Thermal Structure of a Protoplanetary Disk around HD 163296: A Study of Vertical Temperature Distribution by CO Emission Lines

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Abstract

This paper presents observations of a protoplanetary disk around the Herbig Ae star HD 163296 in $^{12}$CO ($J=1$–0), $^{12}$CO ($J=3$–2), $^{13}$CO ($J=1$–0), and $^{12}$CO ($J=3$–2) emission lines. Double-peaked emission profiles originating from the rotating circumstellar disk were detected in all of the lines. The disk parameters were estimated from model calculations in which the radial distribution of the temperature or surface density inside the disk had a power-law form. The surface density should be sufficiently high so that the disk is optically thick for all of the CO lines, as discussed in previous studies based on interferometric observations. The temperature and outer radius of the disk were also confirmed to be consistent with the previous results. Taking advantage of the difference in the position of the photosphere among the CO lines, we revealed the temperature distribution in the vertical direction. The temperature of the $^{13}$CO ($J=3$–2) emitting region is about twice higher than that of any other CO emitting region; the former is 58.5 ± 9.5 K, while the latter is 31 ± 15 K at 100 AU from the central star, suggesting that there are at least two distinct temperature regions. The best-fit temperature for $^{13}$CO ($J=1$–0) that should trace the deepest region of the disk is even lower, implying that there is also a different temperature region deep inside of the disk. Such a vertical temperature distribution in a disk was identified both in T Tauri and Herbig Ae stars (e.g., DM Tau, AB Aur, and HD 31648), and this should be a common feature in protoplanetary disks.

Key words: radio lines: stars — stars: individual (HD 163296) — stars:planetary systems: protoplanetary disks — stars: pre-main-sequence

1. Introduction

Herbig Ae (HAe) stars are widely recognized as intermediate mass counterparts of low-mass T Tauri stars (TTSs) (Waters & Waclkens 1998). In the last few decades, it has been revealed that these stars are commonly accompanied by a circumstellar disk, like TTSs, by direct imaging at infrared and radio wavelengths (Fukagawa et al. 2004; Wisniewski et al. 2008; Mannings & Sargent 1997; Mannings et al. 1997; Piétu et al. 2003). These disks are believed to be the precursors of planetary systems around HAe stars, and are important targets to study the formation process of a planetary system around an intermediate-mass star, and to construct a general scenario for the formation of planetary systems. Recent advanced instruments have revealed their physical properties, such as the disk mass, the radial temperature and surface density distributions, the outer radius of the disk, and the velocity field. The number of well-studied disks around HAe stars, however, is still insufficient to establish a firm understanding of their physical conditions and their statistics; only a few of limited examples of their structure have been deeply analyzed (e.g., Panić et al. 2008; Piétu et al. 2007).

The temperature distribution along the vertical direction of the disk should also be taken into account when one examines how the gas and dust inside the disk evolve. Theoretical studies predict that flared circumstellar disks should have two or more layers with distinct temperature in the vertical direction that are formed by diffusion of stellar radiation scattered at the disk surface (Chiang & Goldreich 1997; D’Alessio et al. 1999; Inoue et al. 2009). To examine the vertical structure of the disks based on observations, it requires examples as many as possible, though several studies have already tried to make vertical temperature or density distributions unveiled (Panić et al. 2008; Dartois et al. 2003). HD 163296 is one of the best targets for this purpose, because it exhibits strong emission from the disk in many CO isotopologue lines. HD 163296 is a star with A3V in spectral type (Meeus et al. 2001). Its luminosity, mass, age, and distance are 30 $L_\odot$, 2.3 $M_\odot$, 4 Myr, and 122 pc, respectively (van den Ancker et al. 1998). Observations at infrared and radio wavelengths revealed the existence of a circumstellar disk with a mass of 0.028 $M_\odot$ and 45° in inclination angle (Mannings & Sargent 1997; Isella et al. 2007; Hughes et al. 2008). HD 163296 is categorized as belonging to group II by the feature of spectral energy distribution (SED), and is expected to have a self-shadowed disk (Acke & van den Ancker 2004; Meeus et al. 2001; Dullemond & Dominik 2004). More recently, imaging studies with IRAM/PBI, SMA, and VLA both in continuum and in the
$^{12}$CO, $^{13}$CO, and C$^{18}$O emission lines were made (Isella et al. 2007), arguing that the disk radius is 550 AU, and that the gas kinematics can be well explained by Keplerian rotation.

This paper presents multi-line observations of HD 163296 with the Nobeyama 45-meter (NRO 45 m) radio telescope and the Atacama Submillimeter Telescope Experiment (ASTE) sub-millimeter telescope, and discusses the vertical temperature distribution inside of the disk. The outline is as follows: details of the observations are described in section 2, and the results are shown in section 3. In section 4, the physical properties of the disk are estimated by model fitting in which power-law distributions of temperature and surface density are assumed. Interpretation of the model fitting results as well as the comparisons with previous interferometric observations are discussed in section 5.

