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NARROW Na AND K ABSORPTION LINES TOWARD T TAURI STARS: TRACING THE ATOMIC ENVELOPE OF MOLECULAR CLOUDS

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ABSTRACT

We present a detailed analysis of narrow Na I and K I absorption resonance lines toward nearly 40 T Tauri stars in Taurus with the goal of clarifying their origin. The Na I λ5890.95 line is detected toward all but one source, while the weaker K I λ7698.96 line is detected in about two-thirds of the sample. The similarity in peak centroids and the significant positive correlation between their equivalent widths demonstrate that these transitions trace the same atomic gas. The absorption lines are present toward both disk and diskless young stellar objects, which excludes cold gas within the circumstellar disk as the absorbing material. A comparison of Na I and CO detections and peak centroids demonstrates that the atomic gas and molecular gas are not co-located, the atomic gas being more extended than the molecular gas. The width of the atomic lines corroborates this finding and points to atomic gas about an order of magnitude warmer than the molecular gas. The distribution of Na I radial velocities shows a clear spatial gradient along the length of the Taurus molecular cloud filaments. This suggests that absorption is associated with the Taurus molecular cloud. Assuming that the gradient is due to cloud rotation, the rotation of the atomic gas is consistent with differential galactic rotation, whereas the rotation of the molecular gas, although with the same rotation axis, is retrograde. Our analysis shows that narrow Na I and K I absorption resonance lines are useful tracers of the atomic envelope of molecular clouds. In line with recent findings from giant molecular clouds, our results demonstrate that the velocity fields of the atomic and molecular gas are misaligned. The angular momentum of a molecular cloud is not simply inherited from the rotating Galactic disk from which it formed but may be redistributed by cloud–cloud interactions.

Key words: circumstellar matter – ISM: clouds – ISM: individual objects (Taurus) – ISM: kinematics and dynamics – stars: formation – stars: kinematics and dynamics

1. INTRODUCTION

T Tauri stars (hereafter, TTSs) are pre-main-sequence optically visible stars named after the brightest member of this class of objects in the Taurus-Auriga molecular cloud (Joy 1942). Optical spectroscopy, and in particular the equivalent width of the H α line, is traditionally used to distinguish between two main subgroups: classical and weak-line TTSs (CTTSs and WTTSs). CTTSs are accreting disk gas as evinced by broad (FWHM ∼ 100 km s⁻¹) permitted H and He lines tracing free-falling gas onto the star, and by optical/UV emission in excess of the stellar photosphere probing the accretion shock at the stellar surface (e.g., Alcalá et al. 2014). On the contrary, WTTSs have weaker emission lines with no evidence of ongoing accretion. Most WTTSs also lack IR excess emission and hence are defined as Class III objects, i.e., TTSs with no circumstellar disks (but some WTTSs have excess emission at longer wavelengths indicative of outer disks or dust belts; see, e.g., Cieza et al. 2013). CTTSs have excess emission at multiple infrared wavelengths, typically starting at near-IR (NIR) wavelengths, and are classified as Class II objects (e.g., Espaillat et al. 2014, pp. 497–520).

High-resolution (R ∼ 30,000) spectroscopy has been vital to identifying and understanding the complex processes associated with star and planet formation. In addition to accreting disk gas, CTTSs eject a fraction of this material, which removes excess angular momentum. Forbidden emission lines blueshifted from the stellar velocity by ∼100 km s⁻¹ trace this phenomenon (see, e.g., Ray et al. 2007 for a review). Forbidden lines also show a second low-velocity component typically blueshifted by less than 10 km s⁻¹ that has been associated with a slow wind whose origin is still debated (for a review see, e.g., Alexander et al. 2014, pp. 475–496; Natta & Ciardi 2007). Finally, permitted lines, including the Hα line, often show complex morphologies indicating that they trace not only accretion but also outflowing material, such as winds originating within a few stellar radii (e.g., Mundt 1984). In this contribution we focus on the Na I and K I resonance lines of TTSs.

While K I lines are generally not discussed in the context of TTSs, several works have presented Na I resonance line profiles of CTTSs, focusing on the high accretors (M > 10⁻³ M⊙ yr⁻¹) such as DL Tau and DR Tau. The profiles are complex: in addition to emission, most spectra present absorption features that vary in width from being unresolved (∼100 km s⁻¹) to (∼10 km s⁻¹) (e.g., Mundt 1984; Edwards et al. 1994). Natta & Giovanardi (1990) proposed that outflowing winds from the star can explain the P Cygni profile detected in about 20% of the Na I lines of CTTSs, usually the most active ones. However, broad (∼100 km s⁻¹) Na I emission profiles as observed in BP Tau are most likely probing free-falling accreting gas similar to the Balmer lines (e.g., Muzerolle et al. 1998). The most common feature in the Na I lines of TTSs is a narrow (∼10 km s⁻¹) sharp absorption close to the stellar radial
velocity (RV) tracing material physically in front of the star. The absorber has been usually associated with cold interstellar medium (ISM) gas (e.g., Mundt 1984), although a circumstellar disk could not be ruled out with the available data (e.g., Appenzeller et al. 2005). A circumstellar origin would be especially interesting in the context of giant exoplanet atmospheres by providing a tracer of disk gas cooler than that being accreted onto the central star, gas that might be accreted onto the giant planets forming in the disk.

Recent transiting observations of hot Jupiters have found that the sodium-to-potassium abundance ratio in the atmosphere of these giant planets can be very different from the solar ratio (e.g., Sing et al. 2015). Detailed theoretical models of planetary atmospheres demonstrate that photochemistry cannot explain such different ratios, and drastic changes to atmospheric temperature profiles or clouds are not supported by the data (e.g., Lavvas et al. 2014). It is suggested that disk evolution might change the Na\(^+\)/K abundance ratios of the gas that giant planets accrete during formation. This hypothesis may be testable using optical spectroscopy of TTSs in different evolutionary stages once the origin of their sodium and potassium lines is established.

This paper focuses on understanding the origin of the narrow and sharp absorption in the Na\(_i\) resonance profiles. Using high-resolution optical spectra for a sample of nearly 40 TTSs in Taurus spanning a range of evolutionary stages (Section 2), we show that (a) K\(_i\) profiles present the same sharp absorptions seen in Na\(_i\) profiles (Section 3) and (b) the absorption does not arise from gas in a circumstellar disk, nor from ISM gas, but rather from atomic gas surrounding the Taurus molecular cloud (Section 4). We also find that the atomic gas is more extended than the molecular gas, as traced by low-J CO rotational lines, and that its rotation axis is almost antiparallel to that of the Taurus molecular cloud. Our results, when combined with those on five giant molecular clouds in the Milky Way (Imara & Blitz 2011), argue against the hypothesis that molecular clouds simply inherit the velocity field and angular momentum of the rotating galactic disk out of which they formed.

