EVOLUTION OF OH AND CO-DARK MOLECULAR GAS FRACTION ACROSS A MOLECULAR CLOUD BOUNDARY IN TAUROS

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ABSTRACT

We present observations of 12CO J = 1-0, 13CO J = 1-0, H1, and all four ground-state transitions of the hydroxyl (OH) radical toward a sharp boundary region of the Taurus molecular cloud. Based on a photodissociation region (PDR) model that reproduces CO and [C i] emission from the same region, we modeled the three OH transitions, 1612, 1665, and 1667 MHz successfully through escape probability non-local thermal equilibrium radiative transfer model calculations. We could not reproduce the 1720 MHz observations, due to unmodeled pumping mechanisms, of which the most likely candidate is a C-shock. The abundance of OH and CO-dark molecular gas is well-constrained. The OH abundance [OH]/[H2] decreases from 8 × 10−7 to 1 × 10−7 as Av increases from 0.4 to 2.7 mag following an empirical law:

[OH]/[H2] = 1.5 × 10−7 + 9.0 × 10−7 × exp(−Av/0.81),

which is higher than PDR model predictions for low-extinction regions by a factor of 80. The overabundance of OH at extinctions at or below 1 mag is likely the result of a C-shock. The dark gas fraction (DGF, defined as the fraction of molecular gas without detectable CO emission) decreases from 80% to 20% following a Gaussian profile:

DGF = 0.90 × exp − (Av−0.79)2.71

This trend of the DGF is consistent with our understanding that the DGF drops at low visual extinction due to photodissociation of H2 and drops at high visual extinction due to CO formation. The DGF peaks in the extinction range where H2 has already formed and achieved self-shielding but 12CO has not. Two narrow velocity components with a peak-to-peak spacing of ~1 km s−1 were clearly identified. Their relative intensity and variation in space and frequency suggest colliding streams or gas flows at the boundary region.

Key words: evolution – ISM: clouds – ISM: individual objects (Taurus) – ISM: molecules

1. INTRODUCTION

The formation of molecular hydrogen is a critical step in the transformation of interstellar gas into new stars. Various complex processes in the transformation between atomic gas and molecular gas result in changes in the physical state of gas. These changes affect the star formation process in galaxies and thus their evolution. It is of great significance to study the physical conditions in regions where the transformation between atomic gases and molecular gases occurs. The boundaries of molecular clouds are locations where the chemical composition changes considerably and primarily atomic gas transforms into molecular gas.

Apart from traditional tracers such as CO and H1, the hydroxyl radical, OH, is thought to be an excellent tracer to determine the physical conditions of the early state interstellar medium (ISM) where CO is absent (Li et al. 2015). Such early state molecular ISM appears in boundary regions. A three-way comparison of H1, OH, and CO lines is expected to show molecular features in OH that are not traced by CO but that highlight the transition from atomic gas (seen in the H1 line) to molecular gas.

Additionally, OH can be the tracer of “J-shocks” (Medling et al. 2015) and “C-shocks” (Anderl et al. 2013). Shock waves play a major role in the ISM (Timmermann 1998). When shock waves propagate through the molecular ISM the ambient gas is compressed, heated, and accelerated. Furthermore, the composition of the gas is significantly changed when chemical reactions occur, especially in the warm, shocked gas located in outermost parts of the transition region. The abundance of OH can vary from 10−3 to 10−11 when a 10 km s−1 C-type shock propagates into a diffuse cloud with nH = 50 cm−3 (Draine & Katz 1986a). Thus, searching for the evidence of shocks at the boundary region via OH lines is of great significance.

The boundary of molecular clouds is the region where all the physical and chemical processes mentioned above take place. As the dramatic changes of species at the boundaries, the physical conditions at the boundaries are distinct from those in other places. A clear example of cloud boundaries can be found in Taurus (Goldsmith et al. 2008) northeast of the TMC1 region. Orr et al. (2014) compared the observations of Taurus boundaries with line intensities produced by the Meudon photodissociation region (PDR) code. They found a low ratio of 12C to 13C ~ 43 and a highly depleted sulfur abundance (by a factor > 50) to explain the very low [C i] emission. Moreover, Goldsmith et al. (2010) found an unexpectedly high degree of excitation of the H2 in the boundary layer of Taurus molecular
cloud. They believed that an enhanced heating rate may be the result of turbulent dissipation.

As we are interested in the changes of chemical composition across the boundaries to study the transition between atomic- and molecular-dominated gas, we need to find a boundary of molecular clouds without significant UV enhancement. \( \text{H}_2 \) can be destroyed by UV photons, making the statistical equilibrium function complex. Moreover, it is easier to detect the emission of molecular tracers such as OH without an enhanced UV field.

We thus observed the Taurus boundary studied by Goldsmith et al. (2010) and Orr et al. (2014), which has a relatively low UV field between \( \chi = 0.3 \) and 0.8 in units of the Draine’s field (Flagey et al. 2009; Pineda et al. 2010) and little foreground or background visual extinction (Padoan et al. 2002), making it favorable for the comparison of observations with physical models.

We have carried out observations of the Taurus boundary in four OH transitions (1612, 1665, 1667, and 1720 MHz) using the 305 m Arecibo Telescope. We made a total of five cuts across the boundary region each with 17 pointings 3 arcminutes apart (Figure 1). We describe the observations of OH across the boundary region and the \( \text{H}_2 \), \( ^{12}\text{CO} \ J = 1-0 \), and \( ^{13}\text{CO} \ J = 1-0 \) map of Taurus molecular cloud in Section 2. We analyze the OH spectrum and derive the physical parameters of \( ^{13}\text{CO} \) across the boundary in Section 3. We use a cylindrical model and RADEX to fit OH lines to determine the physical parameters in Section 4. We discuss the conjugate emission of OH and pumping mechanisms in Section 5. In Section 6 we summarize our results and conclusions from this study.

