Detection of a Molecular Disk Orbiting the Nearby, "Old," Classical T Tauri Star MP Mus[1]

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ABSTRACT

We have used the Atacama Pathfinder Experiment 12 m telescope to detect circumstellar CO emission from MP Mus (K1 IVe), a nearby ($D \sim 100$ pc), actively accreting, ~ 7 Myr-old pre-main sequence (pre-MS) star. The CO emission line profile measured for MP Mus is indicative of an orbiting disk with radius ~ 120 AU, assuming the central star mass is 1.2 $M_\odot$ and the disk inclination is $i \sim 30°$, and the inferred disk molecular gas mass is $\sim 3M_\oplus$. MP Mus thereby joins TW Hya and V4046 Sgr as the only late-type (low-mass), pre-MS star systems within ∼100 pc of Earth that are known to retain orbiting, molecular disks. We also report the nondetection (with the Institut de Radio Astronomie Millimetrique 30 m telescope) of CO emission from another ten nearby ($D \lesssim 100$ pc), dusty, young (age $\sim 10 - 100$ Myr) field stars of spectral type A–G. We discuss the implications of these results for the timescales for stellar and Jovian planet accretion from, and dissipation of, molecular disks around young stars.

Subject headings: circumstellar matter — stars: emission-line — stars: individual (MP Mus)

1. Introduction

Over the past two decades, astronomers have identified a few hundred young (ages ~ 5 to ∼100 Myr) stars, including more than a half-dozen T Tauri and post-T Tauri associations,

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within ∼100 pc of Earth (Kastner et al. 1997; Zuckerman & Song 2004; Torres et al. 2008, and references therein). Most such stars have been identified on the basis of their characteristically large X-ray fluxes, thermal infrared emission from warm circumstellar dust, optical spectral features (principally, strong Li absorption lines), and/or distinctive space velocities (see discussion in Zuckerman & Song 2004). Based on the low frequency of mid- to far-infrared excesses among the nearby, young stellar groups, only a small percentage of such stars evidently retain massive, dusty, circumstellar disks (e.g., Rebull et al. 2008), in contrast to the large disk fractions of pre-main sequence (pre-MS) star populations associated with molecular clouds (e.g., Wyatt 2008). This contrast reflects the relatively advanced ages of the known young stars within ∼ 100 pc and suggests that, while many may still be building terrestrial planets (Melis et al. 2010), most have already moved beyond the epoch of active giant planet formation.

Examples of *actively accreting*, low-mass pre-MS stars (i.e., classical T Tauri stars; cTTS) within ∼100 pc are rarer still (Torres et al. 2008). The archetype of these nearby cTTS systems — which are characterized by their unusually large Hα emission equivalent widths — is the intensively studied TW Hya. At a distance of 56 pc, TW Hya is among the closest known cTTS[2]. With an estimated age of ∼ 8 Myr (Zuckerman & Song 2004; Torres et al. 2008), TW Hya also remains one of the oldest known examples of a cTTS. In the latter regard, however, it is rivaled by two other, nearby systems: the close binary cTTS V4046 Sgr (age ∼ 12 Myr, distance 72 pc; Torres et al. 2008; Kastner et al. 2008b, and references therein) and the cTTS MP Mus (= PDS 66; Mamajek et al. 2002; Argiroffi et al. 2007; Cortes et al. 2009). Estimates of the age and distance of the latter star range, respectively, from 6 Myr to 17 Myr and from 86 pc to 103 pc (Mamajek et al. 2002; Torres et al. 2008). The younger age (hence larger distance) appears more accurate, given the Li absorption line strength of MP Mus (Weise et al. 2010) and its likely association with the ϵ Cha group (Torres et al. 2008). High-resolution (gratings) X-ray spectra of TW Hya, V4046 Sgr, and MP Mus reveal evidence for a significant emission contribution from accretion shocks, as opposed to coronal activity (Kastner et al. 2002; Stelzer & Schmitt 2004; Günther et al. 2006; Argiroffi et al. 2007). This is consistent with observations demonstrating that the Hα and UV emission from each of these three stars is stronger than that typically associated with pure chromospheric activity (Huenemoerder et al. 2007).

