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MODELS OF MOLECULAR LINE EMISSION FROM PROTOPLANETARY DISKS AT SUBARCSECOND RESOLUTION

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RESUMEN

Para obtener una evidencia directa y concluyente de la existencia de discos protoplanetarios (radio $\simeq$ 100 UA) en torno a estrellas jóvenes, se precisan observaciones de líneas moleculares con resoluciones por debajo del segundo de arco. En este trabajo hemos desarrollado un modelo para calcular la emisión de línea molecular que se espera en discos protoplanetarios con dichas resoluciones angulares. Comprobamos también si existe algún instrumento capaz de resolver tales discos. Nuestros resultados preliminares sugieren que la detección de líneas moleculares en discos protoplanetarios resueltos es extremadamente difícil. En concreto, tal detección no parece realizable con la instrumentación actual, pero será ciertamente posible con la nueva generación de interferómetros milimétricos y submilimétricos ahora en proyecto.

ABSTRACT

To get direct conclusive evidence of the existence of protoplanetary disks (radius $\simeq$ 100 AU) around young stars, molecular line observations at subarcsecond resolution are needed. In this work we develop a model to calculate the expected line emission from protoplanetary disks at these high angular resolutions. We also check whether there is any instrument capable of achieving the resolution of such disks. Our preliminary results suggest that the detection of molecular lines from resolved protoplanetary disks is extremely difficult. In particular, this detection does not seem attainable with present instrumentation, but it will certainly be possible with the upcoming new generation of millimeter and submillimeter interferometers.

Key words: **ACCRETION, ACCRETION DISKS — LINE: PROFILES — STARS: CIRCUMSTELLAR MATTER — STARS: PRE-MAIN-SEQUENCE**

1. INTRODUCTION

One of the leading tracks in modern Astronomy is the search for protoplanetary disks around young stars. The presence of such disks plays a central role in the theories of stellar and planetary formation, and their discovery would certainly prove whether our ideas on these fields are correct. In particular we think that stellar accretion disks provide to the young star with the material to keep on growing its mass, since due to the conservation of angular momentum, most of the collapsing material does not accrete directly onto the central star.

Disks could also be necessary for the generation/collimation of stellar jets, which in turn could drive bipolar outflows (see Raga 1995 in these Proceedings). Finally, a gas and dust disk could give rise to the formation of planets. Therefore, disks are somehow the "missing link" that could bring together different aspects of star formation.

The discovery of dusty disks around main-sequence stars, like in β Pictoris (Smith & Terrile 1984), has been a major milestone in the search for stellar disks. Unfortunately, we still have no direct and conclusive evidence of a disk of gas and dust around a young star that could be identified as an accretion disk and that could be properly referred to as "protoplanetary" (i.e., the precursor of a planetary system). However, there is a great deal of evidence about the existence of such disks, all of it pointing to the fact that their radius should be $\sim$ 100 AU for low-mass stars, which roughly coincides with the size of our own solar system. This evidence comes from several directions, for instance: (a) Theoretical models (see, e.g., Tereby, Shu, & Cassen 1984; Morfill 1989), which assume that the angular momentum of the collapsing gas is initially conserved in a rotating disk. (b) Observations of jets that appear collimated from scales of $\sim$ 100 AU (Mundt, Brugel, & Bührke 1987; Reipurth & Cernicharo 1995 in these Proceedings), requires a collimating structure (i.e., a disk) of this size. (c) Indirect observations, i.e., which do not resolve the emission from the disk or which infer its existence from different phenomena in the gas or dust (e.g., Rodríguez et al. 1986; Edwards et al. 1987; Adams, Lada, & Shu 1988; Bertout, Basri, & Bouvier 1988; Kenyon, Hartmann, & Hewett 1988; Keene & Masson 1990; Carr et al. 1993; O'Dell, Wen, & Hu 1993; Stauffer et al. 1994).

2. CONDITIONS FOR A DIRECT DETECTION

In principle, one can think of two conditions which are needed to obtain a direct detection of a protoplanetary disk around a young low-mass star.

