Constraining the sub-au-scale distribution of hydrogen and carbon monoxide gas around young stars with the Keck Interferometer

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ABSTRACT
We present Keck Interferometer (KI) observations of T Tauri and Herbig Ae/Be stars with a spatial resolution of a few milliarcseconds and a spectral resolution of \(\sim 2000\). Our observations span the \(K\) band, and include the \(\text{Br}\gamma\) transition of hydrogen and the \(v = 2 \rightarrow 0\) and \(v = 3 \rightarrow 1\) transitions of carbon monoxide. For several targets, we also present data from Keck/NIRSPEC that provide higher spectral resolution, but a seeing-limited spatial resolution, of the same spectral features. We analyse the \(\text{Br}\gamma\) emission in the context of both disc and infall/outflow models, and conclude that the \(\text{Br}\gamma\) emission traces gas at very small stellocentric radii, consistent with the magnetospheric scale. However, some \(\text{Br}\gamma\)-emitting gas also seems to be located at radii of \(\gtrsim 0.1\) au, perhaps tracing the inner regions of magnetically launched outflows. CO emission is detected from several objects, and we generate disc models that reproduce both the KI and NIRSPEC data well. We infer the CO spatial distribution to be coincident with the distribution of continuum emission in most cases. Furthermore, the \(\text{Br}\gamma\) emission in these objects is roughly coincident with both the CO and continuum emission. We present potential explanations for the spatial coincidence of continuum, \(\text{Br}\gamma\), and CO overtone emission, and explore the implications for the low occurrence rate of CO overtone emission in young stars. Finally, we provide additional discussion of V1685 Cyg, which is unusual among our sample in showing large differences in emitting region size and spatial position as a function of wavelength.

Key words: techniques: interferometric – techniques: spectroscopic – circumstellar matter – stars: pre-main-sequence.

1 INTRODUCTION
Protoplanetary discs are an integral part of the star and planet formation process. Angular momentum conservation demands disc creation during the protostellar collapse process, and these discs then provide a reservoir from which stars and planets accrete material. Gas within 1 au of young stars may reside in protoplanetary discs, infalling streams from inner discs on to the central stars, or in outflows. Observations of gas on sub-au scales can thus constrain the composition and dynamics of inner discs, accretion flows, and outflows.

To probe inner disc gas requires observations with high spatial and spectral resolution. At a distance of 140 pc, 1 au subtends 7 mas. Gas in Keplerian rotation around a solar-mass star at this radius would produce emission lines with velocity widths of 30 km s\(^{-1}\); in the near-IR, this corresponds to a spectral dispersion \(\lambda / \Delta \lambda \approx 10000\).

At smaller radii, or for gas that is infalling or outflowing, linewidths may be higher and the required spectral dispersion somewhat lower.

Spatially resolved spectroscopy at these resolutions is challenging, but has been recently enabled by near-IR interferometers. Most studies have focused on the \(\text{Br}\gamma\) transition of hydrogen (Eisner 2007; Malbet et al. 2007; Tatulli et al. 2007; Kraus et al. 2008a; Eisner et al. 2010; Weigelt et al. 2011). The \(\text{Br}\gamma\) transition, from the \(n = 7 \rightarrow 4\) electronic states, produces a spectral line at 2.1662 \(\mu\)m. This line has been shown to be strongly correlated with accretion on to young stars (Muzerolle, Hartmann & Calvet 1998). While Balmer series hydrogen lines often show profiles associated with winds (or a combination of winds and infall; e.g. Kurosawa, Harries & Symington 2006), \(\text{Br}\gamma\) line profiles are often more consistent with infall kinematics (e.g. Najita, Carr & Tokunaga 1996a).

\(\text{Br}\gamma\) is a prime target for spatially resolved spectroscopy because the line generally has a high flux and large linewidth, and is very common around young stars (e.g. Folha & Emerson 2001). For most objects, spatially resolved data indicate \(\text{Br}\gamma\) emission more compact than the continuum emission; in these cases, the gas probably...
arises in accretion inflows (e.g. Kraus et al. 2008a; Eisner et al. 2010). However, there are exceptions, where extended Brγ emission suggests a wind origin (e.g. Malbet et al. 2007; Tatulli et al. 2007; Weigelt et al. 2011).

Other studies have also targeted or included the CO overtone bandheads (Tatulli et al. 2008; Eisner et al. 2009; Eisner & Hillenbrand 2011). The CO overtone bandheads are made up of numerous lines tracing rovibrational transitions with Δv = 2. Overtone transitions are rare compared to the occurrence rate of Brγ emission, but are found towards a number of young stars (Carr 1989; Najita et al. 1996b, 2000, 2007, 2009; Biscaya et al. 1997; Thi et al. 2005; Berthoud et al. 2007; Brittain et al. 2007; Berthoud 2008; Eisner et al. 2013).

Analyses of spectrally resolved line profiles indicate that CO overtone emission generally arises in the inner ~0.15 au of Keplerian discs (e.g. Najita et al. 1996b, 2009; Thi et al. 2005), consistent with expectations based on the high excitation temperatures of these transitions. Furthermore, the size of the CO-emitting region has been directly measured (interferometrically) for the young star 51 Oph to be ~0.15 au (Tatulli et al. 2008). Spatially resolved observations of this object and others can remove ambiguities inherent in previous modelling of spatially unresolved observations.

Finally, a number of studies have constrained the gas content of inner disc regions indirectly from low-dispersion spectroscopy or continuum data (Eisner et al. 2007b; Isella et al. 2008; Tannirkulam et al. 2008; Eisner et al. 2009). The results of these studies suggest the presence of gas at stellocentric radii smaller than the dust sublimation radius. This compact matter emits as a (pseudo-)continuum, perhaps tracing free–free emission (e.g. Eisner et al. 2009) or emission from highly refractory dust grains (e.g. Benisty et al. 2010).

The Brγ, CO, and continuum emission probably trace different physical components of star+disc systems. Brγ data constrain accretion and outflow processes on sub-au scales, and can distinguish between various accretion and wind-launching models (e.g. Lynden-Bell & Pringle 1974; Königl 1991; Shu et al. 1994; Königl & Pudritz 2000). The CO emission probably traces Keplerian inner discs (e.g. Najita et al. 1996b) on sub-au scales. Continuum emission is dominated by dust near the sublimation radius (e.g. Dullemond & Monnier 2010, and references therein). Observing dust and gas can provide a complete picture of disc inner regions from the stellar surface to the dust sublimation radius.

Here, we use the Keck Interferometer (KI) to spatially and spectrally resolve gas within 1 au of a sample of 21 young stars spanning a mass range from ~0.5 to 10 M⊙. 15 of these objects were included in Eisner et al. (2010), but we include an expanded wavelength coverage here, as well as additional data for many sources. The observations presented here target the Brγ line as well as the spectral region containing the v = 2 → 0 and v = 3 → 1 CO overtone bandheads.

2 OBSERVATIONS AND DATA REDUCTION

2.1 Sample

We selected a sample of young stars (Table 1) known to be surrounded by protoplanetary discs, most of which have been observed previously at near-IR wavelengths with long-baseline interferometers. Our sample includes 11 T Tauri stars, pre-main-sequence analogues of solar-type stars like our own Sun; eight Herbig Ae/Be stars, 2–10 M⊙ pre-main-sequence stars; and two stars (AS 353 A and V1331 Cyg) with heavily veiled stellar photospheres whose spectral types are uncertain. Three FU Ori objects, FU Ori, V1057 Cyg, and V1515 Cyg, are included in a separate publication (Eisner & Hillenbrand 2011).

Among the T Tauri stars in our sample, RY Tau, T Tau A, DG Tau, DK Tau A, GK Tau, DO Tau, DR Tau, SU Aur, and RW Aur A are all in the Taurus/Auriga complex, at an assumed distance of 140 pc (e.g. Kenyon, Dobrzycka & Hartmann 1994). AS 205 A and V2508 Oph reside in the ρ Oph cloud at an assumed distance of 160 pc (Chini 1981). These T Tauri stars span spectral types between M0 and G2, corresponding to stellar masses between ~0.5 and 1.5 M⊙ (e.g. Hartigan, Edwards & Ghandour 1995; White & Ghez 2001; Eisner et al. 2005). The sample also includes objects with a broad range of veiling, including sources like DK Tau A where the circumstellar flux is a small fraction of the stellar flux, and objects like AS 205 A where the circumstellar flux dominates (e.g. Eisner et al. 2005, 2009; Herczeg & Hillenbrand 2014). These stars span a range of >10 in accretion luminosity (e.g. Folha & Emerson 2001; Eisner et al. 2010), and in outflow properties (e.g. Hamann 1994; Hartigan et al. 1995). Among our sample, DG Tau, DO Tau, and AS 205 A have particularly high accretion luminosities (Najita et al. 1996a; Folha & Emerson 2001; Eisner et al. 2010). DG Tau, DO Tau, and DR Tau also have large forbidden line equivalent widths indicative of powerful outflows (Hamann 1994; Hartigan et al. 1995). DG Tau, in particular, stands out because it is a known CO overtone emission source (e.g. Carr 1989).

The Herbig Ae/Be stars in our sample are distributed across several star-forming regions (see Table 1 for distances). These stars span a range of spectral types from A3 to B0, corresponding to stellar masses between ~2 and 10 M⊙ (e.g. Palla & Stahler 1993). The circumstellar emission typically dominates the total flux for these systems, although there is a small range of circumstellar-to-stellar flux ratios across the sample. The selected Herbig Ae/Be stars span a broad range of accretion luminosities (e.g. Eisner et al. 2010), and show a range of outflow strengths (as traced by forbidden line emission; e.g. Corcoran & Ray 1997).

While the spectral types, and hence masses, of AS 353 A and V1331 Cyg are uncertain, they are known to show strong CO overtone emission (e.g. Carr 1989) and the highest equivalent width Brγ emission – suggesting the highest accretion luminosities – of any objects in our sample (e.g. Najita et al. 1996a; Eisner et al. 2010). These objects are also known to drive powerful outflows (e.g. Kuhi 1964; Herbig & Jones 1983; Hartigan, Mundt & Stocke 1986; Mundt & Eisloffel 1998).

2.2 KI data

We briefly summarize the experimental setup and data calibration employed in this work. For additional details, we refer to Eisner et al. (2010), which used the same setup as the work described here.

