POTENTIAL VARIATIONS IN THE INTERSTELLAR N I ABUNDANCE

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ABSTRACT

We present Far Ultraviolet Spectroscopic Explorer (FUSE) and Space Telescope Imaging Spectrograph observations of the weak interstellar N I λ1160 doublet toward 17 high-density sight lines [N(Hi) ≥ 10^{21} cm^{-2}]. When combined with published data, our results reveal variations in the fractional N I abundance showing a systematic deficiency at large N(Hi). At the FUSE resolution (~20 km s^{-1}), the effects of unresolved saturation cannot be conclusively ruled out, although O I λ1356 shows little evidence of saturation. We investigated the possibility that the N I variability is due to the formation of N2 in our mostly dense regions. The 0–0 band of the c1′,0Σ_u^+–X1Σ_g^+ transition of N2 at 958 Å should be easily detected in our FUSE data; for 10 of the denser sight lines, N2 is not observed at a sensitivity level of a few times 10^{14} cm^{-2}. The observed N I variations are suggestive of an incomplete understanding of nitrogen chemistry.

Subject headings: ISM: abundances — ISM: atoms — ISM: clouds — ultraviolet: ISM

1. INTRODUCTION

Elemental abundance studies are important for models of Galactic chemical evolution. Studies of the interstellar oxygen abundance support a relatively constant value of O/Htot = (3.43 ± 0.15) × 10^{-4} out to ~1000 kpc, with any variability less than the 1σ measurement uncertainties (Meyer, Jura, & Cardelli 1998; Cartledge et al. 2001; André et al. 2003). The situation is not as clear for carbon and nitrogen. In this work, we focus specifically on the abundance of interstellar nitrogen.

It is generally believed that interstellar nitrogen is a product of the CNO cycle and recycled into the interstellar medium (ISM) through the winds of low- and intermediate-mass stars (e.g., red giant branch and/or asymptotic giant branch [AGB] stars; Pilyugin, Thuan, & Víchez 2003). In contrast, oxygen is produced in stars during the He-burning phase and is returned to the ISM via supernovae.

Early studies (Lugger et al. 1978; Ferlet 1981; York et al. 1983) of interstellar N I using the Copernicus satellite investigated moderately dense lines of sight and found that N(N I) increases linearly with N(H2) [N(Hi) = 2N(H2) + N(H I)]. Using high-quality Goddard High Resolution Spectrograph (GHRS) data for seven sight lines with N(Hi) ≥ 10^{21} cm^{-2}, Meyer, Cardelli, & Sofia (1997) suggested that the interstellar nitrogen abundance is constant, N/Htot = (7.5 ± 0.4) × 10^{-5}. However, Jenkins et al. (1999) and Sonneborn et al. (2000), using data from the Interstellar Medium Absorption Profile Spectrograph (IMAPS), show a factor of 2 variation in the N I abundance between δ Ori [N i/Htot = (3.97 ± 0.30) × 10^{-5}] and γ Vel [N i/Htot = (7.99 ± 0.47) × 10^{-5}].

In the near ISM, d = 100 pc, N I is more affected by ionization than O I because O I is coupled more strongly to H I by charge-exchange reactions (Sofia & Jenkins 1998; Jenkins et al. 2000; Lehner et al. 2003). Therefore, these near ISM sight lines (Lehner et al. 2003) will not be discussed here. The effects of ionization at larger column densities are thought to be insignificant. In addition, nitrogen is not incorporated into refractory interstellar dust grains (Sofia, Cardelli, & Savage 1994). Nitrogen-bearing interstellar ices (Gibb, Whittet, & Chiar 2001; Chiar et al. 2002) are not expected along our sight lines (A_v ≤ 2.0) since interstellar ices do not form until A_v ≥ 3 (Whittet et al. 2001). However, nitrogen chemistry and N2 formation should become important.

In order to probe the extent of potential variations in the interstellar nitrogen abundance, we have undertaken a survey of the weak interstellar N I doublet λλ1159.817, 1160.937. Use of this doublet removes uncertainty in oscillator strengths (f-values) for different transitions and allows for a direct comparison with the work of Meyer et al. (1997). Our survey utilized archival data from the Far Ultraviolet Spectroscopic Explorer (FUSE; Moos et al. 2000) and the Space Telescope Imaging Spectrograph (STIS) on board the Hubble Space Telescope toward 17 high-density [N/H] ≥ 10^{17} cm^{-2} sight lines.

2. OBSERVATIONS AND DATA REDUCTION

2.1. FUSE Data

The N I data for 16 of the stars studied here, shown in Table 1, were obtained throughout the FUSE prime mission phase (1999 November–2003 March). All of the data were acquired with the star in the large aperture (30' × 30'; low resolution) with the exception of HD 219188, for which the medium aperture (4' × 20'; medium resolution) was utilized. The data cover the wavelength range 905–1185 Å with a spectral resolution equivalent to Δν ~ 20 km s^{-1}. The weak interstellar N I doublet at 1160 Å appears in both the LiF and LiF2 channels and provides a consistency check to rule out the possibility of detector artifacts.