1. *Subarcsecond resolution.* As we mentioned above, the expected radius of these disks is $\sim$ 100 AU. This radius corresponds to $0\farcs7$ at 140 pc, the distance to the Taurus Molecular Cloud, which is the closest star-forming region. Consequently, if we want to resolve a protoplanetary disk, we need to observe with beams under the arcsecond. An additional advantage of high-resolution observations is that the possible contamination of extended and less dense structures (like envelopes) will decrease.

2. *Line observations.* If we observe the continuum emission from the dust in the disk, we can obtain information on the morphology of the disk, as well as estimates of its mass, density, and temperature. When studying spectral lines emitted by the gas, in addition to all that, we could acquire kinematical information, namely the kinematical signatures of rotation.

It seems then that the way to go is to carry out molecular line observations of disks using radio interferometers. First, because they can achieve high angular resolutions. Second, because lines in disks with temperatures $\sim$ 100 K (Beckwith et al. 1990) are more likely to be detected in the radio regime.

3. IS IT POSSIBLE TO RESOLVE 100 AU DISKS WITH MOLECULAR RADIO LINES?

This is certainly the key question when addressing the observational search for protoplanetary disks. There are not many instruments that can reach subarcsecond resolution at present. We thought that the best chance to detect and resolve molecular lines from disks, using presently working instruments, was to study with the Very Large Array (VLA) the inversion transitions of ammonia. The VLA in its B configuration has a resolution of $\sim 0\farcs4$ for these lines at 1.3 cm, which make this instrument especially well suited for the task we are facing. We actually made these observations toward HL Tau and L1551-IRS5, using the NH_3(1,1) and (2,2) lines (Gómez et al. 1993). Unfortunately, we obtained negative results for a sensitivity level $\sigma \simeq 1$ mJy beam^{-1} with 5 km s^{-1} of velocity resolution. With this non-detection, and assuming typical physical parameters for the disks ($T \simeq 100$ K, $R \simeq 100$ AU; see Beckwith et al. 1990), we estimated upper limits to their masses of $0.02[X_{NH_3}/10^{-8}]^{-1}$ and $0.1[X_{NH_3}/10^{-8}]^{-1}$ for the cases of HL Tau and L1551, respectively. These limits should be considered as rough estimates, given the uncertainties in the ammonia abundance and in the physical parameters of the disks.

Now, we wonder whether the resolving of protoplanetary disks will be possible with future instruments, for instance the Millimeter Array of the National Radio Astronomy Observatory, the Submillimeter Array (SMA) of the Smithsonian Astrophysical Observatory (SAO), the Large Millimeter Array of the Nobeyama Radio Observatory, upgrades of present millimeter interferometers (lengthening their baselines), the new VLA receivers at 7 mm (of which there are 10 already working), etc (see Ho 1995 in these Proceedings). For these projects, the questions are: *(1) Will it be possible to detect and resolve protoplanetary disks with them? (2) If so, how would they look like?* These two (specially the first one) are the issues addressed in this work. To answer these questions, we have developed models of molecular line emission from rotating disks.

4. PREVIOUS MODELS OF MOLECULAR LINE EMISSION FROM DISKS

There are several models of molecular line emission from protoplanetary disks that have been presented in the literature. These models have been developed essentially to compare with and to predict results of observations feasible with present telescopes, i.e., with beams $\geq 1''$ that do not resolve the disks. For instance, Beckwith & Sargent (1993), and Omodaka, Kitamura, & Kawazoe (1993) presented models of the emission of the rotational transitions of the CO isotopes at 3 mm, finding a double-peaked line profile, which is typical of rotating disks. In general, the comparison of these models with the observations gives good indirect evidence of the existence of these disks.

There are also models for the emission of larger disk-like structures ($r \geq 1000$ AU) in Keplerian rotation, which also compare well with observations (e.g., GG Tau, Dutrey, Guilloteau, & Simon 1994; GM Aur, Koerner, Sargent, & Beckwith 1993). Although the sizes of these structures are about one order of magnitude larger than the actual accretion disks (which are believed to lie within these larger structures), these works are very important since they give good support to the theoretical expectation of the existence of rotating disks.