2. OBSERVATIONS AND DATA

We carried out observations of OH with the Arecibo Telescope in Project a2813. We extracted \( \text{H}_1 \) data from the Galactic Arecibo L-Band Feed Array-H\( \text{I} \) (GALFA-H\( \text{I} \)) survey and \( ^{12}\text{CO} \ J = 1-0 \) and \( ^{13}\text{CO} \ J = 1-0 \) data from the Five College Radio Astronomy Observatory (FCRAO) Taurus survey.

2.1. OH Observations

The OH observations were taken using the L-band wide receiver (with frequency range 1.55–1.82 GHz) on 2013 October 28–31. We observed four OH transition lines at the rest frequencies of 1612, 1665, 1667, and 1720 MHz with the total power ON mode. Spectra were obtained with the Arecibo WAPP correlator with nine-level sampling and 4096 spectral channels for each line in each polarization. The spectral bandwidth was 3.13 MHz for a channel spacing of about 763 Hz, or 0.142 km s\(^{-1}\). The average system temperature was about 31 K. The main beam of the antenna pattern had a FWHM beam-width of 3\( \arcmin \). Spectra were taken at 17 \( \times \) 5 positions across the Taurus boundary region (TBR), as seen in Figure 1. An integration time of 300 s per
position was used resulting in an rms noise level of about 0.027 K.

2.2. H\textsc{i} Data

H\textsc{i} 21 cm observations of the TBR were extracted from the results of the GALFA-H\textsc{i} survey (Peek et al. 2011). GALFA-H\textsc{i} uses ALFA, a seven-beam array of receivers mounted at the focal plane of the 305 m Arecibo telescope, to map H\textsc{i} emission in the Galaxy. GALFA-H\textsc{i} is a survey of the Galactic interstellar medium in the 21 cm line hyperfine transition of neutral hydrogen which covers a large area (13,000 deg\textsuperscript{2}) with \( \pm 4\\)\' resolution and has a high spectral resolution (0.18 km s\textsuperscript{-1}) with broad velocity coverage (\(-700\) km s\textsuperscript{-1} < \(v_{\text{LSR}}\) < +700 km s\textsuperscript{-1}). Typical rms noise is 80 mK in a 1 km s\textsuperscript{-1} channel.

2.3. \(^{12}\text{CO}\) and \(^{13}\text{CO}\) Data

The \(^{12}\text{CO}\) J = 1-0 and \(^{13}\text{CO}\) J = 1-0 observations were taken simultaneously between 2003 and 2005 using the 13.7 m FCRAO Telescope (Narayanan et al. 2008). The map is centered at \(\alpha\) (2000.0) = 04\textdegree 32\textquoteleft 44\textquoteleft 6, \(\delta\) (2000.0) = 24\textdegree 25\textquoteleft 13\textquoteleft 08\ with an area of \(-98\) deg\textsuperscript{2}. The main beam of the antenna pattern had a FWHM beam-width of 45\textquoteleft" for \(^{12}\text{CO}\) and 47\textquoteleft" for \(^{13}\text{CO}\). The angular spacing (pixel size) of the resampled on-the-fly data is 20\textquoteleft" (Goldsmith et al. 2008), which corresponds to a physical scale of \(\approx 0.014\) pc at a distance of \(D = 140\) pc. The data have a mean rms antenna temperature of 0.28 and 0.15 K in channels of 0.26 and 0.27 km s\textsuperscript{-1} width for \(^{12}\text{CO}\) and \(^{13}\text{CO}\), respectively.

3. ANALYSIS

3.1. Spectral Analysis

The locations of the positions for the telescope pointing used to study the TBR are shown in Figure 1. To examine the transition zone with higher signal-to-noise ratio, we averaged all five cuts of spectra of OH 1612 MHz, 1665 MHz, 1667 MHz, 1720 MHz, \(^{12}\text{CO}\) J = 1-0, \(^{13}\text{CO}\) J = 1-0, and H\textsc{i}, as shown in Figure 2. The \(^{12}\text{CO}\) J = 1-0 and \(^{13}\text{CO}\) J = 1-0 spectra were convolved to the OH beam size of 3\textquoteleft" at each position. The emission lines of OH, \(^{12}\text{CO}\), \(^{13}\text{CO}\) J = 1-0, \(^{13}\text{CO}\) J = 1-0, and the absorption lines of H\textsc{i} are well matched in velocity. Especially, the emission lines of OH 1665 MHz at positions 10–12 all have two components and the spectral of H\textsc{i} at the same point have two corresponding narrow absorption components as shown in Figure 3.

We did Gaussian fitting of the OH 1612 MHz, 1665 MHz, 1667 MHz, and 1720 MHz spectra with two Gaussian components, the fitting of \(^{12}\text{CO}\) and \(^{13}\text{CO}\) spectra with a single Gaussian component, and the fitting of H\textsc{i} spectra with three Gaussian components. We show the spectra and the fitted profiles in Figure 2. The line ratio between OH 1665 MHz and 1667 MHz is greater than one in the outside TBR region (TBR-O) as shown in Figure 2. Under the assumption of local thermal equilibrium (LTE) the line ratio between 1665 and 1667 MHz ranges from 0.6 to 1. The line ratio greater than one indicates a deviation from LTE for OH.

