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CO EMISSION IN THE INNER DISK AROUND YOUNG INTERMEDIATE-MASS STARS

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ABSTRACT

We present observations that indicate viscous heating contributes significantly to the surface heating of the inner disk region (0.1-5 AU) around young intermediate-mass stars, Herbig AeBe stars, when the inner disk is optically thick. Brγ flux is known to scale with accretion rate around young stars. We find a trend between Brγ and CO emissivity, a tracer 1,500 K gas in the gaseous atmospheres of less evolved inner disk regions in a sample of 25 Herbig AeBe stars, the higher mass analog of T Tauri stars. Evolved Herbig circumstellar disks do not follow this trend as closely. A thermal chemical model of the inner disk region of T Tauri stars by Glassgold et al. (2004) explains the strength and line profiles of observed CO rovibrational emission by showing that accretion contributes significantly to heating the protoplanetary disk. This heating produces the required temperatures and column densities for CO emission in the disk. Our results are consistent with these prescribed disk characteristics. Determining conditions and processes in circumstellar disks around young stars will help inform evolutionary theory and constrain timescales of disk dissipation and planet formation.

Subject headings: accretion, accretion disk — circumstellar matter — planetary systems: protoplanetary disks — stars: pre–main-sequence

1. INTRODUCTION

Planets form deep within circumstellar disks around young stars long before the incredibly optically thick disks dissipate enough to allow for observations of the new planets. Understanding how the dust and gas in the disk evolve can help develop early planet formation theory and timescales. Observations of a young star and its orbiting disk are used to measure properties such as the physical structure, chemical composition, and flow dynamics. These measurements can constrain conceptual models that seek to reproduce and predict properties and processes of protoplanetary disks.

The inner disk region is particularly interesting. Extending from .1 to 5 AU, the inner region around our sun would include the terrestrial planets and Jupiter. The challenge in studying this region around young stars is a result of the small angular size the inner disk region subtends – 0.01 arcseconds at the distance of the closest stellar nurseries in the Orion Nebula. For this reason spectroscopy must be used and emission line diagnostics must be found.

Young solar-mass stars, known as T Tauri stars, have been well studied and are characterized by circumstellars disks, outflows, variability, and rich emission line spectrum (Appenzeller & Mundt 1989). Muzerolle et al. (2004) have shown that Brγ, the n=7 to n=4 transition of atomic hydrogen, is a diagnostic for accretion luminosity and supports the magnetospherical accretion model. Magnetoshperical accretion is the process of gas and dust being drawn from the circumstellar disk through funnel flows along magnetic field lines and crashing onto the surface of the star close to the poles at near free-fall speeds. The accretion mechanism for the less studied intermediate-mass analogs of T Tauri stars, Herbig AeBe stars (2-10 $M_\odot$), is still debated. Herbig AeBe stars do not have strong global magnetic fields, an important component for accreting magnetospherically, but also exhibit characteristics supporting magnetoshperical accretion, like high-velocity redshift absorption features denoting matter falling quickly towards the star (Muzerolle et al. 2004). Despite the lack of a definitive accretion mechanism in the literature, Donehew & Brittain (2011) have calibrated the Brγ emission line to the accretion luminosity for Herbig Ae stars – the trend breaks down for Herbig Be stars.

Other known diagnostics of Herbig AeBe stars and their protoplanetary disks are CO rovibrational emission lines, which trace the inner disk region based on their velocity broaden emission line profiles. CO, the second most abundant molecule in disks after molecular Hydrogen, is a sensitive probe of planet forming regions in the disk (Blake & Boogert 2004). It is known that CO can be detected at quantities of much less than an Earth mass.

Because almost all the of material in the inner disk region will accrete onto the star or form into planets, it is important to understand the dynamics in the disk to constrain timescale of planet formation and disk dissipation. Data from the interior of the disks is sparse because of the incredibly optically thick nature of disks, making it difficult to model dynamics. A slightly less formidable task is modeling the static thermal chemical conditions in disk atmospheres which has been conducted by Glassgold et al. (2004) for T Tauri stars. Glassgold and co-authors provide a physical basis for accretion-related processes to affect processes in the disk, like heating (2004). They expect that if accretion is high then the hot gaseous surface

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TABLE 1
PHOENIX Observations

Star	Data
HD 34282	2006 Jan 14
HD 37806	2006 Jan 13
HD 97048	2006 Jan 13
HD 98922	2006 Jan 13
HD 100546	2006 Jan 14
HD 101412	2006 Jan 13
HD 142527	2008 Mar 23
HD 144668	2008 Mar 23
HD 150193	2008 Mar 23
V380 Ori	2006 Jan 13

layer extends deep into the disk where column densities are great, which results in a large CO emission feature. This was supported empirically by a preceding paper by Najita et al. (2003), who showed T Tauri stars follow the same trend of accretion rate (traced by Brγ) correlating with CO luminosity.