### 2. OBSERVATIONS AND DATA REDUCTION

Observations were carried out with the Keck/HIRES spectrograph (Vogt et al. 1994) in two separate campaigns, in 2006 through the program C170Hr (PI, L. Hillenbrand) and in 2012 through the program N107Hr (PI: I. Pascucci). In both campaigns we used the red cross-disperser with the C5 decker and a 1′ × 7″ slit. This configuration covers the 4800–9000 Å spectral range at a resolution of 37,500 as measured from the width of four Th/Ar lines\(^8\) near 5240 Å (but see below for our estimate of the spectral resolution). Exposure times for individual targets are summarized in Tables 1 and 2.

All science targets except TW Hya are known members of the Taurus-Auriga star-forming region (age ~1 Myr, distance ~140 pc; see, e.g., the review by Kenyon et al. 2008). TW Hya is a well-characterized star that is closer to us and belongs to a loose association (Torres et al. 2008). We keep it in our analysis as comparing its Na\(_i\) and K\(_i\) profiles to those of Taurus-Auriga members helps in understanding the origin of the narrow and sharp absorptions in these resonance lines. Targets from the 2006 campaign are mostly accreting classical TTSs with optically thick disks that extend inward close to the stellar surface (Class II spectral energy distribution [SED]; see Table 3. In 2012 we targeted more evolved systems, with lower accretion rates on average, as well as nonaccreting weak-line TTSs with transitional (small NIR but large mid-IR [MIR] and far-IR [FIR] excess emission) or no disks (Class III SED; see Table 4. Two sources, IP Tau and UX Tau A, were observed in both campaigns. The central stars span a large range in spectral type, from M4 to K0; see Tables 3 and 4 and Herczeg & Hillenbrand (2014) for a careful and homogeneous reclassification of Taurus sources and of TW Hya. Along with science targets, we acquired a set of O/B stars to remove telluric lines and photospheric standards (both belonging to the Taurus-Auriga star-forming region, as well as field dwarfs) to correct the science spectra from photospheric absorption features.

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\(^8\) http://www2.keck.hawaii.edu/inst/hires/slittres.html
The data reduction was carried out using the highly automated Mauna Kea Echelle Extraction pipeline written by Tom Barlow. The reduction steps included bias subtraction, flat-fielding, identification of the echelle orders on the images, and extraction of the spectra. Wavelength calibration was done using spectra of ThAr calibration lamps mounted on HIERES and acquired either right before or right after the target exposures. The reduction was performed in air wavelengths, using the keyword “novac” in the pipeline inputs. After spectral extraction, each of the individual one-dimensional spectra was rebinned to a linear wavelength scale. The final products of the reduction are wavelength-calibrated spectra to which heliocentric correction is also applied.

In this work we focus on the two orders that cover the Na D resonance line at 5889.95 Å and the K line at 7698.96 Å. Of these two orders, only that covering the K line has strong telluric contamination; however, no telluric line overlaps with the lines of interest. After telluric removal, the set of nearby telluric absorption and identify those sources with Na and K emission. The removal of photospheric lines follows standard procedures (e.g., Hartigan et al. 1989). In brief, a photospheric standard with spectral type similar to that of the target star is chosen. When necessary, the standard photospheric lines are broadened to match those of the target, and the standard spectrum is shifted in wavelength to the target spectrum. The spectrum of the standard is also veiled to account for the extra emission.

Table 3

<table>
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<tr>
<th>Source</th>
<th>SpTy</th>
<th>Multiplicity</th>
<th>REF</th>
<th>TTSs</th>
<th>SED</th>
<th>REF</th>
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<td>W II/III</td>
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<td>C</td>
<td>T</td>
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Notes:

a For multiple systems we give the separation in arcseconds from the primary.
b Known transition disks are marked with “T.”
c This source has a weak infrared excess at wavelengths longer than 10 μm; it may be transitioning from Class II to III, but the excess is not as large as for classical transition disks (Furlan et al. 2009b).


Table 4

<table>
<thead>
<tr>
<th>Source</th>
<th>SpTy</th>
<th>Multiplicity</th>
<th>REF</th>
<th>TTSs</th>
<th>SED</th>
<th>REF</th>
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<td>1, 9</td>
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<td>3, 14, 11</td>
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<td>M2</td>
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<td></td>
<td>W III</td>
<td>15, 16</td>
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<td>K5</td>
<td>10</td>
<td></td>
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<td>10, 17</td>
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Notes:

a For multiple systems we give the separation in arcseconds from the primary and the flux ratio to the primary when known.
b Known transition disks are marked with “T.”
c Suspected SB1; Nguyen et al. 2012.

This source has a weak infrared excess at wavelengths longer than 10 μm; it may be transitioning from Class II to III, but the excess is not as large as for classical transition disks (Furlan et al. 2006).

e Esplin et al. (2006) report a small excess in the WISE W2 band (4.6 μm) but note that the colors of V410 Tau are consistent with the stellar photosphere at longer wavelengths, as found in Furlan et al. (2009).


known to fill in the absorption lines of young accreting stars. In practice, we veiled the standard spectrum by identifying a flat continuum and a normalization factor that best reproduce the target spectrum in a specified wavelength interval outside of the lines of interest. Finally, we divided the target spectrum by the broadened, veiled, and shifted spectrum of the standard. The photospheric standard GL846 (M0 SpTy) provided a good correction for all stars except three later-type M dwarfs (GH Tau, V710 Tau, V1321 Tau) and 11 K dwarfs (CI Tau, CW Tau, GK Tau, GM Aur, HBC 427, HN Tau, HQ Tau, IT Tau, UX Tau, V773 Tau, V1348 Tau). For the group of late M dwarfs the photospheric standard GL15 (M2 SpTy) was

The quoted separation is between the A and B components. A is a short-period (51 days) double-lined spectroscopic binary (Weltz 1995). In addition, Duchene et al. (2003) and Woitas (2003) identified an additional infrared component (C) within 0.1 from A.

f Cieza et al. (2013) report excess at wavelengths longer than 24 μm for V1321 Tau (also known as RX J0432.8+1735). This source is thought to have a warm debris disk.

used, while for the K dwarfs the standard HR 8832 (K3 SpTy) was applied. The approach described above produces residual line profiles. Care should be taken to interpret these profiles, especially weak and/or narrow excess emission, because NaI and KI photospheric lines are deep and gravity sensitive. However, nearby/older dwarfs are necessary to remove the photosphere because even WTTSs in Taurus present the deep NaI and KI absorption lines we want to investigate. To illustrate the difficulty in creating residual profiles, we show in Figure 1 the original spectra, the veiled/scaled and broadened photospheric standard spectra (red solid line), and residual profiles (black solid line). These stars are chosen to cover the large range of spectral type of our sample and both accreting (CTTSs) and nonaccreting (WTTSs) objects. Because Na and K lines are gravity sensitive, care should be taken in interpreting weak excess emission in the residual profiles, especially if the emission is as broad as that of photospheric lines. The figure also illustrates that the position and width of the narrow Na and K absorption features, which are the focus of this paper, are not affected by the photospheric subtraction.