We show the change of peak intensity of two components in OH 1665 MHz and a single component in \(^{13}\text{CO}\) across the TBR in Figure 4. Component 1 of OH 1665 MHz spectrum at 5.3 km s\textsuperscript{-1} appears after position 4 and gets stronger across the TBR. Component 2 at 6.8 km s\textsuperscript{-1} appears in the TBR-O and gets faint in the inside TBR region (TBR-I) and disappears after position 13. The central velocities of \(^{13}\text{CO}\) shift from 6.3 to 5.7 km s\textsuperscript{-1}. We assume that each component of the OH emission indicates a gas stream. When the intensity of OH component 2 is stronger than that of component 1 in TBR-O, the central velocity of \(^{13}\text{CO}\) is located at 6.3 km s\textsuperscript{-1}. When the intensity of OH component 1 is stronger than that of component 2 in TBR-I, the central velocity of \(^{13}\text{CO}\) is located at 5.7 km s\textsuperscript{-1}. The central velocity of \(^{13}\text{CO}\) shifts in the same way as the central velocity of stronger intensity OH component shifts. In Figure 3 we see that component 2 of OH 1665 gradually becomes fainter and disappears at position 13. At the same time the central velocity of component 1 gradually shifts from 5.3 km s\textsuperscript{-1} at position 9 to 5.8 km s\textsuperscript{-1} at position 13, which indicates that the collision of two streams results in the final central velocity being located between the velocities of the two components. The central velocity of the final combined stream is located closer to component 1, which has a stronger emission line in TBR-I. This is consistent with the assumption of different amounts of \(^{13}\text{CO}\) emission at different velocities. Not only OH 1665 MHz but also \(^{12}\text{CO}\) shows the central velocity shifting after the streams collide from position 10 to position 13 in Figure 3.

We show the change of line width along the cut direction in Figure 5. We can clearly see that the line widths of \(^{12}\text{CO}\) and \(^{13}\text{CO}\) peak at the TLB. This is mainly due to the two gas streams that contribute to the line widths of \(^{12}\text{CO}\) and \(^{13}\text{CO}\). The line width of OH 1667 MHz is much wider than that of other lines in TBR-O. This is mainly caused by the weak emission lines of OH 1667 MHz in TBR-O. Since the height of OH 1667 MHz is small in TBR-O, the fitted Gaussian profile tends to be flatter than that at other positions. So the line width of OH 1667 MHz is two times wider than that of the other three lines in TBR-O. Component 2 of OH 1667 MHz whose central velocity is at 6.8 km s\textsuperscript{-1} is very weak in some positions in TBR-I, which leads to a wider line width of component 1 as shown in Figure 2. The width of component 2 in TBR-I is wider than that of other three lines in TBR-I, which leads to the average line width of OH 1667 behaving in an erratic way. The line width of OH 1665 MHz is nearly constant across the TBR.

The line width of \(^{12}\text{CO}\) is significantly greater than that of \(^{13}\text{CO}\). Opacity may be one of the reasons. Owing to the different abundance of \(^{12}\text{CO}\) and \(^{13}\text{CO}\), \(\tau_{2}\) is almost 70 times larger than \(\tau_{3}\). When \(\tau_{2}\) is much larger than unity, the term \(1-\exp[-\tau_{2}\phi(\Delta v)]\) in the line profile of \(^{12}\text{CO}\) is much wider than that of \(^{13}\text{CO}\), where \(\phi(\Delta v)\) is a Gaussian profile of the velocity offset from line center \(\Delta v\). We made an estimate of the line width ratio between \(^{12}\text{CO}\) and \(^{13}\text{CO}\) only considering the opacity. In TBR-O the optical depth range is from 0.05 to 0.4. We took position 8 having \(\tau_{12}\approx\tau_{13}\approx 0.2\) as an example. The line width ratio between \(^{12}\text{CO}\) and \(^{13}\text{CO}\) is 1.4, which is much less than the observed ratio 2.3. Other broadening mechanisms must occur in the TBR. Park & Hong (1995) took different broadening mechanisms, such as micro-turbulence and macro-turbulence, into consideration and found that the line width ratio between \(^{12}\text{CO}\) and \(^{13}\text{CO}\) can range from 1 to 3 depending on the physical condition of the gas, which just corresponds to the line width ratio between \(^{12}\text{CO}\) and \(^{13}\text{CO}\) in our work. The wider line width of \(^{12}\text{CO}\) may be the result of larger turbulence due to the more extended distribution of \(^{13}\text{CO}\). According to Larson’s law (Larson 1981), a larger scale of a molecular cloud...
leads to a larger velocity dispersion. Considering current geometrical model of photodissociation region (Tielens 2005), the larger self-shielding threshold of $^{13}$CO makes it more constrained to the inner region of the boundary, which yields a narrower line width than that of $^{12}$CO.

We can also see the central velocities of component 1 in OH 1665 MHz shifting from 5.3 to 6.0 km s$^{-1}$ at positions 10–12 in Figure 3. This velocity gradient may be caused by colliding streams or gas flow at the TLB. The description of the OH spectra and components across TBR can be found in Table 1.