2.2.1 Experimental setup

KI was a fringe-tracking long-baseline near-IR Michelson interferometer that combined light from the two 10-m Keck apertures (Colavita & Wisniewich 2003; Colavita et al. 2003, 2013). Each of the 10-m apertures was equipped with a natural guide star adaptive optics system that corrected phase errors caused by atmospheric turbulence across each telescope pupil, and thereby maintained spatial coherence of the light from the source across each aperture. We used...
the ‘self-phase referencing’ (SPR) mode of KI (Woillez et al. 2012), which was implemented as a precursor to the dual-field phase referencing mode (Woillez et al. 2014). In SPR, a servo loop used the phase information measured on the primary (continuum) channel to stabilize the atmospheric phase motions, and enabled longer integration times on the secondary (spectrally dispersed) channel. For the spectrally dispersed channel, we used integration times between 0.5 and 2 s, approximately 1000 times longer than possible with the uncorrected primary side. The spectrally dispersed channel included a grism that, used in first order, passed the entire K-band with a dispersion of $\lambda / \Delta \lambda \approx 2000$. This spectral resolution was confirmed with measurements of

| Source       | $\alpha$  | $\delta$ | $d$  | Spectral type | $m_V$ | $m_K$ | References          |
|--------------|-----------|----------|------|---------------|-------|-------|---------------------|
| Target stars |           |          |      |               |       |       |                     |
| HD 23258     | 04 28 08.9 | +18 05 43.3 | 78   | A0V           | 6.1   | 6.1   | T Tau               |
| HD 23642     | 04 18 24.3 | +17 47 09.0 | 110  | A0V           | 6.8   | 6.8   | DG Tau,DK Tau A,GR Tau,DO Tau,DR Tau,RW AUR A |
| HD 23632     | 04 18 24.3 | +17 47 09.0 | 110  | A0V           | 6.8   | 6.8   | DG Tau,DK Tau A,GR Tau,DO Tau,DR Tau,RW AUR A |
| HD 23753     | 04 28 08.9 | +18 05 43.3 | 78   | A0V           | 6.1   | 6.1   | T Tau               |
| HD 23753     | 04 28 08.9 | +18 05 43.3 | 78   | A0V           | 6.1   | 6.1   | T Tau               |
| HD 23632     | 04 18 24.3 | +17 47 09.0 | 110  | A0V           | 6.8   | 6.8   | DG Tau,DK Tau A,GR Tau,DO Tau,DR Tau,RW AUR A |
| HD 23642     | 04 18 24.3 | +17 47 09.0 | 110  | A0V           | 6.8   | 6.8   | DG Tau,DK Tau A,GR Tau,DO Tau,DR Tau,RW AUR A |
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| HD 23642     | 04 18 24.3 | +17 47 09.0 | 110  | A0V           | 6.8   | 6.8   | DG Tau,DK Tau A,GR Tau,DO Tau,DR Tau,RW AUR A |
| HD 23753     | 04 28 08.9 | +18 05 43.3 | 78   | A0V           | 6.1   | 6.1   | T Tau               |
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| HD 23642     | 04 18 24.3 | +17 47 09.0 | 110  | A0V           | 6.8   | 6.8   | DG Tau,DK Tau A,GR Tau,DO Tau,DR Tau,RW AUR A |

References. (1) Calvet et al. (2004); (2) White & Ghez (2001); (3) Monin, Menard & Duchêne (1998); (4) Muzerolle et al. (2003); (5) Bertout, Siess & Cabirol (2007); (6) Bertout et al. (2007); (7) Herczeg & Hillenbrand (2014); (8) Eisner et al. (2004); (9) Monnier et al. (2006); (10) Eisner et al. (2005); (11) Prato et al. (2003); (12) Eisner et al. (2007c). Calibrator star distances are based on Hipparcos parallax measurements (Perryman et al. 1997).
a neon lamp spectrum. Note, however, that the lines were not fully Nyquist sampled with our detector; spectra were Nyquist sampled at a resolution of \( \sim 1000 \). Neon lamp spectra and/or Fourier transform spectroscopy were also used to determine the wavelength scale for each night of observed data.

While the entire \( K \)-band fell on the detector, vignetting in the camera led to lower throughput towards the band edges. The effective bandpass of our observations is approximately 2.05–2.35 \( \mu \text{m} \). In this paper, we focus on two sub-regions of the \( K \)-band: one centred on the \( \text{Br} \gamma \) feature at 2.1662 \( \mu \text{m} \), and one including the first two CO overtone bandheads, at 2.2936 and 2.3227 \( \mu \text{m} \). The third CO overtone bandhead at 2.3527 \( \mu \text{m} \) is included in the \( K \) bandpass, but in the lower throughput edge region. We therefore exclude it from the analysis below.

### 2.2.2 Observations and data calibration

We obtained KI observations of our sample during nine nights between 2008 April and 2011 November (see Table 2). When observing our sample, targets were interleaved with calibrators every 10–15 min.

We used the count rates in each spectral channel observed during ‘foreground integrations’, corrected for biases (Colavita 1999), to recover crude spectra for our targets. These spectra were measured when no fringes were present, and include all flux measured within the \( \sim 50 \) mas diameter of the instrumental field of view (FOV).

We divided the measured flux versus wavelength for our targets by the observed fluxes from the calibrator stars, using calibrator scans nearest in time to given target scans, and then multiplied the results by Nextgen template spectra (Hauschildt, Allard & Baron 1999) suitable for the spectral types of the calibrators. All calibrators have spectral types earlier than K2 (Table 1), where Nextgen models are well matched to empirical stellar spectra. For our calibration procedure, we prefer Nextgen templates to observed stellar spectra, because it is easier to compile a grid of photospheric spectra that is densely sampled in spectral type.

Instrumental scattered or thermal background light could add continuum emission to the KI data, leading to observed line-to-continuum ratios lower than intrinsic spectral features. To test for such effects, we compared observed and theoretical spectra for several of our main-sequence calibrator stars. Fig. 1 demonstrates that the observed photospheric \( \text{Br} \gamma \) absorption in these ‘check stars’ is consistent with theoretical expectations, across a range of source colours and brightnesses (see Table 1 for spectral types and magnitudes). Thus, the \( \text{Br} \gamma \) spectra derived from the KI data do not seem to be affected substantially by instrumental scattering or background emission.

Table 2. Log of KI observations.

| Source     | Date (UT)       | \( u \) (m)                  | \( v \) (m)                  |
|------------|-----------------|------------------------------|------------------------------|
| RY Tau     | 2008 November 18| 56,56,56,56,47,46,45         | 57,58,59,71,71,72            |
| T Tau A    | 2011 September 13| 52,54                        | 52,54                        |
| DG Tau     | 2008 November 17| 55,56,47,30                  | 52,55,70,78                  |
|            | 2010 November 25| 46,26                       | 71,79                        |
|            | 2011 September 13| 56,56                      | 54,55                        |
|            | 2011 November 7   | 14                          | 81                           |
| DK Tau A   | 2008 November 17| 56,19                       | 56,80                        |
|            | 2011 September 13| 56                          | 59                           |
|            | 2011 November 7   | 56                          | 55                           |
| GK Tau     | 2011 September 13| 55                          | 63                           |
|            | 2011 November 7   | 57                          | 58                           |
| DO Tau     | 2011 September 13| 55                          | 63                           |
|            | 2011 November 7   | 56                          | 59                           |
| DR Tau     | 2008 November 17| 56,56,41,40                 | 60,61,72,72                  |
| SU Aur     | 2011 November 7   | 54                          | 62                           |
| MWC 480    | 2008 November 18| 56,46,46                    | 56,70,71                     |
| RW Aur A   | 2008 November 17| 56,56,33,22                 | 55,58,77,80                  |
|            | 2008 November 18| 35                          | 77                           |
|            | 2010 November 25| 21                          | 81                           |
|            | 2011 September 13| 55                          | 61                           |
| MWC 758    | 2008 November 18| 56,56,59                     | 59,59                        |
| AS 205 A   | 2008 April 25    | 33,32,32                    | 45,45,45                     |
|            | 2009 July 15     | 54,53,51,51,51              | 54,54,52,52                  |
|            | 2010 July 21     | 51,50,49                    | 52,52,51                     |
| MWC 863 A  | 2009 July 15     | 44,44                       | 44,43                        |
| V2508 Oph  | 2008 April 25    | 35,35,31                    | 51,51,50                     |
| MWC 275    | 2008 April 25    | 53,53,51,51                 | 51,51,50,49                  |
|            | 2009 July 15     | 54,54,50,50                | 53,53,49,49                  |
| VV Ser     | 2011 September 13| 51,47                       | 64,64                        |
| AS 353 A   | 2009 July 15     | 52                          | 66                           |
| V1685 Cyg  | 2011 September 13| 44,38                       | 69,70                        |
|            | 2011 September 14| 56,56,38              | 51,54,76                     |
| AS 442     | 2011 September 13| 41,36,20                   | 72,76,82                     |
| V1331 Cyg  | 2009 July 15     | 44,40,39                    | 67,67,71,71                  |
| MWC 1080   | 2009 July 15     | 48,45,44                    | 55,56,60,61                  |
Since CO overtone emission occurs in the red end of the K band, where thermal emission is stronger, uncorrected background emission may be more significant for CO than for the Brγ region. Two of the check stars, HD 144841 and HD 184152, are expected to show some CO overtone absorption. The observed absorption features appear weaker than expected from the synthetic spectra (Fig. 1). The largest discrepancy is seen for HD 184152, one of the faintest objects observed with KI. Uncorrected background emission would be relatively stronger for fainter objects, consistent with this observation. Thus, some caution is required when interpreting the CO overtone emission or absorption features in the KI spectra, particularly for fainter targets.

We measured squared visibilities ($V^2$) for our targets and calibrator stars in each of the 330 spectral channels across the K band provided by the grism. The calibrator stars are main-sequence stars, with known parallaxes, whose K magnitudes are within 0.5 mag of the target K magnitudes (Table 1). We calculated the system visibility appropriate to each target scan by weighting the calibrator data by the internal scatter and the temporal and angular proximity to the target data (Boden et al. 1998). For comparison, we also computed the straight average of the $V^2$ for all calibrator stars used for a given source, and the system visibility for the calibrator observations closest in time. These methods all produce results consistent within the measurement uncertainties. We adopt the first method in our analysis.