2. Observations

2.1. $^{12}$CO ($J = 1–0$) Mapping Observations

Observations of $^{12}$CO ($J = 1–0$) emission line were performed in the winter of 2006 by the NRO 45 m telescope, operated by Nobeyama Radio Observatory (NRO), a branch of National Astronomical Observatory of Japan (NAOJ). To separate the emission originated from the disk associated with the central star from surrounding components, such as an envelope or a remnant cloud, a profile map including the stellar position and its vicinity with sufficient spatial resolution is decisive in identifying the origin of the emission. To obtain such a map, the multi-beam receiver, 25 Beam Array Receiver System (BEARS: Sunada et al. 2000; Yamaguchi et al. 2000), which is capable of simultaneously detecting 25 different locations in double sideband (DSB) operation, was employed as the front-end and tuned at a rest frequency of $^{12}$CO ($J = 1–0$), 115.271 GHz. The half-power beam width (HPBW) is 15" at this frequency, corresponding to 1800 AU at a distance of 122 pc from the Sun. The beam grid spacing of BEARS is 40" ($\approx 5000$ AU) in both RA and Dec directions, but this is much larger than the HPBW, and is therefore insufficient to isolate the star+disk system from the ambient. To fill these gaps among the beams, we also took data at positions shifted by 20" in both RA and Dec directions from the central star. The integration time for the observation was 7 hr. We only show an $80'' \times 80''$ ($\approx 0.05$ pc $\times$ 0.05 pc) region near the star that covers a typical size of the envelope. A digital spectrometer with 32 MHz in bandwidth and 37.8 kHz in frequency resolution was used as the backend. A correction for atmospheric absorption during the observations was made by the chopper-wheel method (Kutner & Ulich 1981), and the intensities were obtained by the antenna temperature, $T_A^*$, in Kelvin. A correction for the main beam efficiency, $\eta_{mb}$, was made when we compared model calculation results (section 4) with the brightness temperature, $T_{mb} = T_A^*/\eta_{mb}$, where $\eta_{mb} = 0.39$ for $^{12}$CO ($J = 1–0$) emission line. The DSB system temperature in $^{12}$CO ($J = 1–0$) mapping observation was between 250 K and 600 K. The accuracy for telescope pointing was regularly checked against the SiO maser VX Sgr, which was about 30' away from HD 163296, and the pointing deviation was achieved in less than $\pm 3''$ during whole observation period. Data reduction and analysis were made with the NEWSTAR software package developed by NRO, which is a front end of AIPS developed at the National Radio Astronomy Observatory (NRAO).

Observations were made in the position-switching mode. It was found that extended CO ($J = 1–0$) emission was present around the region of interest; hence, a careful search is needed to find an off point as close to HD 163296 as possible. The search for off points was conducted with BEARS based on the fact that the systemic velocity of HD 163296 is 6 km s$^{-1}$ (Dent et al. 2005; Isella et al. 2007). An emission-free position applicable as an off point was finally found at about 10' north from HD 163296. Figure 1 is a profile map toward this position, centered at 17$^{h}$56$^m$20$^s$ and $-21^\circ$46$'$23$''$2 (J2000) and covering a $80'' \times 80''$ ($\approx 0.05$ pc $\times$ 0.05 pc) region, showing that there is no prominent emission detected around 6 km s$^{-1}$ in V$_{LSR}$.

2.2. $^{13}$CO ($J = 1–0$) Emission Line Observations

Observations of the $^{13}$CO ($J = 1–0$) emission line were conducted by the NRO 45 m telescope in the winter of 2008. As shown in subsection 3.1, the $^{12}$CO ($J = 1–0$) emission detected around 6 km s$^{-1}$ in V$_{LSR}$ at the central star is isolated. Therefore, $^{13}$CO ($J = 1–0$) observations were made only at the stellar position by a pair of single-beam receivers that enabled us to simultaneously detect both the polarization components in the single sideband (SSB) mode. The receiver was tuned at a $^{13}$CO ($J = 1–0$) rest frequency of 110.201 GHz, and the HPBW was 15" at this frequency. The $\eta_{mb}$, in 2008 at this frequency was 0.4. An Acousto Optical Spectrometer (AOS), whose bandwidth and frequency resolution were 40 MHz and 20 kHz respectively, was used. The system noise temperature during observation was between 300 K and 600 K in the SSB mode. The pointing was regularly checked by the same manner as in $^{12}$CO ($J = 1–0$) observations, described in subsection 2.1. The same off point as that in the $^{12}$CO ($J = 1–0$) observations was used. All observational data when the wind speed exceeded 5 m s$^{-1}$ were flagged out before obtaining the final profile of $^{13}$CO ($J = 1–0$) emission. The resultant total integration time was 8.5 hr on source. Data reduction and analysis were made in the same manner as in the $^{13}$CO ($J = 1–0$) observation described in subsection 2.1.

2.3. $^{12}$CO and $^{13}$CO ($J = 3–2$) Observations with ASTE

Observations of $^{12}$CO and $^{13}$CO ($J = 3–2$) line were carried out in 2006 July with the Atacama Submillimeter Telescope Experiment (ASTE), a 10-m sub-millimeter telescope in Chile (Ezawa et al. 2004). HPBW of the ASTE telescope at 345.79 and 330.59 GHz were $22''$ and $23''$, respectively, which correspond to about 2700–2800 AU at the distance to the target, and the $\eta_{mb}$ was 0.6 around these frequencies. An SIS mixer receiver having DSB response was employed. The typical atmospheric opacity at 220 GHz toward the zenith was 0.05 during the observations, and the system noise temperature of the telescope was 250–300 K in DSB during observations. The digital auto-correlator with 1024 frequency channels was configured so that the total bandwidth was 128 MHz, resulting in a frequency resolution of 125 kHz, or $\sim 0.11$ km s$^{-1}$ at the observed frequencies. Telescope pointing was checked every 1.5–2 hr by cross scanning of Jupiter, and the error was proved
Fig. 1. Profile map of the off positions by the $^{12}$CO ($J = 1–0$) observation. The central position is ($\alpha, \delta$) = ($17^h56^m20^s.0$, $-21^\circ46^m23^s.2$) in J2000, and the angular distance between adjacent points is 40" in both RA and Dec directions.