Radio molecular line emission studies of circumstellar planet-forming disks provide unique insight into the Jovian planet, Kuiper Belt, and comet formation zones within

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[2] The TW Hya Association (TWA) members Hen 3-600 ($D \sim 45$ pc; Huenemoerder et al. 2007, and references therein) and TWA 30AB ($D = 42$ pc; Looper et al. 2010a,b) are the closest known examples of actively accreting, low-mass stars.

the outer regions (tens to hundreds of AU in radius) of pre-MS circumstellar disks (e.g., Zuckerman et al. 1995; Dutrey et al. 1997; Thi et al. 2004). Thus far, however, only four star-disk systems within ~ 100 pc of Earth have been detected in molecular emission lines with a radio telescope: the aforementioned ~ 10 Myr-old, K-type cTTS systems TW Hya (Zuckerman et al. 1995; Kastner et al. 1997) and V4046 Sgr (Kastner et al. 2008b), and the A-type stars 49 Cet and HD 141569 (ages ~ 20 and ~ 5 Myr, respectively; Zuckerman et al. 1995). Detections of a suite of molecular transitions toward TW Hya established that it possesses a rich molecular disk viewed nearly pole-on (Kastner et al. 1997; Thi et al. 2004), while the double-peaked molecular line profiles characteristic of Keplerian rotation observed toward V4046 Sgr (Kastner et al. 2008b) similarly demonstrated that this close (period 2.4 d) binary system is orbited by a circumbinary molecular disk. These single-dish radio molecular line spectroscopy results have subsequently been confirmed via radio interferometric (Submillimeter Array) imaging of CO emission (Qi et al. 2004, 2006; Rodriguez et al. 2010).

In an effort to similarly characterize the gas mass, dynamics, and chemistry within the disk of MP Mus (spectral type K1 IVe), we searched for, and detected, CO emission from MP Mus with the Atacama Pathfinder Experiment (APEX) 12 m telescope[3]. In this paper, we report on these results and their interpretation. We also report the nondetection of CO emission from a sample of ten other nearby ($D \lesssim 100$ pc), dusty, young (ages $\sim$ 10–100 Myr) stars of spectral type A–G with the Institut de Radio Astronomie Millimetrique (IRAM) 30 m telescope.

2. Observations and Results

2.1. IRAM 30 m telescope CO observations of nearby, dusty young stars

We observed the ten stars[4] in Table 1 in the 230.538 GHz $J = 2 \rightarrow 1$ transition of ^{12}CO with the IRAM 30 m telescope in August 2009. These stars (Table 1) were chosen from the list of Rhee et al. (2007) on the basis of large infrared excesses (indicative of disk dust masses $M_d \gtrsim 0.05 M_\oplus$) and estimated ages $\lesssim 100$ Myr. We observed all target stars using IRAM's

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[3] APEX is a collaboration between the Max-Planck-Institut fur Radioastronomie, the European Southern Observatory, and the Onsala Space Observatory.

[4] During the 2009 August IRAM 30 m observing run we also observed the young late-A/early-F star HR 8799, which is orbited by multiple giant planets and debris disks (Marois et al. 2008; Su et al. 2009). As mentioned by Su et al. (2009), our ^{12}CO(2–1) spectrum established that bright interstellar emission is present at the radial velocity of the star, precluding any attempt to constrain its circumstellar gas mass via single-dish CO measurements.

EMIR receivers and VESPA autocorrelator, with velocity resolution of 0.8 km s^{-1}. Spectra were acquired in wobbler switching mode, resulting in flat baselines for individual spectra. Total on-source integration times were between 1 and 2 hours per star. The weather was generally good ($\tau_{225} \sim 0.25$–0.4) throughout the observations, with time-averaged system temperatures in the range 220–510 K. Pointing and focus were checked (against standard pointing sources and planets) every ∼2 hours. Typical pointing errors were $\sim 3''$, i.e., ∼1/4 beamwidth (FWHP $12''$ at 230 GHz).

