

CO J=6–5 observations of TW Hya with the SMA

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ABSTRACT

We present the first images of the 691.473 GHz CO J=6–5 line in a protoplanetary disk, obtained along with the 690 GHz dust continuum, toward the classical T Tauri star TW Hya using the Submillimeter Array. Imaging in the CO J=6–5 line reveals a rotating disk, consistent with previous observations of CO J=3–2 and 2–1 lines. Using an irradiated accretion disk model and 2D Monte Carlo radiative transfer, we find that additional surface heating is needed to fit simultaneously the absolute and relative intensities of the CO J=6–5, 3–2 and 2–1 lines. In particular, the vertical gas temperature gradient in the disk must be steeper than that of the dust, mostly likely because the CO emission lines probe nearer to the surface of the disk. We have used an idealized X-ray heating model to fit the line profiles of CO J=2–1 and 3–2 with χ^2 analysis, and the prediction of this model yields CO J=6–5 emission consistent with the observations.

Subject headings: stars: individual (TW Hya) —stars: circumstellar matter —planetary systems: protoplanetary disks —radio lines: stars —ISM: molecules

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1. Introduction

Disks around pre-main sequence stars are the likely sites of the formation of planetary systems (e.g. Beckwith 1999). Our quantitative understanding of the physical properties of such disks — in particular their sizes, radial and vertical temperature and density structures, and gas survival timescales — has improved dramatically in recent years as (sub)millimeter-wave interferometers have imaged the gas and dust surrounding over a dozen T Tauri and Herbig Ae stars at $\sim 1''$ – $5''$ resolution (eg. Koerner & Sargent 1995; Guilloteau & Dutrey 1998; Dartois et al. 2003; Qi et al. 2003, 2004). Observations and modeling of molecular emission of trace species can be used to derive the density and temperature structure in disks. Although the structure inferred from observations of a single line is not unique, observations of a sufficiently large number of lines of various molecules can be used to constrain the temperature and density independently (van Zadelhoff et al. 2001).

TW Hya is the closest known classical T Tauri star (at a distance of 56 pc), and its circumstellar disk has been imaged in the CO J=3–2 and J=2–1 lines with the SMA (Qi et al. 2004). A detailed comparison of the data with 2D Monte Carlo radiative transfer models was used to constrain the disk properties. One problem with these models was that the predicted CO J=3–2 intensities were always lower than the observed values, no matter what disk parameters were varied (including outer disk radius, inclination angle and molecular depletion factors). Since the disk is externally irradiated, the gaseous component can be detectable through emission lines produced in temperature inversions of the disk atmosphere where CO lines are optically thick. The disk thermal structure is mainly derived from the fitting of the spectral energy distribution (SED), which provides a good description of the dust temperature profile. However, the sampling of the disk temperature distribution by gas and dust is different, as the optically thin dust probes much deeper into the mid-plane and closer to the star in radius. Qi et al. (2004) suggested that the difference between the CO intensity and the canonical model may be due to the higher gas temperature probed by the CO emission than the dust temperature. For this reason, we searched for CO J=6–5 emission, which is expected to be sensitive to the slope of the gas temperature inversion at the surface of the disk.

We present here the first aperture synthesis mapping of CO J=6–5 in a protoplanetary disk, using the Submillimeter Array (SMA). We show that inclusion of additional disk surface gas heating in the disk model, in the form of an idealized X-ray heating model, provides a better fit to both our previous SMA observations of the CO J=3–2 and 2–1 lines, and a much better fit to the observations of the CO J=6–5 line, than the model without additional heating.