Phases are measured in each spectral channel using the same ‘ABCD’ procedure (Colavita 1999) used to determine $V^2$. These phases are then de-rotated so that the average phase of all channels is zero. Next, the phases versus wavelength are unwrapped to eliminate any jumps between $-180^\circ$ and $180^\circ$. After computing weighted average differential phases for each target and calibrator scan, we determine a ‘system differential phase’ using similar weighting employed above to calculate the system visibility.

The system differential phase is subtracted from the target differential phase. Since targets and calibrators are observed at similar airmasses, this calibration procedure removes most atmospheric and instrumental refraction effects. Finally, we remove any residual slope in the differential phase spectrum, since we cannot distinguish instrumental slopes from those intrinsic to the target signal (e.g. Woillez et al. 2012). Since we are focused on small spectral regions around individual spectral features, we are largely insensitive to errors in these calibrations.

The measured fluxes, $V^2$, and differential phases contain contributions from the circumstellar material and from the central stars. To remove the central star, we first estimate its flux in each observed spectral channel using stellar parameters from the literature (see Table 1) and a suitable Nextgen synthetic spectrum. The synthetic spectra are subtracted from the observed KI spectra to produce circumstellar fluxes for each spectral channel\(^1\).

Circumstellar fluxes ($F_{\text{circ}}$), visibilities ($V_{\text{circ}}$), and differential phases ($\Delta \phi_{\text{circ}}$) are given by the following equations (e.g. Eisner et al. 2010):

$$F_{\text{circ}} = F_{\text{meas}} - F_\ast,$$  

$$\Delta \phi_{\text{circ}} = \tan^{-1} \left( \frac{V_{\text{meas}} \sin(\Delta \phi_{\text{meas}})(F_\ast + F_{\text{circ}})}{V_{\text{meas}} \cos(\Delta \phi_{\text{meas}})(F_\ast + F_{\text{circ}}) - F_\ast} \right),$$ 

$$V_{\text{circ}} = \frac{V_{\text{meas}} \sin(\Delta \phi_{\text{meas}})}{\sin(\Delta \phi_{\text{meas}})} \frac{F_\ast + F_{\text{circ}}}{F_{\text{circ}}}. \quad (2)$$

These equations imply that even if a spectral feature is not apparent in the observed spectrum, its presence may be implied in the circumstellar emission. For example, late-type stars have photospheric CO overtone absorption. If no absorption is seen in the observed spectra of such objects, this implies that the photospheric absorption is filled in by circumstellar emission.

One potential pitfall with this procedure is that the Nextgen templates only cover stars up to 10 000 K, while the Herbig Be stars in our sample (V1685 Cyg, AS 442, and MWC 1080) have higher effective temperatures. Such hot stars typically have shallower Brγ absorption than cooler A stars, since the H ionization fraction in the stellar photosphere is higher. Thus, the circumstellar Brγ spectra for these objects may underestimate the true line-to-continuum ratios.

### 2.3 NIRSPECT data

For four of our sample objects, VV Ser, AS 353 A, V1685 Cyg, and AS 442, we obtained NIRSPECT data on 2011 September 15. We used the high-dispersion mode with the 3 pixel slit, which provides a resolving power of $R \approx 24 000$. The NIRSPECT-7 filter was used with an echelle position of 62.25 and a cross-disperser position of 35.45. This provided seven spectral orders covering portions of the wavelength range between 1.99 and 2.39 μm. Included in these orders are the Brγ line and the $v = 2 \rightarrow 0$ and $v = 4 \rightarrow 2$ CO bandheads.

Spectra were calibrated and extracted using the REDSPEC package (e.g. McLean et al. 2003). Reduction included mapping of spatial distortions, spectral extraction, wavelength calibration, heliocentric radial velocity corrections, bias correction, flat fielding, and sky subtraction. We divided our target spectra by the observed spectrum of HD 201320, an A0V star. We interpolated the A0V spectrum over the broad Brγ absorption feature. Finally, we multiplied the divided spectra by an appropriate blackbody template to calibrate the bandpass of the instrument. We did not attempt to flux calibrate the spectra, but instead applied scaling factors so that the NIRSPECT

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\(^1\) For AS 353 A and V1331 Cyg, which appear to be heavily veiled, we assume that 100 per cent of the observed flux comes from circumstellar matter.
data had the same mean flux level (in a given spectral region) as the KI spectra.

3 BASIC RESULTS AND ANALYSIS

In this section, we present the calibrated KI and NIRSPEC data, and discuss physical implications for the distribution of gaseous emission around our sample objects. We begin by comparing the KI spectra with our NIRSPEC observations (where available) and previous data from the literature. We then use the observed V \textsuperscript{2} and Δφ for our sample to derive estimates of the spatial distributions and centroid positions of the emission as a function of wavelength. As we discuss below, Brγ emission is prevalent from the sample, while CO overtone emission is relatively rare. We therefore present the results for the Brγ and CO spectral regions separately in Sections 3.1 and 3.2.

3.1 Spectra and spatial distributions of Brγ emission

Calibrated spectra from KI, observed and with the stellar components subtracted (equation 1), are shown for the Brγ spectral region in Fig. 2. Calibrated and scaled NIRSPEC spectra are plotted in Fig. 3. While the NIRSPEC data have approximately 10 times higher spectral resolution than the KI data, the spatial resolution of the seeing-limited NIRSPEC observations is ~1000 times coarser.

The NIRSPEC data show higher line-to-continuum ratios for the Brγ emission than do the KI data (Fig. 3). Previous near-IR spectroscopy (Folha & Emerson 2001), with a spectral dispersion similar to the NIRSPEC data presented here, also found line-to-continuum ratios of the Brγ emission higher than those seen in our KI data. The lower line-to-continuum ratios in the KI data are due, in part, to the lower spectral dispersion. With >10 times higher dispersion, the NIRSPEC data suffer less dilution of strong spectral features. However, the Brγ lines are well resolved, and dilution is only a minor effect (Fig. 3).

The different FOV of the two instruments may also play a role, with the larger FOV of NIRSPEC potentially sensitive to spatially extended Brγ emission outside of the 50 mas FOV of KI. Brγ emission is seen on ≥1 arcsec scales in some young stars, comprising up to 10% of the total Brγ flux (e.g. Beck, Barv & McGregor 2010). Extrapolating this finding to scales between 50 mas and 1 arcsec may explain the difference between the KI and NIRSPEC spectra. We explore this issue quantitatively in Section 4.

From the KI spectra, we compute the equivalent width of the Brγ line for each source. Following Eisner et al. (2007c), we use these equivalent widths in conjunction with literature photometry and extinction estimates to determine the Brγ line luminosities. These line luminosities are then converted into accretion luminosities using empirically determined relationships for stars with masses <1 M\textsubscript{☉} (Muzerolle et al. 1998) and >1 M\textsubscript{☉} (Mendigutia et al. 2011). These relationships have not been calibrated beyond 6 M\textsubscript{☉}, and may not hold for the most massive Herbig Be stars in our sample, V1685 Cyg and MWC 1080. Equivalent widths, Brγ line luminosities, and accretion luminosities for our sample are listed in Table 3.

In addition to spectra, we measured squared visibilities for our targets, which constrain the relative spatial distributions of continuum and line emission components. We fit the V \textsuperscript{2} data for each source, in each channel, with a simple uniform ring model (e.g. Eisner et al. 2004) to produce a ‘spectral size distribution’ of the emission. The spectral size distributions based on the observed data, and for the circumstellar emission components (equation 3), are shown in Fig. 4.

For the majority of the observed targets, we infer a distinct spatial distribution for Brγ emission and continuum emission (Fig. 4). To quantify the relative distributions, we separate the complex visibility components due to the Brγ line and the continuum, and fit each with uniform ring models (as in Eisner et al. 2010). The estimated sizes for the two components are listed for our sample in Table 4.

The Brγ emission is generally found in a significantly more compact distribution. However, for AS 353 A, V1685 Cyg, and V1331 Cyg, the inferred sizes for the line and continuum emission components are comparable. A few other objects (including DG Tau and DO Tau) show Brγ emission sizes that are a significant fraction of the continuum emission sizes.

Differential phase signatures in the KI data indicate centroid offsets of various line emission components. We convert the measured Δφ values into centroid offsets as follows:

$$\Delta \theta = \Delta \phi \frac{\lambda}{2 \pi B}, \quad (4)$$

where λ is the observed wavelength and B is the projected baseline length. We also compute the centroid offsets for the circumstellar emission components (equation 2). Centroid offsets are plotted in Fig. 5 for the Brγ region.

A number of targets show evidence for position offsets of different velocity components across the spectrally resolved Brγ line (Fig. 5). For example, in RY Tau, the red- and blueshifted components of the emission have opposite (and approximately equal) position offsets. Such a signature resembles expectations for a spatially resolved Keplerian disc of emission. In contrast, MWC 275 shows a significant positional offset of only the redshifted emission component, perhaps arguing for a bipolar infall where one lobe (partially) obscured from view. We model these signatures quantitatively below in Section 4.

3.2 Spectra and spatial distributions of CO overtone emission

KI and NIRSPEC spectra of our sample, covering the spectral region including the CO overtone bandheads, are shown in Figs 6 and 7. Spectral size distributions and centroid offsets across the CO bandheads are shown in Figs 8 and 9, respectively.

Of the 21 objects in our sample, only 2 – AS 353 A and V1331 Cyg – show strong CO overtone emission. CO emission has been observed previously for both of these (e.g. Carr 1989; Biscaya et al. 1997; Prato, Greene & Simon 2003). The line-to-continuum ratio observed here for V1331 Cyg is comparable to that seen in previous observations, including ones with similar resolution to the KI data (Biscaya et al. 1997; Eisner et al. 2013). The line-to-continuum ratio of AS 353 A in our KI and NIRSPEC data is somewhat higher than that seen in previous observations (Carr 1989; Prato et al. 2003), although there does seem to be some variability in the CO emission strength (Biscaya et al. 1997).