3. Results

3.1. $^{12}$CO ($J = 1–0$) and $^{13}$CO ($J = 1–0$)

Figure 2 shows a $^{12}$CO ($J = 1–0$) profile map within the 80" × 80" region centered at HD 163296. A clear double-peaked profile with 4.8σ is seen only at the center panel at 6 km s$^{-1}$ in $V_{\text{LSR}}$ that matches with the systemic velocity of HD 163296 (Dent et al. 2005; Isella et al. 2007). The double-peaked profile has a peak intensity of 1.0 K in $T_{\text{mb}}$ and 3.2 ± 0.1 km s$^{-1}$ in FWHM velocity width. The achieved mean rms noise level after data reduction was 0.21 K. Figure 3a displays the same profile on the central panel in figure 2 in an enlarged view.

Several positions in figure 2, especially 40" away to the west from the center, show an emission feature at $V_{\text{LSR}} = 6$ km s$^{-1}$, but there seems no emission above the 3σ level at this velocity at four positions adjacent to the star (20" apart from the star). To confirm whether there is no significant emission at 6 km s$^{-1}$ in these regions, these four profiles were averaged into one spectrum (figure 4a). There is no emission above the 3σ level at 6 km s$^{-1}$ in figure 4a. The profile detected at the stellar position (figure 4b, or the central panel in figure 2) is compared with that after subtracting the profile in figure 4a (figure 4c). Although the noise level in figure 4c increases due to subtraction, there is no remarkable difference between these two profiles. These comparisons strongly suggest that the double-peaked emission component at the star is isolated and originates from the compact circumstellar disk in Keplerian rotation. The components at $V_{\text{LSR}} = 6$ km s$^{-1}$ in south and west regions ≥ 40" apart from the star in figure 2 might be emissions from a remnant cloud partially remaining around the star+disk system.

The dip at 8 km s$^{-1}$ around the star+disk system (figure 2) is due to weak emission seen at the off points, especially in the northern region (figure 1); in position switching mode, the emission at the off point appears like an absorption dip. The dip dose not affect further analysis since it does not corrupt the original emission profile at 6 km s$^{-1}$. In addition, the strong emission components between 10 and 15 km s$^{-1}$ and at 20 km s$^{-1}$ appear regardless of any positions; these two components probably come from foreground or background clouds that exist coincidentally along a line of sight.

Figure 3b shows a profile of the $^{13}$CO ($J = 1–0$) emission line. Again, a double-peaked profile was clearly detected.
Fig. 2. Profile map of the $^{12}$CO ($J = 1–0$) line around HD 163296. The map center corresponds to the stellar position ($\alpha, \delta$) = (17$^{h}$56$^{m}$21$^{s}$29, −21°57′21″9) in J2000, and the angular distance between adjacent points is 20″ in both RA and Dec directions.

The peak intensity and velocity width are 0.36 K in $T_{\text{mb}}$ and 3.8 ± 0.2 km s$^{-1}$ at FWHM, respectively. The achieved rms noise level is 0.061 K. Since the $^{12}$CO ($J = 1–0$) and $^{13}$CO ($J = 1–0$) emissions are detected in the same velocity range, both emissions should have the same origin. The intensity ratio between $^{12}$CO($J = 1–0$) and $^{13}$CO($J = 1–0$) is less than 5, suggesting that the disk is optically thick. Isella et al. (2007) evaluated the optical depth of the CO emission lines, and concluded that the disk is optically thick. Our model fitting shown in subsection 4.2 also proved that the disk is optically thick for both of the CO lines.

3.2 $^{12}$CO ($J = 3–2$) and $^{13}$CO ($J = 3–2$)

Figure 5 shows a $^{12}$CO ($J = 3–2$) profile map within the 44″ × 44″ region centered at HD 163296; the central panel of figure 5 is also shown in figure 3c in an enlarged view. The achieved rms level was 0.122 K. A clear double-peaked profile at $\sim$6 km s$^{-1}$ is seen only in the central panel. The peak intensity and the velocity width are 1.35 K in $T_{\text{mb}}$ and 3.1 ± 0.1 km s$^{-1}$ in FWHM, respectively. The emission components between 10 and 15 km s$^{-1}$ and at $\sim$20 km s$^{-1}$ in $V_{\text{LSR}}$ appear regardless of the positions, as in the case of $^{12}$CO ($J = 1–0$) (figure 2).

Figure 3d presents the $^{13}$CO ($J = 3–2$) spectrum at the stellar position, showing its double-peaked profile. The peak intensity and velocity width are 0.38 K in $T_{\text{mb}}$ and 3.85 km s$^{-1}$ in FWHM, respectively. As in the case of the $J = 1–0$ lines, the disk seems to be optically thick for the $J = 3–2$ line from the intensity ratio between $^{12}$CO ($J = 3–2$) and $^{13}$CO ($J = 3–2$) (see also subsection 4.2).