2. Observations

The 690 GHz observations of TW Hya were made with the SMA¹ (Ho et al. 2004) on 17 February 2005 in a compact configuration with six antennas under excellent sky conditions with $\tau_{225\text{GHz}} \sim 0.03 - 0.05$. These observations provided 15 independent baselines ranging in length from 16 to 156 meters. Table 1 summarizes the observational parameters (additional CO J=2–1 data was obtained with longer baselines than reported by Qi et al. 2004 and are also summarized here). The synthesized beam sizes were $2''.4 \times 0''.9$ for 690 GHz continuum emission and $3''.9 \times 1''.2$ for CO J=6–5 with natural weighting. The SMA digital correlator was configured with a narrow band of 128 channels over 104 MHz, which provided 0.8 MHz frequency resolution, or 0.35 km s^{-1} velocity resolution at 690 GHz, and several broader bands that together provided 2 GHz for continuum measurements. Calibration of the visibility phases and amplitudes was achieved with observations of Callisto, at intervals of typically 20 minutes. During the observations, Callisto was 40 degrees away from TW Hya and had a diameter of $1''.39$ and a zero-spacing flux density of 45.3 Jy at 690 GHz, which provided the absolute scale for the flux density calibration. The uncertainties in the flux scale are estimated to be 10% according to the uncertainties of the Callisto model. The 4.6 Jy continuum emission from TW Hya is strong enough for self-calibration, and one iteration of phase-only self-calibration with the 690 GHz TW Hya continuum model was performed on the CO J=6–5 data to improve the images. The MIRIAD package was used for imaging.

3. Results

Figure 1 shows the CO J=6–5 channel maps (one channel at velocity 2.9 km s^{-1} in red contours and a second channel at velocity 2.5 km s^{-1} in blue contours) overlaid on the 690 GHz continuum image in gray scale. The velocity gradient along the disk position angle of -27 degrees is consistent with that seen in CO J=2–1 and J=3–2 (Qi et al. 2004).

The disk averaged CO J=6–5 spectrum, along with the CO J=3–2 and 2–1 spectra (in black lines), toward TW Hya at $\sim 2''$ resolution is presented in Figure 2. The spectra predicted by the canonical model from Qi et al. (2004) are shown in solid blue lines. The canonical model, adapted from Qi et al. (2004) by fitting both CO J=3–2 and 2–1 data, is summarized in Table 2 and discussed further below. As shown in Figure 2, the difference between the data and the model becomes substantial as the energy of the CO transitions

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increases. This indicates a steeper vertical temperature profile in the gas than in the dust near the disk surface, which suggests an additional source of gas heating at the disk surface is required.

Chiang & Goldreich (1997) show that the thermal properties of the dust in the upper layers of a disk are uncoupled from those of the gas. The dust temperature is determined only by the absorption of stellar radiation and the re-radiation by the dust, while the gas temperature is determined not only by its collisions with the dust but also by other gas heating and cooling processes. As indicated by Glassgold & Najita (2001), above a certain height, the gas and dust should be treated as distinct (but interacting) thermodynamic systems, and existing disk atmospheres do not give the the correct temperature for the gas. As shown in Figure 2, the canonical model predictions are weaker than the observations, and the CO 6–5 lines shows the largest discrepancy, which is clear evidence that the canonical model needs to be adjusted.

4. Discussion

Both X-ray (Glassgold et al. 2004) and ultraviolet (Jonkheid et al. 2004) radiation are effective in heating the gas in the surface layers of disks. Recent X-ray satellite observations confirm that essentially all young stellar objects are luminous X-ray emitters (Feigelson & Montmerle 1999). Observational constraints on the various aspects of X-ray irradiation of protoplanetary disks are rapidly improving, and it appears that the emitted X-rays can affect the environment of a young star out to hundreds of AU (Glassgold & Najita 2001). Igea & Glassgold (1999) showed that Compton processes increase X-ray penetration through column densities of order 10^{24} - 10^{25} cm^{-2} and so can be important in disk physics. By fitting both ROSAT and ASCA spectra, an X-ray luminosity of $L_x \approx 2 \times 10^{30}$ ergs s^{-1} was derived for TW Hya by Kastner et al. (1999), with prominent line emission at energies ~ 1 keV. With these X-ray parameters, Glassgold et al. (2004) calculated the ionization rate at the top of the disk atmosphere at a radial distance of 1 AU to be $\sim 6 \times 10^{-9}$ s^{-1} . The X-ray luminosity of TW Hya is known to be highly variable (Kastner et al. 1999, 2002) due to flaring events, but the X-ray ionization important for heating should be a time-averaged effect. The model calculations concerning X-ray ionization and its effects on the gas temperature are subject to uncertainty, since the hard X-ray flux (most important for penetrating the disk) assumed in the Glassgold et al. treatment is a simplified representation of the real X-ray emission, which when examined at low resolution is actually broadly distributed from a few tenths to several keV (Kastner et al. 1999; Stelzer & Schmitt 2004).

