The interstellar N_2 abundance towards HD 124314 from far-ultraviolet observations

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The abundance of interstellar molecular nitrogen (N_2) is of considerable importance: models of steady-state gas-phase interstellar chemistry[1,2], together with millimetre-wavelength observations[3,4] of interstellar N_2H^+ in dense molecular clouds predict that N_2 should be the most abundant nitrogen-bearing molecule in the interstellar medium. Previous attempts to detect N_2 absorption in the far-ultraviolet[5] or infrared[6] (ice features) have hitherto been unsuccessful. Here we report the detection of interstellar N_2 at far-ultraviolet wavelengths towards the moderately reddened star HD 124314 in the constellation of Centaurus. The N_2 column density is larger than expected from models of diffuse clouds and significantly smaller than expected for dense molecular clouds[1]. Moreover, the N_2 abundance does not explain the observed variations[7] in the abundance of atomic nitrogen (N I) towards high-column-density sightlines, implying that the models of nitrogen chemistry in the interstellar medium are incomplete[8].

Although N_2 was unsuccessfully searched for with the Copernicus satellite[5], the Far Ultraviolet Spectroscopic Explorer (FUSE) enables sensitive probes of sightlines with large amounts of interstellar extinction. Archival observations of HD 124314 were acquired on 22 March 2000 using the large aperture ($30'' \times 30''$) in the histogram data collection mode. HD 124314 is an O6Vnf star[9] with visual magnitude $V = 6.64$ mag (ref. 10) and a moderate amount of interstellar reddening ($E(B–V) = 0.53$; ref. 11) equivalent to 1.5 magnitudes of visual extinction (Av) that is located at a distance $d = 700^{+1,500}_{-240}$ pc from the Sun. (ref. 12). The data cover the wavelength range 905–1,185 Å with a spectral resolution of about 20 km s^{-1}. FUSE[13,14] is particularly well suited for studies of interstellar N_2, because all electronic ground-state transitions are only observable below 1,000 Å. The instrument generally provides two independent spectra for each wavelength region, which can be cross-checked. For the present study, we focus on the two silicon carbide (SiC) detectors covering wavelengths below 1,000 Å.

The data were reduced and calibrated with version 2.4.1 of the CalFUSE pipeline (ref. 15), which incorporates the appropriate Doppler corrections to remove the effects of spacecraft motion and place the data on the heliocentric velocity scale. Owing to the lack of onboard wavelength calibration, a zero-point uncertainty remains in the dispersion solution. To minimize uncertainties (± 6 km s^{-1} per pixel; ref. 16) caused by the relative wavelength calibration, we used a cross-correlation technique to combine the individual exposures. To fix the absolute heliocentric velocity scale ($V_{\rm helio}$), we used interstellar H_2 lines in the FUSE data and archival CO data from the Space Telescope Imaging Spectrograph (STIS) on board the Hubble Space Telescope (HST), assuming CO and H_2 to be coexistent[17]. The final summed SiC 1B (SiC 2A) spectrum has a signal-to-noise ratio of 45 (50) per 9-pixel-resolution element at 958 Å.

Figure 1 shows the normalized 957–961 Å portion of the FUSE spectrum of HD 124314. Several strong absorption lines due to interstellar molecular hydrogen (H_2), deuterated molecular hydrogen (HD), and N I (refs 18–20) are clearly detected superposed on the broad stellar continuum, revealing at least two, barely resolved, interstellar velocity components. In addition, there are weaker absorption features found in both SiC detector segments at the expected location of the 0–0 band of the $c_4'\,^1\Sigma_u^+ - X\,^1\Sigma_g^+$ transition of N_2 at 958.6 Å with a band oscillator strength ($f_{\rm band}$) of 0.145 (ref. 21). These features are much too narrow to be stellar in nature because the star has a rotational velocity of 300 km s^{-1} (ref. 22). Examination of other, less reddened O6 stars, see Supplementary Fig. 1, reveal no evidence for photospheric absorption at this wavelength. No detector defects are present in either detector and other than N_2, no interstellar species have identified features at this wavelength.