We also independently measured the spectral resolution achieved by HIRES in our observational setting using the strongest telluric lines in the order covering the KI resonance transition. The distribution of FWHMs for nearly 90 telluric lines from spectra obtained in the 2006 and 2012 campaigns is provided in Section 3.1.

Figure 2. Distribution of FWHMs from nearly 90 telluric lines. A Gaussian fit to the distribution results in a mean FWHM of 6.6 km s⁻¹, corresponding to a spectral resolution of ~45,000 and standard deviation of 0.5 km s⁻¹.
shown in Figure 2. A Gaussian fit to the distribution provides a mean of 6.6 km s\(^{-1}\) and a standard deviation of 0.5 km s\(^{-1}\). The spectral resolution of \(\sim 45,000\) that we obtain is slightly better than that reported on the Keck Web site, but consistent with that value within three times the standard deviation.

3. ANALYSIS

As mentioned in the Introduction, sharp absorptions in the Na\(_i\) (D) resonance lines of TTSs were noted early on. In 27 out of our 39 targets we find that a similarly sharp absorption is also present in the K\(_i\) resonance line at 7698.96 Å (see Figures 3–7). We take advantage of the high spectral resolution of HIRES and our large sample of stars covering different evolutionary stages to understand the origin of these sharp features. For each star we calculate the centroid of the absorption and the FWHM and EW of the line (see Tables 5 and 6). We then compare these values to stellar RVs and the velocity and width of low-J CO emission lines tracing the cold (\(\sim 15\) K) molecular gas in the Taurus star-forming region.

To compute stellar RVs, we measure the centroid of two prominent photospheric lines that fall in different spectral orders: the Li doublet at a mean wavelength of 6707.83 Å (our spectral resolution is not sufficient to resolve the doublet) and the Ca line at 6439.07 Å. We apply a Monte Carlo approach to evaluate the uncertainty in the peak centroid by adding a normally distributed noise to each spectrum and computing the RV 1000 times for the same star. This uncertainty is typically \(\sim 0.2\) km s\(^{-1}\) except for HN Tau and V410 Tau, for which RV uncertainties are \(\sim 3\) km s\(^{-1}\); see also Tables 5 and 6. The spectrum of HN Tau has a rather low signal-to-noise ratio (S/N), and the photospheric lines are broad and shallow. Although our RV for HN Tau of 13.8 km s\(^{-1}\) is uncertain, it is consistent with the median heliocentric RV of Taurus members, which is 16.2 km s\(^{-1}\) (Nguyen et al. 2012). V410 Tau has a stellar companion (see Table 4), and its photospheric lines present multiple components; thus, our fit is sensitive to the wavelength region chosen to fit the line. Two targets HBC 427 and V773 Tau are well-known spectroscopic binaries. For these sources we report the barycenter velocity of the systems calculated from multiepoch spectroscopic campaigns (see Table 6). The standard deviation between the RVs obtained from the Li and Ca lines is \(\sim 0.8\) km s\(^{-1}\). Most of the stellar
RVs we report in Tables 5 and 6 are from the Li line, except in four instances where this photospheric line appears slightly asymmetric or flat, making it difficult to have an accurate centroid. In these cases, clearly marked in the tables, we use the RV computed from the Ca line at 6439.07 Å. Comparison of our RVs to literature RVs yields differences (excluding the sources with large uncertainties mentioned above) of at most 4 km s\(^{-1}\), with the standard deviation being \(\sim 1\) km s\(^{-1}\). Thus, unless specified in Tables 5 and 6, we assign a 1σ uncertainty of 1 km s\(^{-1}\) to the stellar RVs reported in this work.

To measure the peak centroid of the molecular gas at the location of our Keck targets, we have used two CO maps of Taurus. One map was obtained with the FCRAO 14 m telescope in the 12CO and 13CO J = 1–0 transitions (beam 45′; Narayanan et al. 2008), while the other is a 12CO J = 1–0 map acquired with the CfA 1.2 m telescope (beam 8′4′; Dame et al. 2001). Ten of our Keck targets\(^\text{11}\) lie outside the higher spatial resolution FCRAO map but are covered by the coarser CfA 12CO map. For all targets we extract the 12CO and the 13CO centroids from the FCRAO map and identify one absorption feature in the Na I profile. Similar narrow absorptions are present in the K I profiles of about two-thirds of the targets.

3.1. Residual Na I and K I Profiles

A comparison of residual Na I and K I resonance profiles and Li photospheric lines is shown in Figures 3–7. Because K I absorption lines are on average a factor of \(\sim 2\) weaker than Na I lines, we have scaled these profiles when needed; scaling factors are provided in the figure captions. In all objects except TW Hya and perhaps V1348 Tau (Figure 6) it is possible to identify one absorption feature in the Na I profile that is narrower than the photospheric Li line and is close to, but not always coincident with, the stellar RV. Similar narrow absorptions are present in the K I profiles of about two-thirds of the targets.