4. Model Fitting

Model fitting is one of the effective methods used to estimate the physical properties of disks around HAe/Be stars (Dullemond et al. 2001; Dullemond 2002; Testi et al. 2003; Natta et al. 2004). We fitted all of the observational profiles, which are two CO isotopologues’ emission lines with two different rotational transitions, with those calculated by the disk model (details in subsection 4.1). We adopted a classical disk model that includes power-law forms of the temperature and the surface density distributions in the radial direction with inner and outer cutoffs (Kitamura et al. 1993). The results are compared with those obtained by millimeter and
Fig. 3. Profiles detected in $^{12}$CO and $^{13}$CO lines toward the stellar position of HD 163296. (a) in $^{12}$CO ($J = 1–0$), (b) in $^{13}$CO ($J = 1–0$), (c) in $^{12}$CO ($J = 3–2$) and (d) in $^{13}$CO ($J = 3–2$).

Fig. 4. (a) Averaged $^{12}$CO ($J = 1–0$) profile of the four locations 20″ away from the central star in figure 2. (b) $^{12}$CO ($J = 1–0$) profile toward HD 163296 in figure 2. (c) Profile after subtracting (a) from (b).

Sub-millimeter interferometers (Isella et al. 2007, details in subsection 5.1). Although interferometric observations can provide detailed geometrical structure with high spacial resolution, it might be unable to detect emission from the diffuse gas uniformly extending away due to the spatial filtering effect. Single-dish telescopes with a large diameter, on the other hand, have higher sensitivity to the weak extended emission, which interferometers can not detect well. Interferometric and single dish observations are, therefore, complementary to each other, and comparing their results is a fruitful way to gain a better understanding of the disk nature.

4.1. Disk Model

Several assumptions for the disk structure and parameters are applied in the model fitting. First, the disk is assumed to have Keplerian rotation, as was proven to be the cases in other HAe stars, such as HD 169142 and HD 31648 (Panić et al. 2008; Mannings et al. 1997). Isella et al. (2007) pointed out the existence of a Keplerian rotating disk around HD 163296 from “a butterfly shape” seen in its position velocity diagram. Secondly, the temperature distribution over the disk, $T(r)$, is assumed to follow a power-law form of the radius with an index of $-0.5$, as described by the following equation:

$$T(r) = T_0 \left( \frac{r}{100\,\text{AU}} \right)^{-0.5},$$

where $r$ is the radius in cylindrical coordinate system centered on the star and $T_0$ is the temperature at $r = 100\,\text{AU}$ (Hayashi et al. 1985; Beckwith et al. 1990). This assumption implies
that the temperature is constant along the vertical direction (z) at a certain r. In reality, a circumstellar disk should have a temperature distribution along the z-direction. An elaborate disk model (e.g., Chiang & Goldreich 1997; Tanaka et al. 2005) predicts that the surface regions where the stellar radiation can penetrate and heat directly will have higher temperature than that in the interior regions, forming 2-layer temperature structure. A single-layer temperature model, however, can still be applicable because an optically thick line should have a “photosphere” at each r, and its characteristic temperature can be uniquely determined. That is, the vertical temperature distribution can be traced by a series of different temperatures of each CO emission line.

Thirdly, the radial distribution of the surface density over the disk, $\Sigma(r)$, is also assumed to follow a power-law form of the radius with its index of $-1.0$ (Isella et al. 2007), as described by

$$\Sigma(r) = \Sigma_0 \left( \frac{r}{100 \text{AU}} \right)^{-1.0},$$

where $\Sigma_0$ is the surface density at $r = 100$ AU. Fourthly, we assumed that the density distribution in the vertical direction can be achieved by hydrostatic equilibrium. The density distribution, $\rho(r, z)$, is therefore expressed by

$$\rho(r, z) = \rho(r, 0) \exp \left\{ - \frac{z}{H(r)} \right\},$$

where $\rho(r, 0)$ is the density at the mid-plane of the disk, and $H(r)$ is the scale height, given by

$$H(r) = \sqrt{\frac{2r^2 k_B T(r)}{GM_*$m}}.$$

where $k_B$ is the Boltzmann constant, $G$ is the gravitational constant, $M_*$ is the mass of the central star, and $m$ is the mean mass of gas molecules. Thus, $\rho(r, 0)$ in equation (3) becomes

$$\rho(r, 0) = \frac{\Sigma(r)}{\sqrt{\pi} H(r)}.$$  

Fifthly, local thermodynamic equilibrium (LTE) is assumed. The number density of H$_2$ at the position of the photosphere of each CO line can be estimated by equation (3). As shown in subsection 4.2, the number density of H$_2$ at the $^{12}$CO ($J = 3–2$) photosphere is calculated to be $\sim 10^7$ cm$^{-3}$ at $r = 100$ AU, and is higher than the typical value of the critical density for $^{12}$CO ($J = 3–2$) ($\sim 5 \times 10^4$ cm$^{-3}$ at 60 K, fitting temperature of this line discussed in subsection 4.2) by more than two orders of magnitude. The LTE assumption is sometimes inadequate for the analysis of protoplanetary disks, since it tends to overestimate the excitation temperature for a higher transition with a high critical density. However, Pavlyuchenkov et al. (2007) evaluated many types of model calculations, and found that the LTE approximation seems to be valid for the cases of $J = 4–3$ or a lower transition of CO. The LTE assumption is, therefore, applicable in our model calculation for the $J = 1–0$ and $J = 3–2$ transitions of $^{12}$CO and $^{13}$CO.