3.2. $^{13}$CO Column Density Calculation

From the fitting result of $^{12}$CO J = 1-0 and $^{13}$CO J = 1-0 above, we can calculate the column density of $^{13}$CO. The column density of $^{13}$CO in the upper level ($J = 1$) can be
Figure 3. Average spectra of all five cuts of OH 1612 MHz, 1665 MHz, 1667 MHz, 1720 MHz, $^{12}$CO $J = 1-0$, $^{13}$CO $J = 1-0$, and HI at positions 8–13. The $^{12}$CO $J = 1-0$ and $^{13}$CO $J = 1-0$ spectra were convolved to the OH beam size of 3′ at each position. The vertical dashed lines indicate the central velocities of the two components of OH 1665 MHz at position 10.

Figure 4. Change of peak intensity of the two components of OH 1665 and the single component of $^{13}$CO across the TBR. The upper stripe indicates the intensity of component 2 in OH 1665 MHz across the TBR. The middle oblique stripe indicates the intensity of $^{13}$CO. The bottom stripe indicates the intensity of component 1 in OH 1665 MHz across the TBR. The color indicates the value of peak intensity of each spectrum at each position. The peak intensity of $^{13}$CO shown in the oblique stripe is one-fourth of the observed peak intensity. A more detailed discussion is in Section 3.1.
written as

$$N_{u, \text{CO}} = \frac{8\pi kv^2}{hc^3A_{ul}} \int T_b(V)dV,$$
(1)

where $k$ is Boltzmann’s constant, $h$ is Planck’s constant, $c$ is the speed of light, $A_{ul}$ is the spontaneous decay rate from the upper level to the lower level, and $T_b$ is the brightness temperature. A convenient form of this equation is

$$\left( \frac{N_{u, \text{CO}}}{\text{cm}^{-2}} \right) = 3.6 \times 10^{14} \int \left( \frac{T_b}{\text{K}} \right) d\left( \frac{V}{\text{km s}^{-1}} \right).$$
(2)

The total $^{13}$CO column density $N_{\text{tot}}$ is related to the upper-level column density $N_u$ through (Li 2002)

$$N_{\text{tot, CO}} = f_u f_r f_b N_{u, \text{CO}}.$$  
(3)

In the equation above, the level correction factor $f_u$ can be calculated analytically under the assumption of LTE as

$$f_u = \frac{Q(T_{ex})}{g_u \exp \left( \frac{h\nu}{kT_{ex}} \right)},$$
(4)

where $g_u$ is the statistical weight of the upper level, $T_{ex}$ is the excitation temperature and $Q(T_{ex}) = kT_{ex}/hB_0$ is the LTE partition function, where $B_0$ is the rotational constant (Tennyson 2005). A convenient form of the LTE partition function is $Q(T_{ex}) \approx T_{ex}/2.76$ K. The correction factor for opacity is defined as

$$f_r = \frac{\int \tau_{13}dv}{\int (1 - e^{-\tau_{13}})dv},$$
(5)

and the correction for the background

$$f_b = \left[ 1 - \frac{e^{\tau_{bg}} - 1}{e^{\tau_{bg}} - 1} \right],$$
(6)

where $\tau_{13}$ is the opacity of the $^{13}$CO transition and $T_{bg}$ is the background temperature, assumed to be 2.7 K.

The $^{13}$CO opacity is estimated as follows. Assuming equal excitation temperatures for the two isotopologues, the ratio of the brightness temperature of $^{12}$CO to that of $^{13}$CO can be written as

$$\frac{T_{b,12}}{T_{b,13}} = \frac{1 - e^{-\gamma_{12}}}{1 - e^{-\gamma_{13}}}. $$
(7)

Assuming $\gamma_{12} \gg 1$, the opacity of $^{13}$CO can be written as

$$\gamma_{13} = -\ln \left( 1 - \frac{T_{b,13}}{T_{b,12}} \right).$$
(8)

The excitation temperature $T_{ex}$ is obtained from the $^{12}$CO intensity. First, the maximum intensity in the spectrum of each pixel is found. This quantity is denoted by $T_{max}$. The excitation temperature is calculated by solving the following equation:

$$T_{max} = \frac{h\nu}{k} \left[ \frac{1}{e^{\frac{T_{ex}}{T_{bg}}} - 1} - \frac{1}{e^{\frac{T_{max}}{T_{bg}}} - 1} \right],$$
(9)

where $h$, $k$, and $\nu$ are Planck’s constant, Boltzmann’s constant, and the central frequency of $^{12}$CO $J = 1 \rightarrow 0$ line (115.27 GHz), respectively.

To examine the LTE assumption when calculating the physical parameters of CO, we used a spherical 1D non-LTE spectral analysis radiative transfer model, RADEX (van der Tak et al. 2007) to derive the excitation temperature of $^{12}$CO and $^{13}$CO. We took position 10 as an example. We assumed the number density of H$_2$ to be 400 cm$^{-3}$, which is given by Orr et al. (2014). We also assumed the kinetic temperature to be 15 K, which is widely applied in the relatively diffuse region in the Taurus molecular cloud (e.g., Goldsmith et al. 2008). The resulting excitation temperature of $^{12}$CO and $^{13}$CO are $T_{ex,^{12}CO} = 7.7$ K and $T_{ex,^{13}CO} = 6.8$ K, with a difference of about 10%. The assumption that the excitation temperatures of $^{12}$CO and $^{13}$CO are equal seems reasonable. Owing to the difference of excitation temperature between $^{12}$CO and $^{13}$CO, the derived column density of $^{13}$CO also has an error about 10%.

We show the change of excitation temperature of $^{13}$CO and the change of column density of $^{13}$CO along the cut direction in Table 2 and Figure 6. The excitation temperature $T_{ex}$ of $^{13}$CO increases across the boundary. The column density of $^{13}$CO shows a peak at position 13 and 14 inside the boundary.