We used the CLASS[5] radio spectral line data reduction package to sum over individual spectral scans obtained for each star, and then to subtract a linear-fit baseline from each of the resulting integrated spectra, calculating channel-to-channel noise levels in the process. No CO emission lines were evident in any of the resulting spectra obtained for the ten sample stars. Upper limits on main-beam brightness temperature T_{mb} (assuming $F_{eff} = 0.94$ and $\eta_{mb} = 0.52$ for measurements at 230 GHz with the IRAM 30 m telescope) and velocity-integrated CO line intensity I are reported in Table 1 as the values $3\sigma_T$ and $3\sigma_I$, respectively, where σ_T is the efficiency-corrected rms channel-to-channel noise in the CO spectrum and $\sigma_I = \sigma_T\sqrt{\Delta v \delta v}$, with velocity resolution $\delta v = 0.8$ km s^{-1} and an assumed linewidth $\Delta v = 3$ km s^{-1}.

2.2. APEX 12 m telescope CO observations of MP Mus

Service-mode APEX 12 m telescope observations of MP Mus (J2000 coordinates α =13:22:07.55, δ =−69:38:12.2) in the 345.796 GHz $J = 3 \rightarrow 2$ transition of ^{12}CO were performed on 15 and 16 April 2010 UT. The receiver was SHFI/APEX2, using the facility FFTS backend with velocity resolution 0.21 km s^{-1}. Spectra were acquired in position switching mode using the wobbler. Total on-source integration time was 138 min. The weather was generally good throughout the observations ($\tau_{225} \sim 0.2$; pwv 1.8 mm; time-averaged system temperature ~ 500 K). The best focus was established at the beginning of each day's observations, and regular pointing checks (using nearby planets and quasars as references) indicated pointing errors were $\lesssim 2''$, i.e., $\sim \frac{1}{8}$ beamwidth (FWHP $17.5''$ at 345 GHz). APEX spectra of MP Mus were reduced using CLASS, as described in §2.1.

The resulting, integrated, baseline- and beam-efficiency-corrected spectrum (assuming $\eta_{mb} = 0.73$ for measurements at 345 GHz with the APEX 12 m telescope) is presented in Fig. 1. This spectrum clearly reveals the detection of ^{12}CO(3–2) emission from MP Mus. From a Gaussian fit to the line profile, we find the central velocity to be $+3.9 \pm 0.3$ km s^{-1}

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[5] See http://iram.fr/IRAMFR/GILDAS/

with respect to the local standard of rest (LSR). This translates to a heliocentric velocity of 11.3 ± 0.3 km s^{-1}, which is consistent with the systemic velocity of MP Mus as determined from optical spectroscopy (11.6 ± 0.2 km s^{-1}; Torres et al. 2006). The integrated line intensity obtained from the best-fit Gaussian is 0.21 ± 0.03 K km s^{-1}.

3. Analysis

3.1. MP Mus: constraints on molecular disk radius and mass

Given the signal-to-noise ratio of the CO(3–2) data obtained for MP Mus (Fig. 1), we cannot unambiguously determine the underlying emission line profile. However, the steep sides and possible central valley (i.e., double-peaked appearance) of the MP Mus CO emission line are features expected in the case of an orbiting molecular disk (e.g., Beckwith & Sargent 1993). Hence, we fit the profile with a parametric representation of the line profile predicted by the Keplerian disk model of Beckwith & Sargent (1993) as described in Kastner et al. (2008a). Provided the observed line profile is well fit, this method yields an estimate of outer disk rotation velocity v_d — where v_d is equivalent to the half-value of the velocity separation of the red and blue peaks in the double-peaked line profile predicted for Keplerian rotation — as well as measures of the slopes of the inner and outer portions of the line profiles (p_d and q, respectively). The value of q serves as an indication of the slope of the disk radial temperature profile ($T \propto r^{-q}$), while p_d indicates the degree of central filling of the line profile by emission from gas at low radial velocities (e.g., for a nearly edge-on disk, $p_d = 1$ would correspond to a sharp outer edge and values $p_d < 1$ would indicate lack of a sharp edge).

The observed line profile is overlaid with the best-fit model profile in Fig. 1. The comparison confirms that the CO line emission profile of MP Mus is consistent with that of a molecular disk in Keplerian rotation. The best-fit Keplerian model parameter values (and formal uncertainties on these values) are $v_d = 1.6 \pm 0.16$ km s^{-1}, $q = 0.5 \pm 0.2$, and $p_d = 0.25 \pm 0.1$. The best-fit value of q is compatible with standard models of Keplerian disks (e.g., Beckwith & Sargent 1993).