Finally, the abundance ratios of H$_2$ to $^{12}$CO and $^{12}$CO to $^{13}$CO are assumed to be $10^4$ and $60$, respectively, which are the typical values in the interstellar medium (Frerking et al. 1982; Wannier et al. 1982). The disk is assumed to be heated only by a stellar radiation and accretion heating is neglected. This is a reasonable approximation for a disk with a modest accretion rate, such as the HD 163296 case ($7.6 \times 10^{-8} M_\odot$ yr$^{-1}$: Garcia Lopez et al. 2006).
The best-fit temperatures and the outer radius at 0.1, 0.3, 1, and 3 g cm$^{-2}$ in $\Sigma_0$ where the fitting solution for all the CO lines simultaneously exist are provided in table 2, and the fitting results are shown in figure 6. Note that the observed profiles shown in figure 6 were re-sampled with a velocity resolution of 0.08 km s$^{-1}$ for $^{12}$CO ($J=1–0$) line and 0.11 km s$^{-1}$ for the others to directly compare with the model calculations. As shown in table 2, the fitting temperature of $^{12}$CO ($J=3–2$) shows the highest value among all of the CO lines. Figure 7 shows the fitting temperature at several specific $\Sigma_0$ between 0.003 and 3 g cm$^{-2}$. It is essential to ascertain the goodness of the solution obtained in the model fitting. We regarded the results as an acceptable fit when the following two conditions were met simultaneously: (i) to exclude the case of a large deviation in amplitude of the profiles, the residual in absolute deviation of the solution obtained in the model fitting. We regarded the results as an acceptable fit when the following two conditions were met simultaneously: (i) to exclude the case of a large deviation in amplitude of the profiles, the residual in absolute deviation of the profiles over the range of $T_{\text{mb}} \geq 2\sigma$ should be less than the uncertainty (1 $\sigma$) for the integrated intensity, (ii) to exclude the case of a large deviation in the line shape, more than 80% of the channels over $T_{\text{mb}} \geq 3\sigma$, should agree with the model calculations within 2 $\sigma$.

4.2. Fitting Results

The best-fit $T_0$ values for the $^{12}$CO ($J=3–2$) line given in table 2 are between 58.5 $\pm$ 9.5 K, and this range is significantly higher than those estimated for the other CO lines, 31 $\pm$ 15 K when $\Sigma_0$ is greater than 0.1 g cm$^{-2}$. This difference in the best-fit $T_0$ implies that the disk is composed of at least two layers with distinct temperatures. The uncertainty of the fitting temperature is smaller for a higher surface density, or large optical depth in the disk. For a lower surface density, the fitting temperature range becomes drastically larger, or no solution exists; the $^{13}$CO ($J=1–0$) emission line, for instance, does not have any fitting temperature at $\Sigma_0$ less than 0.1 g cm$^{-2}$. The fitting errors in temperature at 0.1 g cm$^{-2}$ in $\Sigma_0$ are more than 30% for $^{13}$CO ($J=1–0$) line and more than 20% for $^{13}$CO ($J=3–2$) line, respectively. Those at greater than 0.3 g cm$^{-2}$ in $\Sigma_0$, on the other hand, are less than 20% for all of the CO lines, and the fitting temperatures are gradually

All parameters regarding the object, listed in table 1, should be taken into account in the model calculation for the best accuracy, but some of them rarely affect the disk property. Emission profiles are mostly characterized by three parameters, $T_0$, $\Sigma_0$, and the outer radius of the disk ($r_{\text{out}}$), and these are regarded as being variables. The other parameters are fixed to be constants, as listed in table 1.

In actual calculations, $\Sigma_0$ was fixed in each run, and the possible fitting range of $T_0$ was searched. $\Sigma_0$ was set to be between 0.003 and 3 g cm$^{-2}$. The search for $T_0$ in upper range of $\Sigma_0$ was stopped at 3 g cm$^{-2}$, because $T_0$ in each CO line is well confined due to an asymptotic behavior of the fitting temperature in a large $\Sigma_0$ region, and the result remains almost the same. The intensity is affected by both $T_0$ and $\Sigma_0$, and the outer radius of the disk ($r_{\text{out}}$), and these are regarded as being variables. The other parameters are fixed to be constants, as listed in table 1.

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The possible range of the fitting values obtained by Isella et al. (2007) for the central star were estimated to be $26^{+100}_{-100}$ AU and the minimum surface density at 10 AU from the central star was consistent with the one derived by interferometric observations.}

5. Discussion

5.1. Comparison with Observation by Interferometers

High-resolution images of HD 163296 were taken with interferometers at multi-wavelengths (the IRAM/PBI, SMA, and VLA) both in continuum and in the emission lines of $^{12}\text{CO}$, $^{13}\text{CO}$, and $^{18}\text{O}$ (Isella et al. 2007). They compared the observational results of the CO emissions with those predicted by the self-consistent disk model to estimate the physical disk properties. Although the assumptions in the model calculations were slightly different from each other, the temperature and the minimum surface density of the disk derived in subsection 4.2 showed a reasonable agreement with the values obtained by Isella et al. (2007): the temperature at 100 AU and the minimum surface density at 10 AU from the central star were estimated to be $26^{+100}_{-100}$ K and $1 \pm 0.1$ g cm$^{-2}$ from our $^{13}\text{CO}$ ($J=1-0$) observations, and they were within the possible range of the fitting values obtained by Isella et al. (2007): $30 \pm 10$ K and $4^{+7}_{-10}$ g cm$^{-2}$, respectively. The radius derived from single-dish observations, which generally have higher sensitivity to weaker emission, was $550 \pm 100$ AU, and was consistent with the one derived by interferometric observations.