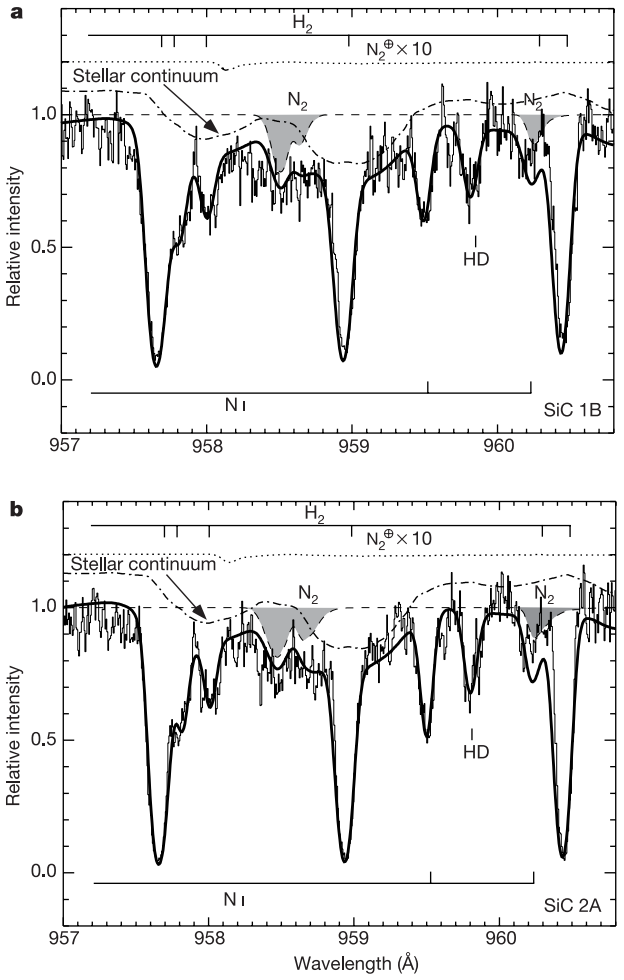

Figure 1 The N_2 portion of the normalized FUSE spectra of HD 124314. **a**, The SiC 1B data and **b**, the SiC 2A data (thin histograms). The thick solid line is the best fit of the data for the wavelength range 951–968 Å. Note that only the range from 957–961 Å is displayed here. All obvious interstellar absorption features (for example, H_2, N I, and so on) in this region are marked. The dot-dashed line is a stellar continuum model[23] with estimated stellar parameters of $T_{\rm eff} = 37{,}500$ K and $\log(g) = 3.5$. The stellar He II line at 959 Å line changes dramatically with the stellar parameters—and this directly affects the longer-wavelength N_2 trough at 958 Å. Inclusion of the c_3 N_2 band at 960 Å is vital in constraining the N_2 abundance. Therefore, the choice of stellar model does not change our detection of interstellar N_2. Before being incorporated into the profile-fitting program, the stellar model was rotationally broadened to 300 km s^{-1} (ref. 22). The offset between the data and the stellar model is caused solely by the line wing opacity (τ) of H_2. The best fit required two velocity components separated by 14 km s^{-1} for H_2, HD and N I, and similar results are obtained when using the O I velocity separation. Unrealistic parameter values resulted for a two-component fit to N_2. However, limiting the fit to one component in N_2, at the higher velocity, produced convergent fits. The dashed line filled with shading represents the normalized N_2 absorption profiles ($e^{-\tau}$). Our detection of interstellar N_2 is not contaminated by telluric N_2 (dotted line), which has been scaled by a factor of ten and shifted up to 1.2 for the sake of clarity.

Many of the other N_2 bands are undetected owing to severe blending with more abundant species (for example, H I and H_2). For completeness, we have included the 0–0 band of the $c_3{}^1\Sigma_u^+ - X^1\Sigma_g^+$ transition of N_2 at 960.3 Å ($f_{band} = 0.056$) in our study because individual oscillator strengths (*f*-values) are available (G. Stark, personal communication), and although this band is blended with absorption from N I at 960.201 Å and H_2 P(5) at 960.271 Å, the blending is not as severe as for the other stronger N_2 bands. Additionally, there are two N_2 bands outside the fitted wavelength range that are relatively unblended, but are so weak ($f_{band} \approx 0.02$) that they are not detectable.