The time-tagged and histogram data were reduced and calibrated with CalFUSE, version 2.2.2 (Dixon & Sahnow 2003). CalFUSE provides the appropriate Doppler corrections to remove the effects of the spacecraft motion and places the data on the heliocentric velocity scale (V_hel). The wavelength solution provides good relative calibration across the LiF channels. In order to minimize the uncertainties in the relative wavelength calibration between exposures, the data were co-added.

1 Based on observations made with the NASA-CNES-CSA Far Ultraviolet Spectroscopic Explorer, which is operated for NASA by the Johns Hopkins University under NASA contract NAS 5-32985, and the NASA/ESA Hubble Space Telescope, obtained from the Multimission Archive at the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under the NASA contract NAS 5-26555.

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3 The CalFUSE Pipeline Reference Guide is available at http://fuse.pha.jhu.edu/analysis/pipeline_reference.html.
with a cross-correlation technique. We used interstellar H$_2$ lines in several of the FUSE channels to fix the velocity scale ($V_\text{helio}$). The final summed spectra (near 1160 Å) have signal-to-noise (S/N) ratios between $\sim$20 and $\sim$300 per resolution element for all data sets. S/N ratios greater than 30 were obtained utilizing focal plane splits or other similar procedures.

### 2.2. STIS Data

STIS observed HD 147888 (N $\lambda$ l1161) for 1656 s on 2000 August 17, HD 24534 (O $\lambda$ l1356) for 2945 s on 2001 March 25, and HD 219188 (O $\lambda$ l1356) for 1200 s on 2001 September 27. The N $\lambda$ l1161 data for HD 147888 used the E140H grating centered at 1271 Å and the 0′$\lambda$2 by 0′$\lambda$09 aperture resulting in a resolving power ($R$) of about 100,000 ($\Delta$e $\sim$ 2.8 km s$^{-1}$). The O $\lambda$ l1356 data utilized the same grating, but with the 0′$\lambda$1 by 0′$\lambda$03 aperture centered on 14146 for HD 24534 and on 1271 for HD 219188 resulting in $R$ $\sim$ 200,000 ($\Delta$e $\sim$ 1.5 km s$^{-1}$).

The E140H setup, centered at 1271 Å and used to measure N $\lambda$ toward HD 147888, is not ideal since the stronger N $\lambda$ line is not obtained. In addition, the MgF$_2$ detector windows severely attenuate the flux below 1200 Å. N $\lambda$ l1161 can only be detected in relatively dense sight lines or with long exposure times. With the exception of HD 147888, examination of the archival data for other sight lines did not reveal evidence of N $\lambda$ l1161 because of the relatively low S/N ratio ($\lesssim$15 per resolution element).

The data were reduced and extracted with the CALSTIS pipeline, version 2.13b. The subtraction of background and scattered light from the echelle data employs the algorithm of Lindler & Bowers (2000). CALSTIS provides the appropriate Doppler corrections to place the spectra on the $V_\text{helio}$ scale. The spectrum of HD 147888 at 1161 Å has a S/N ratio of $\sim$12 per resolution element. For O $\lambda$ l1356 toward HD 24534 and HD 219188, we obtained S/N ratios of $\sim$70 and 48 per resolution element, respectively.

### 3. RESULTS AND DISCUSSION

Figure 1 shows the apparent column density (ACD) profiles, N$_{\text{A}}(\lambda)$, for both members of the weak interstellar N $\lambda$ doublet toward two stars from our stellar sample. See Sembach & Savage (1992) for a detailed discussion of the apparent optical depth method. The excellent overall agreement between the N$_{\text{A}}(\lambda)$ profiles for both members of the N $\lambda$ doublet implies that the apparent column densities are the true column densities. Table 1 presents our N $\lambda$ column densities, the average of both members of the doublet except HD 147888 (assumed to be unsaturated). Also presented are the measured equivalent widths ($W_\lambda$) of the N $\lambda$ doublet for each star. Finally, Table 1 shows the available Copernicus, International Ultraviolet Explorer, GHRS, IMAPS, and STIS measurements of N(1), N(H$_\alpha$), and N(O $\lambda$).
the observed variability is real. Figure 2 (bottom) depicts \( N(\text{N}^+)/N(\text{O}^+) \) as a function of \( N(H_{\text{tot}}) \). The data point for HD 147888, the densest sight line presented here, is high because O i is slightly depleted (Cartledge et al. 2001). The large scatter in N/O supports that the variation in N i is not an artifact introduced by the larger uncertainties for \( N(H_{\text{tot}}) \).

