Interferometric Observations of Formaldehyde in the Protoplanetary Disk around LkCa 15

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Abstract

Emission from the 2_{12}−1_{11} line of H₂CO has been detected and marginally resolved toward LkCa 15 by the Nobeyama Millimeter Array. The column density of H₂CO is higher than that observed in DM Tau and than predicted by theoretical models of disk chemistry; also, the line-intensity profile is less centrally peaked than that for CO. A similar behavior is observed in other organic gaseous molecules in the LkCa 15 disk.

Key words: ISM: molecules — stars: individual (LkCa 15) — stars: pre-main-sequence — circumstellar matter

1. Introduction

It is now well-established that more than 50% of young T Tauri stars are surrounded by a disk of circumstellar material. These disks are important because they are the birth sites of planetary systems. The spectral energy distributions indicate that disk masses are in the range of ∼10⁻³ – 10⁻¹ M☉, which is consistent with the solar nebula model proposed for the origin of our own solar system (e.g., Beckwith, Sargent 1996). Interferometer observations in the dust continuum and CO line emission have spatially resolved some of these disks (e.g., Saio et al. 1995; Dutrey et al. 1996; Hogerheijde et al. 1997; Guilloteau, Dutrey 1998; Mundy et al. 2000; Duvert et al. 2000), which are found to have radii of ∼100 – 800 AU. However, our quantitative understanding of the physical properties of such disks, e.g. their radial and vertical temperature and density structures, or their gas survival timescales, is still poor. Another important question is the chemical evolution of gas and dust as it is transported from the interstellar medium to the interiors of circumstellar disks, and the impact of this chemistry on the nature of icy planetesimals, such as comets and Kuiper Belt objects (van Dishoeck, Blake 1998; Ehrenfreund et al. 1997).

We are involved in a project to systematically investigate the physical and chemical properties of circumstellar disks. Single-dish spectra of simple molecules such as CO, HCO⁺, CN, HCN, CS, and H₂CO have been obtained at the IRAM 30 m telescope, JCMT and CSO (van Zadelhoff et al. 2001; Thi 2002, Thi et al. in preparation). The ratios of high-J and low-J lines indicate that the detected gaseous molecules reside in a low-temperature (e.g. ∼30 K) region, which corresponds to disk radii beyond ∼100 AU, assuming the temperature distribution in typical disk models. In addition to single-dish observations, interferometer observations of low-J transition lines of several molecular species have been performed by Duvert et al. (2000) and Qi (2001). Although interferometer observations of molecular lines in disks are still rare because of the faintness of the objects, they provide an important probe of the physical and chemical gradients in the disks; the line intensities depend on the density, temperature, and molecular abundance, which can be affected by various chemical processes in each region of the disk.

In this paper we report on observations of the H₂CO 2_{12}−1_{11} line at 140.84 GHz toward LkCa 15 using the Nobeyama Millimeter Array (NMA). LkCa 15 is a relatively old (∼1 × 10⁷ yr) solar-mass T Tauri star located in the outer regions of the Taurus molecular cloud at ∼140 pc. Its disk mass is estimated to be ∼0.02 – 0.06 M☉ from dust continuum observations (i.e. Thi 2002; Kitamura et al. 2002). The formaldehyde molecule is of special interest, because its line ratios are sensitive to the temperature and density (e.g. Mangum, Wootten 1993). Single-dish observations of various H₂CO lines have been obtained by Thi (2002) using the IRAM 30 m telescope and JCMT. It is also one of the most complicated molecules detected so far in disks, serves as a probe of grain-surface chemistry, and can rapidly polymerize to create complex organic solids under appropriate conditions (Schutte et al. 1993). Observations of the transitions in the 1.3 mm atmospheric window using OVRO and a comparison with
the data presented here will be reported in a forthcoming paper.

2. Observations

We observed the $2_{12} - 1_{11}$ line of H$_2$CO toward LkCa 15 with the NMA in 2000 – 2001. The results presented here are based primarily on 16 hr of array measurements using six antennas in the NMA low-resolution (D) configuration, under clear-sky conditions. Similar quality data were obtained over a 6-hr period in the high-resolution (AB) configuration, but no line emission was detected. The beam sizes of the D and AB configurations are about 4.′′5 and 1.′′2, respectively.