In addition to AS 353 A and V1331 Cyg, a number of targets show tentative evidence of CO overtone emission (Fig. 6). DG Tau and DO Tau both exhibit circumstellar CO emission features, although such features are absent in the calibrated (star+circumstellar) spectra. There are also hints of circumstellar CO emission in DK Tau A and GK Tau, although the calibrated spectra show CO absorption. Thus, any inferred CO emission in these objects depends on the accuracy of the removal of stellar CO absorption.

In Section 2.2.2, we suggested that CO overtone absorption features in faint objects might appear weaker in observed spectra than their intrinsic values, perhaps because of uncorrected thermal background emission. DG Tau, DK Tau A, GK Tau, and DO Tau are all
Figure 2. Flux versus wavelength for our sample objects measured with KI. This figure focuses on the spectral region around the Brγ transition. The solid histogram shows the observed spectrum for the target, and the grey histogram shows the flux of the circumstellar component only. For clarity of presentation, we have not plotted the error bars associated with the circumstellar fluxes; the magnitudes of the uncertainties are indicated in the upper-right corners. Dotted grey lines indicate the central (rest) wavelength of the Brγ transition, 2.1662 µm.
Figure 2 – continued

Figure 3. Spectra of Brγ emission for four of our sample objects obtained with NIRSPEC (black curves). We also plot the KI spectra as grey histograms, and the NIRSPEC data smoothed to the KI spectral resolution as dotted black histograms.
The stellar parameters are not known for AS 353 A and V1331 Cyg. Observations from L−R for V1685 Cyg show unusually large changes with wavelength, even though the estimated sizes of CO-emitting regions have large uncertainties. In contrast, the CO emission in DG Tau and DO Tau appears more compactly distributed than the continuum emission.

The centroid offsets determined for the CO spectral region are noisy (Fig. 9), and it is difficult to discern clear signatures at the wavelengths of the CO overtone bandheads. However, one target, V1685 Cyg, does appear to have emission from the CO bandheads that is spatially offset from the continuum emission.

4 KINEMATIC MODELLING

Following Eisner et al. (2010), we model our KI data with both disc and infall/outflow models. The properties of these models are similar to Eisner et al. (2010), although we explore a substantially larger range of parameter values here. We describe the models below, and refer to Eisner et al. (2010) for details of how each model parameter affects synthetic data. We will use the same models developed for the KI data to interpret the NIRSPEC spectra.

The disc and outflow models are both fitted to the KI Brγ data. The KI data in the CO spectral region are typically noisier than in the Brγ region, making it difficult to constrain models well. We will therefore pursue a less rigorous modelling effort in this spectral region, restricting our attention to disc models, and comparing to data rather than performing rigorous fits.

As in Eisner et al. (2010), we make the simple assumption that continuum emission is confined to a ring whose annular width is 20 percent of its inner radius. This assumption is consistent with models where continuum emission traces dust near the sublimation radius (e.g. Dullemond, Dominik & Natta 2001; Eisner et al. 2004; Isella & Natta 2005). The size of the continuum ring is determined from a fit of a uniform ring model to V2 data in spectral regions adjacent to those where Brγ or CO emission is observed (Tables 4 and 5). We determine the ring radius, Rring, for all position angles and inclinations considered for our gaseous disc models. The temperature of the ring is set so that the continuum flux level matches the observed spectral energy distribution.

Table 3. Properties derived from KI Brγ spectra.

| Source     | EW (Å) | LBrγ/(10^-4 L⊙) | Lacc/L⊙ | Lacc/Lnu |
|------------|--------|-----------------|----------|-----------|
| RY Tau     | −2.4   | 4.5             | 1.6      | 0.2       |
| T Tau A    | −7.0   | 13.9            | 6.8      | 0.9       |
| DG Tau     | −6.9   | 3.2             | 1.1      | 1.2       |
| DK Tau A   | −1.3   | 0.4             | 0.1      | 0.1       |
| GK Tau     | −3.5   | 0.9             | 0.2      | 0.2       |
| DO Tau     | −11.9  | 4.1             | 1.5      | 1.1       |
| DR Tau     | −7.6   | 3.4             | 1.1      | 1.2       |
| SU Aur     | −0.0   | 0.0             | 0.0      | 0.0       |
| MWC 480    | −8.1   | 10.2            | 6.8      | 0.4       |
| RW Aur A   | −5.7   | 2.2             | 0.7      | 0.4       |
| MWC 758    | −1.8   | 2.5             | 1.9      | 0.2       |
| AS 205 A   | −3.7   | 5.3             | 2.0      | 1.5       |
| MWC 863 A  | −6.2   | 8.1             | 5.5      | 0.3       |
| V2508 Oph  | −6.5   | 4.7             | 1.7      | 0.5       |
| MWC 275    | −6.3   | 15.3            | 9.7      | 0.2       |
| VV Ser     | −5.1   | 18.2            | 11.4     | 0.2       |
| AS 353 A   | −13.1  | 1.6             | 1.2      | –         |
| V1685 Cyg  | −12.1  | 674.1           | 304.9    | 0.1       |
| AS 442     | −4.5   | 53.0            | 30.1     | 0.2       |
| V1331 Cyg  | −14.0  | 31.8            | 19.0     | –         |
| MWC 1080   | −5.2   | 1196.3          | 513.8    | 0.1       |

Notes. The stellar parameters are not known for AS 353 A and V1331 Cyg, and hence we cannot estimate L⊙ for these objects. In our analysis, we assume that the total luminosity is equal to the accretion luminosity for these two targets.
Figure 4. Uniform ring angular diameters of our sample, plotted in the spectral region around Brγ. Angular sizes computed directly from the observed V2 are plotted with black histograms. Angular sizes of only the circumstellar emission, determined using equation (3), are shown with grey histograms.
Table 4. Inferred sizes of $Br_\gamma$ emission regions.

| Source     | $\theta_{Br_\gamma}$ (mas) | $R_{Br_\gamma}$ (au) | $\theta_{continuum}$ (mas) | $R_{cont}$ (au) |
|------------|----------------------------|----------------------|----------------------------|-----------------|
| RY Tau     | <0.10                      | <0.01                | 2.57 ± 0.02                | 0.18 ± 0.01     |
| T Tau A    | <0.19                      | <0.01                | 1.54 ± 0.07                | 0.11 ± 0.01     |
| DG Tau     | 1.67 ± 0.06                | 0.12 ± 0.01          | 2.40 ± 0.03                | 0.17 ± 0.01     |
| DK Tau A   | 1.49                       | 0.10                 | 1.86 ± 0.05                | 0.13 ± 0.01     |
| GK Tau     | <0.10                      | <0.01                | 2.08 ± 0.03                | 0.15 ± 0.01     |
| DO Tau     | 1.36 ± 0.07                | 0.10 ± 0.01          | 2.54 ± 0.01                | 0.18 ± 0.01     |
| DR Tau     | 0.68 ± 0.16                | 0.05 ± 0.01          | 1.72 ± 0.04                | 0.12 ± 0.01     |
| SU Aur     | <5.00                      | <0.35                | 2.67 ± 0.02                | 0.19 ± 0.01     |
| MWC 480    | <0.10                      | <0.01                | 2.75 ± 0.01                | 0.19 ± 0.01     |
| RW Aur A   | <0.16                      | <0.01                | 1.51 ± 0.06                | 0.11 ± 0.01     |
| MWC 758    | <0.21                      | <0.02                | 2.36 ± 0.02                | 0.18 ± 0.01     |
| AS 205 A   | 1.42 ± 0.10                | 0.11 ± 0.01          | 2.52 ± 0.04                | 0.20 ± 0.01     |
| MWC 863 A  | 0.97 ± 0.19                | 0.07 ± 0.01          | 3.84 ± 0.01                | 0.29 ± 0.01     |
| V2508 Oph  | 0.56 ± 0.42                | 0.04 ± 0.03          | 3.81 ± 0.02                | 0.30 ± 0.01     |
| MWC 275    | 0.45 ± 0.40                | 0.03 ± 0.02          | 3.13 ± 0.02                | 0.19 ± 0.01     |
| VV Ser     | 0.52 ± 0.23                | 0.08 ± 0.04          | 2.39 ± 0.03                | 0.37 ± 0.01     |
| AS 353 A   | 1.06 ± 0.09                | 0.08 ± 0.01          | 1.47 ± 0.06                | 0.11 ± 0.01     |
| V1685 Cyg  | 2.19 ± 0.03                | 1.10 ± 0.02          | 2.34 ± 0.03                | 1.17 ± 0.02     |
| AS 442     | <0.31                      | <0.09                | 1.60 ± 0.05                | 0.48 ± 0.02     |
| V1331 Cyg  | 0.80 ± 0.13                | 0.28 ± 0.05          | 0.86 ± 0.12                | 0.30 ± 0.04     |
| MWC 1080   | 0.42 ± 0.44                | 0.21 ± 0.22          | 2.66 ± 0.03                | 1.33 ± 0.02     |

Notes. Angular ring diameters ($\theta$) are converted into linear ring radii using the distances listed in Table 1.

$^a$Note that DK Tau A, GK Tau, and SU Aur do not show strong $Br_\gamma$ emission features (Fig. 2), and so the $Br_\gamma$ sizes listed for those objects are not particularly meaningful.

The brightness profile of the gaseous disc is parametrized with a power law as

$$B_{\text{disc}}(R) = B_{\text{in}} \left( \frac{R}{R_{\text{in}}} \right)^{-\alpha}.$$  \hspace{1cm} (5)

The value of $\alpha$ depends on the temperature profile and surface density profile of the disc. For optically thin gas following a surface density profile similar to the minimum mass solar nebula (Weidenschilling 1977), and heated by thermal radiation from the central star, $\alpha \approx 2$. However, the temperature and surface density profiles

4.1 Keplerian disc models

We assume that while the continuum emission is confined to a ring, the gaseous emission resides in a disc extending from $R_{\text{in}}$ to $R_{\text{out}}$. Both the disc and the ring of continuum emission have a common inclination, $i$, and position angle, PA, that are free parameters.
Figure 5. Centroid offsets of our sample, plotted in the spectral region around Brγ. Black histograms show the offsets derived for the observed data, and grey histograms show the centroid offsets for the circumstellar component of the emission, determined using equation (2).
are not well constrained, and so we leave $\alpha$ as a free parameter in our modelling. Instead of using $B_{in}$, we normalize the brightness profile so that the resulting spectrum has a specified line-to-continuum ratio, $L/C$. $L/C$ is defined as the ratio of the total flux of the gaseous emission, integrated over space and velocity, to the continuum flux level.