4. SIMULATION OF OH EMISSION LINE WITH RADEX

We assume a cylindrical geometry to model the linear boundary region of the cloud. We adopted the results of “cylindricalized” Meudon PDR model by Orr et al. (2014) and applied a spherical 1D non-LTE spectra analysis radiative transfer model, RADEX (van der Tak et al. 2007), to generate a sky-plane image of the TBR for the transitions of OH.

4.1. Density Profile of TBR

We modeled the linear boundary as a cylinder with a radius-dependent H$_2$ volume density structure of the following form (King 1962),

$$n_{H_2}(r) = \begin{cases} n_0 a^2/(r^2 + a^2) & : r \leq R \\ 0 & : r > R \end{cases},$$
(10)

This functional form was used in analysis of the Taurus region by Pineda et al. (2010).

This profile has a flat high-density center which transitions to a region of power-law decay and finally at a truncating radius, the density is set to zero. It assumes only three parameters: the
Table 1
The Change of OH Spectral Lines Across the Boundary in Taurus

| Position   | Offset (') | 1612 MHz | 1665 MHz | 1667 MHz | 1720 MHz |
|------------|------------|----------|----------|----------|----------|
|            |            | \(\epsilon_1\) | \(\epsilon_2\) | \(\epsilon_1\) | \(\epsilon_2\) | \(\epsilon_1\) | \(\epsilon_2\) | \(\epsilon_1\) | \(\epsilon_2\) |
| 1 (outer)  | -24.0      | we\(^{e}\) | a\(^{d}\) | n | e | n | we | n | we |
| 7 (T_{B} peak) | -6.0      | we | a | n | e | we | we | n | e |
| 9 (boundary) | 0.0       | e\(^{e}\) | wa\(^{f}\) | e | e | e | we | a | e |
| 11 (N_{CO} peak) | 6.0       | e(\(\rightarrow\)f) | n\(^{b}\) | e(\(\rightarrow\)) | e(\(\rightarrow\)) | e(\(\rightarrow\)) | we | a(\(\rightarrow\)) | we |
| 12 (N_{CO} peak) | 9.0       | e(\(\rightarrow\)) | n | e(\(\rightarrow\)) | we | e(\(\rightarrow\)) | n | a(\(\rightarrow\)) | n |
| 17 (inner)  | 24.0       | e(\(\rightarrow\)) | n | e(\(\rightarrow\)) | n | e(\(\rightarrow\)) | n | a(\(\rightarrow\)) | n |

Notes.
- \(\epsilon_1\) means the component at 5.3 km s\(^{-1}\).
- \(\epsilon_2\) means the component at 6.8 km s\(^{-1}\).
- \(e\) means weak emission.
- \(d\) a means absorption.
- \(e\) \(e\) means emission.
- \(f\) \(w\) means weak absorption.
- \(g\) \(w\) means the shifting of central velocity of component 1.
- \(n\) \(n\) means neither emission nor absorption.

Table 2
Parameters along the Boundary

| Position | \(T_{c,1/\alpha}\) (K) | \(N_{H_2}\) \((10^{14} \text{ cm}^{-2})\) |
|----------|-----------------|-----------------|
| 1        | 6.5             | 2.5             |
| 2        | 6.3             | 2.3             |
| 3        | 5.9             | 2.8             |
| 4        | 5.8             | 3.1             |
| 5        | 5.6             | 3.2             |
| 6        | 5.6             | 4.0             |
| 7        | 6.3             | 5.6             |
| 8        | 6.3             | 5.6             |
| 9        | 6.9             | 13              |
| 10       | 7.6             | 39              |
| 11       | 7.8             | 33              |
| 12       | 7.7             | 42              |
| 13       | 7.6             | 59              |
| 14       | 8.5             | 58              |
| 15       | 8.5             | 34              |
| 16       | 8.0             | 20              |
| 17       | 8.5             | 23              |

Figure 6. Change of column density of \(^1\)CO along the cut direction.

central core density \(n_c\), a parameter characterizing the width of the central core \(a\), and the truncating radius \(R\). Orr et al. (2014) fitted the profile with visual extinction data for this region. The fitted values for the density profile parameters are \(n_c = 626 \text{ cm}^{-3}\), \(a = 0.457 \text{ pc}\), and \(R = 1.80 \text{ pc}\). The axis of the cylindrical distribution is centered 11.5 to the southwest of the boundary position between position 12 and position 13.

The \(H_2\) volume density of 17 observed points along the boundary is obtained from Orr et al. (2014).

4.2. RADEX Fitting Results

RADEX takes the following inputs: kinetic temperature \(T_k\), density of \(H_2\) \((n_{H_2})\), \(H_2\) ortho-to-para ratio \(\text{OPR}\), background temperature \(T_{bg}\), column density of OH \((N_{OH})\), and line width \((\Delta V_{OH})\). Rates for collisional excitation of OH are taken from Offer et al. (1994).

The \(n_{H_2}\) is an input parameter estimated based on the cylindrical model in Orr et al. (2014). The Galactic background emission is estimated to be about 0.8 K by extrapolating the standard interstellar radiation field (ISRF) to the L band (Winnberg et al. 1980). \(T_{bg} = 3.5\) K is thus used in the simulation.

