The Abundance of Interstellar Nitrogen

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ABSTRACT

Using the HST Goddard High Resolution Spectrograph (GHRS), we have obtained high S/N echelle observations of the weak interstellar N I λλ1160, 1161 absorption doublet toward the stars γ Cas, λ Ori, ν Ori, κ Ori, δ Sco and κ Sco. In combination with a previous GHRS measurement of N I toward ζ Oph, these new observations yield a mean interstellar gas-phase nitrogen abundance (per 10^6 H atoms) of 10^6 N/H = 75 ± 4 (±1σ). There are no statistically significant variations in the measured N abundances from sightline to sightline and no evidence of density-dependent nitrogen depletion from the gas phase. Since N is not expected to be depleted much into dust grains in these diffuse sightlines, its gas-phase abundance should reflect the total interstellar abundance. Consequently, the GHRS observations imply that the abundance of interstellar nitrogen (gas plus grains) in the local Milky Way is about 80% of the solar system value of 10^6 N/H = 93 ± 16. Although this interstellar abundance deficit is somewhat less than that recently found for oxygen and krypton with GHRS, the solar N abundance and the N I oscillator strengths are too uncertain to definitively rule out either a solar ISM N abundance or a 2/3 solar ISM N abundance similar to that of O and Kr.

Subject headings: ISM: abundances — ISM: atoms
1. Introduction

Accurate measurements of the elemental abundances in the interstellar medium are crucial to studies ranging from the chemical evolution of the Galaxy (Timmes, Woosley, & Weaver 1995) to the composition of interstellar dust grains (Snow & Witt 1996). Since it is difficult to obtain such data, the traditional approach has been to adopt the solar system values as "cosmic" current-epoch abundance standards. Recently, sensitive UV measurements of very weak interstellar absorption lines with the Goddard High Resolution Spectrograph (GHRS) onboard the Hubble Space Telescope (HST) have begun to seriously challenge these solar standards. In particular, based on GHRS observations of the O I \( \lambda 1356 \) absorption in 13 sightlines, Meyer, Jura, & Cardelli (1998) have measured a total (gas plus dust) abundance of interstellar oxygen that is 2/3 of the solar value. Cardelli & Meyer (1997) have found similar results for interstellar krypton which is important since Kr, as a noble gas, should not be depleted much into dust grains. These findings are also consistent with the subsolar CNO abundances that have been measured in nearby B stars and are likely reflective of the current ISM abundance pattern (Gies & Lambert 1992, Kilian 1992, Cunha & Lambert 1994, Kilian, Montenbruck, & Nissen 1994). Since the solar system abundances are presumably representative of the ISM at the time of the Sun's formation 4.6 Gyr ago and the ISM abundances should slowly increase over time (Audouze & Tinsley 1976, Timmes et al. 1995), a 2/3 solar standard for the local ISM today is difficult to understand in the context of Galactic chemical evolution models.

Among the abundant CNO elements, nitrogen can potentially provide the best test of a subsolar ISM abundance pattern since it is the least likely to be significantly depleted into dust grains. For example, using the wavenumber-integrated cross-section of the 2.96 \( \mu m \) N–H stretch (Tielens et al. 1991), the ISO spectrum of the star VI Cyg No. 12 (Whittet et al. 1997) limits the solid-state N abundance in the N–H stretch to \( 10^6 \) N/H < 1 in this
heavily reddened sightline. \textit{Copernicus} observations (Ferlet 1981, York et al. 1983, Keenan, Hibbert, \& Dufton 1985) of various N I transitions in the ultraviolet have yielded a mean interstellar gas-phase N abundance that is 50\% to 80\% of the solar value \((10^6 \text{N/H} = 93 \pm 16)\) (Grevesse \& Noels 1993). However, the scatter in these data is too great to discriminate the 0.2 dex difference between a solar and a B-star nitrogen abundance. Since this scatter is at least partially due to the errors in measuring the weakest and most optically thin N I lines, the greater sensitivity of GHRS makes it possible to establish a more accurate set of interstellar nitrogen abundances. In this Letter, we present the results of such an effort involving new GHRS observations of the very weak N I intersystem doublet at 1159.817 and 1160.937 Å toward six stars.