The N_2 absorption spectrum of the c_4' and c_3 transitions consists of many rotational lines[21] under interstellar conditions. Our profile synthesis code[7] explicitly treats the N_2 excitation and uses the laboratory wavelengths and *f*-values[21] for the individual rotational lines, thereby reproducing the true N_2 line profiles. To evaluate whether the observed spectral features are due to interstellar N_2, we independently compared the 958 Å region of the SiC 1B and SiC 2A data to a synthetic spectrum combining a stellar model[23] and interstellar medium absorption from H_2 ($J = 0$–5), HD, N I, and N_2. The total synthetic spectrum was convolved to the FUSE resolution and then fitted to the data using a χ^2 minimization technique. No attempt was made to fit the weak CO band at 956 Å (ref. 24) because it does not significantly affect our fit. The profile synthesis parameters—temperature (*T*), Doppler broadening parameter (*b*-value) and column density (*N*)—were adjusted until a minimum χ^2 was obtained. Our best fits are shown overlying the data in Fig. 1 and the results are listed in Table 1. The apparent slight mismatch of some features in Fig. 1 (for example, the N I line at 960.2 Å) arise because the fit is based on a larger spectral region (951–968 Å) than is shown. Two velocity components are required to fit the interstellar H_2, HD, and N I, whereas only one component is required for N_2. It is important to note that because of the low instrumental resolution, we cannot reliably constrain the *b*-value for N_2. For numerical stability, the *b*-values of all species in the fit were constrained to coincide. Given that N_2 is likely to be restricted to the densest gas along the line of sight, its *b*-value might be smaller than that found for the other species. Therefore, our derived N_2 column must be treated as a lower limit.

Another consideration that needs to be addressed is the presence, if any, of telluric N_2 absorption. FUSE observations are designed to stop science exposures when the limb angle (θ_L) reaches 15°. There are a small number of exposures in the FUSE archives that extend below this, but the data quality is too low to place useful limits on the contribution expected from terrestrial N_2. The Hopkins Ultraviolet Telescope detected telluric N_2 absorption towards only those observations that went below $\theta_L < 15°$ (P. Feldman, personal communication). All our observations were taken with $\theta_L > 20°$, so we calculated the expected contribution of telluric N_2 (that is, $N(N_2)_{telluric}$) using the National Space Science Data Center MSIS model of the Earth's atmosphere[25] for the date of our observation, the satellite's altitude of 750 km, and $\theta_L = 20°$. At this altitude, the space density of telluric N_2 is 2,200 cm^{-3} with a characteristic temperature of 1,100 K. We find $N(N_2)_{telluric} = 1.1 \times 10^{12}\,cm^{-2}$ for $\theta_L = 20°$. As shown in Fig. 1, telluric N_2 with these characteristics does not significantly contribute to the observed spectrum.

To further assess our N_2 detection, we used ultra-high-resolution archival O I, S I, and CO STIS/HST data. HST observed HD 124314 on 10 April 1999 at a velocity resolution of 1.5 km s^{-1}. The normalized spectra are shown in Fig. 2. Because CO is a tracer of gas shielded from dissociating ultraviolet radiation[17,26,27], the facts that

Table 1 **Results from profile synthesis**

Species	$N_{SiC\ 2A}$	Literature values[7,10]
$N(H_2)$ (component 1)	$(1.5 \pm 0.2) \times 10^{20}\,cm^{-2}$	…
$N(H_2)$ (component 2)	$(1.4 \pm 0.2) \times 10^{20}\,cm^{-2}$	$(3.3 \pm 0.4) \times 10^{20}\,cm^{-2}$
T_{1-0} (component 1)	340 ± 100 K	…
T_{1-0} (component 2)	38 ± 3 K	54 K
N(N I) (component 1)	$(8.5 \pm 1.0) \times 10^{15}\,cm^{-2}$	…
N(N I) (component 2)	$(1.9 \pm 0.3) \times 10^{17}\,cm^{-2}$	$(2.21 \pm 0.27) \times 10^{17}\,cm^{-2}$
$N(N_2)$ (component 2)	$(4.6 \pm 0.8) \times 10^{13}\,cm^{-2}$*	…
T_{N_2} (component 2)	36 ± 5 K	…
V_{helio} (component 1)	3.0 ± 0.5 km s^{-1}†	….
V_{helio} (component 2)	−17.0 ± 0.5 km s^{-1}	…
b-value (component 1)	6.0 ± 0.5 km s^{-1}	…
b-value (component 2)	7.0 ± 0.5 km s^{-1}	…
Reduced χ^2	2.47	…

