Error (LU) | Model Uncertainty (LU) |
|---------|---------------|------------|------------------------|-----------------------|
| O iii   | 1667          | <500       | ...                    | ...                   |
| O iv]   | 1400          | 1980 ± 220 | ± 1100                 | ...                   |
| O vi    | 1032, 1038    | 5724 ± 570 | ± 1100                 | ...                   |
| C iii   | 977           | 1260 ± 270 | ...                    | ...                   |
| C iv    | 1548, 1551    | 5820 ± 280 | $^a$                   | ...                   |
| Si ii   | 1532          | 2430 ± 200 | $^b$                   | ...                   |
| Si iv   | 1394, 1403    | 1430 ± 120 | ± 160                  | ...                   |
| N ii    | 1085          | 8500 ± 730 | ...                    | ...                   |
| N iii   | 990           | 2300 ± 115 | ...                    | ...                   |
| N iv    | 1485          | 1984 ± 170 | ± 450                  | ...                   |
| Al ii   | 1671          | 5608 ± 525 | ...                    | ...                   |
| He ii   | 1640          | 1850 ± 180 | $^a$                   | ...                   |
| Ne vi   | 999, 1005     | <4100      | ...                    | ...                   |

* Upper limits are 90% confidence.

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Note.—LU = photons s$^{-1}$ cm$^{-2}$ sr$^{-1}$.

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**Fig. 2.**—Same as Fig. 2, but for the L channel.
We detect high-stage ions of two noble gases in our spectra, He ii λ1640 and Ne vi λ999, 1005. Although the features corresponding to the Ne vi lines are statistically significant, the poor fit to the underlying H₂ bands prevents us from placing more than an upper limit to these features. Because of the lack of detection of any O i λ1356, we do not expect any contamination of the He ii line with O i λ1641. The He ii line is much brighter than would be expected in a solar-abundance CIE model (in ratio to C iii and O iii). This could be due to depletion of C and O to ≲0.1 times solar. A depletion of this magnitude would be significantly higher than the accepted values for the ISM.

In Figure 3, we show equivalent solar-abundance emission measures (EMs) and limits for several species. The results are not entirely consistent between species. For example, higher EMs are necessary to explain the Si iv and He ii emission than are compatible with the amount of C iii emission. The questionable Ne vi detections would indicate an EM 10 times that suggested by the O vi measurements. The bulk of the inconsistency in Ne vi is likely to be due to undersubtraction of the underlying H₂. Much of the inconsistency in other lines is likely due to non-CIE effects that are present in gas being heated or cooling at these temperatures. Some portion of the difference could be due to abundance variations (with ISM depletions of O and C higher than those of Ne, He, and Si), although the suggested depletions are much higher than the accepted ISM values. In future work, we will derive constraints to non-CIE cooling models and abundances using these line ratios.

5. CONCLUSIONS

We have presented the FUV spectra of a 30° region around the NEP. We detect a variety of emission lines from high- and low-ionization gas. The high-ionization lines, taken on a per-species basis, are consistent with emission measures from 0.001 to 0.005 cm⁻³ pc throughout the T = 10⁴.5–10⁵.5 K range. For those few species that have multiple lines in the band, the calculated temperatures tend to fall near the CIE peak abundance for the species. Despite this, a linear combination of CIE models with a restricted abundance versus T gradient does not provide a good fit to the spectrum. This is likely due to non-CIE effects and abundance variations that are not directly T-related. It is also likely that many lines include some resonantly scattered stellar radiation. Modeling this scattering will be a significant portion of our continued research.

We have discerned line emission from species that are expected to exist in the WNM and WIM. We interpret these lines as resonantly scattered stellar radiation. In the future, we will investigate whether spatial variation of the Al ii and Si ii features can indicate the effect of grain formation and destruction on the gas-phase abundances of these elements.

Despite relatively low Galactic N(H i) in this direction, we see a substantial amount of H₂ fluorescence. Further modeling of the H₂ fluorescence is necessary to fully understand faint spectral features that could be related to H₂ or due to unrelated atomic lines.

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