Motivated by the X-ray observations, we focus on X-ray effects on the disk surface to

describe the additional surface heating. In order to model the effects of X-rays in heating the gas in the upper atmosphere of the TW Hya disk, we follow the Glassgold et al. (2001, 2004) scheme to estimate the gas temperature for the region of the disk probed by CO rotational lines. The X-ray heating at the disk surface is expressed as

$$\Gamma_X = 4.8 \times 10^{-11} \text{erg} \zeta_X \left(\frac{\Delta\epsilon_h}{30\text{eV}} \right) n_H \quad (1)$$

in terms of a mean heating energy per ionization, $\Delta\epsilon_h$ and the X-ray ionization rate $\zeta_X = 6 \times 10^{-9} \text{s}^{-1} \left(\frac{AU}{r} \right)^2$, which is adopted from Glassgold et al. 2004 for TW Hya where r is the cylindrical radius from the disk axis.

The dust-gas cooling rate is taken to be

$$\Lambda_{dg} = 2 \times 10^{33} \text{erg} \text{cm}^3 \text{s}^{-1} \left[\frac{\frac{\rho_d}{\rho_g} 500\text{\AA}}{0.01} \frac{\alpha}{a} \frac{1}{0.5} \right] T^{0.5} (T - T_d) n_H^2 \quad (2)$$

where α is the accommodation coefficient (from equation 3 of Glassgold et al. 2004), T is the gas-kinetic temperature, and T_d is the mean dust temperature. When $T > T_d$ the dust cools the gas. The net volumetric gain rate of gas energy due to collisions with dust is then proportional to the local dust-to-gas ratio $\frac{\rho_d}{\rho_g}$ and inversely proportional to the mean dust radius a . With the heating of the gas by X-rays balanced by the dust-gas cooling rate, we can calculate the difference of gas and dust temperature at each locale within the disk. Figure 3 shows the gas–dust temperature differences overlaid with the dust temperature contours from the TW Hya model (Calvet et al. 2002). By incorporating these temperature difference into the disk model, we can fit the CO lines using the χ^2 analysis in the (uv) plane to estimate the goodness of fit for the various disk parameters, including the outer radius R_{out} and the inclination angle i , $(v \sin i)_{100AU}$. A similar χ^2 analysis to determine best fit disk parameters was carried out on the disk of DM Tau by Guilloteau and Dutrey (1998). The χ^2 analysis in the visibility plane is essential to avoid the non-linear effects of deconvolution in the imaging process.

We adopt the disk physical density and temperature structure as derived by Calvet et al. (2002), where we take the disk temperature as the dust temperature, and we use the difference between the gas and dust temperature derived by balancing the relevant heating and cooling processes. We produce a grid of models with a range of various disk parameters and depletion schemes to simulate the disk as imaged by a telescope with the resolution constrained only by the grid sampling (typically of order 5-10 AU in the outer disk, or $0''.1 - 0''.2$). We use a 2D Monte Carlo model (Hogerheijde & van der Tak 2000) to calculate the radiative transfer and molecular excitation, and we produce simulated observations of the model disks with the MIRIAD software package using the UVMODEL routine to select synthetic visibility

observations at the observed (u, v) spacings. Then the χ^2 distance is calculated between the simulated visibility and the CO J=3–2 and J=2–1 data with sufficient signal-to-noise. The best fit parameters as derived by minimizing the χ^2 distance are shown in Table 2 (details to be presented in a future paper). The simulated spectra of the CO lines including X-ray heating are shown in Figure 2 with red solid lines. Including X-ray heating improves the agreement of the model with the data. Note that the CO J=6–5 model prediction is based only on the lower transition lines.