We vary the \(T_{c}\), \(H_2\), \(\text{OPR}\), and \(N_{OH}\) to find the optimum model by minimizing \(\chi^2\) for the four OH lines, defined as

\[
\chi^2 = \frac{1}{N} \sum_{i=1}^{N} \left( \frac{I_{\text{model}} - I_{\text{obs}}}{\sigma^2_{\text{obs}}} \right)^2 ,
\]

where \(I_{\text{obs}}\) is the four observed by OH lines’ intensities, \(I_{\text{model}}\) is the model lines generated by RADEX, and \(\sigma^2_{\text{obs}}\) is the rms of the four observed OH lines.

We varied \(T_{c}\), \(\text{OPR}\), and \(N_{OH}\) to obtain the best fit to the observation at position 1 shown in Figure 7. The best-fitting \(T_{c}\), \(\text{OPR}\), and \(N_{OH}\) are 31 K, 0.2, and \(3.7 \times 10^{14} \text{ cm}^{-2}\), respectively. We also calculated the column density of OH at position 1 (assuming it to be optically thin with no background emission) from the integrated intensity (in K km s\(^{-1}\)) of the 1667 MHz line through (e.g., Turner & Heiles 1971; Knapp &
Kerr 1973):

\[
\frac{N_{\text{OH}}}{\text{cm}^{-2}} = 2.22 \times 10^{14} \int \frac{T_B(V)dV}{K \text{ km s}^{-1}}.
\]

(12)

With these assumptions \(N_{\text{OH}}\) is \(0.5 \times 10^{14} \text{ cm}^{-2}\). When the excitation temperature of OH is so low that the background cannot be neglected, we have a correction factor \(F_{bg}\) (e.g., Harju et al. 2000; Suutarinen et al. 2011)

\[
F_{bg} = \frac{1}{1 - T_{bg}/T_{ex}}.
\]

(13)

When \(T_{bg} \approx 3.5, K\) and \(T_{ex} \approx 4, K\), \(F_{bg} \approx 8\), which yields \(N_{\text{OH}} \approx 4 \times 10^{13} \text{ cm}^{-2}\), which is almost the same as the fitted \(N_{\text{OH}}\) from RADEX (denoted \(N_{\text{OH,RADEX}}\)). The problem with using the "LTE method" is that we do not know the excitation temperature of OH. Instead we have to assume an excitation temperature for OH, which has a major effect on the correction factor \(F_{bg}\). Only with a statistical equilibrium calculation (e.g., RADEX) can we know the excitation temperature of OH exactly. We should be cautious about the low excitation temperature of OH, otherwise we may underestimate the column density of OH by a factor of eight or more in many conditions where the LTE method is used.

Compared with \(N_{\text{OH,RADEX}}\), the calculated \(N_{\text{OH}}\) through Equations (12) and (13) (noted as \(N_{\text{OH,LTE}}\) representing the "LTE method") is almost the same as \(N_{\text{OH,RADEX}}\). The fitted opacity (Table 3) based on the model is relatively smaller (\(\tau \approx 0.04-0.3\)), which is consistent with the assumption of optical thin in the "LTE method."

Equation (12) is used to calculate \(N_{\text{OH}}\) and assumes LTE, but the observed line ratio between OH 1665 and 1667 MHz is obviously greater than one, indicating that the OH at position 1 is far from LTE. The critical density of OH HFS lines at 10–50 K is 1–20 cm\(^{-3}\), indicating that OH excitation is dominated by a collision in TBR with \(n = 70–600 \text{ cm}^{-3}\). Compared with OH, low-J \(^{12}\)CO lines have a larger critical density of about 2000 cm\(^{-3}\). In most cases when collision dominate the excitation, the LTE assumption is reasonable. Surprisingly, OH HFS lines are far from LTE, which has a low critical density. \(^{12}\)CO is consistent with LTE as discussed in Section 3.2 with RADEX analysis. Considering for the complex energy level of OH, some pumping mechanism must be operative to yield the non-LTE of OH. We will have a detailed discussion of this in Section 5. A most possible mechanism is C-shock. The line ratio between 1665 and 1667 MHz and the integrated intensity of 1667 MHz across the boundary are listed in Table 4. In TBR-O the line ratio is greater than one. In TBR-I the line ratio is between \(\approx 0.5\) and \(\approx 0.8\), which is within the range allowed by LTE.

The change of physical parameters across the boundary is partially listed in Table 5.

![Figure 7. Observed OH lines (black) and the simulated OH profiles (red) using RADEX at position 1.](image)

Table 3

| Position | \(T_{ex}\) (K) | \(\tau\) | \(T_{A}\) (K) |
|----------|----------------|--------|-------------|
| 1:612    | 3.1            | 0.045  | -0.025      |
| 1:665    | 4.1            | 0.163  | 0.098       |
| 1:667    | 3.8            | 0.331  | 0.062       |
| 1:720    | 5.4            | 0.024  | 0.055       |