5. A MODEL FOR OBSERVATIONS THAT COULD RESOLVE PROTOPLANETARY DISKS

Here we address the problem of calculating the intensity and profiles of the molecular line emission from a protoplanetary disk given a density and temperature structure, and observed with subarcsecond resolution.

5.1. Assumptions and Projected Velocity

As a first approach, we have used a simple geometry for the disk. We assume that the disk is geometrically thin and in Keplerian rotation. For this thin disk we do not consider the vertical structure in temperature and density. We will consider just the radial structure of these variables. We also assume local thermodynamic equilibrium (LTE). We think that these approximations are good enough to start with. In particular, the thin disk approximation is good since protoplanetary disks are geometrically thin (scale height $\simeq$ 10% of radius, see, e.g., Beckwith & Sargent 1993). The regions of the disk which contribute significantly to the molecular line emission studied here have densities that are high enough ($\sim 10^{11}$ cm^{-3}, see Morfill, Tscharnuter, & Völk 1985) to make the LTE approximation acceptable. Note that we are not modeling emission lines produced in the atmosphere of the disk (like, for example, the CO IR bands calculated by Calvet et al. 1990). With such approximations, each position on the disk can be characterized by its temperature and its surface density. From these two quantities we can obtain the emission intensity as a function of position and velocity, and therefore, a spectrum for a given angular resolution.

From Fig. 1, we can see that the projected velocity of the gas in a rotating disk, as seen by the observer is

$$v_r = v \sin i \sin \theta \, . \tag{1}$$

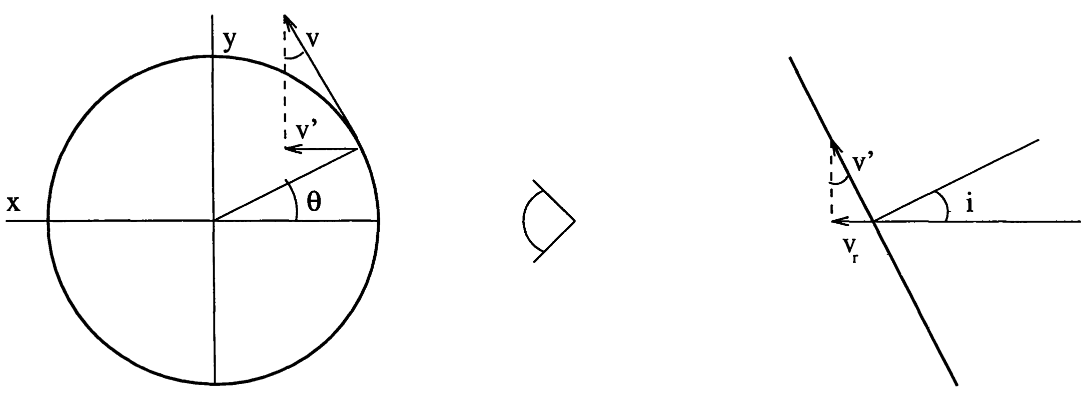

Fig. 1.— Projected velocity v_r of a particle in the disk rotating at velocity v around the star, as seen by an observer looking from right to left in the figure. The angle between the line of sight and the disk rotation axis is labeled as i.