The value $(\frac{\rho_d}{\rho_g})/a$ is constrained by the χ^2 fit to be around 4×10^{-4} with a in μm . If the local dust-to-gas ratio is around 0.01, then the mean dust radius is around $25\mu\text{m}$, which seems large for the surface of the disk. If dust settles in the mid-plane, then the local dust-to-gas ratio might be lower, and if it were as low as 0.001, then the mean dust radius would be around micron size or smaller, which seems more plausible.

Even though the disk model with X-ray heating can effectively match the various CO observations of TW Hya, especially the line intensity at $\sim 2''$ resolution, the predicted width of CO J=6–5 line is nearly 50% larger than observed. In the model, the CO J=6–5 emission originates mostly from the upper layers of the inner 60 AU of the disk, consistent with the double-peaked appearance in the model spectra, as the density of the outer disk is so low that CO J=6–5 becomes sub-thermally excited. The narrow observed linewidth of CO J=6–5 suggests that most of the emission is actually coming from the outer part of the disk (less contribution from the velocity projection from the regions with high Keplerian rotation). There are at least two scenarios that could account for this: (1) There is not much CO in the inner disk. Although it is possible to make the model CO J=6–5 spectra narrower by blanking out the CO emission from the inner 20 AU, it would then be hard to fit both the CO J=3–2 and 2–1 lines simultaneously, and also begs the question as to the origin of the CO M-band $v=1-0$ emission (Rettig et al. 2004). (2) The gas temperature of CO in the inner 20 AU is actually lower than predicted by the models, possibly due to either additional cooling or perhaps shadowing induced by a puffed up inner rim of the disk, so that the emission from the higher excitation J=6–5 line is suppressed but with little effect on the lower excitation J=3–2 and 2–1 lines. Clearly the current model is still too simplified to fit all the CO lines perfectly. Further analysis of the thermal structure in the inner disk will hopefully help to resolve this puzzle.

5. Summary

We have presented the first imaging of the CO J=6–5 emission from the disk around a classical T Tauri star, TW Hya. Using a 2D Monte Carlo simulation with a physical

description of the disk and an idealized X-ray heating model, we are able to simultaneously reproduce the line intensities of CO J=6–5, J=3–2 and J=2–1 molecular line emission. Some puzzles remain, however, in particular the observed CO J=6–5 line width that appears to be narrower than predicted by this model.

Circumstellar disks evolve from gas-rich structures with 1% of the total mass in dust to disks that appear to be completely devoid of gas and dominated by emission from the dust particles generated by planetesimal collisions. Theoretical studies indicate short gas dispersal timescales (Hollenbach et al. 2000). Studies of the gas component of the disk are needed to obtain detailed information on the mechanisms of disk dispersal. SMA observations of multiple CO transitions toward TW Hya show that additional gas heating is needed at the surface of the disk to explain the measured line intensities and ratios. Detailed modeling with realistic X-ray ionization rates derived from the observed X-ray spectrum of TW Hya, as well as other surface heating processes (especially UV heating) will be essential to understand the nature of the gas in the disk of TW Hya, and hence the gas evolution in protoplanetary disks in general.