Five sources (DO Tau, CI Tau, HQ Tau, IT Tau, and V836 Tau) present one additional narrow absorption that is more offset from the stellar RV (see Figure 8). Except for CI Tau and HQ Tau, this extra absorption is only clearly detected in the Na I profiles. For IT Tau the additional absorption is at \(v_{\text{helio}} \sim -2\) km s\(^{-1}\), about 18 km s\(^{-1}\) blueshifted from the

\(^{11}\) The targets that are not covered by the FCRAO map are DR Tau, NN Tau, UX Tau, DM Tau, GM Aur, HBC 427, V710 Tau, V836 Tau, V1321 Tau, and V1348 Tau.
Table 6
2012 Campaign: Heliocentric Radial Velocities, Widths, and EWs of Selected Lines

<table>
<thead>
<tr>
<th>Source</th>
<th>RV (km s(^{-1}))</th>
<th>FWHM (km s(^{-1}))</th>
<th>EW (mA)</th>
<th>RV (km s(^{-1}))</th>
<th>FWHM (km s(^{-1}))</th>
<th>EW (mA)</th>
<th>RV (km s(^{-1}))</th>
<th>S/N</th>
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</tr>
<tr>
<td>Anon 1</td>
<td>16.3</td>
<td>16.1</td>
<td>10.7</td>
<td>110</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CI Tau</td>
<td>19.1(^{b})</td>
<td>19.1</td>
<td>11.3</td>
<td>218</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>CoKu Tau4</td>
<td>17.9, 17.1</td>
<td>16.3, 15.5</td>
<td>7.4, 7.5</td>
<td>128, 121</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>DH Tau</td>
<td>16.4</td>
<td>17.8</td>
<td>7.6</td>
<td>114</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DM Tau</td>
<td>18.5(^{c})</td>
<td>21.5</td>
<td>6.8</td>
<td>90</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DN Tau</td>
<td>17.6(^{c})</td>
<td>18.1</td>
<td>9.1</td>
<td>142</td>
<td></td>
<td></td>
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<tr>
<td>DS Tau A</td>
<td>16.2</td>
<td>15.6</td>
<td>5.8</td>
<td>72</td>
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<tr>
<td>FM Tau</td>
<td>16.0</td>
<td>15.6</td>
<td>7.1</td>
<td>83</td>
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<td>GM Aur</td>
<td>15.6</td>
<td>16.2</td>
<td>7.0</td>
<td>87</td>
<td></td>
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<td></td>
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<tr>
<td>GO Tau</td>
<td>17.2, 17.5</td>
<td>18.1, 18.3</td>
<td>6.7, 6.0</td>
<td>106, 86</td>
<td></td>
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<tr>
<td>HBC 427</td>
<td>14.35(^{d})</td>
<td>16.2</td>
<td>7.1</td>
<td>123</td>
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<td>HQ Tau</td>
<td>17.1</td>
<td>19.1</td>
<td>9.9</td>
<td>169</td>
<td></td>
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<tr>
<td>IP Tau</td>
<td>16.1</td>
<td>17.3</td>
<td>6.8</td>
<td>86</td>
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<tr>
<td>IT Tau A</td>
<td>16.1</td>
<td>17.5</td>
<td>8.5</td>
<td>146</td>
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<td>UX Tau A</td>
<td>16.5</td>
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<td>8.3</td>
<td>150</td>
<td></td>
<td></td>
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<tr>
<td>VY Tau</td>
<td>17.1</td>
<td>20.9</td>
<td>7.8</td>
<td>119</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>V414 Tau</td>
<td>16.0(^{d})</td>
<td>14.6</td>
<td>8.1</td>
<td>117</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>V710 Tau A</td>
<td>20.0</td>
<td>21.4</td>
<td>8.3</td>
<td>126</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>V773 Tau</td>
<td>16.8(^{d})</td>
<td>15.6</td>
<td>9.4</td>
<td>146</td>
<td></td>
<td></td>
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<tr>
<td>V836 Tau</td>
<td>19.2(^{c})</td>
<td>20.1</td>
<td>5.6</td>
<td>57</td>
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<tr>
<td>V1321 Tau</td>
<td>21.3</td>
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<td>7.5</td>
<td>133</td>
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<tr>
<td>V1348 Tau</td>
<td>15.4(^{d})</td>
<td>22.9(?)</td>
<td>8.4(?)</td>
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</table>

Notes. Sources that have been observed more than once have multiple entries for the RV and FWHM. The reported optical RVs have a typical uncertainty of 1 km s\(^{-1}\), while CO RVs have 0.2 km s\(^{-1}\) (see Section 3 for further details). Two components are present in the K\(\lambda\) absorption line toward CI Tau and HQ Tau (see Figure 8); hence, we fit these profiles with the sum of two Gaussian curves.

\(^{a}\) The symbol ‘\(^{c}\)’ indicates that the stellar RV is computed from the Ca line (6439.07 Å) instead of being computed from the Li line.

\(^{b}\) Suspected spectroscopic binary (Nguyen et al. 2012).

\(^{c}\) Known spectroscopic binaries. We report and use the velocity of the barycenter of the systems as in Steffen et al. (2001) for HBC 427 and Rivera et al. (2015) for V773 Tau.

\(^{d}\) Two components are visible in the Li line. The single Gaussian fit we perform here is sensitive to how much of the continuum is included in the fit. The reported stellar RV is the mean of 1000 Gaussian fits to the Li line, as discussed in Section 5; its uncertainty is 3 km s\(^{-1}\).

stellar RV, while for DO Tau and V836 Tau it is at \(~7.3\) km s\(^{-1}\), 10 and 12 km s\(^{-1}\) blueshifted from the stellar RV. CI Tau and HQ Tau are at a projected distance of only 0.5 degrees from each other, and both present extra absorption at higher velocities, specifically at 23.4 and 27.3 km s\(^{-1}\), respectively. This implies that the absorption is redshifted by 4.3 and 10.2 km s\(^{-1}\) from the stellar RV.

As previously reported in the literature, Na\(\lambda\) profiles of TTSs present a range of morphologies. More than half of our sample stars (23/39) show Na\(\lambda\) emission, with the highest accretors having FWHMs clearly broader than photospheric lines (see, e.g., CY Tau and DO Tau in Figure 3). Magneto-spheric infall is the most likely origin of this emission, but stellar winds may also contribute. Conversely, the Na\(\lambda\) emission of WTTs is similar in width to (or narrower than) photospheric lines (see Figure 6). While some of this excess emission may result from an improper photospheric subtraction (see Section 2 for details), the stellar chromosphere may also contribute. Broad absorptions in the Na\(\lambda\) profiles that are clearly outside the range of photospheric velocities are detected toward five stars (DF Tau, DG Ta, DL Tau, DO Tau, and DR Tau; see Figure 14). The restricted velocity range adopted in Figures 3–5 only shows the blueshifted component of the broad absorption, which is associated with ejected material.

However, in all cases there is also redshifted Na\(\lambda\) absorption that traces infalling disk gas onto the star (see appendix). We note that for all of the sources in our sample, K\(\lambda\) profiles are less complex than Na\(\lambda\) profiles. This is evident both in the sample of high accretors (\(M \geq 10^{-8} M_{\odot}\) yr\(^{-1}\); only DG Tau and DO Tau have a broad blueshifted K\(\lambda\) absorption beyond the photospheric line) and in the sample of low/no accretors (see, e.g., the presence of only one absorption line in the K\(\lambda\) residual profile of IT Tau and V773 Tau). In the next sections, we will discuss the origin of the narrow Na and K absorptions, excluding the second components seen in five stars with velocities differing significantly from the stellar velocity.