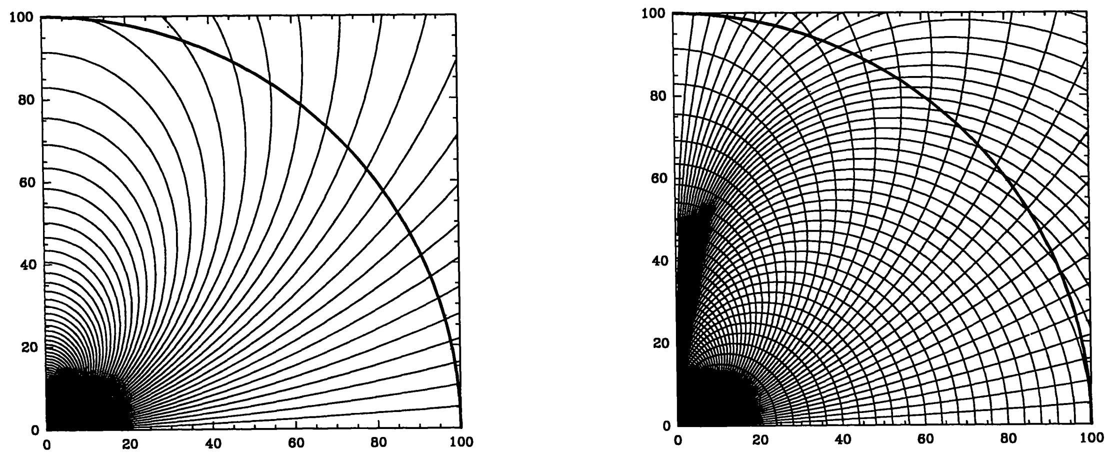

Fig. 2.— (Left) Isovelocity lines in a quadrant of a disk with inclination angle $i = 60°$. The observer would be looking from right to left. The interval between adjacent lines is 0.1 km s^{-1}. The thick curve is the outer boundary of the disk. (Right) Example of the kind of grid used in the integration. It is formed by the isovelocity lines and their perpendicular lines. Units the axes are AU.

Since the gas is moving in Keplerian orbits, the lines with the same projected velocity are those of the form

$$r = \frac{GM}{v_r^2} \sin^2 i \sin^2 \theta \ . \tag{2}$$

These lines are shown in Fig. 2 (left).

The grid used in the integration of the line flux was build with the isovelocity lines and their perpendicular lines (of the form $r = A\sqrt{\cos\theta}$, where A is a constant), so that all the cells have the same velocity resolution. This grid avoids a possible overestimate of the fluxes in the inner disk and makes the integration easier. An example of the grid is shown in Fig. 2 (right).

5.2. The Equations

We consider for each cell in the grid a temperature and a surface density that follow the power laws postulated for accretion disks around young stars (see, e.g., Adams et al. 1988), i.e.,

$$T(r) = T_\circ \left(\frac{r}{r_\circ}\right)^{-q} \text{, and} \tag{3}$$

$$\Sigma(r) = \Sigma_\circ \left(\frac{r}{r_\circ}\right)^{-p} \ . \tag{4}$$

Since we do not consider the vertical temperature structure and we are assuming LTE, we can use the simple isothermal transfer equation

$$I_\nu(r) = B_\nu(T_{\rm bg})e^{-\tau} + B_\nu(T)(1 - e^{-\tau}) \ . \tag{5}$$

For the optical depth, we have to consider the contribution of both, the continuum and the line emission, $\tau = \tau_c + \tau_l$, where

$$\tau_c = \kappa_\nu \frac{\Sigma(r)}{\cos i} = 0.1 \left(\frac{\nu}{10^{12}\,\rm Hz}\right)^\beta \frac{\Sigma(r)}{\cos i} \ , \tag{6}$$

using the normalization by Hildebrand (1983) for the dust opacity, κ_ν, and

$$\tau_l = \int_0^\infty \kappa_l \, ds \simeq \frac{A_{ij}c^2}{8\pi\nu^2} \frac{g_i}{g_j} \left[1 - \exp\left(-\frac{h\nu}{kT}\right)\right] N_j \Psi(\nu) \ , \tag{7}$$

where A_{ij} is the Einstein coefficient for the line emission, g_i and g_j are the statistical weights of the upper and lower states respectively, N_j is the column density of molecules in the lower state, and $\Psi(\nu)$ is the thermal line profile. These last two parameters take the form

$$N_j = \frac{N\, g_j \exp\left(-\frac{E_j}{kT}\right)}{Q} \text{ , and} \tag{8}$$

$$\Psi(\nu) = \frac{c}{\nu}\left(\frac{m_{\rm mol}}{2\pi kT}\right)^{\frac{1}{2}} \exp\left[-\frac{m_{\rm mol}(v-v_\circ)^2}{2kT}\right] , \tag{9}$$

with N being the total column density of the emitting molecule, E_j the energy of the j state, Q the partition function, $m_{\rm mol}$ the molecular mass, and $v_\circ$ the rest velocity in the star-disk system.