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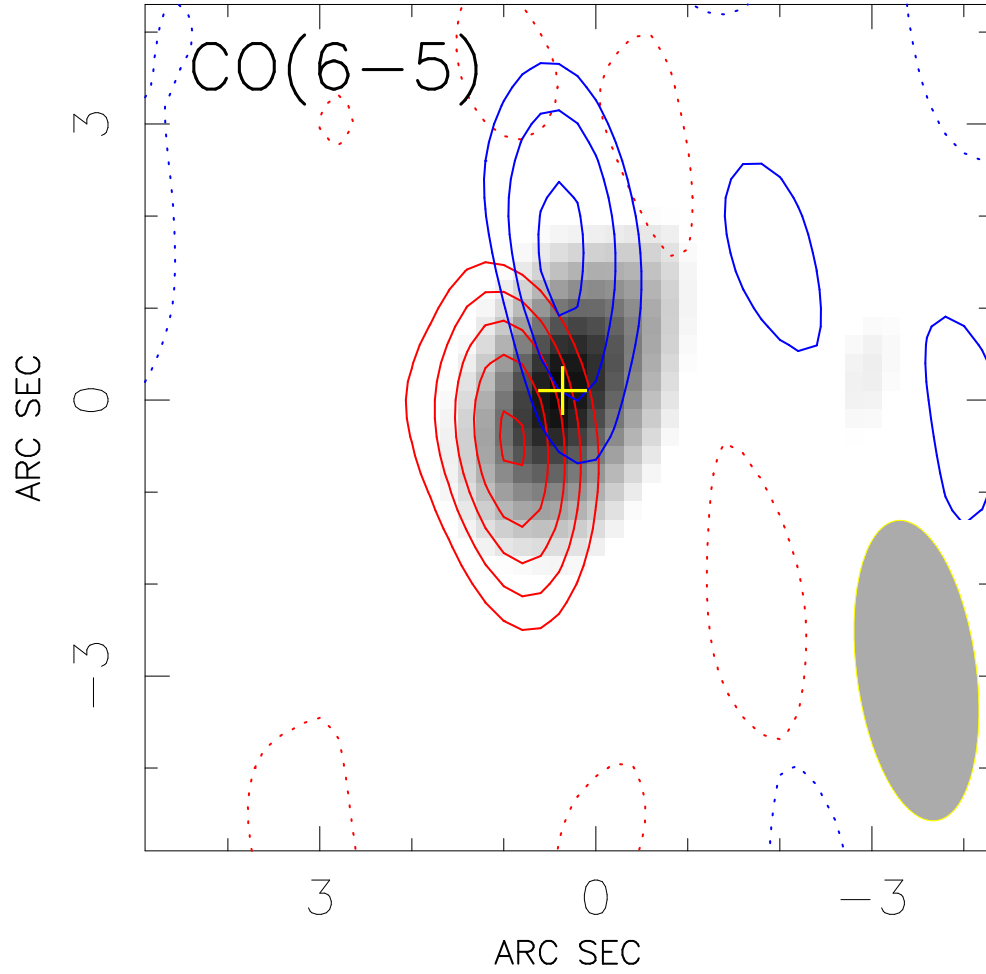


Fig. 1.— CO J=6–5 velocity channel maps (*red*: 2.9 km s^{-1} , *blue*: 2.5 km s^{-1}) from TW Hya, overlaid on the 690 GHz dust continuum map (*gray scale*). The cross indicates the position of the continuum peak.