We assume the gas to be in Keplerian rotation, with a radial velocity profile

$$v_{\text{obs}}(R) = \sqrt{\frac{GM_*}{R}} \cos(\theta) \sin(i).$$

(6)

Here, $M_*$ is the stellar mass, $\theta$ is the azimuthal angle in the disc for a given $(x, y)$ in Cartesian coordinates, and $i$ is the disc inclination. For simplicity, we do not enter exact values of $M_*$ for each source into the model (these are not determined to high accuracy for most objects). Rather, we assume a stellar mass of 1 M$_\odot$ for the T Tauri stars in our sample, 3 M$_\odot$ for the Herbig Ae stars, and 10 M$_\odot$ for the Herbig Be stars V1685 Cyg and MWC 1080.

To minimize the number of free parameters in our model grid, we set $R_{\text{out}} = R_{\text{ring}}$. Thus, we assume that any gaseous emission that may exist at stellocentric radii larger than $R_{\text{ring}}$ is hidden by the optically thick dust disc. This may not be an accurate assumption, especially for CO emission where models suggest that excitation in disc surface layers is possible (e.g. Glassgold, Najita & Igea 2004; Gorti & Hollenbach 2008). We therefore relax this assumption when modelling the CO emission (Section 4.4).

We explore the following values of free parameters in our grid of Keplerian disc models: $R_{\text{in}} = 0.01, 0.02, 0.03, 0.04, \text{and } 0.05 \text{ au}$; position angle = $0^\circ$, $25^\circ$, $50^\circ$, $75^\circ$, and $90^\circ$; inclination = $5^\circ$, $25^\circ$, $50^\circ$, and $75^\circ$; $L/C = 0.1, 0.25, 0.5, 0.75, \text{and } 1.0$; and $\alpha = 2, 3, \text{and } 4$. Our grid contains 1500 models, compared to the 243 disc models computed in Eisner et al. (2010).

4.2 Infall/outflow models

We construct models consisting of a face-on ring of continuum emission (described above) and a bipolar conical gas infall/outflow. We assume an infall/outflow cone with an opening angle of 5°, a position angle, PA, and an inclination with respect to the plane of the sky, $\phi$. We allow the infall/outflow to extend from an outer radius, $R_{\text{out}}$, to an inner radius, $R_{\text{in}}$. In contrast to the disc model considered above, $R_{\text{out}} \neq R_{\text{ring}}$ here.

The velocity of material in this cone is described as a radial power law as

$$v_{\text{obs}}(R) = v_{\text{in}} \left( \frac{R}{R_{\text{in}}} \right)^{-\beta} \sin \phi.$$  

(7)

Here, the velocity of material at the inner edge of the infall/outflow structure, $v_{\text{in}}$, is chosen to produce a specified linewidth of the emission,

$$\Delta v = v_{\text{in}} \sin \phi.$$  

(8)

Examination of equations (7) and (8) shows that the velocity profile depends on $\Delta v$, $v_{\text{in}}$, and $\beta$, but not directly on $\phi$. The geometry of the outflow of the sky depends on PA, as well as on $R_{\text{in}}$ and $R_{\text{out}}$, but again not explicitly on $\phi$. We thus fix $\phi = 45^\circ$ in our models.

We include another cone, reflected through the origin, with the same velocity profile multiplied by $-1$. The brightness distribution of the infall/outflow cones is

$$B_{\text{infall/outflow}}(R) = B_{\text{in}} \left( \frac{R}{R_{\text{in}}} \right)^{-\alpha}.$$  

(9)

where $B_{\text{in}}$ is chosen to reproduce a specified line-to-continuum ratio. As above, $L/C$ is defined as the total, integrated flux of the gaseous emission over the continuum flux. $\alpha$ combines the temperature and surface density profile of the infall/outflow structure into a single parameter. Finally, we include as a free parameter a factor by which the flux in one of the two cones or ‘poles’ of the infall/outflow may be scaled. We denote this factor as $f_\phi$, since it represents an asymmetry in the model.

We explore the following values of free parameters in our grid of infall/outflow models: $R_{\text{in}} = 0.01, 0.02, 0.03, \text{and } 0.04 \text{ au}; R_{\text{out}} = 0.05, 0.1, 0.5, \text{and } 1 \text{ au}$; position angle = $0^\circ$, $20^\circ$, $40^\circ$, $60^\circ$, and $80^\circ$; $\beta = 1, 2, \text{and } 3$; $\Delta v = 250, 375, \text{and } 500 \text{ km s}^{-1}$; $L/C = 0.1, 0.5, \text{and } 1.0$; $\alpha = 2, 3, \text{and } 4$; and $f_\phi = 0.1, 0.5, \text{and } 1.0$. The computed
Figure 6. Flux versus wavelength for our sample objects measured with KI. This figure focuses on the spectral region around the CO rovibrational overtone transitions. The solid histogram shows the observed spectrum for the target, and the grey histogram shows the flux of the circumstellar component only. For clarity of presentation, we have not plotted the error bars associated with the circumstellar fluxes; the magnitudes of the uncertainties are indicated in the upper-right corners. Dotted grey lines indicate the central (rest) wavelengths of the $v = 2 \rightarrow 0$ bandhead at 2.2936 $\mu$m and the $v = 3 \rightarrow 1$ bandhead at 2.3227 $\mu$m.
Figure 7. Spectra of CO overtone emission from four of our sample objects obtained with NIRSPEC (black curves). These spectra, obtained in two separate orders, cover the $v = 2 \rightarrow 0$ and $v = 4 \rightarrow 2$ bandheads. We also plot the KI spectra as grey histograms.
Figure 8. Uniform ring angular diameters of our sample, plotted in the spectral region around the CO overtone bandheads. Angular sizes computed directly from the observed $V^2$ are plotted with black histograms. Angular sizes of only the circumstellar emission, determined using equation (3), are shown with grey histograms.
grid includes 19,440 infall/outflow models, compared to the 2916 models included in Eisner et al. (2010).

4.3 Results for the Brγ spectral region

After computing synthetic fluxes, $V^2$, and $\Delta \phi$ values for grids of both disc and infall/outflow models, we compute the $\chi^2$ residuals between these and the observed quantities from KI. The total $\chi^2$ is given by

$$\chi^2_{\text{tot}} = (\chi^2_{\text{flux}})^2 + (\chi^2_{V^2})^2 + (\chi^2_{\Delta \phi})^2.$$ (10)

Finally, we minimize $\chi^2_{\text{tot}}$ to determine the ‘best-fitting’ model. Even though this grid of models samples significantly more parameter values than previous work, it remains sparsely sampled, and hence we cannot give rigorous error intervals on the fitted parameters.

The best-fitting models are illustrated in Fig. 11. Reduced $\chi^2$ values, and parameters of the best-fitting models, are listed in Table 6.

Disc models and infall/outflow models generally produce fits of comparable quality. This differs from the modelling in Eisner et al. (2010), and reflects the better fits of disc models that are achieved with the larger grid of models used here. However, we do confirm that for objects with the highest signal-to-noise data, infall/outflow models are generally preferred. This preference is based largely on the differential phase data, which can constrain asymmetric structures compatible with infall/outflow models but inconsistent with disc models. For the brighter sources in our sample, the differential phase data have high enough signal-to-noise to discern such asymmetries.

For a handful of targets, neither model provides a particularly good fit to the combined KI data set. Formally, the worst fits are obtained for RW Aur, V2508 Oph, AS 353 A, and V1685 Cyg (Table 6), although the $\chi^2$ values are all smaller than unity, suggesting that none of the fits are terrible. Examination of Fig. 11 suggests that the fits for RW Aur, V2508 Oph, and AS 353 A may have higher $\chi^2$ values simply because of somewhat higher scatter in the data. However, V1685 Cyg is a bright source with high signal-to-noise, and the fits are clearly inconsistent with the observed $V^2$ data. The model places Brγ emission on compact scales, while the lack of a clear $V^2$ signature suggests a similar spatial distribution of line and continuum emission. The best-fitting model selected the largest values of $R_{\text{in}}$ and $R_{\text{out}}$ available, 0.04 au and 1 au, respectively. For comparison, the continuum size is 1.17 au (Table 4). A better fit to the data would likely be achieved with a Brγ distribution centred closer to the continuum emission region.

We noted above that the Brγ spectra measured with NIRSPEC have higher line-to-continuum ratios than the KI spectra. For this reason, we did not attempt to model the NIRSPEC data at the same time as the KI data set. We will now attempt to reconcile the best-fitting models, determined for the KI data, with the NIRSPEC spectra.

First, we compute the expected Brγ spectra for our best-fitting models at the spectral resolution of the NIRSPEC data. Given the similar quality of the disc and outflow model fits for these objects (Table 6), we adopt the disc models for computational expediency. We adjusted $L/C$ to maintain a constant line flux between the KI and NIRSPEC data, but left all other model parameters unchanged. Synthetic NIRSPEC spectra for the best-fitting disc models are shown as solid curves in Fig. 12.

For AS 353 A and V1685 Cyg, the best-fitting model did not fit the KI spectra perfectly (owing to limited model grid sampling), and so we tweaked the model to yield superior fits to the NIRSPEC data without altering the fit quality to the KI data. For AS 353 A, we changed $R_{\text{in}}$ from 0.01 to 0.003 au, and for V1685 Cyg we increased $L/C$ by $\sim 30$ per cent. These ‘tweaked’ models are shown with dotted lines in Fig. 12.

As expected, synthetic spectra from our best-fitting models, after minor tweaking where appropriate, underpredict the Brγ lines seen in NIRSPEC data. We speculated above that NIRSPEC may be sensitive to spatially extended Brγ emission on scales beyond the sensitivity of KI. The relevant spatial scales would be beyond a few au, which would correspond to Keplerian velocities of $\sim 50$ km s$^{-1}$ for these objects. We added Gaussians with full width at half-maximum...
Figure 9. Centroid offsets of our sample, plotted in the spectral region around the CO overtone bandheads. Black histograms show the offsets derived for the observed data, and grey histograms show the centroid offsets for the circumstellar component of the emission, determined using equation (2).
(FWHM) between 25 and 75 km s$^{-1}$ to the synthetic spectra, to simulate the addition of an extended emission component. The dashed curves in Fig. 12 show that adding these low-velocity, possibly spatially extended emission components can indeed produce resultant spectra similar to the observed NIRSPEC spectra.