With these parameters, if we know the abundance of the molecule, we can substitute Eqs. 6 and 7 into Eq. 5, and obtain the intensity in each cell. Then, the observed flux results to be

$$S_\nu(X,Y,v) = \sum_{\rm beam} I_\nu(x,y,v)\, A(x,y)\, P(x,y) \tag{10}$$

i.e., the sum over the beam of the intensity (I_ν), times the cell area (A), times the Gaussian beam pattern (P).

5.3. Input Parameters

We applied the equations in §5.2 to the particular case of a disk with the parameters given by Beckwith et al. (1990) for HL Tau: stellar mass $M_\star = 0.55\ M_\odot$, disk mass $M_d = 0.1\ M_\odot$, $T_\circ = 307$ K, $r_\circ = 1$ AU, $q = 0.5$, $p = 1.5$, inner radius of the disk = 0.01 AU and outer radius = 100 AU. We assume a distance of = 140 pc (Elias 1978). We made calculations for different inclination angles i. There is a large uncertainty about the value of β, the exponent in Eq. 6. It depends on the properties of the dust, and could vary between 0 and 2 (see, e.g., Draine & Lee 1984; Wright 1987; Beckwith & Sargent 1991). We calculated the resulting line intensities for $\beta = 1$ (as assumed by Beckwith et al. 1990), and for $\beta = 1.5$, to check for its possible influence on the final results.

6. MODEL RESULTS

In our first calculations, we have computed the line profiles for three molecules, and compared with the detection capabilities of present and future radio interferometers. These lines are:

1. NH_3(1,1) and (2,2) ($\lambda = 1.3$ cm), to compare with the observations carried out with the VLA in the B configuration (Gómez et al. 1993).

2. CS(J $= 1 \rightarrow 0$) ($\lambda = 7$ mm), mainly to test the capabilities of the VLA with its new Q-band receivers.

3. CO(J $= 2 \rightarrow 1$) ($\lambda = 1.3$ mm), and CO(J $= 3 \rightarrow 2$) ($\lambda = 0.87$ mm), which can be used to compare, among others, with the detection capabilities of the SAO Submillimeter Array.

We have to point out that these are just the first examples we have calculated. Obviously, these studies can be extended to calculate the emission of other molecular lines and to compare with other telescopes. We also note that, with the adopted input parameters (§5.3), the line emission from these molecules is optically thick, and therefore the model results are valid for their rarer isotopes, as long as their emission remains optically thick in protoplanetary disks.

As an example, in Fig. 3 we show two spectra of CO(J $= 3 \rightarrow 2$) with $0''\!.4$ resolution for a disk with $i = 30°$ and $\beta = 1.5$, one at the central position, and the other one at the position where the maximum intensity of the line over the continuum appears. The latter position is located one beam away form the center along the major axis of the projected disk. Fig. 4 shows channel maps of that line at selected velocities, smoothed up to 1 km s^{-1} of spectral resolution, and subtracting the continuum.

A summary of our preliminary results is presented in Table 1, in which we compare the model results with the sensitivity of several present and future instruments that could achieve subarcsecond resolutions. In this table, column 1 is the line used in the calculation, column 2 is the telescope used to compare with the results, column 3 is the angular resolution, column 4 is the inclination angle, columns 5 and 6 are the maximum intensity of the line over the continuum for $\beta = 1$ and 1.5, respectively, and column 7 is the 1σ sensitivity of