5.2. Thermal Structure of the Disk

As described in subsection 4.2, the disk is arguably optically thick in CO emissions. Taking advantage of different mass opacity of isotopologues whose emission lines reflect the temperature at each photosphere having different mass opacity, different temperatures can be explained by the temperature distribution along the vertical direction, as predicted by theoretical studies (e.g., Chiang & Goldreich 1997).

To examine the vertical temperature distribution in detail, we derived the column densities of H$_2$ that satisfy the optical depth for each CO emission line to be unity ($N_{r_{\text{out}}=1}$) from

$$N_{r_{\text{out}}=1} = \frac{3k_B T_{\text{ex}} \Delta V_{\text{gas}}}{8\pi^2 B \mu^2 \cos \theta} \frac{1}{(J+1)} \exp \left[ \frac{hBJ(J+1)}{k_B T_{\text{ex}}} \right] \left[ 1 - \exp \left( \frac{h\nu_0}{k_B T_{\text{ex}}} \right) \right]^{-1},$$

where

$$k_B = 8 \times 10^{-27} \text{erg} \text{K}^{-1},$$

$$B = 4 \times 10^{-6} \text{cm}^{-1/2} \text{g}^{-1} \text{cm}^3 \text{K}^{-1},$$

and

$$\Delta V_{\text{gas}} = 3 \times 10^{17} \text{cm}^3 \text{s}^{-1}.$$

\[1\]

Table 2. Best-fit parameters at $r_{\text{out}} = 550$ AU.

| $\Sigma_0$ [g cm$^{-2}$] | $^{12}\text{CO}$ ($J=3-2$) | $^{13}\text{CO}$ ($J=3-2$) | $^{12}\text{CO}$ ($J=1-0$) | $^{13}\text{CO}$ ($J=1-0$) |
|--------------------------|-----------------|-----------------|-----------------|-----------------|
| 0.1                      | $63^{+5}_{-5}$  | $38^{+8}_{-8}$  | $35^{+3}_{-4}$  | $26^{+8}_{-6}$  |
| 0.3                      | $59^{+4}_{-4}$  | $33^{+2}_{-2}$  | $32^{+4}_{-4}$  | $21^{+4}_{-6}$  |
| 1                        | $55^{+5}_{-5}$  | $30^{+5}_{-5}$  | $30^{+3}_{-3}$  | $19^{+3}_{-3}$  |
| 3                        | $53^{+5}_{-4}$  | $28^{+5}_{-5}$  | $29^{+3}_{-3}$  | $18^{+3}_{-2}$  |
Fig. 8. (upper panels) Column densities in \( N(H_2) \) that are required to become \( r_{\text{th}} = 1 \) for each CO emission line. The radial temperature dependence is set to be \( T(r) = 30(r/100\ AU)^{-0.5} \) [K] (left) and \( T(r) = 60(r/100\ AU)^{-0.5} \) [K] (right), respectively. Note that the vertical axes are reversed. (lower panels) The vertical distance from the mid-plane of the disk normalized by the scale height of the local temperature in the case of \( \Sigma_0 = 0.1 \) g cm\(^{-2}\). These vertical locations of each CO line correspond to the location corresponding to \( N_{r_{\text{th}}}=1 \) shown in the upper panel.

where \( B \) is the rotational constant of a molecule, \( \mu \) is the permanent dipole moment, \( T_{\text{ex}} \) is the excitation temperature, \( \Delta V_{\text{gas}} \) is the velocity width of a gas molecule, \( \theta \) is the inclination angle, \( h \) is the Planck constant, \( J \) is the rotational quantum number, and \( \nu_0 \) is the frequency of the transition (Scoville et al. 1986). Note that \( N_{r_{\text{th}}}=1 \) is the value obtained by integrating the number density from the disk surface to the disk interior along a line of sight.

In this paper, we adopted \( \Delta V_{\text{gas}} = \Delta V_{\text{th}} \) for simplicity, where \( \Delta V_{\text{th}} \) is the thermal-velocity width of gas molecules, expressed by

\[
\Delta V_{\text{gas}} \equiv \Delta V_{\text{th}} = \sqrt{\frac{8\ln 2k_B T(r)}{m_{\text{CO}}}}. \tag{7}
\]

Turbulent velocity (\( V_{\text{turb}} \)) can also contribute to \( \Delta V_{\text{gas}} \). Hughes et al. (2011) derived a turbulent line width of \( \sim 0.3 \) km s\(^{-1}\) for the disk around HD 163296 by fitting profile with high spectral resolution. Previous observations also revealed that \( V_{\text{turb}} \) in a disk around TTS or HAe star is comparable to \( \Delta V_{\text{th}} \): 0.07–0.15 km s\(^{-1}\) in DM Tau (Dartois et al. 2003; Simon et al. 2001) and 0.38 km s\(^{-1}\) in AB Aur (Piétu et al. 2005). In such cases, however, the line profile calculated by the model is not altered significantly by \( \Delta V_{\text{turb}} \) because the line shape is mainly determined by the Keplerian rotation velocity. This assumption probably produces a factor of uncertainty for the estimation of \( N_{r_{\text{th}}}=1 \), but does not significantly affect the following discussion.