Given an estimate for the mass of MP Mus, $M_\star$, the best-fit value of v_d can be used to place constraints on the molecular disk outer cutoff radius $R_{out,CO}$ for an assumed disk inclination i (e.g., Zuckerman et al. 2008, and references therein). Adopting $M_\star = 1.2\ M_\odot$ (based on comparison with pre-MS evolutionary tracks; Mamajek et al. 2002) and $i = 32^\circ$ (based on the morphology of the disk as detected in coronagraphic imaging of starlight reflected off of dust; Cortes et al. 2009), the result $v_d = 1.6$ km s^{-1} implies $R_{out,CO} \approx 120$

AU. This is somewhat smaller than the outer disk radius inferred (also on the basis of coronagraphic imaging) by Cortes et al. (2009), i.e., $R_{out,d} \approx 170$ AU, assuming a distance to MP Mus of 86 pc. However, given the uncertainties in our line profile analysis as well as in the mass, age, and distance of MP Mus (§4) — and the possibility that the (3–2) transition of CO is not well excited within the outermost regions of the disk — it appears our estimate of the radius of the molecular disk is in reasonable agreement with the dust disk radius as measured coronagraphically.

The best-fit Keplerian model ^{12}CO(3–2) line profile area is slightly larger than that obtained from the Gaussian fit (§2.1), i.e., 0.26 ± 0.03 K km s^{-1}. This is a factor ~ 7 weaker than the integrated ^{12}CO(3–2) line intensity of TW Hya as measured with the JCMT (Kastner et al. 1997), suggesting that the intrinsic total ^{12}CO(3–2) line intensity of MP Mus is a factor ~ 3 smaller than that of TW Hya, after accounting for the difference in JCMT and APEX beam sizes and assuming MP Mus lies at ~ 100 pc (§4). The measured total APEX ^{12}CO(3–2) line intensity of MP Mus is equivalent[6] to an integrated line flux of 10.5 ± 1.5 Jy km s^{-1}. This result can be used to estimate the molecular gas mass of the MP Mus disk (e.g., Zuckerman et al. 2008, and references therein) — albeit with large uncertainties, especially given that thus far we have no measurements of other CO isotopes and (hence) no means to estimate the ^{12}CO(3–2) line optical depth (τ_{32}) other than the foregoing rough comparison with TW Hya. Adopting the standard assumptions of a CO:H$_2$ number ratio of 10^{-4} and molecular gas excitation temperature $T_{ex} = 40$ K, and assuming $\tau_{32} = 3$ (i.e., a factor ~ 3 smaller than that inferred for TW Hya; Kastner et al. 2008b, and references therein) we obtain a molecular (H$_2$) gas mass of $\sim 9 \times 10^{-6}\ M_\odot$ (i.e., $\sim 3 M_\oplus$). This inferred disk gas mass, which scales approximately linearly with τ_{32} if the ^{12}CO(3–2) is optically thick, is somewhat less than the circumstellar dust mass of 17 $M_\oplus$ determined for MP Mus by Carpenter et al. (2005) on the basis of the star's 1.2 mm flux.

3.2. Other nearby, dusty, young stars: gas mass upper limits

We used the same method just described for MP Mus to estimate molecular gas mass upper limits for the dusty disks of the ten stars observed with, but not detected by, the IRAM 30 m. The results, obtained under the assumptions CO:H$_2 = 10^{-4}$, $T_{ex} = 40$ K, and $\tau_{21} = 1$, are reported in Table 1. These upper limits are of course subject to the same uncertainties just described in the case of MP Mus. Nevertheless, the results in Table 1 indicate that, for these ten stars, the disk gas masses are constrained to be of order of (or smaller than) a few

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[6] See http://www.apex-telescope.org/telescope/efficiency/

times the dust masses inferred from far-IR (IRAS) data, provided the CO emission is not optically thick or that gas-phase CO in these disks is not severely depleted relative to H_2.