Table 4

| Position | Ratio(1665/1667) | Intensity(1667) (K km s\(^{-1}\)) |
|----------|-----------------|-------------------------------|
| 1        | 1.6 ± 0.18      | 0.21 ± 0.02                   |
| 2        | 1.2 ± 0.14      | 0.20 ± 0.02                   |
| 3        | 1.3 ± 0.13      | 0.22 ± 0.02                   |
| 4        | 1.2 ± 0.12      | 0.24 ± 0.02                   |
| 5        | 1.5 ± 0.14      | 0.29 ± 0.02                   |
| 6        | 1.6 ± 0.13      | 0.26 ± 0.02                   |
| 7        | 1.3 ± 0.10      | 0.35 ± 0.02                   |
| 8        | 1.2 ± 0.08      | 0.31 ± 0.02                   |
| 9        | 1.1 ± 0.05      | 0.42 ± 0.02                   |
| 10       | 0.51 ± 0.02     | 0.49 ± 0.01                   |
| 11       | 0.54 ± 0.02     | 0.53 ± 0.02                   |
| 12       | 0.52 ± 0.02     | 0.50 ± 0.01                   |
| 13       | 0.61 ± 0.02     | 0.49 ± 0.01                   |
| 14       | 0.69 ± 0.02     | 0.48 ± 0.01                   |
| 15       | 0.72 ± 0.02     | 0.42 ± 0.01                   |
| 16       | 0.77 ± 0.03     | 0.40 ± 0.01                   |
| 17       | 0.83 ± 0.04     | 0.37 ± 0.01                   |
4.3. The Effect of the H\textsubscript{2} Ortho-to-para Ratio (OPR) on Fitting

Owing to the different cross sections between OH and two spin symmetries of H\textsubscript{2}, i.e., ortho-H\textsubscript{2} and para-H\textsubscript{2} (Offer et al. 1994), the OPR plays a significant role in the excitation of OH. The exact value of the OPR is important for producing the observed OH 1665/1667 intensity ratio in certain positions, such as for position 9, as shown in Figure 8. Overall the derived column density is insensitive to the numerical value of the OPR, such as for position 10 as shown in Figure 8. We will discuss this issue in a separate paper and focus on the dark gas and OH abundance content in the present work.

4.4. Physical Parameter Analysis

We define the CO-dark molecular gas (DMG) fraction or dark gas fraction (DGF) as

\[
\text{DGF} = 1 - \frac{N_{\text{CO}} \times 10^4}{N_{\text{H}_2}},
\]

which represents the fraction of H\textsubscript{2} that cannot be traced by CO emission. \(N_{\text{CO}}\) is obtained from the LTE calculation in Section 3.2 with the assumption that the abundance ratio of \(^{12}\text{CO}\) to \(^{13}\text{CO}\) is 65 (Langer & Penzias 1993; Liszt 2007). \(N_{\text{H}_2}\) is obtained from integration of the density profile in Section 4.1 along the line of sight and the visual extinction is obtained from the relation \(N(\text{H}_2)/A_V = 9.4 \times 10^{20} \text{ cm}^{-2} \text{ mag}^{-1}\), assuming that the hydrogen is predominately in molecular form and standard grain properties are appropriate for the diffuse ISM (Orr et al. 2014). We averaged the column density of H\textsubscript{2} within the OH beam size (\(\sim 3''\)) at each position to make all the calculations refer to the same beam size. The variation of \(T_K\), \(N_{\text{OH}}\), \(N_{\text{DGF}}/N_{\text{H}_2}\), and DGF across the boundary as a function of extinction \(A_v\) is shown in Figure 9. When the extinction \(A_v\) increases from 0.4 to 2.6 mag, the kinetic temperature, the abundance of OH, and the DGF all decrease. Especially, the DGF decreases from 80% to 20%, which means the amount of molecular gas that cannot be traced by CO is three times larger than that of molecular gas traced by CO when the extinction is below 1.4 mag. Empirically, CO intensities have been used as an indicator of the total molecular mass in the Milky way and in galaxies through the so-called “X-factor” with numerous well-known caveats. In other words, we may seriously underestimate the amount of molecular gas through “X-factor” in low-extinction clouds or regions of galaxies.

We parametrize the trend of \(N_{\text{OH}}/N_{\text{H}_2}\) and DGF in an exponential law and a Gaussian profile, respectively, as shown in Figure 10. The trend of \(N_{\text{OH}}/N_{\text{H}_2}\) can be fitted as

\[
\frac{N_{\text{OH}}}{N_{\text{H}_2}} = 1.5 \times 10^{-7} + 0.9 \times 10^{-7} \times \exp \left( -\frac{A_v}{0.81} \right).
\]

### Table 5
Change of Physical Parameters Across the Boundary in Taurus

| Position | Offset | \(T_K\) (K) | \(N_{\text{OH}}\) (10\(^4\) cm\(^{-2}\)) | \(A_v\) (mag) | \(N_{\text{OH}}/N_{\text{H}_2}\) (10\(^{-7}\)) | DGF* |
|----------|--------|-------------|----------------------------------|----------------|----------------------------------|------|
| 1 (outer) | -24.0  | ...         | 37                               | 2.9            | 0.4                              | 7.2\(\pm\)0.2 |
| 7 (H\textsubscript{2} peak) | -6.0   | 25          | 35                               | 2.9            | 1.3                              | 3.5\(\pm\)0.7 |
| 9 (boundary) | 0.0    | 26          | 32                               | 1.5            | 4.9                              | 3.7\(\pm\)0.4 |
| 11 (N\textsubscript{H} peak) | 6.0    | 10          | 27                               | 1.5            | 4.5                              | 2.4\(\pm\)0.5  |
| 12 (N\textsubscript{CO} peak) | 9.0    | 23          | 26                               | 2.1            | 2.5                              | 1.9\(\pm\)0.2  |
| 17 (inner) | 24.0   | ...         | 3.3                              | ...            | 1.5                              | 2.3\(\pm\)0.3  |

\* DGF means dark gas fraction.
remains roughly a constant 2.5 across the boundary as a function of extinction. As the error in the last three points (owing to there being slightly more H$_2$ traced by CO than that calculated by almost 50%) becomes slightly negative when the high extinction is high enough, $^{12}$CO can be formed and survive. At this point the molecular gas can be well traced by $^{13}$CO so that the DGF also drops at a high visual extinction between 0.3 and 2 mag, with neither the low extinction ($<0.3$ mag) nor the high extinction ($>2$ mag) showing significant deviation. In regions with sufficiently low visual extinction, H$_2$ cannot survive due to the destruction by UV photons. On the other hand, when the visual extinction is high enough, $^{12}$CO can be formed and survive. At this point the molecular gas can be well traced by $^{13}$CO so that the DGF also drops at a high visual extinction. When the visual extinction is between 0.4 and 1.3 mag, the abundance of H$_2$ is already a layer fraction of the total hydrogen abundance, but $^{13}$CO has not formed completely so that the DGF peaks under these conditions.