\( N_{r_{\text{th}}}=1 \) for each CO emission line provides the information about the vertical location of the photosphere of each CO emission line. Figure 8 shows \( N_{r_{\text{th}}}=1 \) and vertical locations of photospheres of each CO emission line. The results are provided in the case of \( T_0 = 30 \) K and 60 K, which are the representative values of the low-temperature interior and the high-temperature surface, respectively, as described in subsection 4.2. To derive the location of each photosphere, on the other hand, we select \( \Sigma_0 = 0.1 \) g cm\(^{-2}\) as the representative case, since this value is consistent with the results by Isella et al. (2007). In both cases shown by figure 8, \( N_{r_{\text{th}}}=1 \) results in the descending order of \(^{12}\)CO \((J=3–2)\), \(^{12}\)CO \((J=1–0)\),
$^{13}$CO ($J = 3-2$) and $^{13}$CO ($J = 1-0$), implying that the photosphere of $^{12}$CO ($J = 3-2$) emission is located uppermost among the four CO lines. The total geometric cross section of grains per hydrogen atom ($\sigma_o$) in interstellar medium is $\sim 10^{-21}$ cm$^2$ at visible wavelength (Stahler & Palla 2004), hence the column density that makes the optical depth for the stellar radiation unity is $10^{21}$ cm$^{-2}$. The grazing angle is assumed to be 0.05 in the Inoue, Oka, and Nakamoto (2009) calculation; hence, the column density of the upper layer should be about $5 \times 10^{19}$ cm$^{-2}$. This column density is consistent with the one above the photosphere of $^{12}$CO ($J = 3-2$) at $r \gtrsim 100$ AU, as shown in figure 8. $N_{t_{\tau_0}=1}$ of $^{12}$CO ($J = 1-0$) decreases faster than that of $^{13}$CO ($J = 3-2$) at $r > 300$ AU in the case of $T_0 = 30$ K because CO molecules is not sufficiently excited to the $J = 3$ level due to lower temperatures. The same phenomenon is seen in $^{13}$CO as well. From comparisons between the fitting temperature and the vertical locations of the photosphere of each CO line, the general trend is that the farther away the layer is from the mid-plane of the disk, the warmer it reaches. This is quite reasonable because the gas around the disk surface should be heated more by the radiation from the central star.

When we derived $N_{t_{\tau_0}=1}$ shown in figure 8, we assumed that the disk temperature is uniform in the vertical direction. These considerations, however, might be invalid as a consequence of the vertical temperature distribution; the $^{12}$CO ($J = 3-2$) emission line originates from an upper layer of the disk, but this could also contribute significantly to the other CO lines. We therefore evaluated how strongly such an upper layer affects the other CO emissions. Figure 9 shows how strongly the $^{12}$CO ($J = 1-0$) is emitted from above the photosphere of $^{12}$CO ($J = 3-2$). In this figure, we first calculate the optical depth of the $^{12}$CO ($J = 1-0$) emission line in the region above the photosphere of $^{12}$CO ($J = 3-2$), and then evaluate the intensity of $^{12}$CO ($J = 1-0$), which was compared with that originated from the region at the fitting temperature. The contribution of the high-temperature layer is less than 10% of the $^{12}$CO ($J = 1-0$) intensity, and can be safely neglected. Therefore, the estimated vertical location of each CO emission layer in figure 8 is validated.

As shown in figure 7, the temperatures of the $^{12}$CO ($J = 1-0$) and $^{13}$CO ($J = 3-2$) layers are almost the same when $\Sigma_0 > 0.1$ g cm$^{-2}$. The temperature of the $^{13}$CO ($J = 1-0$) layer seems to be even lower. Such a vertical thermal structure of irradiated accretion disks around TTS has been theoretically predicted. D’Alessio et al. (1999) constructed detailed vertical structure models of irradiated accretion disks, and extensively explored the dependence of the structure and the emission properties on the mass accretion rate, viscosity parameter, and disk radius. Inoue, Oka, and Nakamoto (2009) also proposed a 3-layer disk model. The middle layer can form where the optical depth for the radiation reprocessed by the upper layer is less than unity. Our results suggest the existence of such a three-layer structure.

6. Summary

This paper presents observational results of the disk around HD 163296 in the $^{12}$CO ($J = 1-0$), $^{12}$CO ($J = 3-2$), $^{13}$CO ($J = 1-0$), and $^{13}$CO ($J = 3-2$) emission lines. Double-peaked profiles originating from a rotating circumstellar disk were successfully detected in all of the CO lines. The physical parameters of the disk, such as the temperature distribution, surface density distribution and outer radius, were estimated by model fitting utilizing a disk model. These physical values obtained by single dish observation were confirmed to be consistent with the results of interferometric observations (Isella et al. 2007).