In this paper we show that the trend found by Najita et al. (2003) with T Tauri stars is followed by Herbig AeBe stars with optically thick inner disks. In section 2 we discuss observations and present our sample. We present CO data which we reduced, in section 3.1 and the correlation found in our sample in section 3.2. We discuss the implications of our findings in section 4.

2. DATA AND OBSERVATIONS

2.1. *Data*

Our sample consisted of 25 total Herbig Ae stars including 3 that are known to have transitional disks. For our purposes we sought the brightest sources spanning A9-B6, with flux measurement of both H I (Brγ) and CO v=1-0 P(26) and P(30) emission. The literature provides the majority of our data. Brγ measurements are found in Donehew & Brittain (2011) Donehew Ph.D. Thesis (2011), and Garcia Lopez et al. (2006). CO measurements are from Brittain et al. (2007), Brittain et al. (2009), Blake & Boogert (2004), and Troutman (2010). Table 1 contains the objects we observed and the dates they were observed. The Brγ and CO measurements for all stars in the sample are reported in Table 2 and ancillary stellar parameters are listed in Table 3.

2.2. *Observations and Reduction*

We reduced ten Herbig spectra and three standard star spectra taken with the PHEONIX spectrograph (R = 50,000 - 80,000; .34” slit) on the 8.1 meter Gemini South telescope in central Chile. Multiple observing runs spanned January 13, 2006 to March 24, 2008. Systematic effects were removed by using flats and darks taken with each grating setting. Background emissions were corrected by nodding the telescope in the ABBA pattern between positions spaced by a small distance, usually 15”, along the slit and combining the 30 seconds exposures as (A-B-B+A)/2. Total integration time per star ranged from 2-12 minutes. To extract the 1-D spectrum, the full width at half-maximum (FWHM) of the spatial profiles in each of the two 2-D spectra rows where combined. Before removing the telluric absorption lines, we wavelength calibrated the spectra by aligning then with an atmospheric transmittance function model and then dividing out the standard star spectrum taken on the corresponding observing night (Zeta Ori on January 13 and 14, 2006, and HR 7121 on March 23, 2008). To compensate for the effect of varied telluric absorption line strengths when viewing the science and standard star at different air masses, we raised the standard star spectra to the power of the ratio of science star airmass and the standard star airmass.

TABLE 2
Flux Values

Star	$F_{Br\gamma}$ (10^{-14} erg s^{-1} cm^{-2})	F_{CO} [a] (10^{-14} erg s^{-1} cm^{-2})
51 Oph	$462^{b}\pm25$	$24^{e}\pm5$
AB Aur	$340^{c}\pm17$	$7.8^{e}\pm2$
HD 34282	$<32^{b}$	$<0.21^{f}$
HD 36112	$56^{c}\pm4$	$0.37^{g}\pm0.8$
HD 37806	$112.8^{c}\pm5.9$	$3.1^{f}\pm0.7$
HD 97048	$152^{b}\pm3$	$1.0^{f}\pm0.2$
HD 98922	$291^{d}\pm10$	$13^{f}\pm2.5$
HD 100453	$27.7^{d}\pm3.2$	$<0.07^{g}$
HD 100546	$539^{d}\pm19$	$1.2^{f}\pm0.3$
HD 101412	$12.2^{d}\pm1$	$1.5^{f}\pm0.3$
HD 104237	$635^{d}\pm22$	$13^{g}\pm2.7$
HD 139614	$30.3^{d}\pm3$	$0.33^{g}\pm0.07$
HD 141569	$36^{b}\pm2$	$<0.03^{e}$
HD 142527	$52^{b}\pm8.7$	$4.3^{f}\pm0.9$
HD 149914	$18^{b}\pm4.5$	$<0.32^{e}$
HD 150193	$152^{d}\pm7$	$3.0^{f}\pm0.7$
HD 163296	$373^{c}\pm11$	$4.5^{e}\pm0.9$
HD 169142	$142^{d}\pm7$	$<0.12^{g}$
HD 250550	$58^{c}\pm2$	$4.6^{e}\pm0.9$
HD 259431	$954^{e}\pm150$	$3.7^{e}\pm0.8$
HR 5999	$489^{b}\pm25$	$8^{f}\pm2$
MWC 480	$188^{c}\pm5$	$0.67^{g}\pm0.2$
SAO 185668	$125^{c}\pm4$	$<0.02^{e}$
V380 Ori	$179^{c}\pm4$	$3.0^{f}\pm0.6$
VV Ser	$137^{c}\pm3$	$0.41^{g}\pm0.09$