It is interesting to note that the NIRSPEC data are sensitive not only to larger spatial scales, but also potentially to smaller spatial scales than the KI data. The higher dispersion of NIRSPEC means that more extreme velocities – which likely trace matter at the smallest stellocentric radii – can be constrained. The tweaked model for AS 353 A is a case in point, where the NIRSPEC data compel us to consider a model extending to higher velocities and smaller spatial scales.

Fig. 12 shows that the best-fitting disc models produce double-peaked line profiles at the spectral resolution of the NIRSPEC data. With the addition of spatially extended emission, the central dip in the line profiles is filled in, and the observed NIRSPEC data can be reproduced. If our explanation of the discrepancy between NIRSPEC and KI spectra as the result of extended emission is incorrect, then disc models would be ruled out. As discussed in Eisner et al. (2010), infall/outflow models can produce narrower line profiles while still reproducing the KI $V^2$ and differential phase data. However, infall/outflow models would still struggle to simultaneously reproduce the NIRSPEC and KI data (which are not consistent with each other), precluding a simple alternative explanation.

**Table 5.** Inferred sizes of CO emission regions.

| Source     | $\theta_{v=2\rightarrow0}$ (mas) | $R_{v=2\rightarrow0}$ (au) | $\theta_{v=3\rightarrow1}$ (mas) | $R_{v=3\rightarrow1}$ (au) | $\theta_{\text{continuum}}$ (mas) | $R_{\text{cont}}$ (au) |
|------------|----------------------------------|-----------------------------|----------------------------------|-----------------------------|----------------------------------|------------------------|
| DG Tau     | 1.44 ± 0.18                      | 0.10 ± 0.01                 | 1.00 ± 1.25                      | 0.07 ± 0.09                 | 2.37 ± 0.03                      | 0.17 ± 0.01             |
| DO Tau     | <0.52                            | <0.04                       | <0.12                            | <0.01                       | 1.87 ± 0.04                      | 0.13 ± 0.01             |
| AS 353 A   | 1.38 ± 0.17                      | 0.10 ± 0.01                 | 1.46 ± 0.13                      | 0.11 ± 0.01                 | 1.51 ± 0.06                      | 0.11 ± 0.01             |
| V1685 Cyg  | 2.61 ± 0.44                      | 1.31 ± 0.22                 | 3.10 ± 1.36                      | 1.55 ± 0.68                 | 2.21 ± 0.03                      | 1.11 ± 0.02             |
| V1331 Cyg  | 0.74 ± 0.15                      | 0.26 ± 0.05                 | 0.90 ± 0.19                      | 0.32 ± 0.07                 | 0.87 ± 0.12                      | 0.30 ± 0.04             |

*Notes.* Angular ring diameters ($\theta$) are converted into linear ring radii using the distances listed in Table 1.
Figure 11. Synthetic data for best-fitting disc and infall/outflow models (dotted and dashed curves) plotted atop the 1σ region allowed by the observed data (grey shaded regions).
Figure 11  – continued
Figure 11 – continued
Figure 11 – continued
4.4 Modeling results for the CO spectral region

Given the relatively poor quality of the KI data in the CO spectral region, we do not attempt a rigorous $\chi^2$ minimization over our model grid. Instead we assume that the CO emission traces Keplerian discs in our targets (as suggested by previous line profile modelling; e.g. Najita et al. 1996b), and perform a by-eye minimization over varied model parameters. We do not consider infall/outflow models for the CO data. We perform this analysis for the subsample of objects with detected CO overtone emission, listed in Table 5.

For each source, we use as a starting point the best-fitting disc model determined for the Brγ spectral region (Table 6). For the Brγ modelling, we described the radial brightness distribution with a single parameter, $\alpha$. This is appropriate, since the Brγ emission arises from a single transition, and so there is no explicit dependence of the synthetic spectrum on temperature (although the transition requires population of the $n = 7$ state of hydrogen, which implies a gas temperature $\gtrsim 10,000$ K).

In contrast, the CO bandheads are made up of multiple transitions, and the synthetic spectrum depends explicitly on temperature. We therefore replace $\alpha$ with exponents on power-law profiles of gas temperature and surface density. We assume that the temperature power law has an exponent of $-0.5$, similar to values used in previous modelling of CO overtone emission (e.g. $\sim -0.4$ to $-0.75$ used by Najita et al. 1996b; Carr, Tokunaga & Najita 2004). We take the surface density power-law exponent to be $-1.5$, as calculated for the protosolar nebula (Weidenschilling 1977); this value is also consistent with previous modelling of spatially resolved observations of inner disc emission across a broad wavelength range (e.g. Kraus, Preibisch & Ohnaka 2008b). These profiles are used with CO line opacities from HITEMP (Rothman et al. 2005) to calculate the emergent spectrum as a function of disc radius.

Synthetic spectra, $V^2$, and $\Delta \phi$ for these models are shown as dotted curves in Fig. 13. These models do not match the data well. In all the cases, the models produce too much emission in between the first two overtone bandheads. The lines in this spectral region are relatively stronger in cooler CO gas, at temperatures $\lesssim 2000$ K. Because our models assume a radial temperature gradient, they all include contributions from such cool gas at larger radii.

The synthetic data for the models generated from Table 6 are also discrepant from the $V^2$ data in most cases. For DO Tau, the model

### Table 6. Results of kinematic modelling of KI Brγ data.

| Source     | $\chi^2$ | $R_{in}$ (au) | PA (°) | $i$ (°) | $L/C$ | $\alpha$ | $\chi^2$ | $R_{out}$ (au) | PA (°) | $\beta$ (km s$^{-1}$) | $L/C$ | $f_\phi$ | $\alpha$ |
|------------|----------|---------------|--------|--------|-------|----------|----------|---------------|--------|----------------------|-------|----------|----------|
| Disc models |          |               |        |        |        |          |          |               |        |                      |       |          |          |
| RY Tau     | 0.11     | 0.01          | 25     | 75     | 0.2    | 2        | 0.16     | 0.04          | 0.10   | 40                   | 3     | 250      | 0.1      | 1.0      | 3        |
| T Tau A    | 0.48     | 0.01          | 90     | 25     | 0.8    | 4        | 0.55     | 0.01          | 0.50   | 0                   | 3     | 250      | 0.5      | 1.0      | 3        |
| DG Tau     | 0.56     | 0.01          | 75     | 50     | 0.8    | 2        | 0.66     | 0.02          | 0.50   | 0                   | 1     | 375      | 1.0      | 1.0      | 2        |
| DK Tau A   | 0.21     | 0.01          | 90     | 25     | 0.1    | 4        | 0.22     | 0.01          | 0.50   | 40                   | 3     | 250      | 0.1      | 1.0      | 3        |
| DK Tau     | 0.49     | 0.01          | 75     | 75     | 0.2    | 2        | 0.52     | 0.04          | 0.50   | 60                   | 1     | 250      | 0.1      | 1.0      | 2        |
| DO Tau     | 0.49     | 0.01          | 90     | 25     | 1.0    | 3        | 0.48     | 0.01          | 0.10   | 20                   | 2     | 250      | 1.0      | 0.5      | 2        |
| DR Tau     | 0.40     | 0.01          | 75     | 25     | 0.5    | 3        | 0.40     | 0.03          | 0.50   | 0                   | 3     | 250      | 0.5      | 1.0      | 3        |
| SU Aur     | 0.04     | 0.01          | 50     | 50     | 0.2    | 3        | 0.05     | 0.01          | 0.05   | 20                   | 3     | 250      | 0.1      | 1.0      | 2        |
| MWC 480    | 0.67     | 0.01          | 90     | 25     | 0.8    | 3        | 0.47     | 0.02          | 0.05   | 20                   | 3     | 250      | 0.5      | 0.1      | 2        |
| RW Aur A   | 0.89     | 0.02          | 90     | 75     | 0.2    | 2        | 0.93     | 0.01          | 0.50   | 60                   | 2     | 500      | 0.5      | 1.0      | 3        |
| MWC 758    | 0.20     | 0.01          | 0      | 25     | 0.1    | 2        | 0.20     | 0.02          | 0.50   | 0                   | 2     | 250      | 0.1      | 0.5      | 3        |
| AS 205 A   | 0.58     | 0.01          | 0      | 75     | 0.2    | 3        | 0.63     | 0.01          | 1.00   | 0                   | 1     | 500      | 0.5      | 1.0      | 2        |
| MWC 863 A  | 0.39     | 0.01          | 0      | 25     | 0.5    | 2        | 0.33     | 0.01          | 0.05   | 2                   | 250   | 0.5      | 0.1      | 3        |
| V2508 Oph  | 0.73     | 0.04          | 50     | 25     | 0.5    | 5        | 0.76     | 0.01          | 0.50   | 0                   | 3     | 250      | 0.5      | 1.0      | 1        |
| MWC 275    | 0.37     | 0.01          | 0      | 25     | 0.5    | 3        | 0.35     | 0.01          | 0.05   | 0                   | 2     | 250      | 0.5      | 0.5      | 3        |
| VV Ser     | 0.21     | 0.01          | 90     | 75     | 0.5    | 2        | 0.21     | 0.02          | 0.50   | 0                   | 1     | 500      | 0.5      | 1.0      | 2        |
| AS 353 A   | 0.92     | 0.01          | 90     | 25     | 0.8    | 2        | 0.87     | 0.02          | 0.10   | 60                   | 2     | 375      | 1.0      | 1.0      | 2        |
| V1685 Cyg  | 0.74     | 0.02          | 90     | 50     | 0.8    | 2        | 0.68     | 0.04          | 1.00   | 80                   | 1     | 500      | 0.5      | 1.0      | 1        |
| AS 442     | 0.34     | 0.01          | 90     | 50     | 0.5    | 2        | 0.35     | 0.01          | 0.05   | 0                   | 3     | 250      | 0.5      | 1.0      | 3        |
| V1331 Cyg  | 0.55     | 0.05          | 25     | 5      | 0.8    | 2        | 0.48     | 0.01          | 0.50   | 60                   | 2     | 375      | 1.0      | 1.0      | 1        |
| MWC 1080   | 0.27     | 0.01          | 50     | 25     | 0.5    | 2        | 0.26     | 0.04          | 0.50   | 40                   | 2     | 500      | 0.5      | 1.0      | 2        |
To find models that reproduce the observations better, we allow $R_{in}$ and $R_{out}$ to vary. Given that cool CO emission is inconsistent with the data, we make the further assumption that $R_{out} = 1.2R_{in}$; i.e. we restrict the CO emission to a narrow spatial and temperature distribution. Synthetic data from models with CO confined to such rings are shown as solid curves in Fig. 13. These models provide superior fits to the data than the ones based entirely on the Brγ emission geometry.