Results for SiC 1B agree within their mutual uncertainties to those for SiC 2A reported here.
*Average of SiC 1B and SiC 2A results.
†Set to coincide with the STIS/HST heliocentric velocity scale.

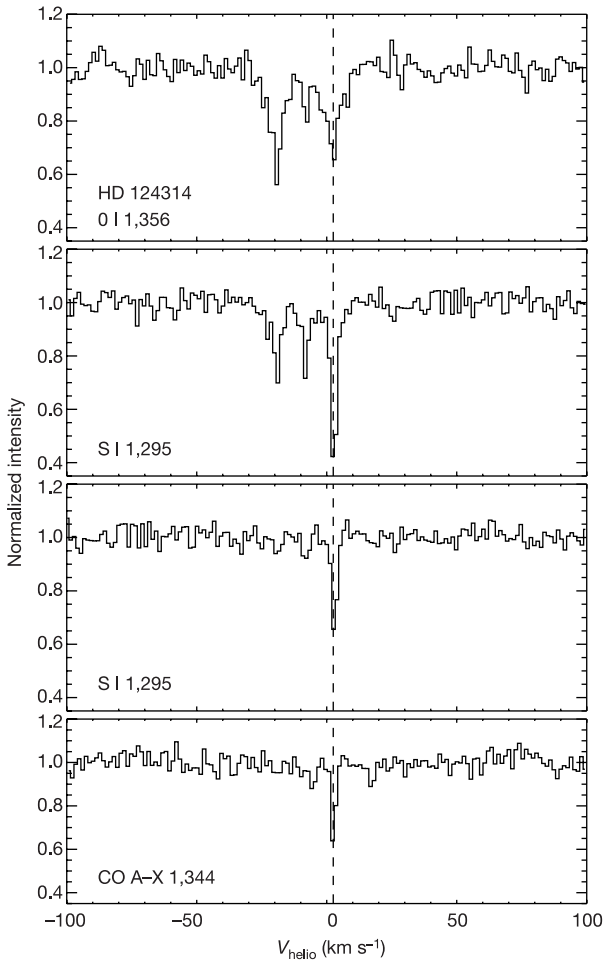

Figure 2 The normalized archival STIS/HST spectra of O I, S I and CO. This data reveals at least three velocity components in Interstellar O I line at 1,356 Å (two are dominant) and S I line at 1,295 Å, but only one component in Interstellar S I line at 1,296 Å and CO bands at 1,344 Å, 1,322 Å and 1,301 Å. These data indicate that the CO component is the densest interstellar cloud along the line of sight. Using a curve-of-growth analysis, the measured CO column density is well determined as: $N(CO) = (7.6 \pm 1.1) \times 10^{13}\,cm^{-2}$. We cannot accurately derive the *b*-value from these optically thin lines. We find that the S I doublet is slightly saturated. A curve of growth calculated for these two data points yields a S I column density of $N(S\,I) = (1.6 \pm 0.2) \times 10^{13}\,cm^{-2}$ and a *b*-value of 1.0 ± 0.1 km s^{-1} for the longer-wavelength component. The velocity separation of 22 km s^{-1} between the two dominant O I components is similar (within the uncertainties of the FUSE data) to the velocity separation of 14 km s^{-1} we find from our analysis of H_2. The dashed line at ~3 km s^{-1} represents the velocity to which the longer-wavelength H_2 component was normalized. The agreement in velocity separation between the two measured H_2 components and the two strongest O I components provides strong support for the adopted velocity structure used in our model. The fact that both N_2 and CO are found in the single densest component provides further support for the first detection of interstellar N_2.