In order to test whether the observed N i variability is due to observational effects (i.e., saturation), we calculated curves of growth for four stars that exhibited deviant behavior (e.g., HD 179406) and six stars that did not. The curve-of-growth results agree with those obtained from the ACD method. Additionally, our results compare favorably with previous N i measurements (Hoopes et al. 2003; P. Sonnentrucker 2003, private communication). We believe saturation effects to be minimal since \( t_{\text{sat}}/t_{\text{gas}} = 1.4 \) and since O i shows little evidence of saturation (e.g., Cartledge et al. 2001).

A second source of systematic error could arise if the intrinsic absorption profile consisted of a narrow, but unsaturated, feature plus broad shallow wings. In such a scenario, the weak N i doublet associated with the broad component could be too weak to be detected at a low S/N ratio. If enough of the H i column density is located in the broad component, this could skew the N i/H_{\text{tot}} ratio to systematically low values. We can investigate this possibility in two ways: (1) through a comparison of the measured Doppler-broadening parameter (\( b \)-value) for the N i and hydrogen lines and (2) by comparing N i/H_{\text{tot}} versus distance to test whether systematically lower ratios are caused by additional weak kinematic components for the longer lines of sight (Spitzer 1985).

Unfortunately, both the Ly\( \alpha \) line of H i and the \( J = 0, 1 \) lines of H\( \alpha \) typically lie on the square-root part of the curve of growth for these sight lines and are insensitive to the \( b \)-value. However, \( b \)-values can nominally be measured for the \( J \geq 2 \) lines of H\( \alpha \). The published \( b \)-values for HD 73882, HD 110432, HD 185418, and HD 192639 (Rachford et al. 2001; Sonnentrucker et al. 2002; P. Sonnentrucker 2003, private communication) all show comparable or smaller \( b \)-values for H\( \alpha \) than for N i, indicating that all the N i is detected. Additionally, no statistically significant slope of N i/H_{\text{tot}} versus stellar distance (125 pc \( \leq d \leq 2 \) kpc) is found for our sample. These points argue against the intrinsic line shape contributing to the N i/H_{\text{tot}} deficiencies reported herein.

3.1. N\( _2 \)

Based on models of steady state, gas-phase interstellar chemistry, N\( _2 \) is expected to be the most abundant nitrogen-bearing molecule in dense clouds. Viala (1986) predicts that at the column densities of the sight lines studied here \( [N(H_{\text{tot}})] \) of a few times \( 10^{21} \) cm\(^{-2} \), the N\( _2 \) column densities should be on the order of 15% of the N i abundance or \( N(N_{\text{tot}}) \approx 10^{16} \) cm\(^{-2} \). Inclusion of time dependence or depletion onto grain mantles (Bergin, Langer, & Goldsmith 1995) could result in a slightly smaller gas-phase N\( _2 \) abundance. However, N\( _2 \) is still predicted to be the most abundant nitrogen-bearing molecule.
The strongest band of $N_2$, covered by FUSE, is the 0–0 band of the $\epsilon^\prime \Sigma^+_2 \rightarrow \chi \Sigma^+_2$ transition of $N_2$ at 958 Å. Other $N_2$ bands reside in the far-ultraviolet but are blended with more abundant species (e.g., $H_2$). Utilizing the laboratory wavelengths and $f$-values for the 0–0 band (Stark et al. 2000), we created several synthetic $N_2$ spectra, assuming level populations for excitation temperatures between 10 and 1000 K (see McCandliss 2003). Our synthetic spectrum is saturated for $N(N_2) = 10^{15}$ cm$^{-2}$. Therefore, we searched our FUSE data for the presence of $N_2$.

The top panel of Figure 3 exhibits the 958 Å portion of the spectrum toward HD 210839 [$E(B-V) = 0.62$ mag], and the bottom panel shows our synthetic $N_2$ spectrum for $N(N_2) = 10^{15}$ cm$^{-2}$, 10% of that predicted. The lower column density incorporates the effects of four velocity components detected in O I 1356 (André et al. 2003) along the line of sight with similar amounts of material. There is no evidence of $N_2$ in the spectrum of HD 210839 to a level of a few times $10^{14}$ cm$^{-2}$. Examination of the 10 densest sight lines that have FUSE data also shows a similar dearth of $N_2$. Hence, gas-phase $N_2$ cannot explain the observed N I variability. Quantitative limits on $N_2$ will be presented in a subsequent paper.

4. SUMMARY

Our data show that the interstellar N I abundances relative to H I and O I appear to vary. Very high resolution studies of these and other sight lines will help to verify and expand the findings reported here. Although $N_2$ is expected to be the most abundant nitrogen-bearing molecule in moderately dense [log $N(H_2) \geq 10^{21}$ cm$^{-2}$] clouds (e.g., Viala 1986), our data do not support the predicted abundances. The presence of an anticorrelation above $N(H_{tot}) = 10^{21}$ cm$^{-2}$ suggests that the mostly likely explanation for the interstellar N I variability is the need for a better understanding of nitrogen chemistry. However, differences in the mixing processes of products from AGB stellar outflows and supernovae may also contribute.

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