For all sources, our models produce CO emission at temperatures $\geq 3000$ K; since the HITEMP opacities do not cover higher temperatures, we cannot constrain $T$ more precisely. The inner radius of the CO emission in models for AS 353 A and V1331 Cyg are comparable to the continuum radii. For V1685 Cyg, the model places the CO emission at radii $\sim 0.1$ au. For DG Tau, the CO emission is located interior to the continuum emission, although this is not well constrained by the data. The ring model shown in Fig. 13 represents CO at a radius of $\sim 0.1$ au.

V1685 Cyg also shows a clear differential phase signature in the CO bandhead wavelengths. To model this, we introduce a spatial offset of $\sim 0.5$ mas ($\approx 0.5$ au) between the centroid of the CO emission ring and the centroid of the continuum emission. Physically, such an offset seems difficult to explain with a model where gas and dust trace the same physical component. However, if the CO traces a different source than the continuum, for example a binary companion at $\sim 0.5$ au separation, then such a large offset could arise (see Section 5.4).

5 DISCUSSION

5.1 Continuum emission

The inferred sizes of continuum emission regions for our sample are between $\sim 0.1$ and $1.3$ au (Table 4), compatible with previous measurements (e.g. Eisner et al. 2007a, 2009). In Fig. 14, we plot the continuum sizes for each source, ordered by source luminosity. The luminosity is the sum of the stellar luminosity (from the literature) and the accretion luminosity listed in Table 3. The continuum size generally increases with source luminosity, and the relationship is consistent with an origin of the continuum emission in dust sublimation fronts (e.g. Monnier & Millan-Gabet 2002; Eisner et al. 2004; Monnier et al. 2005).

However, the continuum may not trace dust only. Previous work suggested that the continuum emission from young stars – including many in our sample – contained contributions from matter hotter than dust sublimation temperatures, perhaps tracing free–free emission from H or H$^+$. If some of the continuum emission is due to opacity from hot gas, measured continuum radii may lie between the compactly distributed hot gas and cooler dust at larger radii.

5.2 Brγ emission

Most objects in our sample show Brγ emission with a compact distribution. Inferred sizes of the Brγ emission are typically $\leq 0.05$ au, considerably smaller than continuum sizes (Table 4). Kinematic modelling confirms that Brγ emission extends to such small stellocentric radii for nearly all targets (Table 6).

Magnetospheric accretion models predict that matter falling in along stellar magnetic field lines will glow brightly near to the stellar...
Figure 13. Synthetic spectra, $V^2$, and $\Delta \phi$, computed for disc models, compared to KI data and NIRSPEC spectra (where available). Dotted curves show synthetic data for the best-fitting models determined for the Brγ emission, listed in Table 6. To better fit the data, we adjusted these models by varying $R_{\text{in}}$ and $R_{\text{out}}$ for all sources, and introducing a spatial offset between CO and continuum for V1685 Cyg (solid curves). As described in Section 4.4, these models confine CO emission to disc regions with fractional widths of 20 per cent and temperatures $\gtrsim 3000$ K.
We see no obvious correlation between the inferred spatial distribution of \( \text{Br}\gamma \) emission and stellar properties. Fig. 14 shows that most objects in our sample, including low-luminosity T Tauri stars and the most luminous Herbig Be star in the sample, have \( \text{Br}\gamma \) emission distributed on more compact scales than the continuum emission. Similarly, the spatial distribution of \( \text{Br}\gamma \) emission shows no clear dependence on accretion luminosity alone, or on stellar mass. There is some dependence of the relative sizes of \( \text{Br}\gamma \) and continuum emission on the ratio of accretion to stellar luminosity: accretion-dominated sources tend to have relatively more extended \( \text{Br}\gamma \) emission (Fig. 14). However, the clearest correlation is that objects where the \( \text{Br}\gamma \) emission is distributed on scales comparable to the continuum all exhibit CO overtone emission.

5.3 CO overtone emission

CO overtone emission, when detected in our sample, generally has a spatial distribution similar to the continuum emission (Table 5). For DG Tau and DO Tau, we inferred a more compact distribution of CO emission relative to the continuum, although the difference is not highly significant for DG Tau. Furthermore, uncertainties arising from subtraction of late-type stellar photospheric CO absorption in DO Tau may lead to an inflated line-to-continuum ratio, and perhaps an underestimate of the stellocentric radius of the circumstellar CO emission.

Fig. 14 shows that the location of the CO overtone emission is generally similar to the continuum distribution. Moreover, the \( \text{Br}\gamma \) emission is distributed on spatial scales comparable to both the CO and continuum emission for these objects. With the relatively large uncertainties in the CO emission sizes (recall that the data in this spectral region are noisier), the line and continuum emission distributions appear roughly comparable across the sub-sample of CO overtone emitters.

The coincidence of continuum and line emission is consistent with an origin of the line emission in disc surface layers. While the inferred CO distributions for DG Tau and DO Tau allow the possibility of gas in an optically thin disc mid-plane within the dust sublimation radius, the extended \( \text{Br}\gamma \) emission in these sources argues that hot gas may also be co-located with the dust disc. Furthermore, the inferred narrow distribution of CO emission (Section 5.3).
4.4) is compatible with the expected widths of dust inner rims (e.g. Isella & Natta 2005). Thus, one might interpret the data for these objects as a dust sublimation front that emits continuum emission, and a hot surface layer atop the dust where excited gas produces line emission.

Dust emission may not be confined to inner rims, but could arise in centrifugally launched winds (Bans & Königl 2012). Indeed, dusty wind models can produce continuum emission distributed over a range of radii similar to that predicted for inner rims. Gaseous emission may also arise in jets or winds close to the star, and such outflows are traced by forbidden line emission for DG Tau, DO Tau, AS 353 A, and V1331 Cyg (e.g. Hamann 1994; Hartigan et al. 1995). For DG Tau, [Fe II] emission has been inferred to originate in a disc wind within 0.2 arcsec of the central star (Pyo et al. 2003). A dusty wind beneath a hot, dust-free wind region may provide a viable alternative explanation for co-spatial line and continuum emission.

Spatially extended emission from Brγ or CO requires an excitation source. Sources showing CO emission, requiring excitation to $\gtrsim 3000$ K, might also be able to excite nearby gas to $\gtrsim 10000$ K, thereby producing Brγ emission. Such high-temperature gas could also produce free–free emission, perhaps emitting the continuum that is roughly spatially coincident with both the CO overtone and Brγ emission in these objects. However, the fact that inferred continuum sizes for these sources are compatible with expected dust sublimation radii (Section 5.1) suggests that the continuum may trace dust.

While thermal emission from the central star is insufficient to heat gas at these stellocentric radii to such high temperatures, nonthermal X-ray or UV radiation can excite CO and other gaseous emission (e.g. Glassgold et al. 2004; Gorti & Hollenbach 2008). Perhaps DG Tau, DO Tau, AS 353 A, V1685 Cyg, and V1331 Cyg have particularly high accretion rates or active accretion shocks, producing larger X-ray or UV fluxes than other sources in our sample.

5.4 The peculiar case of V1685 Cyg

The differential phase data for V1685 Cyg suggest a large spatial offset, $\sim 0.5$ au, between the CO emission and the continuum emission (Fig. 13). If the CO and continuum arise at different radii, a disc warp might help explain the observed centroid offset (see e.g. Eisner & Hillenbrand 2011). Alternatively, if the continuum and CO emission arise from the same stellocentric radius, but at different heights, geometric effects may explain the centroid offset. For example, if the continuum traces an optically thick dusty rim, then some parts of the rim may be obscured (e.g. Dullemont et al. 2001; Isella & Natta 2005); in contrast, an optically thin surface layer of CO might be completely visible. Finally, if the CO traces outflowing matter while the continuum traces a disc that could obscure part of the outflow, the two components could be spatially offset.

The offset between the CO and continuum emission centroids may be linked to the peculiar $V^2$ versus wavelength exhibited by V1685 Cyg over the $K$ band (Fig. 10). Explaining the $V^2$ is difficult because of the lack of a corresponding signature in the flux spectrum; the spectrum for V1685 Cyg increases monotonically across the $K$ band, similar to other sample objects. Whatever causes the large, non-monotonic changes in $V^2$ with wavelength does not produce a corresponding spectral signature in the flux data.

The shape of the spectral size distribution for V1685 Cyg is similar to the expected spectrum for hot H$_2$O vapour and CO (as noted previously by Eisner et al. 2007b, based on spatially resolved data in five bins across the $K$ band). These opacity sources are known to produce absorption in the extended molecular envelopes of AGB stars, which leads to $V^2$ signatures that are the inverse of that seen for V1685 Cyg (e.g. Eisner et al. 2007a). We speculate that a binary model, where the secondary resembles an AGB star, could explain the data for V1685 Cyg.

A faint secondary might not strongly affect the total flux of the system. However, if placed far from the primary, such a companion could produce resolved visibilities. At a separation of $\sim 5$ mas, a secondary with 5 per cent of the primary flux would lead to an $\sim 20$ per cent reduction in $V^2$. Absorption features in the secondary spectrum would change the flux ratio as a function of wavelength, leading to higher (i.e. less resolved) $V^2$ where the molecular opacity is strongest. If CO overtone absorption were present in the companion, this scenario might also help to explain the extended spatial distribution and large centroid offset of the CO observed towards V1685 Cyg.

6 SUMMARY

We presented $K$-band observations of a sample of 21 young stars at an angular resolution of a few milliarcseconds and a spectral resolution of 2000 from the KI. We also presented seeing-limited NIRSPEC spectra of four of these targets with a dispersion of 24 000. From these data, we derived flux spectra, emission size scale versus wavelength, and emission centroids versus wavelength. We obtained these quantities across the entire $K$ band, but restricted our analysis to the spectral regions around the Brγ line and the CO overtone bandheads.

