Constraining the Evolution of Molecular Gas in Weak-Line T-Tauri Stars

1. Motivation

The formation of planets from protoplanetary disks is greatly influenced by the presence or absence of gas in these disks. The mass and lifetime of gas in disks obviously constrains the mass and formation-time of gas-giant planets. Moreover, even trace amounts of gas can influence the evolutionary process of solid particles from submicron size to planetary sizes. A number of papers have recently detailed the influence of gas friction on relatively small and medium sized particles (Klahr, Hubertus, & Lin 2000; Takeuchi & Artymowicz 2001; Takeuchi and Lin 2003) and on the eccentricities of large objects like planetesimals and planets, which influences the collision frequencies, planetary buildup timescales, and orbital stability of planets (Ida et al. 2000; Kominami & Ida 2002; Bryden et al. 2000). For these reasons, it is critical to establish the timescales during which gas persists around young stars.

Since molecular hydrogen is not easily observed from the ground, carbon monoxide (CO) is often used to trace gaseous disks. Although CO may freeze out onto dust particles in the cold, outer ($> 30 - 100$ AU) regions of disks, CO sub-millimeter transitions are very sensitive probes of warm gas in the inner, planet forming region. In this proposal we focus on constraining the gas disk content around both "weak-line" T-Tauri stars (WTTSs) and "classical" T-Tauri stars (CTTSs). CTTSs exhibit evidence for gas and dust rich disks thought to be remnants of the star formation process itself. WTTSs lack such evidence. Compared to the strong Hα emission of CTTSs, due to disk accretion, WTTSs have weak Hα emission. They are also young, < 10 Myr. Recently, new *Spitzer* surveys and sensitive sub-millimeter surveys have revealed evidence for tenuous dust emission associated with a few WTTSs. The question arises: do these very young (1–3 Myr old) T-Tauri stars—lacking evidence for active accretion, yet exhibiting evidence for tenuous dust emission—retain any remnant gas?

In a Cores to Disks (c2d) *Spitzer* Legacy Project, Padgett et al. (2006) have detected, in the Taurus, Ophiuchus, and Lupus dark clouds, two WTTSs with 70 μm excess emission. 70 μm emission is thought to trace cool dust at 10–100 AU. Cieza et al. (2007) detect with *Spitzer* an additional two WTTSs with 24 μm excess, indicative of warm dust located between 1–10 AU. In addition to these WTTSs, Andrews & Williams (2005) detect the sub-millimeter continuum of five "class III" T-Tauri stars, tracing dust at ~ 30 AU. We add to this sample the Taurus dark cloud object and binary CTTS St 34, around which White & Hillenbrand (2005) have detected a long-lived accretion disk. Lastly, McCabe et al. (2006) detect the WTTS binary WSB 28 with one component showing evidence for a 10 μm excess yet lacking accretion. Although the SMT's beam size would encompass both components of the binary, it would still be useful to place gas mass upper limits on the pair.

While there have been previous searches for CO around extremely young (~ 1 Myr) pre-main sequence stars (e.g. Dutrey et al. 1996) and mature, main sequence objects (e.g. Zuckerman, Forveille, & Kastner 1995), the sample selected for this proposal is unique in several aspects. First, unlike previous surveys which observed mainly A-type stars, we will specifically target solar mass objects to infer the evolutionary timescales of the gaseous disks around solar analogs. The CO results will place valuable constraints on the gas mass and its distribution as a function of target age.

Likewise, it will constrain evolutionary time scales of gas dissipation and the formation of gas–giant planets.

2. Model Predictions

In preparation for the *Formation and Evolution of Planetary Systems* (FEPS) *Spitzer* Legacy program, Gorti & Hollenbach (2003) have constructed a chemical/thermal model of the gas in debris disk systems. In these models, the vertical structure of the gas disk is set self-consistently by the gas temperature, which is calculated at each radius and height by equating the heating to the cooling. In addition, the chemistry is calculated, assuming as a first approximation that chemistry is steady state, self-consistently with the temperature and density at each spatial point. The model's main parameters are the mass of small (less than 1 mm radius) dust particles, the mass of the gas, the radial surface distribution of gas and dust, and the mass and frequency-dependent luminosity of the central star. One of the preliminary (but not too surprising) results of the models is that the CO sub-millimeter lines are one of the most sensitive probes of the presence of gas in the inner regions where CO does not freeze.