The disk must be optically thick for all of the CO lines. Taking advantage of the difference in the position of the photosphere among the CO lines, we revealed the temperature distribution in the vertical direction. It has been proven that there are at least two distinct temperature layers, possibly three layers, from model fittings. The temperature in the uppermost $^{12}$CO ($J = 3-2$) emitting layer is estimated to be 58.5 $\pm$ 9.5 K at 100 AU from the central star, and it is about twice higher than that in the inner regions emitting the other CO lines, 31 $\pm$ 15 K at 100 AU. Since the vertical temperature distribution inside of a disk is commonly suggested for both TTS and HAe stars (DM Tau, AB Aur, and HD 31648), such a temperature distribution may be ubiquitous in protoplanetary disks (Piétu et al. 2007). The temperature and density structure of protoplanetary disks are still open questions. Better knowledge, such as the radial and vertical density distribution, will be provided by high-resolution observations in the upcoming ALMA era.
References

Acke, B., & van den Ancker, M. E. 2004, A&A, 426, 151
Beckwith, S. V. W., Sargent, A. I., Chini, R. S., & Güsten, R. 1990, AJ, 99, 924
Chiang, E. I., & Goldreich, P. 1997, ApJ, 490, 368
D’Alessio, P., Calvet, N., Hartmann, L., Lizzo, S., & Cantó, J. 1999, ApJ, 527, 893
Dartois, E., Dutrey, A., & Guilloteau, S. 2003, A&A, 399, 773
Dent, W. R. F., Greaves, J. S., & Coulson, I. M. 2005, MNRAS, 359, 663
Dullemond, C. P. 2002, A&A, 395, 853
Dullemond, C. P., & Dominik, C. 2004, A&A, 417, 159
Dullemond, C. P., Dominik, C., & Natta, A. 2001, ApJ, 560, 957
Ezawa, H., Kawabe, R., Kohno, K., & Yamamoto, S. 2004, Proc. SPIE, 5489, 763
Frerking, M. A., Langer, W. D., & Wilson, R. W. 1982, ApJ, 262, 590
Fukagawa, M., et al. 2004, ApJ, 605, 53
García Lopez, R., Natta, A., Testi, L., & Habart, E. 2006, A&A, 459, 837
Grady, C. A., et al. 2000, A&A, 544, 895
Hayashi, C., Nakazawa, K., & Nakagawa, Y. 1985, in Protostars & planets II, ed. D. C. Black & M. S. Matthews (Tucson: University of Arizona Press), 1100
Hughes, A. M., Wilner, D. J., Andrews, S. M., Qi, C., & Hogerheijde, M. R. 2011, ApJ, 727, 85
Hughes, A. M., Wilner, D. J., Qi, C., & Hogerheijde, M. R. 2008, ApJ, 678, 1119
Inoue, A., Oka, A., & Nakamoto, T. 2009, MNRAS, 393, 1377
Isella, A., Testi, L., Natta, A., Neri, R., Wilner, D., & Qi, C. 2007, A&A, 469, 213
Kitamura, Y., Omukai, T., Kawabe, R., Yamashita, T., & Handa, T. 1993, PASJ, 45, L27
Kutner, M. L., & Ulrich, B. L. 1981, ApJ, 250, 341
Mannings, V., Koerner, D. W., & Sargent, A. I. 1997, Nature, 388, 555
Mannings, V., & Sargent, A. I. 1997, ApJ, 490, 792
Meeus, G., Waters, L. B. F. M., Bouwman, J., van den Ancker, M. E., Waelkens, C., & Malfait, K. 2001, A&A, 365, 476
Natta, A., Testi, L., Neri, R., Shepherd, D. S., & Wilner, D. J. 2004, A&A, 416, 179
Pavlyuchenkov, Ya., Semenov, D., Henning, Th., Guilloteau, S., Piétu, V., Launhardt, R., & Dutrey, A. 2007, ApJ, 669, 1262
Panić, O., & Hogerheijde, M. R., Wilner, D., & Qi, C. 2008, A&A, 491, 219
Piétu, V., Dutrey, A., & Guilloteau, S. 2007, A&A, 467, 163
Piétu, V., Dutrey, A., & Kahane, C. 2003, A&A, 398, 565
Piétu, V., Guilloteau, S., & Dutrey, A. 2005, A&A, 443, 945
Scoville, N. Z., Sargent, A. I., Sanders, D. B., Claussen, M. J., Masson, C. R., Lo, K. Y., & Phillips, T. G. 1986, ApJ, 303, 416
Simon, M., Dutrey, A., & Guilloteau, S. 2001, ApJ, 545, 1034
Stahler, S. W., & Palla, F. 2004, The formation of stars (New York: Wiley-VCH)
Sunada, K., Yamaguchi, C., Kuno, N., Okumura, S., Nakai, N., & Ukita, N. 2000, ASP Conf. Ser., 217, 19
Tanaka, H., Himeno, Y., & Ida, S. 2005, ApJ, 625, 414
Testi, L., Natta, A., Shepherd, D. S., & Wilner, D. J. 2003, A&A, 403, 323
van den Ancker, M. E., de Winter, D., & Tjin A Djie, H. R. E. 1998, A&A, 330, 145
Wannier, P. G., Penzias, A. A., & Jenkins, E. B. 1982, ApJ, 254, 100
Waters, L. B. F. M., & Waelkens, C. 1998, ARA&A, 36, 233
Wisniewski, M., Clampin, M., Grady, C. A., Ardila, D. R., Ford, H. C., Golimowski, D. A., Illingworth, G. D., & Krist, J. E. 2008, ApJ, 682, 548
Yamaguchi, C., Sunada, K., Iizuka, Y., Ishii, H., & Noguchi, T. 2000, Proc. SPIE, 4015, 614