References. — [b] Garcia Lopez et al. (2006).
[c] Donehew and Brittain (2011).
[d] Donehew (2011), Ph.D. Thesis.
[e] Brittain et al. (2007).
[f] This work.
[g] Troutman (2010), Ph.D. Thesis.

Note. — [a] The dominate source of error is slit loss and is estimated to be ±20 percent.
Bold star names denote stars with evolved inner disk regions.

3. RESULTS

3.1. *CO*

Figure 1 displays the reduced spectra of 10 Herbig AeBe stars centered around the CO v =1-0 P(26) line (v= 2032.35 cm^{-1}). Most of the stars show apparent emission features while two (HD 34282 and HR 5999) are nearly flat. P(26) flux values are measured from these spectra and used in the correlation plot in Figure 2.

3.2. *Correlation*

We find that the flux of CO emission correlates with the flux of Brγ for Herbig AeBe stars with optically thick inner disk regions and this is shown in Figure 2. Also in Figure 2 is a least-squares fit of the stars excluding the known evolved disks. The slope of the fit is 0.59 with a one-sigma error of 0.05. The more evolved disks, like transitional disks and debris disks, did not follow this trend. The flux of Brγ is known to scale with the accretion rate (Donehew & Brittain 2011), thus our results can

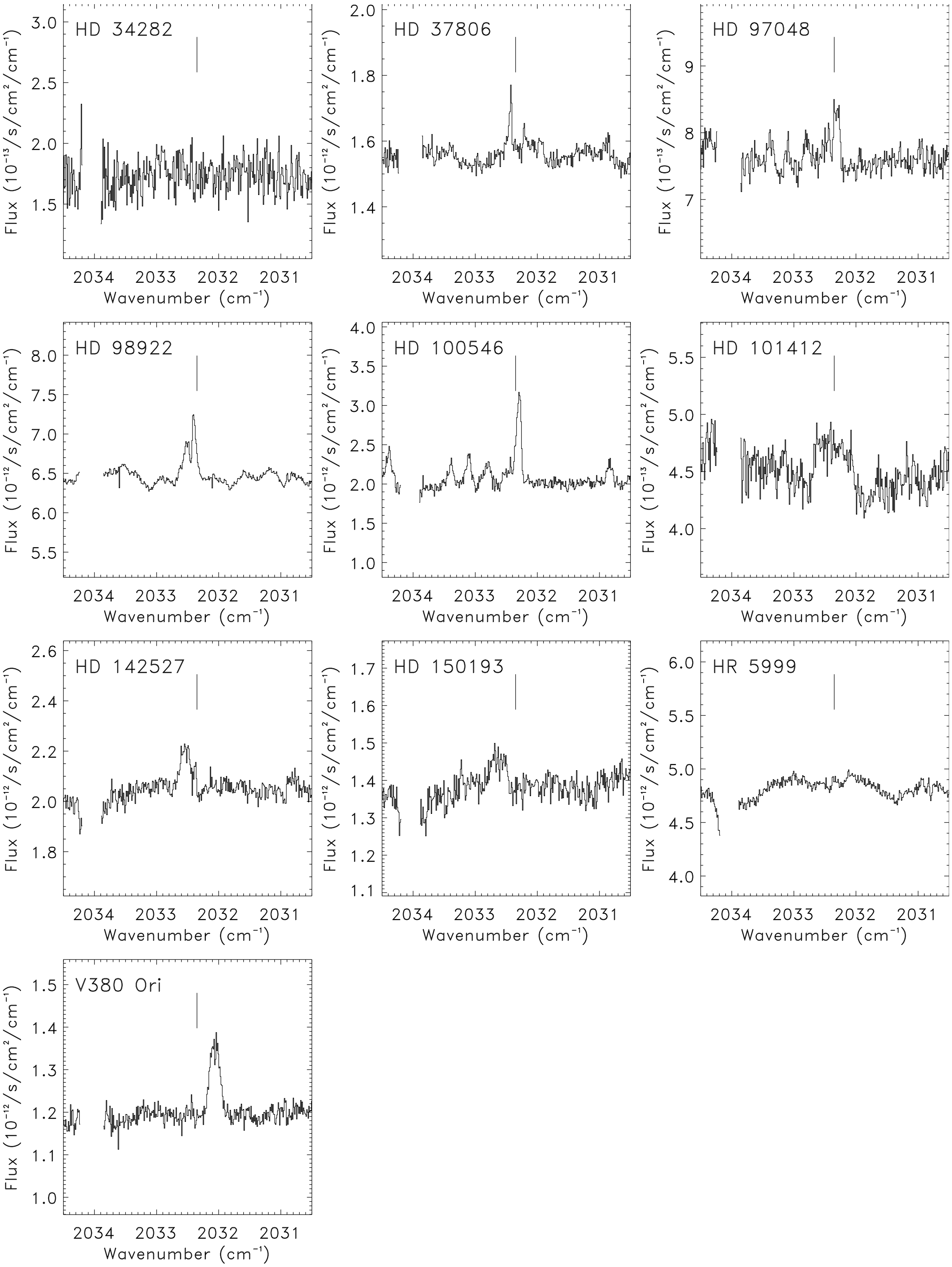

FIG. 1.— Spectra of the CO v =1-0 P(26) line (v= 2032.35 cm^{-1}).

TABLE 3
ANCILLARY PARAMETERS