A dust continuum emission at $\lambda = 2$ mm was detected with a good signal-to-noise ratio with the NMA SIS double sideband (DSB) receivers. The zenith DSB system temperatures during the observations were typically 200 K. For back ends, the Ultra Wide Band Correlator (UWBC, Okumura et al. 2000) and a high-dispersion FX correlator were operated simultaneously. Phase-switching techniques were used to separate the continuum visibility data for the lower $128.840 \pm 0.512$ GHz and upper $140.840 \pm 0.512$ GHz sidebands from the UWBC. Spectral line visibility data collected by the FX correlator were obtained by subtracting the continuum level, which was estimated by averaging the line-free channels.

The response across the observed passband for each sideband was determined from 40-min observations of 3C 454.3. The gain calibrator 0446+112, used to determine the flux density scale, was observed every 20 min. The 2 mm flux density of 0446+112 was estimated to be 1.57 mJy, leading to an integrated line intensity of 820 mJy km s$^{-1}$. This is similar to the value obtained from single-dish data at the IRAM 30 m telescope by Thi (2002), which is about 664 mJy km s$^{-1}$, as is the estimated line width of $\sim 4$ km s$^{-1}$. The interferometer observations therefore trace the same gaseous component detected by the IRAM 30 m telescope.

3. Results

3.1. Detection of H$_2$CO in the Disk of LkCa 15

The continuum emission from the LkCa 15 disk was clearly detected; an image using only the low-resolution configuration upper sideband data is shown in figure 1. The total dust flux at 141 GHz is 25 mJy and is unresolved, leading to an upper limit to the dust disk radius of $\sim 550$ AU.

The line spectrum for a 10″ box centered on the stellar position is shown in figure 2. Emission was detected in the range $\pm 2.5$ km s$^{-1}$ around the stellar velocity $v_0 = v_LSR = 6$ km s$^{-1}$. Since the signal-to-noise ratio is not high enough to draw a image with the velocity bin of $\sim 0.7$ km s$^{-1}$ adopted in figure 2, we integrated the data from $v - v_0 = -2$ to $+2.6$ km s$^{-1}$ to obtain figure 3. The contour interval is 21 mJy beam$^{-1}$, which corresponds to the 1 σ r.m.s. noise level. The position of the H$_2$CO emission coincides with that of the dust continuum. It should also be noted that previous CO observations show no foreground or background molecular gas towards the object (Duvert et al. 2000). We therefore conclude that the H$_2$CO emission arises from the disk around LkCa 15.

The line spectrum is consistent with the double-peaked shape characteristic of Keplerian disk velocity fields, although we could not detect any gradients in the channel maps with higher kinematic resolution (e.g. 1 km s$^{-1}$) because of the low signal-to-noise ratio.

The H$_2$CO disk is marginally resolved; it is more extended than the continuum image, which is typical for molecular line images because of the increased opacity as compared to that of the dust (Dutrey et al. 1996). The H$_2$CO disk elongation from north-west to south-east is caused by the disk inclination from the line of sight. Interferometer maps of CN line emission show similar elongation along the same direction, and CO observations reveal a velocity gradient that runs along this major axis (Duvert et al. 2000; Qi 2001). The radius of the H$_2$CO disk, measured at the 2-σ level, is about 650 AU, which is similar to the CO disk radius deduced from Plateau de Bure interferometer observations (Duvert et al. 2000).

The total flux density of the H$_2$CO line averaged over the 4.6 km s$^{-1}$ interval at the stellar velocity is about 180 mJy, leading to an integrated line intensity of 820 mJy km s$^{-1}$. This is similar to the value obtained from single-dish data at the IRAM 30 m telescope by Thi (2002), which is about 664 mJy km s$^{-1}$, as is the estimated line width of $\sim 4$ km s$^{-1}$. The interferometer observations therefore trace the same gaseous component detected by the IRAM 30 m telescope.

3.2. Molecular Column Density

The peak flux of the H$_2$CO line is about 95 mJy beam$^{-1}$, which corresponds to an antenna temperature ($T_A^* \equiv T_A^{\star}$) of 0.28 K for a 4″.48 × 4″.13 synthesized beam. The averaged antenna temperature of the line within the 2 σ contour is about 0.16 K. Considering typical disk models, because the gas density is higher than the critical density of the line, $\sim 10^5$ cm$^{-3}$, the line is almost in local thermodynamic equilibrium (LTE). Since the disk image is marginally resolved, it is not likely that the beam-filling factor is much smaller than unity. If the line is optically thick, with the above two conditions, the antenna temperature should be close to the kinetic temperature of the molecular gas. The observed antenna temperature, however, is much lower than the kinetic temperature of molecular gases in typical disk models, $\geq 20$ K. Hence, the molecular line is likely to be optically thin. In this subsection we derive the molecular column density in the disk using LTE models.