N_2 and CO both occur in the same velocity component, that the velocity separation in O I and H_2 agree, and that the CO component is aligned in velocity with the higher-velocity O I component strongly supports our claim of the first detection of interstellar N_2. Our N_2 detection is further supported by the fact that the excitation temperatures of H_2 (1–0) and of N_2 agree for the longer-wavelength component. Although the N_2 *b*-value is not reliably determined, we use the S I *b*-value to improve our estimate and find $N(N_2) = (4.6 \pm 0.8) \times 10^{13}\,cm^{-2}$. We note that S I may be more extended than CO or N_2 in interstellar space. Because nitrogen has a lower cosmic abundance compared to either carbon or oxygen, we believe that $N(N_2)$ should not be larger than N(CO) and should the true N_2 *b*-value be much smaller than that for S I (although this is unlikely), significant amounts of N_2 (that is, $N(N_2) > 10^{14}\,cm^{-2}$) could be present. Our firm lower limit to $N(N_2)$ is not sensitive to the *b*-value or the choice of stellar model used to represent the stellar continuum. Taken together, these data strongly indicate that N_2 has been detected for the first time in the interstellar medium and with a column density of $N(N_2) > 3.8 \times 10^{13}\,cm^{-2}$.

From our analysis of the O I line at 1,356 Å, we find $N(O\,I) = (6.77 \pm 0.50) \times 10^{17}\,cm^{-2}$ for the component near 3 km s^{-1}. Using the observed $N(O\,I)/N(H_{tot})$ ratio $(4.74 \pm 0.81) \times 10^{-4}$ (ref. 11), this component contains $N(H_{tot}) = 1.5 \times 10^{21}\,cm^{-2}$, where $N(H_{tot}) = N(H\,I) + 2N(H_2)$. The amount of interstellar reddening for this component can be determined from the dust-to-gas ratio[28], which yields $E(B–V) = 0.26\,mag^{-1}$. Assuming that the ratio of total to selective extinction is 3.1 (ref. 29), we find that the total visual extinction is 0.8 mag. When we compare our results to models of interstellar gas-phase chemistry[1], none of the standard cloud models explain our observations. The observed N_2 fractional abundance is more than two orders of magnitude too low for dense cloud models and approximately two orders of magnitude larger than expected from models of diffuse clouds. The fact that N I shows a deficiency in its relative abundance for lines of sight with $N(H_{tot}) > 10^{21}\,cm^{-2}$ would argue that dense cloud chemistry should be important for interstellar nitrogen. However, the measured N_2 abundance and upper limits for other sightlines[7] do not account for the observed variations. Additionally, we find that the fractional abundance of N_2 towards HD 124314 is $N_2/H_2 = 3.3 \times 10^{-7}$, similar to those estimated from N_2H^+ observations[4] of dark molecular clouds. Therefore, the far-ultraviolet lines of N_2 provide a unique probe of interstellar nitrogen chemistry in the transition region from diffuse to dense molecular gas. □

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A precision measurement of the mass of the top quark

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The standard model of particle physics contains parameters—such as particle masses—whose origins are still unknown and which cannot be predicted, but whose values are constrained through their interactions. In particular, the masses of the top quark (M_t) and *W* boson (M_W)[1] constrain the mass of the long-hypothesized, but thus far not observed, Higgs boson. A precise measurement of M_t can therefore indicate where to look for the Higgs, and indeed whether the hypothesis of a standard model Higgs is consistent with experimental data. As top quarks are produced in pairs and decay in only about 10^{-24} s into various final states, reconstructing their masses from their decay products is very challenging. Here we report a technique that extracts more information from each top-quark event and yields a greatly improved precision (of ± 5.3 GeV/c^2) when compared to previous measurements[2]. When our new result is combined with our published measurement in a complementary decay mode[3] and with the only other measurements available[2], the new world average for M_t becomes[4] 178.0 ± 4.3 GeV/c^2. As a