3.2. Empirical Trends

In this section we present empirical trends between the narrow and sharp Na\(\lambda\) and K\(\lambda\) absorption features, extinction along the line of sight, stellar RVs, and the velocity of the cold molecular gas in Taurus.

As mentioned earlier, a deep narrow Na\(\lambda\) absorption is present in all spectra except those of V1348 Tau and TW Hya, while K\(\lambda\) absorption is present in two-thirds of the spectra. With perhaps the exception of V836 Tau, the Na\(\lambda\) lines appear highly saturated; hence, their EWs cannot be used to infer the
column density of the absorbing material. Saturation is also common in the KI lines when detected. For both transitions, line FWHMs span a larger range of values (by a factor of $\sim 3$) than RVs and are not correlated with them. When absorptions are present in both the NaI and KI profiles, their RVs are the same within our $\sim 1 \text{ km s}^{-1}$ velocity accuracy, the median absolute value of their difference being 0.6 km s$^{-1}$. This is illustrated in the upper left panel of Figure 9, where a linear fit to the centroids of the NaI and KI absorptions results in a slope very close to unity. Although the EWs of the absorption lines are more sensitive to the photospheric subtraction than peak centroids, and hence less accurate, the NaI and KI EWs are correlated. The Kendall $\tau$ test (see, e.g., Press et al. 1993, p. 77) on the subset of sources with detections in both lines returns $\tau = 0.4$ and a probability of $5 \times 10^{-4}$ that the variables are uncorrelated. These results demonstrate that there is a significant positive correlation between the NaI and KI EWs, with the KI absorption, when detected, being a factor of $\sim 2$ lower than the NaI absorption (Figure 9, upper right panel). The fact that Na and K sharp absorptions occur at the same heliocentric RV and their EWs are positively correlated strongly suggests that the two atomic transitions trace the same gas. One notable difference in their absorption profiles is the line width: many NaI absorption lines are spectrally resolved (the mean FWHM is 8.2 km s$^{-1}$), while most KI lines are unresolved with a mean FWHM of 6.3 km s$^{-1}$, the same as that measured for telluric lines. We will discuss this further in Section 4.

We also test whether there is any correlation between the optical extinction along the line of sight ($A_V$) and the NaI and KI EWs, line-to-continuum ratios, and RVs. It is known that extinctions are rather uncertain and depend on the specific technique and wavelength range used to derive them (see, e.g., discussion in Edwards et al. 2013; McJunkin et al. 2014). Recently, Herczeg & Hillenbrand (2014) have recomputed spectral types, extinctions, and accretion in a homogeneous way for over 280 nearby TTSs using an improved technique that fits simultaneously these three parameters to flux-calibrated optical spectra. All but four of our sources overlap with their sample; hence, we use this homogenous set of $A_V$ for our analysis. In spite of a relatively large scatter, which may be due to our use of photospheric templates to compute the residual profiles of these gravity-sensitive lines, the Kendall $\tau$ test

12 The line-to-continuum ratio is defined here as the depth of the absorption line with respect to the local continuum.
suggests a moderate positive correlation between the line EWs and $A_V$, $\tau = 0.4$, and a lower probability that the variables are uncorrelated for Na ($5 \times 10^{-3}$) than for K ($7 \times 10^{-2}$) (see also Figure 9, lower left panel). The Na I line-to-continuum ratios are less correlated with $A_V$, but a modest correlation remains between the K I line-to-continuum ratios and $A_V$, $\tau = 0.4$, and probability of being uncorrelated of $2 \times 10^{-2}$ (Figure 9, lower right panel). Finally, the RVs of the Na I lines are not correlated with $A_V$ ($\tau = 0.01$ and probability of 0.9). These results hint to a possible relation between the gas probed via the Na and K absorption lines and the location of our targets in the Taurus molecular cloud.

We now turn to the comparison between the RVs of the Na and K absorption features and the stellar RVs provided in Tables 5 and 6. A histogram of the difference between these quantities is shown in Figure 10. According to the nonparametric Kolmogorov–Smirnov (K-S) statistics, there is a $\sim 12\%$ probability that the two velocity distributions are drawn from the same parent population, in other words, they are statistically indistinguishable. Indeed, for many sources the Na and Li RVs are the same given our velocity uncertainty. However, there are sources for which the absorption lines are clearly redshifted (e.g., VY Tau, DM Tau, UX Tau A) or blueshifted (e.g., BP Tau, CY Tau, V819 Tau) with respect to the stellar RV; see Figures 3–7. This group comprises CTTSs and WTTSs, Class II and III SEDs, as well as transition disks (TDs). One thing in common to these sources with deviant velocities is that they lie at the edge of the Taurus molecular cloud; see Section 4. Thus, atomic Na and K gas is not always associated with the immediate circumstellar environment.

In further comparing the stellar and Na I RVs with the velocity of the molecular gas, we restrict ourselves to CO spectra with an S/N greater than 5, thus excluding HN Tau, DM Tau, HBC 427, GM Aur, VY Tau, V1321 Tau, and V1348 Tau. As already reported in the literature (e.g., Hartmann et al. 1986), we do not find any statistically significant difference between the stellar RVs and the RVs of the molecular CO gas at the source location (K-S probability $\sim 12\%$; see also Figure 10). This is expected because stars form in molecular clouds, thus inheriting the cloud velocity field, and clouds are not dispersed in $\sim$1–2 Myr. Interestingly, the distributions of RVs for the atomic and molecular components are statistically different, with a K-S probability of only 0.6% that they are drawn from the same parent population; see also

Figure 5. Same as Figure 3. All K I profiles are multiplied by a factor of 1.5.
Figure 10. This strongly suggests that the molecular gas and atomic gas are not co-located. Sources with low-S/NC O detections but strong NaI absorption, such as VY Tau and DM Tau, further strengthen this statement (see Figure 6) and suggest that the atomic gas is more extended than the molecular gas. We also note that the FWHMs of the 12CO lines are much narrower than those of the NaI lines and would all appear unresolved at the resolution of our optical spectra. However, this difference in FWHMs may be due to a combination of saturation of the NaI lines and the presence of other atomic clouds along the line of sight; hence, it does not further constrain the spatial location of the molecular and atomic gas.