Star	Spectral Type	Distance[a] (pc)	K[b] (mag)	M (mag)	EW (Brγ)[b,c] (Angstroms)	$L_{Br\gamma}$ (10^{29} erg s^{-1})	L_{CO} (10^{29} erg s^{-1})
51 Oph	B9.5[b]	124±4	4.29	···	-5.6	···	4.5[k]
AB Aur	A0[b]	124±21	···	···	···	···	1.8[k]
HD 34282	A0[b]	191±89	···	6.16[g]	···	<13.8[j]	···
HD 36112	A5[d]	279±93	···	···	···	···	0.35[h]
HD 37806	A2[d]	490±394	···	3.79[g]	···	···	···
HD 97048	A0[b]	158±17	5.94	4.56[f]	-8.4	···	···
HD 98922	B9[b]	1149±934	···	2.24[g]	···	···	···
HD 100453	A9[b]	122±10	···	···	···	···	<0.013[h]
HD 100546	B9[e]	97±4	···	3.8[g]	···	···	···
HD 101412	B9.5[d]	600±120	···	5.14[i]	···	···	···
HD 104237	A0[b]	115±5	···	···	···	···	2.1[h]
HD 139614	A7[b]	157	···	···	···	···	0.098[h]
HD 141569	B9.5[b]	116±9	6.82	···	-4.5	···	<0.005[k]
HD 142527	F6[b]	233±69	4.98	3.5[g]	-1.2	···	···
HD 149914	B9[b]	135±11	5.69	···	-0.8	···	<0.07[k]
HD 150193	A1[b]	216±100	···	3.93[g]	···	···	···
HD 163296	A1[b]	119±12	···	···	···	···	0.75[k]
HD 169142	A5[b]	145	···	···	···	···	<0.029[h]
HD 250550	B9[d]	606±367	···	···	···	···	20.2[k]
HD 259431	B2[f]	290±84	···	···	···	960[k]	3.7[k]
HR 5999	A6[b]	163±17	4.39	2.57[g]	-6.5	···	···
MWC 480	A3[d]	137±31	···	···	···	···	0.15[h]
SAO 185668	B6[g]	600	···	···	···	···	<0.08[k]
V380 Ori	A1[d]	350±812	···	4.07[f]	···	···	···
VV Ser	B9[b]	250[h]±50	···	···	···	···	0.31[h]

REFERENCES. — [b] Garcia Lopez et al. (2006).

[d] Manjo et al. (2006).

[e] Brittain et al. (2009).