2. Observations

Observations of the interstellar N I \(\lambda\lambda 1160,1161\) absorption toward the stars \(\gamma\) Cas, \(\lambda\) Ori, \(\iota\) Ori, \(\kappa\) Ori, \(\delta\) Sco, and \(\kappa\) Sco were obtained with GHRS in 1996 August and 1997 January using the echelle-A grating and the 2'0 large science aperture. The observations of each star consist of multiple FP-Split exposures that are divided into four subexposures taken at slightly different grating positions so as to minimize the impact of the GHRS Digicon detector’s fixed pattern noise (FPN) on the reduced data. Each subexposure was sampled twice per diode at a velocity resolution of 3.5 km s\(^{-1}\).

The data were reduced using the Cardelli \& Ebbets (1994) recipe to maximize the S/N ratio of GHRS spectra. In brief, this process involves: (1) merging the FP-Split subexposures in diode space so as to create a template of the FPN spectrum, (2) dividing each subexposure by this FPN spectrum, (3) aligning the rectified subexposures in wavelength space using the interstellar lines as a guide, and (4) summing the aligned subexposures to produce the net N I spectrum of each star. As illustrated in Figure 1, the
resulting continuum-flattened spectra reveal convincing detections of the interstellar N I λ1160 absorption in all of the six sightlines comprising our sample. The S/N ratios of these spectra range from 150 to 250. Our measured equivalent widths for the N I λ1160 and λ1161 lines are listed in Table 1 along with the previously reported GHRS measurements toward ζ Oph (Savage, Cardelli, & Sofia 1992).

The N I column densities given in Table 1 were calculated using the Hibbert, Dufton, & Keenan (1985) oscillator strengths. The uncertainties in these theoretically-determined $f$-values should be no more than the quoted 20% (Hibbert et al. 1985) since Sofia, Cardelli, & Savage (1994) have empirically verified that they are consistent with the accurate $f$-values appropriate for the stronger N I λ1200 transitions. The λ1160,1161 absorption is generally weak enough for $N$(N I) to be confidently derived under the assumption that the lines are optically thin. However, based on the relative N I line strengths toward λ Ori and δ Sco, a slight correction for saturation was applied using a Gaussian curve-of-growth with respective $b$-values of $5.0^{+0.5}_{-0.2}$ and $10.0^{+1.0}_{-0.5}$ km s$^{-1}$. The resultant N I column densities are 5% and 6% greater than their weak line limits, respectively. The N I column density uncertainties given in Table 1 reflect the estimated errors in the measured equivalent widths and the saturation corrections (where applied).

3. Discussion

With an ionization potential of 14.534 eV, N I should be the dominant ion of N in H I regions, and little N I should originate from H II regions. Consequently, the ratio of $N$(N I) to the total H column density [$N$(H) = 2$N$(H$_2$) + $N$(H I)] should accurately reflect the interstellar gas-phase N/H abundance ratio. The values of $N$(H) listed in Table 1 were calculated from the H$_2$ column densities measured by Savage et al. (1977) (and Jenkins, Savage, & Spitzer 1986 for κ Sco) and the weighted means of the Bohlin, Savage, & Drake
(1978) (Jenkins et al. 1986 in the case of $\kappa$ Sco) and Diplus & Savage (1994) $N(H\ I)$ data. The resulting $N(N\ I)/N(H)$ ratios for the 7 GHRS sightlines yield a weighted mean (Bevington 1969) interstellar gas-phase N abundance of $10^6 N/H = 75 \pm 4 (\pm 1\sigma)$ that is about 80% of the Grevesse & Noels (1993) solar abundance ($10^6 N/H = 93 \pm 16$). The spread in the GHRS nitrogen abundances is about $\pm 0.1$ dex with the most discrepant values being those of $\delta$ Sco and $\kappa$ Sco at 1.6$\sigma$ above and 1.1$\sigma$ below the mean, respectively. It is worth noting that these two sightlines also have the most discrepant $N(H\ I)$ measurements in our sample.