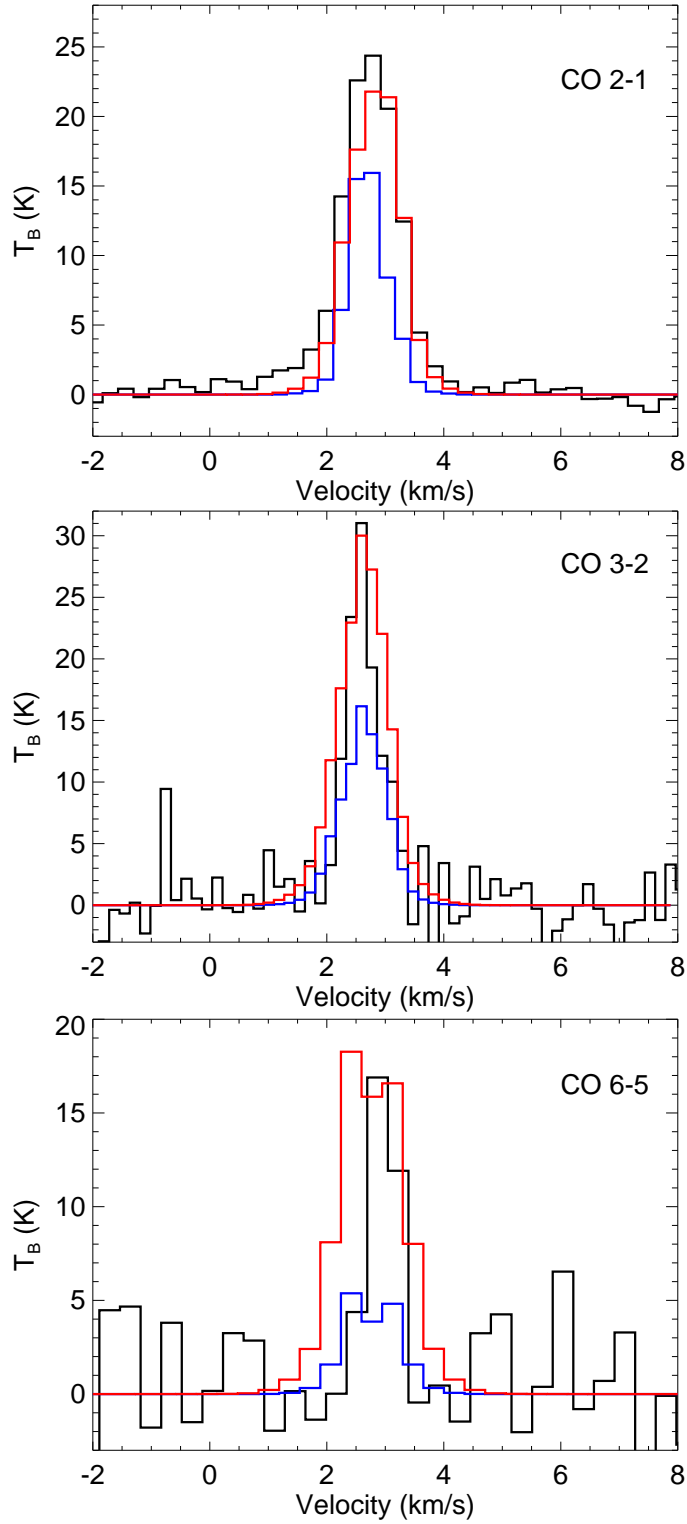


Fig. 2.— The CO $J=2-1$, $3-2$ and $6-5$ spectra at the continuum (stellar) position. The spectra in black are the SMA data, and the red and blue spectra are the simulated models with and without X-ray heating.