The averaged antenna temperature, 0.16 K, leads to an averaged upper level column density of $\sim 5.4 \times 10^{11}$ cm$^{-2}$ from the formula $N_{up} = 8\pi k \nu^2 T_A \Delta v / (hc^3 A_{ul})$, in which $A_{ul} = 5.3 \times 10^{-5}$ s$^{-1}$ is the Einstein A coefficient (e.g. Goldsmith, Langer 1999). The total column density of ortho H$_2$CO can be calculated from $N_{tot} = N_{up} Q / (g_{up}\exp(-E/kT))$, where $Q$ is the rotational partition function, $g_{up} = 15$ is the degeneracy of the upper state, and $E = 21.9$ K is the upper state energy. Theoretical models of disk chemistry predict gaseous
organic molecules exist predominantly in regions where \( T \gtrsim 20 \) K (section 4), while recent disk radiative transfer models predict that the surface region of the disk can be heated to temperatures of \( \sim 50 \) K by the central star (Chiang, Goldreich 1997; D’Alessio et al. 1998). For \( T_{\text{ROT}} \) values of 20 or 50 K, the column density of ortho \( \text{H}_2\text{CO} \) is \( 5.4 \times 10^{12} \text{ cm}^{-2} \) or \( 1.1 \times 10^{13} \text{ cm}^{-2} \), respectively, in LTE. The unknown ortho–para ratio is another uncertainty in estimating the total column density of \( \text{H}_2\text{CO} \). In interstellar clouds the formaldehyde ortho-para ratio ranges from 1.5 – 3.0 (e.g. Mangum, Wootten 1993). Hence, the total \( \text{H}_2\text{CO} \) column density averaged within the 2 \( \sigma \) contour, which corresponds to a region of about 970 AU \( \times \) 1250 AU, is estimated to be \( 7.2 \times 10^{12} \text{ – } 1.9 \times 10^{13} \text{ cm}^{-2} \).

4. Discussion

DM Tau is another T Tauri star/disk system toward which \( \text{H}_2\text{CO} \) has been detected (Dutrey et al. 1997). The estimated molecular column density is \( \sim 1 \times 10^{12} \text{ cm}^{-2} \), which is much smaller than that in LkCa 15. Observations of other molecular lines also show that the column densities of gaseous organic molecules are higher in LkCa 15 than in DM Tau by a factor of \( \sim 10 \) (Qi 2001).

The molecular abundances in the outer regions (\( R \gtrsim 100 \) AU) of disks have been theoretically investigated by several groups (Aikawa, Herbst 1999, 2001; Willacy, Langer 2000; Aikawa et al. 2002; van Zadelhoff et al. 2003). In all such models, the chemistry is intimately tied to the physical state of the gas and the properties of the disk. For example, the upper panel of figure 4 shows the vertical and radial distribution of \( \text{H}_2\text{CO} \) in the model by van Zadelhoff et al. (2003). They adopted the disk model of D’Alessio et al. (1999), and solved the ultra-violet (UV) radiation transfer and chemical reaction network, which includes gas-phase chemistry, freeze-out and evaporation, but no active surface chemistry. Near the disk surface, molecules are dissociated by UV radiation from the interstellar field and central star. In the disk midplane organic molecules are heavily depleted onto grains, since the densities are very high and the temperature is lower than 20 K, the sublimation temperature of the dominant carbon reservoir, CO. Thus, in the outer reaches of circumstellar disks, gaseous molecules exist in high abundance only in an intermediate height layer that is heated by the infrared radiation from the surface layer yet shielded from the harsh UV radiation field. Specifically, formaldehyde is found to have a maximum gas-phase abundance in gas at \( A_V \sim 0.4 – 10 \) mag from the disk surface.
Model comparisons with observations require knowledge of the molecular column density versus distance from the central star, and the lower panel of figure 4 shows the H$_2$CO column density as calculated by van Zadelhoff et al. (2003). Their result is in reasonable agreement with observations of DM Tau, but smaller than that needed to reproduce the LkCa 15 observations. Clearly, there must be some difference in the physical structure or evolutionary paths of DM Tau and LkCa 15 which causes the chemical variation seen in these two objects. Interestingly, the models predict that the molecular column densities do not significantly depend on either the disk mass or age; that the mass of the intermediate molecular layer does not depend on the total disk mass as long as the disk is as thick as $A_V \gtrsim 20$ mag, and that the chemical timescale in the intermediate layer is relatively short, $\sim 10^3 - 10^5$ yr. On the other hand, X-rays from the central star may cause variations in the molecular abundances, since the X-ray-induced UV destruction of CO can supply the additional carbon needed to form other species. Neither DM Tau nor LkCa 15 has been detected by ROSAT X-ray surveys. However, considering the high time variability of X-rays from T Tauri stars, reobservation of these objects with Chandra would be highly desirable. Dust coagulation and sedimentation could also cause variations of the molecular abundances since such processes would significantly change the temperature distribution and UV radiation field within the disks. Indeed, recent studies on the spectral energy distribution indicate the coagulation and settling of dust in several T Tauri and Herbig Ae/Be disks, including LkCa 15 (Chiang et al. 2001; D'Alessio et al. 2001). Finally, active grain surface chemistry with evaporation may enhance the H$_2$CO abundance, and may cause variations of the molecular abundances among objects, if they have different temperature or grain size.