We analysed the Brγ emission in the context of both disc and infall/outflow models. We generated a larger grid of models than in previous work, which allowed us to more fully explore the parameter space. We found that disc and infall/outflow models typically produced fits of comparable quality, but that sources with the highest signal-to-noise data preferred infall/outflow models. Based on this preference, and other lines of evidence in the literature, we argued that infall/outflow models are more likely for our sample in general.

All best-fitting models to the Brγ observations indicated gas extending to small stellocentric radii, $\lesssim 0.05$ au, consistent with accreting matter on the magnetospheric scale. However, some Brγ emitting gas also seems to be located at radii $\gtrsim 0.1$ au, perhaps tracing the inner regions of magnetically launched outflows. The fitted radial brightness profiles of the Brγ emission varied across our sample, reproducing the range of average inferred sizes of the Brγ-emitting regions.

The average size scales of the Brγ emission for our sample are inferred to be smaller than the continuum emission distribution in most cases, consistent with previous work. However, for a handful of objects, the Brγ and continuum emission distributions are nearly coincident. These objects join the small number of other targets with previously detected Brγ emission (Malbet et al. 2007; Tatulli et al. 2007; Weigelt et al. 2011). The sources with relatively extended Brγ emission are also the objects in our sample that show CO overtone emission.

CO overtone emission is detected from five objects. Strong emission is detected from AS 353 A and V1331 Cyg. Weaker emission is detected from V1685 Cyg, but strong signatures are seen in the spatially resolved KI data. Emission features are seen in DG Tau and DO Tau, although these detections depend on the subtraction of photospheric absorption features from the late-type central stars. The CO emission is distributed on scales comparable to continuum...
and Brγ emission for AS 353 A, V1331 Cyg, and V1685 Cyg. For DG Tau and DO Tau, the CO appears to be located at smaller radii, although there is additional uncertainty on this result related to the subtraction of photospheric CO features.

For each of these sources, we computed synthetic spectra, V2, and differential phases for a disc model, and compared with KI and NIRSPEC observations across the CO bandheads. To fit the data, we required a narrow spatial distribution of CO with a temperature ≳3000 K. Models with the CO confined to disc regions with fractional widths of 20 per cent matched the data well.

The near-coincidence of CO, Brγ, and continuum emission for the sub-sample of objects identified as CO emitters suggests these systems share peculiar properties. We speculated that these objects may have unusually active accretion processes that can generate non-thermal excitation of gas at large stellocentric radii. We also argued that while the continuum emission may trace dust sublimation fronts, the line emission may arise in hot, non-thermally-excited atmospheres above these dusty rims. Alternatively, dusty winds with overlying, non-thermally-excited, dust-free regions may explain the atmospheres above these dusty rims.

Finally, we discussed the unusual behaviour of V1685 Cyg. This target shows a large spatial offset between the CO and continuum emission, as well as a peculiar broad-band behaviour of the V2. We suggested that a faint binary companion with strong molecular absorption features (perhaps resembling an AGB star) might explain these observations.

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REFERENCES

Acke B., van den Ancker M. E., Dullemont C. P., 2005, A&A, 436, 209
Bans A., Königl A., 2012, ApJ, 758, 100
Beck T. L., Bary J. S., McGregor P. J., 2010, ApJ, 722, 1360
Benisty M. et al., 2010, A&A, 511, 74
Berthoud M. G., 2008, PhD thesis, Univ. Cornell
Berthoud M. G., Keller L. D., Herter T. L., Richter M. J., Whelan D. G., 2008, PhD thesis, Univ. Cornell
Bertout C., Siess L., Cabrit S., 2007, A&A, 473, L21
Biscaya A. M., Rieke G. H., Narayanan G., Luhman K. L., Young E. T., 1997, ApJ, 491, 359
Boden A. F., Colavita M. M., van Belle G. T., Shao M., 1998, in Reasenberg P. D., ed., Proc. SPIE Conf. Ser. Vol. 3350, Astronomical Interferometry. SPIE, Bellingham, p. 872
Brittain S. D., Simon T., Najita J. R., Rettig T. W., 2007, ApJ, 659, 685
Calvet N., Muzerolle J., Briceño C., Hernández J., Hartmann L., Saucedo J. L., Gordon K. D., 2004, AJ, 128, 1294
Carr J. S., 1989, ApJ, 345, 522
Carr J. S., Tokunaga A. T., Najita J., 2004, ApJ, 603, 213
Chini R., 1981, A&A, 99, 346
Colavita M. M., 1999, PASP, 111, 111
Colavita M. M., Wizinowich P. L., 2003, in Traub W. A., ed., Proc. SPIE Conf. Ser. Vol. 4838, Interferometry for Optical Astronomy II. SPIE, Bellingham, p. 79
Colavita M. et al., 2003, ApJ, 592, L83
Colavita M. M. et al., 2013, PASP, 125, 1226
Corcoran M., Ray T. P., 1997, A&A, 321, 189
Dullemond C. P., Monnier J. D., 2010, ARA&A, 48, 205
Dullemond C. P., Dominik C., Natta A., 2001, ApJ, 560, 957
Eisner J. A., 2007, Nature, 447, 562
Eisner J. A., Hillenbrand L. A., 2011, ApJ, 738, 9
Eisner J. A., Lane B. F., Hillenbrand L., Akeson R., Sargent A., 2004, ApJ, 613, 1049
Eisner J. A., Hillenbrand L. A., White R. J., Akeson R. L., Sargent A. I., 2005, ApJ, 623, 952
Eisner J. A. et al., 2007a, ApJ, 654, L77
Eisner J. A., Chiang E. I., Lane B. F., Akeson R. L., 2007b, ApJ, 657, 347
Eisner J. A., Hillenbrand L. A., White R. J., Bloom J. S., Akeson R. L., Blake C. H., 2007c, ApJ, 669, 1072
Eisner J. A., Graham J. R., Akeson R. L., Najita J., 2009, ApJ, 692, 309
Eisner J. A. et al., 2010, ApJ, 718, 774
Eisner J. A. et al., 2013, MNRAS, 434, 407
Folha D. F. M., Emerson J. P., 2001, A&A, 365, 90
Glassgold A. E., Najita J., Igea J., 2004, ApJ, 615, 972
Gorti U., Hollenbach D., 2008, ApJ, 683, 287
Hamann F., 1994, ApJS, 93, 485
Hartigan P., Mundt R., Stocke J., 1986, AJ, 91, 1357
Hartigan P., Edwards S., Ghandour L., 1995, ApJ, 452, 736
Hauschildt P. H., Allard F., Baron E., 1999, ApJ, 512, 377
Herbig G. H., Jones B. F., 1983, AJ, 88, 1040
Herczeg G. J., Hillenbrand L. A., 2014, ApJ, 786, 97
Isella A., Natta A., 2005, A&A, 438, 899
Isella A., Tatulli E., Natta A., Testi L., 2008, A&A, 483, L13
Kenyon S. J., Dobrzycka D., Hartmann L., 1994, AJ, 108, 1872
Königl A., 1991, ApJ, 370, L39
Konigl A., Pudritz R. E., 2000, Protostars and Planets IV. Univ. Arizona Press, Tuscan, p. 759
Kraus S. et al., 2008a, A&A, 489, 1157
Kraus S., Preibisch T., Ohnaka K., 2008b, ApJ, 676, 490
Kuhl L. V., 1964, ApJ, 140, 1409
Kurosawa R., Harries T. J., Symington N. H., 2006, MNRAS, 370, 580
Lynden-Bell D., Pringle J. E., 1974, MNRAS, 168, 603
McLean I. S., McGregor M. R., Burgasser A. J., Kirkpatrick J. D., Prato L., Kim S. S., 2003, ApJ, 596, 561
Malbet F. et al., 2007, A&A, 464, 43
Mendigutia I., Calvet N., Montesinos B., Mora A., Muzerolle J., Eiroa C., Oudmaijer R. D., Merin B., 2011, A&A, 535, A99
Momin J.-L., Menard F., Duchene G., 1998, A&A, 339, 113
Monnier J. D. et al., 2005, ApJ, 624, 852
Monnier J. D. et al., 2006, ApJ, 647, 444
Mundt R., Eislöffel J., 1998, AJ, 116, 860
Muzerolle J., Hartmann L., Calvet N., 1998, AJ, 116, 2965
Muzerolle J., Calvet N., Hartmann L., D'Alessio P., 2003, ApJ, 597, L865
Najita J., Carr J. S., Tokunaga A. T., 1996a, ApJ, 456, 292
Najita J., Carr J. S., Glassgold A. E., Shu F. H., Tokunaga A. T., 1996b, ApJ, 462, 919
Najita J. R., Edwards S., Basri G., Carr J., 2000, Protostars and Planets IV. Univ. Arizona Press, Tucson, p. 457
Najita J. R., Carr J. S., Glassgold A. E., Valenti J. A., 2007, in Reipurth B., Jewitt D., Keil K., eds, Protostars and Planets V. Univ. Arizona Press, Tuscan, p. 759
Palla F., Stahler S. W., 1997, ApJ, 481, 784
Perryman M. A. C. et al., 1997, A&A, 323, L49
Prato L., Greene T. F., Simon M., 2003, ApJ, 584, 853
Pyy T.-S. et al., 2003, ApJ, 590, 340
Rothman L. S. et al., 2005, J. Quant. Spectrosc. Radiat. Transfer, 96, 139
Shu F., Najita J., Ostriker E., Wilkin F., Ruden S., Lizano S., 1994, ApJ, 429, 781
Tannirkulam A. et al., 2008, ApJ, 677, L51
Tatulli E. et al., 2007, A&A, 464, 55
Tatulli E. et al., 2008, A&A, 489, 1151
Thi W.-F., van Dalen B., Bik A., Waters L. B. F. M., 2005, A&A, 430, L61
Weidenschilling S. J., 1977, Ap&SS, 51, 153
Weigelt G. et al., 2011, A&A, 527, A103

White R. J., Ghez A. M., 2001, ApJ, 556, 265
Woillez J. et al., 2012, PASP, 124, 51
Woillez J. et al., 2014, ApJ, 783, 104

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