It is important to emphasize that the parameterized trends above can only be applied to the molecular gas with visual extinction between 0.4 and 1.3 mag for which we have OH data and have modeled the lines successfully.

5. CONJUGATE EMISSION OF OH

As shown in Figure 2 OH 1612 MHz lines appear to be absorption lines and OH 1720 MHz lines appear to be emission lines outside the boundary. However, it is quite different inside the boundary. OH 1612 MHz lines appear to be emission lines and OH 1720 MHz lines appear to be absorption lines inside the boundary. This inversion of satellite lines is known as conjugate emission of OH.

The mechanism for producing conjugate emission is asymmetrical in pumping, due to quantum selection rules in the OH rotational transition ladder as shown in Figure 11. The 18 cm OH maser lines result from hyperfine transitions in the $^2$P$_{3/2}/^2$P$_{1/2}$ level, which is the ground state. The 1720 MHz line is produced by a transition from a $F=2$ to...
The result is that for a column density per velocity interval just below $10^{15}$ cm$^{-2}$ km$^{-1}$ s, the 1720 MHz line is inverted and the 1612 MHz line is anti-inverted. The reverse behavior occurs for column density just above $10^{15}$ cm$^{-2}$ km$^{-1}$ s (van Langevelde et al. 1995).

The fitted column densities $N_{\text{OH}}$ in Section 4.2 are all below $5.2 \times 10^{14}$ cm$^{-2}$ and the line widths at all positions are greater than 1 km s$^{-1}$. Thus the observed physical condition do not correspond to the reverse condition mentioned above. RADEX can not reproduce the OH 1720 MHz absorption when fitting OH lines inside the boundary as shown in Figure 12. There must be other pumping mechanisms, such as FIR emission from dust grains (Sivagnanam 2004), chemical pumping (Elitzur 1992), shocks (Pihlström et al. 2008), and/or a combination of these factors to invert the satellite lines of OH. RADEX takes into account none of the above. Given the lack of protostars or H II regions in the whole Taurus neighborhood and the possible existence of colliding streams seen in our data, we propose low-velocity shocks as the main reason for the inversion of OH satellite lines.

6. SUMMARY AND CONCLUSIONS

We have mapped a sharp boundary region of the Taurus molecular cloud in the four ground-state transitions of the hydroxyl (OH) radical with the Arecibo telescope. We then carried out a combined analysis of our OH data along with HI, $^{12}$CO J = 1-0, $^{13}$CO J = 1-0, with the non-LTE spectral analysis radiative transfer model, RADEX. Our main findings are the following.

1. The two main lines are seen in emission in all the positions across the boundary region. However, the characteristics of the two satellite lines show significant differences across the boundary region. The satellite lines at 1612 and 1720 MHz show absorption and emission, respectively, outside the boundary and emission and absorption, respectively, inside the boundary.

2. Our cut perpendicular to the boundary shows that OH has two kinematic components and one component shift from 5.3 to 6 km s$^{-1}$, which seems to indicate colliding streams or gas flow at the boundary region.

3. We have used a cylindrical model and RADEX to fit the OH lines to determine the physical parameters, including $T_r$, OPR, and $N_{\text{OH}}$ across the boundary. All the physical parameters can be well-constrained. The excitation of OH is far from LTE.

4. We have derived the OH abundance ($N_{\text{OH}}/N_{\text{H}_2}$) profile across the boundary. $N_{\text{OH}}/N_{\text{H}_2}$ decreases from $8 \times 10^{-7}$ to $1 \times 10^{-7}$ as $A_V$ increases from 0.4 to 2.7 mag, following an exponential law \[
\frac{[\text{OH}]}{[\text{H}_2]} = 1.5 \times 10^{-7} + 9.0 \times 10^{-7} \times \exp(-A_V/0.81)
\]

5. We obtained the fraction of CO-DMG (DGF) across the boundary. The DGF decreases from 0.8 to 0.2 following a Gaussian profile \[
\text{DGF} = 0.90 \times \exp \left( -\frac{(A_V - 0.7)^2}{0.71} \right)
\]

This trend of the DGF is expected from theory. The DGF drops at low visual extinction due to the reduced
abundance of H₂, and drops at high visual extinction due to the complete conversion of carbon to CO. The DGF is thus maximum in the range where H₂ has already formed but \(^{12}\)CO has not formed completely. This is of significance in estimating the amount of molecular gas in low-extinction clouds or regions of galaxies with similar condition.

6. We detected the conjugate emission of OH 1612 MHz and 1720 MHz components. The complementary switching between emission and absorption of 1612 MHz and 1720 MHz, respectively, suggests that an incompletely modeled pumping mechanism must be operative, the most likely of which is C-shock.

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