To summarize, we find that (i) NaI and KI absorption lines trace the same atomic gas, but NaI profiles are often spectrally resolved while KI lines are not; (ii) there is a modest correlation between the EW of these absorption features and $A_V$; and (iii) although there is no statistical difference between the stellar RV distribution and either the NaI or CO RVs, the RVs of the atomic gas and molecular gas are unlikely to be drawn from the same parent population.

4. ORIGIN OF THE NARROW ABSORPTION IN THE NAI AND KI PROFILES

Previous studies of Na absorption lines could not distinguish between a disk and an interstellar/cloud origin because they investigated fewer stars, mostly CTTSs with Class II SEDs, at a lower spectral resolution than achieved here. By extending our sample to include WTTSs and Class III SEDs and with a precision in RV of $\sim 1\, \text{km s}^{-1}$, we can exclude that the sharp and narrow NaI and KI absorption lines trace circumstellar disk gas. There are three main observables pointing against a disk origin. First, strong absorption features are also detected toward objects that are not surrounded by disks (e.g., Anon 1) or have only tenuous dust disks more akin to debris disks (e.g., V1321 Tau). Second, if the absorbing material were disk gas, there should be only one narrow absorption feature toward single stars, and its velocity should be coincident with the stellar RV. As discussed in the previous subsection, this is not the case for several systems. Third, as will be shown later in this section, there is a spatial gradient in the RV of the NaI lines indicating a location in the distributed gas rather than the immediate circumstellar environment.
Redfield & Linsky (2008) constructed an empirical dynamical model of the local ISM (inside the Local Bubble, i.e., within about 100 pc) using UV Hubble Space Telescope spectroscopy toward 157 sight lines. While their model relies on the more numerous Ca II absorption lines, they find that all Na I absorption components have companion Ca II absorption at the same velocity. This indicates that the gas detected by the Ca II absorption is physically associated with that detected with the Na I line. Nine of their stars are in the direction of the Auriga cloud. We use the cloud heliocentric velocity vectors they derive (their Table 16) to compute the RV of the Local Bubble gas at the location of each of our targets. With a mean predicted RV of 20 km s$^{-1}$ and minimum and maximum of 19 and 23 km s$^{-1}$, respectively, the gas in the Local Bubble cannot be responsible for the average Na I RV of 17.6 km s$^{-1}$ and the larger range of velocities (from $\sim$13 to 23 km s$^{-1}$) we find in our sample. Only 13 out of 38 unique Keck targets have RVs consistent with those predicted by the Local Bubble model of Redfield & Linsky (2008), and the K-S test gives a probability of only $3 \times 10^{-3}$ that the two velocity distributions are drawn from the same parent population. In addition, of the nine stars in the direction of the Auriga cloud, only one of them has a detected Na I absorption component with an EW of only $\sim$3 mÅ (Farhang et al., 2015), much smaller than the absorption we measure toward our TTSs. We conclude that the Na I and K I absorption features we detect are not associated with Local Bubble gas. This conclusion is also consistent with the lack of absorption in the Na I and K I profiles of TW Hya, which is at only $\sim$50 pc from the Sun (Mamajek, 2005), albeit in a different direction from Taurus.

The distribution of interstellar gas and its kinematic beyond the Local Bubble is less well established. Welty & Hobbs (2001) obtained high-resolution (FWHM $\sim$ 0.4–1.8 km s$^{-1}$) spectra of K I absorption toward 54 Galactic OBA stars. One of them, HD 27778 (62 Tau), is in the direction of the Taurus star-forming region at a projected separation of $\sim$1°.5 from DF Tau and $\sim$1°.9 from DG Tau and FZ Tau. At a distance of 225 pc, as measured by Hipparcos (ESA 1997), HD 27778 is not a Taurus member but likely belongs to the older Cas-Tau OB association located behind the Taurus molecular cloud (e.g., Mooley et al., 2013). The K I profile obtained by Welty & Hobbs (2001) shows two deep and spectrally resolved absorptions at $\sim$14.8 km s$^{-1}$ (consistent with the DF Tau and DG Tau Na I and K I velocities) and $\sim$18.5 km s$^{-1}$ (slightly lower than the FZ Tau velocities). The Na I absorption profile along the same line of sight is highly saturated (see their Figure 2), because sodium is $\sim$15 times more abundant than potassium. This means that the identification of individual clouds is more challenging using Na I lines even at high spectral resolution. Saturation and blending of clouds at similar velocities might explain why many Na I absorption lines toward the Taurus TTSs are resolved at our spectral resolution, $\sim$4 times

![Figure 7. Same as Figure 3 but for sources that have multiple observations. The K I profiles of CoKu Tau4 are multiplied by a factor of 2. The sharp absorptions in the Na I and K I are not time variable. Note that the IP Tau 2006 Na I and the Li heliocentric velocities are both $\sim$1.8 km s$^{-1}$ smaller than in the 2012 spectra, while the difference between the Na I and Li lines remains the same in the two epochs. This shows that the absolute wavelength calibration can be off by up to $\sim$2 km s$^{-1}$, perhaps depending on the source centering, as found in the comparison between our and literature RVs (Section 3).](image-url)
lower than that of Welty & Hobbs (2001), while most KI lines remain unresolved. As pointed out in Section 3.2, this is clearly the case for HQ Tau and CI Tau, where two cloud components are detected in the KI but remain blended in the NaI profiles. Welty & Hobbs (2001) model the KI profile observed toward HD 27778 with six atomic clouds in the foregrounds; four of them have RVs within 2 km s$^{-1}$ of the median stellar RVs of Taurus members. For these clouds they estimate KI column densities between $1.4 \times 10^{11}$ and $1.9 \times 10^{11}$ cm$^{-2}$, which correspond to an average $\sim 6 \times 10^{20}$ cm$^{-2}$ hydrogen column given their empirical relation between K and H column densities. As a comparison, McJunkin et al. (2014) find H column densities of $\sim (2.5-10) \times 10^{20}$ cm$^{-2}$ toward 12 TTSs in Taurus from neutral hydrogen absorption against broad Ly$\alpha$ emission profiles. These column densities are consistent with each other, about two orders of magnitude larger than the H column densities measured inside the Local Bubble (Redfield & Linsky 2008), but rather typical to ISM clouds (Welty & Hobbs 2001).