[f] Hillenbrand et al. (1992).

[g] Maifiat et al. (1998).

[h] Troutman (2010), Ph.D. Thesis.

[k] Brittain et al. (2007).

NOTE. — [a] Distances determined from Hipparcos measurements presented by SIMBAD except for SAO 185668 from distance modulus and HD 259431 (Brittain et al. 2007), HD 169142 and HD 139614 (Troutman 2010, Ph.D. Thesis), and HD 101412 (Donehew 2011, Ph.D. Thesis).

[c] The typical uncertainty in the equivalent widths for most of our stars is less than 0.2 A.

[i] This M magnitude was converted from the IRS Spitzers flux density (1 Jy).

[j] Garcia Lopez et al. (2006) did not report an EW for Brγ so we had to start with the reported L_{acc} and use their empirical relation (Eq 1 therein) to get to L_{γ}.

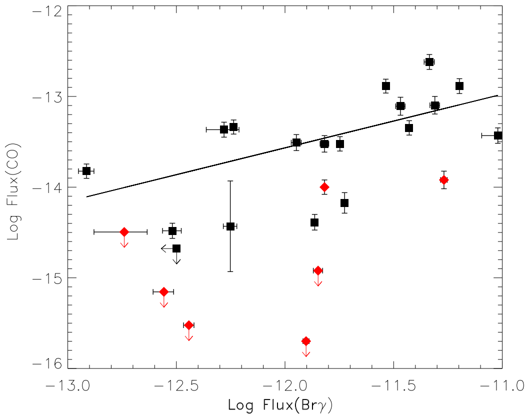

FIG. 2.— Comparison of the Brγ flux and CO 1-0 P(26) or P(30) emission line flux for 25 Herbig AeBe stars. Stars with known evolved disks are distinguished from the rest of the sample by red diamonds. Optically thick disks are black squares. Upper limits are denoted by arrows. The solid line shows a least-squares fit to the measured values excluding evolved disks.

be interpreted as consistent with a correlation between the accretion process onto the star and the luminosity of CO emission. The flux of Brγ and CO are expected to correlate if viscous heating significantly affects the temperature structure of the disk.

In the literature, emission lines are converted to luminosity and the luminosities are the usual quantities that are compared. We intentionally bypass this convention and compare the flux values of the emission lines because when calculating the luminosity, the distance of the sources must be used and this introduces a quadratic trend, d^2. This d^2 factor would be the dominate trend in a correlation plot and would make it difficult to distinguish any other trends in the data.

4. DISCUSSION

4.1. *Disk Heating*

The trend we find between accretion rate and CO rovibrational emissivity for our sample of Herbig AeBe stars with optically thick inner disks indicates that viscous heating contributes to surface heating in the inner disks. This finding is consistent with a similar study of T Tauri stars (Najita et al 2003). This trend is expected by the thermal-chemical modeling of disk atmospheres around T Tauri stars by Glassgold et al. (2004).

4.2. *Evolved Disks*

Seven of our 25 Herbig stars have been found to show evidence for an evolved inner disk region. Evolved disks are characterized by dips in their SEDs corresponding to a lack of material (or optically thin material) in their inner disk regions. Of these seven stars, only one (SAO 185668) seems to be a significant outliner. In this case, the flux of Brγ over predicts the flux of CO. A possible explanation for measuring a low CO flux and a moderate accretion rate is that the inner region may lack a molecular gas component in the inner disk. The spectral type of SAO 185568 is B6. (Donehew & Brittain 2011) found that Herbig Be stars have a higher Brγ flux to CO flux, like SAO 188568, suggesting that Herbig Be stars have an addition source of hydrogen emission, probably stellar winds.

5. CONCLUSION

We find that the Brγ flux of Herbig Ae stars with optically thick inner disks correlates with the rovibrational CO flux similar to the correlation found with T Tuari stars by (Najita et al. 2003). This indicates that viscous heating contributes significantly to the surface heating of the inner disk region as expected by the thermal chemical model of (Glassgold et al. 2004). Simultaneous observations of Brγ and CO P(26) emission would tighten the correlation that we found. Increasing the size of our sample or including stars with flux measurements covering additional orders of magnitude would strengthen our conclusion. Our empirical result can be used to calibrate future models. Improved models should be able to aid in understanding the static properties and overall evolution of the inner disk region and their implications for early planet formation.

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