4. Discussion

With our CO detection of a disk orbiting MP Mus, this star joins ∼8 Myr-old TW Hya and ∼ 12 Myr-old V4046 Sgr as the only late-type (therefore low-mass) pre-MS stars within ∼ 100 pc of Earth that are known to retain orbiting molecular disks. In all three cases, the circumstellar gas masses inferred from far-IR and radio emission lines — a few to a few hundred $M_\oplus$ (Kastner et al. 1997; Rodriguez et al. 2010; Thi et al. 2010, and references therein) — are similar to the dust masses determined from far-IR and (sub)mm photometry. This implies dust-to-gas ratios near unity in the outer ($\gtrsim$ 10 AU) regions of these disks and/or, in the case of gas mass estimates based on radio CO lines, that gas-phase CO is severely depleted relative to H_2.

The overall similarity of MP Mus to the TW Hya and V4046 Sgr star-disk systems favors the younger end of the range of ages estimated to date for MP Mus. This is consistent with the recent results of Weise et al. (2010), who estimated an age of 7 ± 3 Myr based on the Li absorption line strength of MP Mus. An age of ∼ 7 Myr would, in turn, imply the distance to MP Mus is ∼ 100 pc (Torres et al. 2008). For such a distance, the mass of MP Mus could be ∼ 20% larger than previously determined (i.e., closer to 1.4 $M_\odot$), depending on the adopted theoretical pre-MS evolutionary tracks (Mamajek et al. 2002, and references therein). If so, the CO and dust disk radii would be correspondingly larger than the estimates stated in §3.1.

Given the relatively advanced pre-MS evolutionary states of TW Hya, V4046 Sgr, and MP Mus, their circumstellar environments likely are in transition from predominantly primordial material to "debris" disks that are populated by dust grains generated via collisions between rapidly growing planetesimals (Cortes et al. 2009, and references therein). The stars for which we failed to detect molecular gas (Table 1) likely fall into this latter category; all of the Table 1 stars have disk dust masses much smaller than those of TW Hya, V4046 Sgr, and MP Mus, and all have ages ≥10 Myr. The comparison of the residual gas masses of the three nearby cTTS with the gas mass upper limits in Table 1 thereby further reinforces the notion that the gaseous disks required to spawn Jovian planets dissipate rapidly, i.e., within the first few Myr of pre-MS evolution (Zuckerman et al. 1995).

"Transition disks" usually display evidence for inner (radii ∼ a few AU) disk clearings that may be the results of recent or ongoing planet formation (e.g., Calvet et al. 2005). In this respect, MP Mus, TW Hya, and V4046 Sgr are typical of transition disk systems; all three lack the significant near-IR excesses, indicative of hot dust in inner disks, that are characteristic of rapidly accreting cTTS in molecular clouds (e.g., Meyer et al. 1997). At the same time, like certain cTTS in Taurus that display transition disks (DM Aur and GM Aur; Calvet et al. 2005), all three nearby, late-type stars with detectable circumstellar CO emission also display spectral evidence for ongoing accretion — evidence that (to our knowledge) is lacking in the cases of the Table 1 stars. The fact that TW Hya, V4046 Sgr and MP Mus are evidently still accreting from their "transition disks" may indicate that they are orbited by young planets (see discussion in Salyk et al. 2007). Regardless, the detections of CO in the dusty disks of MP Mus, TW Hya and V4046 Sgr suggest that the presence of residual disk molecular gas is closely linked to (likely enables) sustained accretion activity at advanced pre-MS ages.