Do the NaI and KI narrow absorption features trace atomic gas associated with the Taurus molecular cloud or rather ISM gas beyond the Local Bubble? To answer this question, we plot the location of our TTSs on the sky and color-code the RV of the absorbing material toward them (see Figure 11). The figure reveals that nearby sources have similar velocities and a clear spatial gradient in RVs with lower RVs NW and higher RVs SE. Several authors have argued that linear velocity gradients in giant molecular clouds are the result of large-scale cloud rotation (e.g., Blitz 1993, p. 125). Following common practice and assuming solid-body rotation (e.g., Goodman et al. 1993), we fit a plane to identify the best-fit linear velocity gradient and measure its magnitude ($\Omega$) and direction ($\theta$), i.e., the direction of increasing velocity measured east of north. The rotation axis of the cloud is then $\theta + 90^\circ$. With this approach we find that $\theta \sim 125^\circ$ (P.A. of the rotation axis 215$^\circ$), which is the same as Galactic rotation, $\Omega \sim 0.11$ km s$^{-1}$ pc$^{-1}$, and the mean LSR cloud velocity is 7.2 km s$^{-1}$. To demonstrate that a plane is a good fit to the velocity map, we show in Figure 12 a position–velocity diagram passing through the center of the CO map, where the position is the offset of each star along the direction perpendicular to the rotation axis. As expected for gas rotating as a solid body, we see a linear trend in the velocity as a function of offset from the rotation axis. Thus, it appears that the atomic gas associated with the Taurus molecular cloud rotates in the same direction of Galactic rotation (Kleiner & Dickman 1985). Evidence for global rotation of the Taurus complex has been recently reported by Rivera et al. (2015) from the RVs and

13 We use the RV of the NaI lines because we have more detections in this line than in the KI line and have already demonstrated that when both lines are detected there is a good coincidence between their RVs.

14 These values are obtained including V1348 Tau. If we exclude this source, we find P.A. = 214$^\circ$ and $\Omega = 0.11$ km s$^{-1}$ pc$^{-1}$, basically the same as those reported in the text.
proper-motion measurements for seven well-known Taurus members. These authors find velocity gradients of \( \sim 0.1 \) km s\(^{-1}\) pc\(^{-1}\) and positive direction of rotation with respect to Galactic rotation, as we find from the study of the Na I lines.

Velocity gradients in Taurus have also been measured using other tracers, and it has long been known that the Taurus velocity field is rather complex even on large \( \sim 10 \) pc scales (e.g., Shuter et al. 1987). Here we are particularly interested in comparing the atomic and the molecular components. Figure 13 shows the Na I velocities (as stars) superimposed on the higher spatial resolution \(^{13}\)CO FCRAO map\(^{15}\). The \(^{13}\)CO gas shows an SE–NW gradient with a rotation axis of 25°, \( \Omega \sim 0.25 \) km s\(^{-1}\) pc\(^{-1}\), and a systemic LSR velocity of 6.4 km s\(^{-1}\).

\(^{15}\) We use the FCRAO map because it has higher spatial resolution and only four sources are detected beyond this map in the coarser CfA survey.
The rotation of the $^{13}$CO is almost antiparallel to that of the Na I gas and retrograde with respect to differential galactic rotation. Interestingly, Ballesteros-Paredes et al. (1999) find that the HI $21$ cm emission has also a velocity offsets of a few kilometers per second and a larger velocity dispersion ($\sim 5$–$10$ km s$^{-1}$ LSR) than the molecular CO gas, resembling the one we see in the Na I and K I absorption lines. Position–velocity diagrams along some directions show a different axis of rotation from the CO gas (e.g., Figure 3(a) of Ballesteros-Paredes et al. 1999), but the magnitude and direction of rotation of the HI emitting gas have not been quantified. As a note, the magnetic field in Taurus has a mean P.A. of $25^\circ$ ($=205^\circ$), the same as the CO and Na I rotation axes. This is consistent with the classic theory of isolated low-mass star formation, whereby cores contract more along magnetic fields, resulting in a rotating flattened morphology perpendicular to the field axis (e.g., Shu et al. 1987). What is surprising is that the atomic gas and molecular gas rotate in almost opposite directions. What is the relation between the atomic and molecular gas?

The larger velocity dispersion in the Na I and K I absorptions and in the HI $21$ cm emission compared to the CO peak velocities suggests that the atomic gas is more widely distributed. Indeed, these atomic tracers are detected even at locations where molecular CO gas is not detected. Thus, they appear to trace the atomic gas that is the leftover of star formation. In addition, the mere detection of alkali metals in the gas phase implies that there are regions warmer than those traced by CO, regions that are not shielded from the ambient FUV radiation, or else Na and K would be depleted onto the surface of dust grains (e.g., Barlow 1978). We can further place an upper limit on the gas temperature that would result in thermal broadening (for the moment we neglect turbulence) by assuming that each atomic cloud is spectrally unresolved at our 6.6 km s$^{-1}$ resolution (such as, for instance, toward BP Tau or V819 Tau). Sodium gives a more stringent constraint than potassium, given its lower atomic mass, but not a tight one: the gas temperature should be $\lesssim 2000$ K for sodium lines to be unresolved at our spectral resolution. A much tighter constraint comes from the higher-resolution spectra of Welty & Hobbs (2001). These authors measure K I line width parameters ($b \sim 1.667$ FWHM) for over 100 ISM clouds, including those in

![Figure 12](image1.png)

Figure 12. Perpendicular offset of each TTS from the Na I cloud rotation axis (P.A. = $210^\circ$) as a function of the Na I LSR velocity. The linear trend between the two quantities shows that a plane is a good fit to the velocities.

![Figure 13](image2.png)

Figure 13. Color-coded image of the $^{13}$CO integrated intensity in three LSR velocity intervals: 3–5 km s$^{-1}$ is coded blue, 5–7 km s$^{-1}$ green, and 7–9 km s$^{-1}$ red; see also Goldsmith et al. (2008). Our TTSs are shown with stars, the color-coding representing their Na I RV also in LSR. We included one additional velocity bin (9–11 km s$^{-1}$ LSR, orange) to cover the larger velocity range seen in the Na I and K I absorption lines. White arrows show the position angles of $^{13}$CO and the Na I rotation axis; velocity gradients are perpendicular to each axis. Note that the $^{13}$CO and the Na I axes are almost antiparallel. The magnetic field direction is at a P.A. of $25^\circ$ ($205^\circ$), very similar to the rotation axis of the molecular gas and the Na I gas.
the direction of HD 27778, and find a distribution peaking at $\sim 0.7 \text{ km s}^{-1}$. Assuming an isotropic turbulence of $\sim 0.5 \text{ km s}^{-1}$, which seems to be common to many lines of sight, implies an atomic gas temperature of $\sim 100 \text{ K}$. Gas as cold as CO ($\sim 15 \text{ K}$) would result in $b$-values much smaller than typically observed. These results suggest that the gas associated with the alkali metals is much warmer than the molecular gas.