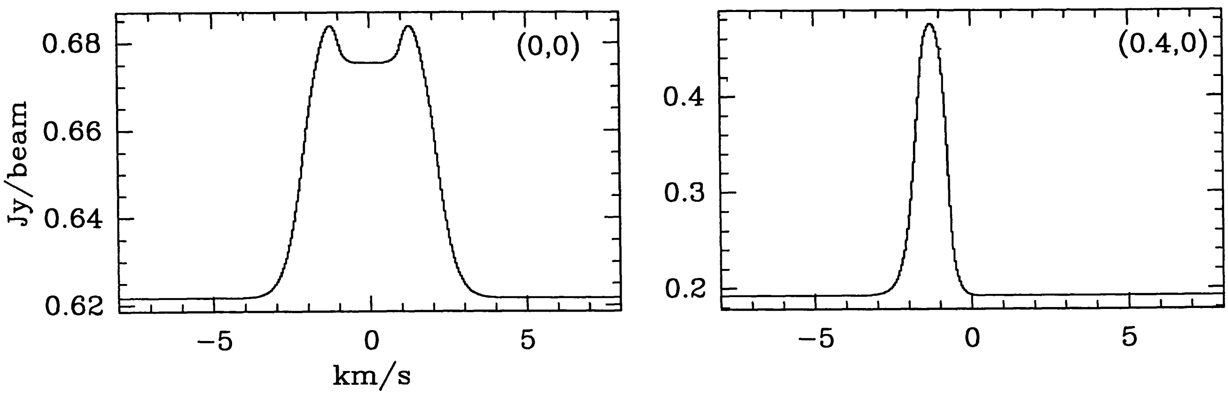

Fig. 3.— Calculated spectra of the CO(J = 3 → 2) transition, in a disk with the parameters mentioned in §5.3, with $i = 30°$, $\beta = 1.5$, and angular resolution of 0.″4. The positions in the disk are indicated in the upper right-hand corner of each spectrum, in arcsec, in a coordinate system where the x axis is parallel to the major axis of the projected disk (see Fig. 4).

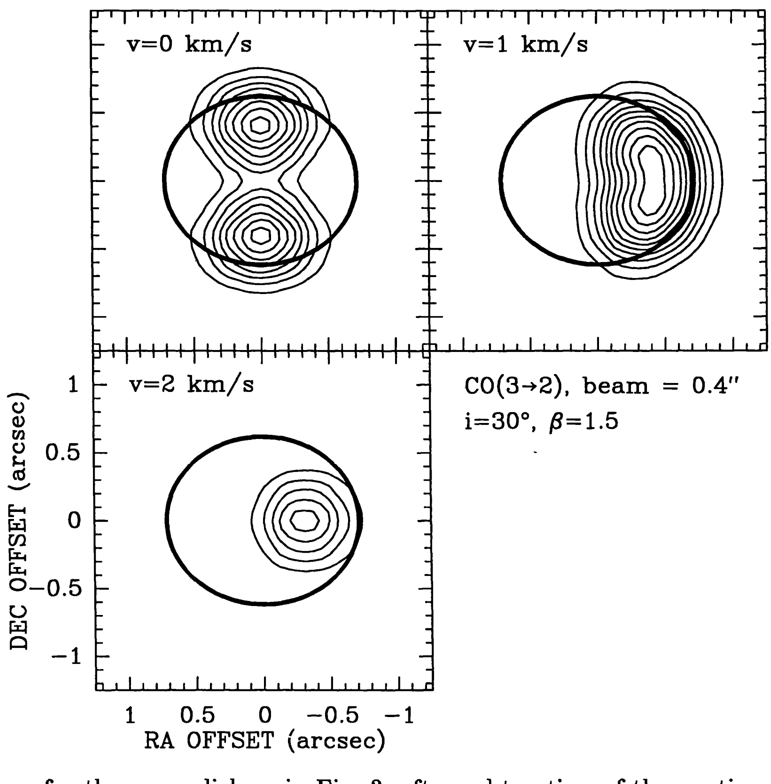

Fig. 4.— Channel maps for the same disk as in Fig. 3, after subtraction of the continuum. The velocity of the contours with respect to the rest velocity of the star-disk system is shown in the upper left-hand corner of each map. Data were smoothed to a velocity resolution of 1 km s^{-1}. The thick ellipse is the outer boundary of the disk. Data points were calculated with a spacing of half a beam. The lowest contours and the increment step are 0.02 Jy beam^{-1}.