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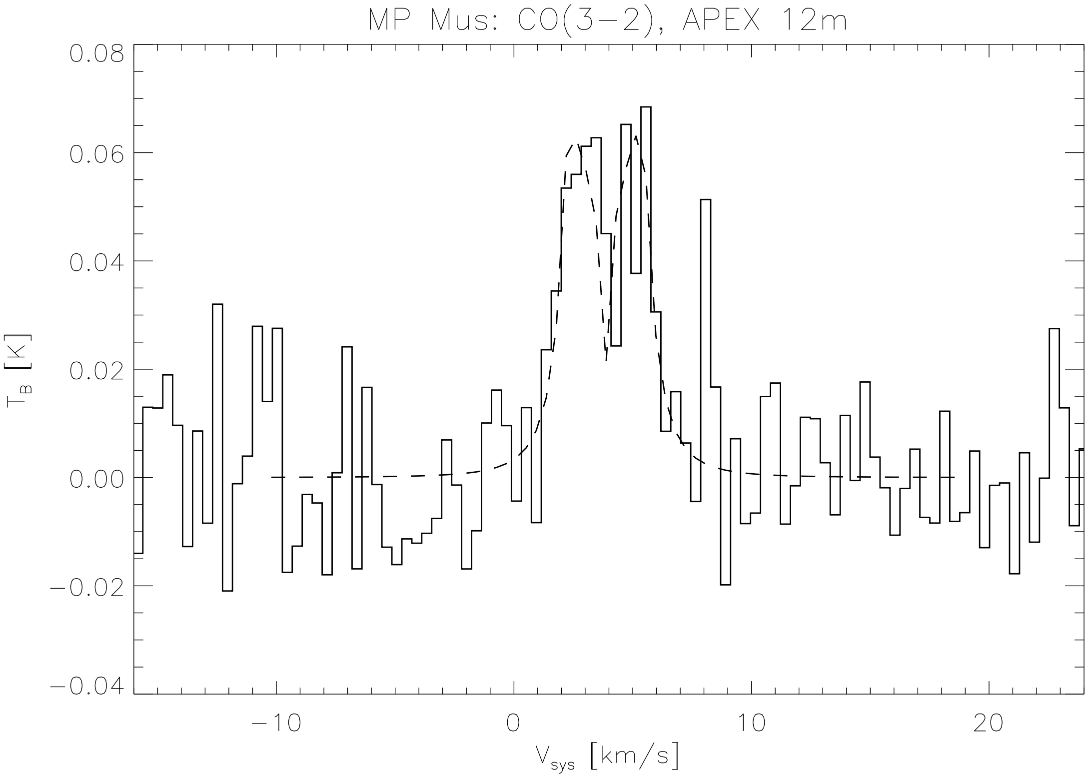

Fig. 1.— ^{12}CO(3–2) line profile of MP Mus as measured by the APEX 12 m telescope and spectrometer (solid line) overlaid with best-fit Keplerian disk model profile (dashed line). Ordinate is velocity with respect to the local standard of rest and abscissa is main-beam brightness temperature. The spectrometer data have been Hanning smoothed to a velocity resolution of 0.4 km s^{-1}. The rms noise level of the spectrum is 13 mK per 0.4 km s^{-1} bin.

Table 1: IRAM 30 m CO Observations of Nearby, Dusty Stars

HD	α	δ	sp. type^a	D^a	age^a	${M_d}^a$	$3\sigma_T$	$3\sigma_I$		M_g
	(J2000)			(pc)	(Myr)	($M_\oplus$)	(mK)	(K km s^{-1})	(Jy km s^{-1})	($M_\oplus$)
15745	02:32:55.81	37:20:01.0	F0	64	30?	0.09	75	0.40	3.2	< 0.6
21997	03:31:53.64	−25:36:50.9	A3	74	50?	0.22	126	0.66	5.2	< 1.3
30447	04:46:49.52	−26:18:08.8	F3	78	< 100	0.13	147	0.77	6.0	< 1.7
32297	05:02:27.43	07:27:39.6	A0	112	20?	0.46	93	0.50	3.9	< 2.2
38206	05:43:21.67	−18:33:26.9	A0	69	50	0.06	156	0.81	6.4	< 1.4
85672	09:53:59.15	27:41:43.6	A0	93	30?	...	69	0.36	2.8	< 1.1
107146	12:19:06.50	16:32:53.8	G2	29	< 100	0.09	57	0.30	2.4	< 0.09
131835	14:56:54.46	−35:41:43.6	A2	111	10	0.2	207	1.1	8.4	< 4.8
191089	20:09:05.21	−26:13:26.5	F5	54	< 30	0.03	132	0.69	5.4	< 0.7
221853	23:35:36.15	08:22:57.4	F0	71	< 100	0.05	57	0.30	2.4	< 0.6

a) Spectral types, distances, ages, and estimated dust masses as listed in Rhee et al. (2007).