In models of photodissociation regions, temperatures of several hundred kelvin also trace the transition zone where ionized carbon is converted into atomic carbon. This zone is well outside the cold and FUV-shielded core where most of the hydrogen is in H$_2$ and most of the carbon in CO (e.g., Roellig et al. 2007). Recently, Herschel/HIFI observations demonstrated that a significant fraction, between 20% and 75%, of the ISM gas that is undetected in H$_\alpha$ and CO is bright in the [C ii] FIR line at 158 $\mu$m (Langer et al. 2014). Orr et al. (2014) compared [C i], [C ii], and CO emission lines toward a linear edge region in the Taurus molecular cloud. While the strength of the [C ii] lines is well correlated with that of CO lines (and its $^{13}$CO isotopologue), the [C ii] lines are only detected (at a low S/N) in two locations outside of the region where most of the molecular emission occurs (see their Figure 1). A comparison of [C ii] peak centroids and Na i and K i absorption toward the same line of sight would be very valuable to test if these transitions probe similar or larger regions.

To summarize, the available data suggest that the Na i and K i absorption lines trace the warm ($\sim 100 \text{ K}$) atomic envelope of the cold molecular CO gas in Taurus. Its extent may be comparable to that of the H i $21 \text{ cm}$ and/or the [C ii] FIR emission. The finding that the rotation axes of the atomic and molecular gas are not aligned is not unique to the Taurus region. Imara & Blitz (2011) compared the velocity gradient $P. A.$ of the molecular (CO) and atomic (H i $21 \text{ cm}$ emission) gas of five giant molecular clouds in the Milky Way. Except for Orion A, they find that the positional angles of the molecular and atomic morphological axes are widely separated, by as much as $130^\circ$ in the case of the Rosetta molecular cloud, and there is no correlation between the atomic and molecular gas rotation axes. Their results demonstrate that giant molecular clouds do not simply inherit their present velocity field from the atomic gas from which they formed and suggest that a disordered or turbulent component may play an important role in setting the rotation axes. Our analysis of Taurus extends this finding to a smaller molecular cloud and shows that Na i and K i resonance absorption lines can also be used to trace the structure of the atomic gas associated with molecular clouds.

Figure 14. Sources with broad Na i absorptions. A black solid line shows the residual Na i $\lambda 5890$, profile while a red dashed line shows the K i $\lambda 7699$ line. Normalized residual profiles for the H$\alpha$ (green dot-dashed line) and the [O i] $\lambda 6300$ (blue dotted line) lines are also superimposed. The velocity scale is larger than in previous figures to show both the broad blue- and redshifted absorptions. All velocities are in the stellocentric reference frame.
5. CONCLUSIONS AND PERSPECTIVES

Narrow Na I absorption resonance lines have long been known to be common in the optical spectra of TTSs. However, their origin remained elusive. Here we have presented a detailed analysis of the Na I and K I resonance lines toward nearly 40 TTSs in Taurus spanning a range of evolutionary stages. Our main findings can be summarized as follows.

1. The peak centroids of the Na I at 5889.95 Å and K I at 7698.96 Å are identical within our velocity uncertainty, and their EWs are positively correlated. This demonstrates that the two transitions trace the same atomic gas.

2. Several of the Na I and K I absorption lines have RVs substantially different from the stellar RV and are detected even toward stars with no circumstellar disks. This demonstrates that Na I and K I do not trace circumstellar disk gas; hence, these features cannot be used to investigate the Na/K ratio in disks, which is relevant for giant exoplanet atmospheres.

3. The Na I and K I RVs have a large spread (∼10 km s\(^{-1}\)) that cannot be accounted for by gas in the Local Bubble.

4. The distribution of Na I RVs in equatorial coordinates shows a clear gradient, suggesting that the absorption is associated with the Taurus molecular cloud. Assuming that the gradient is due to cloud rotation, the atomic gas rotates along an axis parallel to the magnetic field lines and prograde with respect to differential galactic rotation. This is different from the molecular gas, which is known to have a retrograde motion.

5. The atomic gas traced by Na I and K I absorption lines is more extended and warmer than the molecular gas traced by low-J CO rotational lines.

The almost antiparallel rotation axis between the atomic and molecular gas cannot be explained by simple top-down formation scenarios according to which molecular clouds inherit the velocity field and angular momentum from the rotating galactic disk within which they form. A similar result is found by Imara & Blitz (2011) when analyzing the rotational axes of the atomic and molecular gas from five giant molecular clouds in the Milky Way. In their study, they used the H \(\alpha\) 21 cm emission as a tracer of the atomic envelope of molecular clouds. Our results suggest that Na I and K I absorption lines can also be used to trace that atomic gas. A direct comparison of these two different tracers would be extremely valuable. With the Gaia-ESO survey acquiring high-resolution UVES spectra of ∼5000 stars in the Milky Way (Smiljanic et al. 2014), Na I and K I absorption lines may be used to trace the kinematic of the atomic gas associated with the molecular gas of several other nearby star-forming regions.

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Facility: Keck.

APPENDIX

BROAD Na I AND K I ABSORPTION FEATURES

The five objects with broad Na I absorptions are among the highest accretors in our sample (\(M \sim 10^{-8}\) \(M_\odot\) yr\(^{-1}\); e.g., Gullbring et al. 1998 Hartmann et al. 1998; White & Ghez 2001). As shown in Figure 14, broad absorptions are both on the blue and on the red side of the Na emission. A red absorption at several hundred kilometers per second is a signature of mass infall (e.g., Edwards et al. 1994). Conversely, the broad absorptions located between −150 and −50 km s\(^{-1}\) are most likely associated with material ejected from the star. Blueshifted absorptions are also present in the K I profiles of DG Tau and DO Tau, but they are much weaker than those in the Na I line. The inference of mass ejection is confirmed by the velocity coincidence of these absorption features with absorptions in the H\(\alpha\) line and emission in the [O I] \(\times 6300\) line, a known tracer of jets/outflows (e.g., HEG95). We note that in the case of DR Tau the absorption in the H\(\alpha\) line is very shallow and difficult to see with the scaling used in Figure 14, while the [O I] jet emission is more pronounced in the older and lower-resolution spectra by HEG95 (their Figure 5). A notable difference between the blue absorption in the Na I and H\(\alpha\) lines is that the latter are broader, suggesting that Na traces only specific regions along the jet. In addition, the fact that these velocities are smaller than the peak velocities of the forbidden oxygen emission lines indicates that H\(\alpha\) and Na I absorptions mostly trace ambient material shocked to lower speeds.

REFERENCES

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