sensitivity of the mentioned telescopes after 10 h of observing time, and with a velocity resolution of 1 km s^{-1}. Note that for the CS line we have compared our results with the sensitivity of the VLA with 9 Q-band receivers (available presently), as well as with the hypothetical sensitivity it could obtain if the 27 antennas of the array were equipped with Q-band receivers.

Table 1.— Line Intensities and Telescope Sensitivities[a]

line	telescope	beam	i	I_ν(max) (Jy beam^{-1}) $\beta=1$	I_ν(max) (Jy beam^{-1}) $\beta=1.5$	S/N 1σ (Jy beam^{-1}) $\Delta v = 1$ km s^{-1} $\Delta t = 10$ h
NH_3(1,1)	VLA (27 antennas)	0″.4	60°	9.6×10^{-4}	1.0×10^{-3}	2.0×10^{-3}
			30°	1.3×10^{-3}	1.3×10^{-3}	
CS($1\rightarrow0$)	VLA (9 receivers)	0″.3	60	1.7×10^{-3}	1.8×10^{-3}	4.4×10^{-3}
			30	1.9×10^{-3}	2.1×10^{-3}	
	VLA (27 receivers)	0″.47	60	2.6×10^{-3}	2.9×10^{-3}	1.4×10^{-3}
			30	3.9×10^{-3}	4.3×10^{-3}	
CO($2\rightarrow1$)	SMA (6 antennas)	0″.4	60	5.9×10^{-2}	8.1×10^{-2}	3.3×10^{-2}
			30	9.6×10^{-2}	1.2×10^{-1}	
CO($3\rightarrow2$)	SMA (6 antennas)	0″.4	60	9.4×10^{-2}	1.3×10^{-1}	8.4×10^{-2}
			30	1.7×10^{-1}	2.1×10^{-1}	

[a]Summary of the calculation results for different molecular lines, and comparison with the sensitivities of some present and future instruments. We chose angular resolutions close to 0″.4, even though the mentioned interferometers can achieve higher resolutions.

7. PRELIMINARY CONCLUSIONS

Examining Table 1, we can extract three main conclusions:

1. The presently working interferometers (VLA for NH_3 lines, VLA for CS with 9 receivers) seem unable to detect resolved protoplanetary disks using a reasonable amount of observing time. This is also consistent with our non-detection of NH_3 lines (Gómez et al. 1993).

2. Future interferometers (VLA in Q-band with 27 receivers, SMA) could reach such a detection. However this detection could be difficult, since these lines are expected to be at a 3σ level for the quoted telescopes. In this case, larger collecting areas in the interferometers could be determinant to guarantee a real chance of success.

3. Variations in the inclination angle of the disk and the dust emissivity parameter (β) can account for a difference of a factor of two in the expected line emission. This could be critical for an eventual detection, since we are dealing with an extremely weak line emission. The variations are mainly due to the presence of the continuum emission from the disk, since the thicker the continuum emission, the lower the observed line emission over this continuum is. If the continuum is optically thick, it will mask any line emission from the disk, as it could be the case for very massive disks or even edge-on disks. Therefore, in a real detection experiment, it will be best to choose candidate stars whose disk continuum emission is not optically thick, while the line emission is still thick.

8. FUTURE PROSPECTS

We plan to extend this study to include other molecular lines, and other interferometers that are currently in project. Although the approximations used here seem in principle valid, we also plan to refine our calculations to include the vertical structure of the disk in both temperature and density, turbulence in the gas, etc. However, we think that at this stage of the calculations we can start to get a view of what can be done in the future with the new generation of telescopes to come. It seems that, although difficult, the direct detection of resolved protoplanetary disks is possible with the upcoming instrumental projects.

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