In the top panel of Figure 2, the interstellar gas-phase N abundances are plotted as a function of the fractional abundance of molecular hydrogen, $f(H_2) = 2N(H_2)/N(H)$, in the GHRS sightlines. As discussed by Cardelli (1994), this parameter separates sightlines rather distinctly into groups with low and high $f(H_2)$ values that are indicative of the physical differences between UV transparent and $H_2$ self-shielding environments. Since the former type of environment is typically less hospitable to grains, higher gas-phase abundances of an element in the low $f(H_2)$ group than in the high group is a sign of both the presence of that element in dust and changes in the elemental dust abundance due to grain growth and/or destruction. Figure 2 clearly shows that the gas-phase abundance of interstellar N does not increase with decreasing $f(H_2)$ and is thus consistent with the expectation that nitrogen is not depleted much into dust grains.

In the bottom panel of Figure 2, the interstellar gas-phase N/Kr abundance ratio is plotted as a function of $f(H_2)$ for the four GHRS sightlines in common between this study and that of Cardelli & Meyer (1997). Krypton can be used as a hydrogen-like benchmark in interstellar abundance studies since it should not be depleted into grains and Kr/H exhibits a tight spread of $\pm 0.05$ dex among the ten sightlines studied by Cardelli & Meyer (1997). Although the N/Kr sample is too small for definitive conclusions, it does appear from Figure
that the spread in $N/Kr$ is tighter than that in $N/H$. In particular, the sightline (δ Sco) that stands out the most with a solar abundance in terms of $N/H$ drops back to the pack in terms of $N/Kr$. The most likely explanation for this behavior is an underestimate of the $H$ column density toward δ Sco. Apart from this sightline, the spread in $N/H$ is comparable to those found for $Kr/H$, $O/H$ (Meyer et al. 1998), and $C/H$ (Cardelli et al. 1996, Sofia et al. 1997) with GHRS. In any case, the δ Sco discrepancy is small enough that omitting this sightline from the sample would only slightly reduce the weighted mean $N$ abundance from $10^6 N/H = 75 \pm 4$ to $73 \pm 5$. The bottom line is that the GHRS measurements yield an interstellar nitrogen abundance that is about 80% of the solar value with no statistically significant variations from sightline to sightline.

As discussed by Meyer et al. (1998), a subsolar abundance pattern in the local ISM today implies that something unusual happened to either the Sun or the local ISM in the context of standard Galactic chemical evolution models which predict that the ISM metallicity should slowly increase over time. The fact that the GHRS interstellar abundances of $C$, $N$, $O$, and $Kr$ vary little from sightline to sightline makes it difficult to understand this anomaly simply in terms of a typical ISM abundance fluctuation. Possible explanations include the early enrichment of the solar system by a local supernova (Reeves 1978, Lee 1979, Olive & Schramm 1982), a recent infall of metal-poor gas in the local Milky Way (Comeron & Torra 1994, Meyer et al. 1994, Roy & Kunth 1995), or an outward diffusion of the Sun from a birthplace at a smaller galactocentric distance (Wielen, Fuchs, & Dettbarn 1996). A key prediction of the infall model is that the mixture of metal-poor gas with the local ISM would lower the abundances of all of the heavy elements below their solar values by a similar amount. The supernova enrichment hypothesis, on the other hand, would create uneven elemental overabundances in the Sun relative to the ISM that would reflect the nucleosynthetic yields of one or more supernova events. For example, the relative yield of $O$ to $N$ in Type II supernovae (Olive & Schramm 1982) is appreciably greater than
their relative present-day interstellar abundances.