Figure 1 shows the predicted integrated line intensities from these preliminary models for a G star at a fiducial distance of 30 pc, which is representative of the sample of stars we propose to observe in all respects except distance (see below). In these models, the surface density of gas and dust are proportional to r^{-1} but the results are not sensitive to the exact power law, as long as the exponent is greater than -2. The disk has an outer edge of 30 AU, which can either be thought of as a true physical edge (caused by photoevaporation for example), or as the radius beyond which CO freezes onto dust[1]. The dust size distribution has an $a^{-3.5}$ power law distribution extending from micron size to millimeter size. Plotted are the line strengths of the main isotope CO 3-2, 2-1, and 1-0 lines as a function of the gas mass, for two different amounts of dust mass: 10^{-6} and 10^{-9} solar masses. Recall that dust is defined here as particles smaller than 1 mm, the dust that millimeter continuum observations detect, so that a large amount of the solid material could be hidden in larger objects like planets. During the planet formation process, the dust to gas mass ratio can vary widely, in both directions, from the interstellar value of 10^{-2} due to gas dispersal and coagulation of dust particles.

We propose to answer this question by attempting to detect CO in a sample of nearby T Tauri stars. In 2 hour of on-source integration time on the SMT, we can achieve a 5σ detection limit of 0.07 K km s^{-1} for ^{12}CO $J = 2-1$ and 0.14 K km s^{-1} for ^{12}CO $J = 3-2$ for a line width of 2 km/s.[2] At these limits, we will be sensitive to total gas masses of $10^{-6} - 10^{-5}$ $M_{\odot}$, or $10^{-3} - 10^{-2}$ $M_{\rm Jupiter}$. Therefore, in the context of these model calculations, these observations will place definitive constraints on the time scales to form gas-giant planets around solar mass stars and be sensitive enough to trace amounts of circumstellar gas.

3. Proposed Observations

[1]The true freezeout radius may be somewhat larger, but this would only increase our CO line strength and make this proposed survey even more sensitive to gas mass.

[2]For these sensitivity calculations, we assumed system temperatures of 450 K at 230 GHz and 850 K at 345 GHz.

Table 1 lists the targets we propose to observe. Since we will have detailed information on each of these stars, we aim to observe all of them with the SMT, which will allow us to make global statements concerning their molecular gas content.

We will integrate 2 hours on source in order to achieve the sensitivity limits that will allow us to trace as little as $10^{-6} - 10^{-5}$ $M_\odot$ of molecular gas. Assuming an equal factor of time on the off-position, and additional 20% overhead for slewing, tuning, and observing standard spectra, the total time per source will be 2.4 hours. The total time then to observe all sources in our sample will then be 29 hours. We request five observing blocks: two from 23h–9h LST to observe our Taurus objects and three from 15h–18h LST to observe the Ophiuchus/Lupus objects; because of Ophiuchus's and Lupus's low declinations at the SMT, they are visible for only a few hours. We will preferentially try to observe CO(3-2), weather permitting, for our targets since that transition is ~ 3 times more sensitive to gas mass than CO(2-1). If CO(3-2) observations are not feasible, we will observe CO(2-1) only. Since some of our objects are not outside a CO-emitting molecular cloud, there may be significant confusion. To measure those objects' intrinsic CO emission we would then need to spend additional time (~ 15 min per source) making a small CO map of the gas cloud around each source.

References

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Table 1: Source List

N	Source	α (J2000)	δ (J2000)	Distance (pc)
Taurus objects				
1	FW Tau	04:29:29.70	26:16:53.48	
2	RX J0432.8+1735	04:32:53.23	17:35:33.68	140
3	V807 Tau	04:33:06.63	24 09 55.14	
4	HQ Tau	04:35:47.34	22:50:21.70	
5	LkHa 332/G1	04:42:07.77	25:23:11.80	
6	St 34	04:54:23.70	17:09:54.00	
7	LkCa 19	04:55:36.96	30:17:55.31	
Ophiuchus/Lupus objects				
8	RX J1603.2-3239	16:03:11.81	-32:39:20.20	150
9	RX J1622.6-2345	16:22:37.58	-23:45:50.76	
10	WSB 28	16:26:20.90	-24:08:51.00	
11	ROXs 36	16:29:54.58	-24:58:45.84	