The spatial distribution of molecules is another interesting issue concerning the chemical and physical structure of protoplanetary disks. Theoretical models predict that the H$_2$CO column density is fairly insensitive to the total H$_2$ column density, and thus to the disk radius. On the other hand, CO is one of the most volatile species after molecular hydrogen, with a sublimation temperature of only $\sim 20$ K, which is reached in the midplane at $R \sim 100$ AU. This causes a steep gradient in the radial distribution of the CO column density. In our observations, the H$_2$CO line intensity is less centrally peaked than that of CO, which was observed by Duvert et al. (2000). However, we cannot exclude the possibility that the flat distribution of the H$_2$CO emission intensity is caused by the low spatial resolution and/or low signal-to-noise ratio of our observations; the central region of the Keplerian disk corresponds to the wing component of the line spectrum, which is more easily affected by noise than velocities corresponding to the outer regions of the disk.

In order to test these possibilities, we observed the LkCa 15 disk with the high-resolution (1.2") configuration of the NMA for 4 nights. Unfortunately, clear-sky conditions were present for only 6 hr, leading to a noise level of 82 mJy beam$^{-1}$ or 3.1 K. Since the peak antenna temperature of 0.28 K in the D configuration corresponds to 3.6 K in a 1.2" beam, these high-resolution observations do not add any significant constraints on the spatial distribution of H$_2$CO. Some quantitative constraints are given as follows. If the temperature of the H$_2$CO at $R = 150$ AU is similar to that at $R = 600$ AU, the ratio of the total H$_2$CO column density at these radii should be proportional to that of brightness (i.e., mean antenna temperature), and is less than $3.1/0.16 \sim 19$. If the molecular layer in the inner radius has a higher temperature than that at the outer radius, we obtain a weaker constraint. Assuming temperatures of 50 K and 20 K at $R = 150$ AU and 600 AU, respectively, the column density ratio is less than 40. Observations with higher sensitivity and higher spatial resolution are therefore critical for an improved understanding of the molecular distributions and chemical variations of the molecular abundances since such processes would significantly change the temperature distribution and UV radiation field within the disks.

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**Fig. 4.** Distributions of abundance and column density of H$_2$CO predicted by van Zadelhoff et al. (2003). It is their model with Spectrum B; including excess UV radiation from the central star with a spectrum similar to that observed for TW Hya. The gray scale in the upper panel shows regions in which H$_2$CO abundance relative to hydrogen nuclei is $< 5 \times 10^{-13}$ (white), $5 \times 10^{-13} - 1 \times 10^{-12}$ (the darkest gray), $1 \times 10^{-12} - 1 \times 10^{-11}$, $1 \times 10^{-11} - 1 \times 10^{-10}$ and $1 \times 10^{-10} - 2.5 \times 10^{-10}$ (the lightest gray). The line contours depict the temperature distribution. The lower panel presents the radial distribution of the H$_2$CO column density integrated in the vertical direction.


cal processes within protoplanetary disks.

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