If the solar N abundance and the N I λλ1160,1161 oscillator strengths are accurate, the GHRS observations imply that nitrogen is somewhat more abundant in the ISM than the 2/3 solar values measured for oxygen and krypton (Meyer et al. 1998, Cardelli & Meyer 1997). This N enhancement is illustrated in Figure 2 in terms of the N/Kr abundance ratio. Although it should be small, the presence of any N in grains can only serve to push this ratio (or N/O) further from the equal deficit (with respect to the solar abundances) fiducial. Thus, it would appear that nitrogen presents a problem for the constant subsolar ISM abundance pattern predicted by the infall model. Furthermore, a higher value of N/O in the present-day ISM than in the Sun is what one might expect if the protosolar nebula was enriched by a local Type II supernova. However, these conclusions are not yet definitive because the solar abundances and the N I λλ1160,1161 f-values are still uncertain enough that neither a subsolar ISM N abundance similar to that of O and Kr or a solar ISM abundance can be ruled out. Indeed, the quality of the GHRS data is now high enough that the limitations in comparing the interstellar C, N, O, and Kr abundances no longer lie in the measurements themselves but in the accuracy of the weak line oscillator strengths and the solar abundances.

Defining an accurate set of ISM elemental abundances is also important in determining the composition of interstellar dust grains. Based on the B-star CNO abundances and the GHRS data on O and Kr in the ISM, a general consensus has been developing that a subsolar B-star standard may be the most appropriate for this work (Sofia et al. 1994, Savage & Sembach 1996, Snow & Witt 1996). However, applying this standard to GHRS measurements of the interstellar gas-phase carbon abundance (Cardelli et al. 1996, Sofia et al. 1997) yields a C dust fraction (10^6 C/H ≈ 100) that is appreciably smaller than that typically required (10^6 C/H ≈ 300) by models to explain the total optical/UV dust opacity
Mathis (1996) has recently developed a model that reduces this solid carbon requirement to $10^6 \text{C/H} \approx 150$ and other low-C models may soon follow. If N/O is indeed overabundant in the ISM with respect to the Sun, the same could also be true of C/O and thus somewhat relax the carbon constraints on these models. Such a C/O overabundance would be expected in the scenario where the early solar system is enriched by a nearby Type II supernova (Olive & Schramm 1982). In any case, our GHRS observations of interstellar nitrogen allow for the possibility that at least some elements do not follow the same subsolar abundance pattern set for the ISM by O and Kr.

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Fig. 1.— *HST* GHRS echelle spectra of the interstellar N I $\lambda\lambda159.817,1160.937$ absorption doublet toward $\delta$ Sco, $\lambda$ Ori, $\kappa$ Ori, $\kappa$ Sco, $\gamma$ Cas, and $\iota$ Ori at a velocity resolution of 3.5 km s$^{-1}$. The normalized spectra are displayed from top to bottom in order of decreasing total hydrogen column density in the observed sightlines. The measured S/N ratios of these spectra are all in the 150 - 250 range. The measured equivalent widths of the N I lines are listed in Table 1.

Fig. 2.— Interstellar nitrogen abundances measured with GHRS as a function of the logarithmic fraction of hydrogen in molecular form, $f(H_2) = 2N(H_2)/N(H)$, in the observed sightlines. In the top panel, the N abundances are plotted in terms of $10^6$ N/H as taken from Table 1. The short-dashed line among the data points represents the weighted mean interstellar gas-phase N abundance (per $10^6$ H atoms) of $10^6$ N/H = 75 ± 4. This N abundance is about 80% of the Grevesse & Noels (1993) solar value ($10^6$ N/H = 93 ± 16) represented by the long-dashed line. In the bottom panel, the N/Kr abundance ratio is plotted for the four sightlines in common between this paper and the Kr study of Cardelli & Meyer (1997). The short-dashed line among the data points represents the weighted mean interstellar gas-phase N/Kr abundance ratio of $10^{-3}$ N/Kr = 82 ± 5. The solar value of N/Kr ($10^{-3}$ N/Kr = 55 ± 13) represented by the long-dashed line incorporates the solar Kr abundance measured by Anders & Grevesse (1989).
Table 1. The GHRS Interstellar Nitrogen Abundances