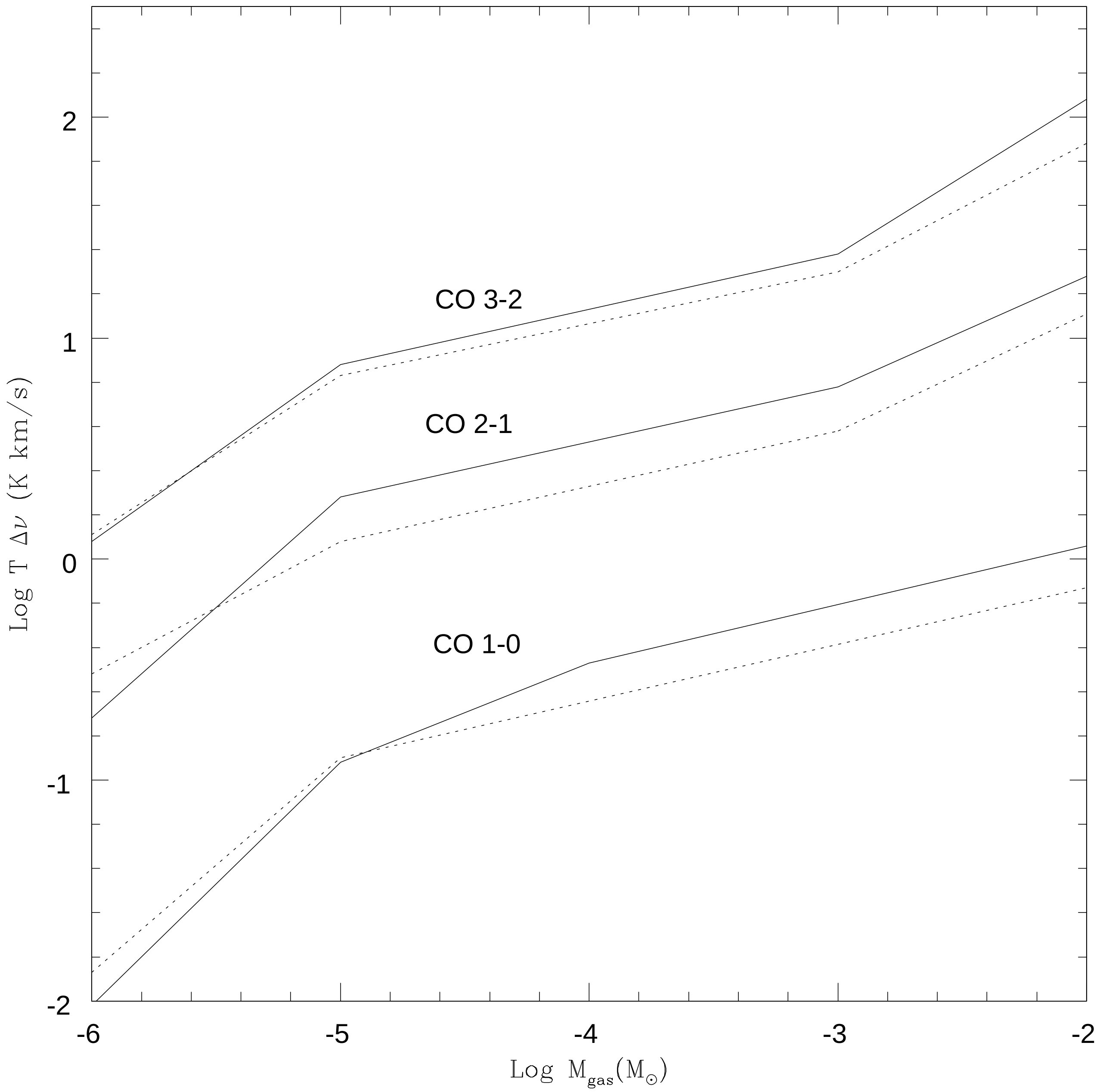

Figure 1: Predicted integrated line intensities for the ^{12}CO $J = 1 - 0$, $J = 2 - 1$, and $J = 3 - 2$ rotational transitions as a function of total gas mass for the debris disk model by Gorti & Hollenbach (2003). The solid and dotted lines show the predicted intensities for a dust mass of 10^{-6} $M_{\odot}$ and 10^{-9} $M_{\odot}$ respectively. With the SMT, we can achieve a 5σ sensitivity of 0.07 K km/s at 230 GHz and 0.14 K km/s at 346 GHz, and detect as little as 10^{-6} $\mathrm{M}_{\odot}$ (0.001 $\mathrm{M}_{\mathrm{Jupiter}}$). By observing a sample of stars in the ages less than 100 Myr, we will place stringent limits on the amount of molecular gas around young solar mass stars. (Note: this plot is for objects at $\sim$ 30 pc whereas our sources are at $\sim$ 150 pc.)