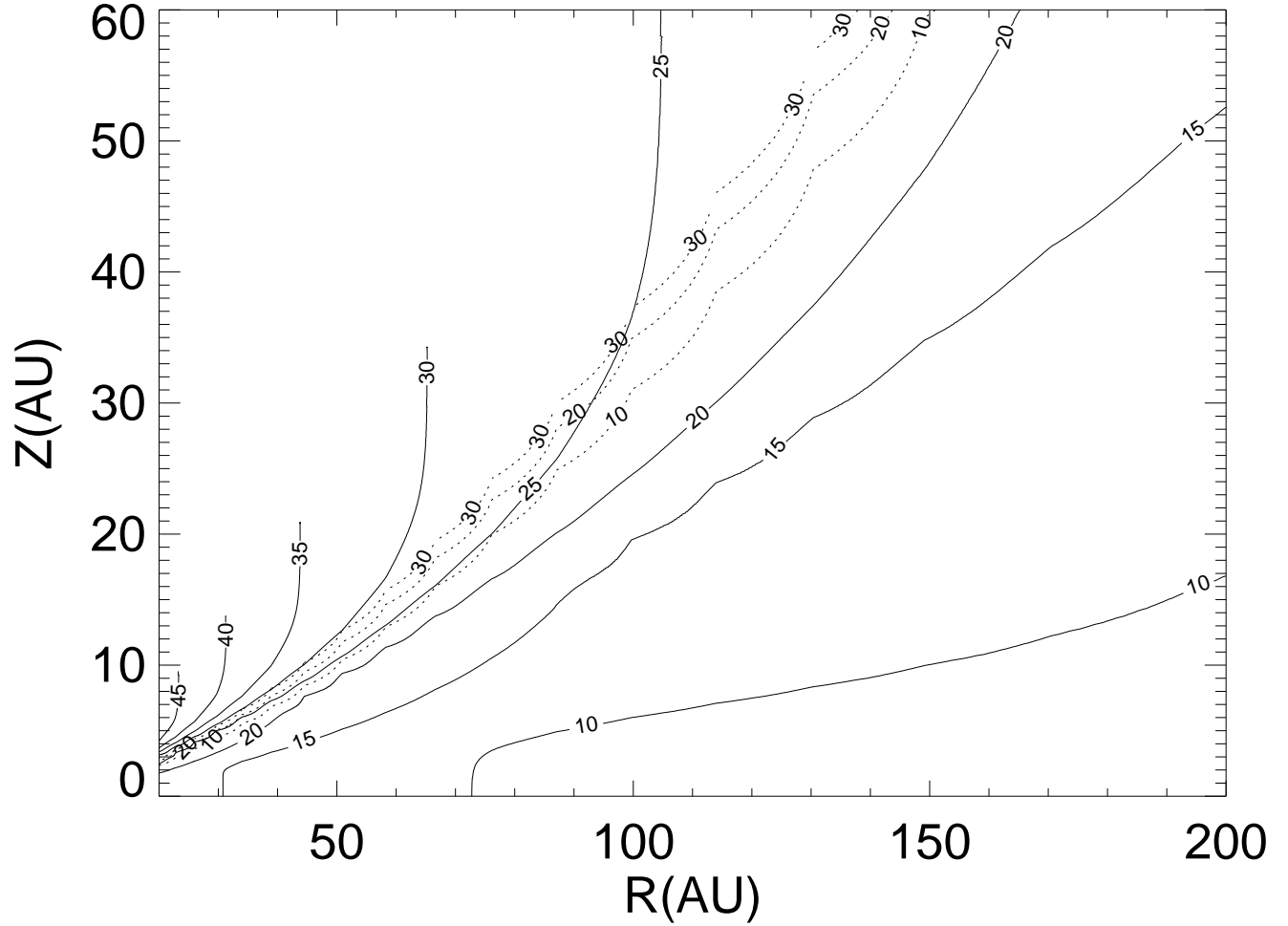


Fig. 3.— The dust temperature contours (in solid lines) from the TW Hya model (Calvet et al. 2002) and the gas–dust temperature differences (in dotted lines) due to the X-ray gas heating on the disk surface.

Table 1. Observational Parameters for SMA TW Hya

	CO 3–2	CO 2–1	CO 6–5
Rest Frequency:	345.796 GHz	230.538 GHz	691.473 GHz
Synthesized beam:	$2''.7 \times 1''.6$ PA 18.7°	$2''.7 \times 1''.7$ PA 9.9°	$3''.3 \times 1''.3$ PA 7.5°
R.M.S. ^a (continuum):	35 mJy/beam	1.8 mJy/beam	110 mJy/beam
Dust flux:	1.62 ± 0.05 Jy	0.54 ± 0.03 Jy	4.62 ± 0.54 Jy
Channel spacing:	0.18 km s^{-1}	0.26 km s^{-1}	0.35 km s^{-1}
R.M.S. ^a (line):	1.0 Jy/beam	0.11 Jy/beam	5.3 Jy/beam
Peak intensity	31.0 K	24.4 K	16.9 K

^aSNR limited by the dynamic range.

Table 2. Model Parameters Used in Simulating TW Hya emission

Parameters	
Physical Structure	Irradiated accretion disk (Calvet et al. 2002)
Stellar Mass	$0.77 M_{\odot}$
Disk Size	R_{in} 4 AU, $R_{out,edge}$ 172 AU
Disk PA	-27.4°
Inclination Angle	6°
Turbulent Velocity	0.12 km s^{-1}
CO Depletion Factor	$V_c=10^{-1.2}$, ($V_j=10^{-2.2}$ for $T \leq 22 \text{ K}$)