<table>
<thead>
<tr>
<th>Star</th>
<th>$N(H)^a$ (cm$^{-2}$)</th>
<th>$\log f(H_2)^b$</th>
<th>$W_{\lambda}(1160)^c$ (mÅ)</th>
<th>$W_{\lambda}(1161)^c$ (mÅ)</th>
<th>$N(N\ I)^d$ (cm$^{-2}$)</th>
<th>$10^6 N/H^e$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu$ Ori</td>
<td>1.5 (0.2) $\times 10^{20}$</td>
<td>-5.17</td>
<td>1.00 (0.15)</td>
<td>&lt; 0.30</td>
<td>9.87 (1.48) $\times 10^{15}$</td>
<td>68 (13)</td>
</tr>
<tr>
<td>$\gamma$ Cas</td>
<td>1.5 (0.2) $\times 10^{20}$</td>
<td>$&lt; -2.36$</td>
<td>1.15 (0.12)</td>
<td>0.40 (0.12)</td>
<td>1.15 (0.11) $\times 10^{16}$</td>
<td>78 (14)</td>
</tr>
<tr>
<td>$\kappa$ Sco</td>
<td>1.8 (0.3) $\times 10^{20}$</td>
<td>$&lt; -5.73$</td>
<td>1.10 (0.15)</td>
<td>0.40 (0.15)</td>
<td>1.11 (0.14) $\times 10^{16}$</td>
<td>61 (12)</td>
</tr>
<tr>
<td>$\kappa$ Ori</td>
<td>3.4 (0.3) $\times 10^{20}$</td>
<td>-4.55</td>
<td>2.60 (0.15)</td>
<td>0.65 (0.15)</td>
<td>2.54 (0.14) $\times 10^{16}$</td>
<td>75 (12)</td>
</tr>
<tr>
<td>$\lambda$ Ori</td>
<td>6.5 (1.2) $\times 10^{20}$</td>
<td>-1.39</td>
<td>4.95 (0.20)</td>
<td>1.45 (0.20)</td>
<td>5.15 (0.30) $\times 10^{16}$</td>
<td>79 (15)</td>
</tr>
<tr>
<td>$\delta$ Sco</td>
<td>1.2 (0.2) $\times 10^{21}$</td>
<td>-1.36</td>
<td>11.20 (0.30)</td>
<td>3.30 (0.30)</td>
<td>1.17 (0.06) $\times 10^{17}$</td>
<td>98 (14)</td>
</tr>
<tr>
<td>$\zeta$ Oph</td>
<td>1.4 (0.1) $\times 10^{21}$</td>
<td>-0.20</td>
<td>7.56 (0.74)</td>
<td>2.68 (0.99)</td>
<td>1.05 (0.13) $\times 10^{17}$</td>
<td>75 (11)</td>
</tr>
</tbody>
</table>

$^a$ $N(H) = 2N(H_2) + N(H\ I)$ is the total hydrogen column density ($\pm 1\sigma$) in the observed sightlines. These values reflect the $H_2$ column densities measured by Savage et al. 1977 (Jenkins, Savage, & Spitzer 1986 in the case of $\kappa$ Sco) and the weighted means of the Bohlin, Savage, & Drake 1978 (Jenkins et al. 1986 in the case of $\kappa$ Sco) and Diplas & Savage 1994 $N(H\ I)$ data.

$^b$ $f(H_2) = 2N(H_2)/N(H)$ is the fractional abundance of hydrogen nuclei in $H_2$ in the observed sightlines.

$^c$ The measured equivalent widths ($\pm 1\sigma$) of the $N\ I$ 1159.817 and 1160.937 Å absorption lines. The value listed for $\lambda 1161$ toward $\nu$ Ori is a 2$\sigma$ upper limit.

$^d$ The derived $N\ I$ column densities ($\pm 1\sigma$) in the observed sightlines. The $\zeta$ Oph value is taken from the analysis of Savage, Cardelli, & Sofia 1992. The $\lambda$ Ori and $\delta$ Sco values are corrected for a slight amount of saturation using respective Gaussian $b$-values ($\pm 1\sigma$) of 5.0$^{+\infty}_{-2.5}$ and 10.0$^{+\infty}_{-5.0}$ km s$^{-1}$. The other sightlines are assumed to be optically thin in the $N\ I$ transitions.

$^e$ The abundance of interstellar gas-phase nitrogen ($\pm 1\sigma$) per $10^6$ H atoms in the observed sightlines. The uncertainties reflect the propagated $N(H)$ and $N(N\ I)$ errors.