SPATIALLY AND SPECTRALLY RESOLVED HYDROGEN GAS WITHIN 0.1 AU OF T TAU AND HERBIG Ae/Be STARS

J. A. Eisner, J. D. Monnier, J. Woillez, R. L. Akesson, R. Millan-Gabet, J. R. Graham, L. A. Hillenbrand, J.-U. Pott, S. Ragland, and P. Wizinowich

1 Steward Observatory, University of Arizona, Tucson, AZ 85721, USA
2 Astronomy Department, University of Michigan, Ann Arbor, MI 48109, USA
3 W.M. Keck Observatory, Kamuela, HI 96743, USA
4 NASA Exoplanet Science Institute, Caltech, Pasadena, CA 91125, USA
5 Astronomy Department, University of California, Berkeley, CA 94720, USA
6 Astrophysics Department, California Institute of Technology, Pasadena, CA 91125, USA
7 Max-Planck-Institut für Astronomie, Königstuhl 17, D-69117 Heidelberg, Germany

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ABSTRACT

We present near-infrared observations of T Tauri and Herbig Ae/Be stars with a spatial resolution of a few milliarcseconds and a spectral resolution of ~2000. Our observations spatially resolve gas and dust in the inner regions of protoplanetary disks, and spectrally resolve broad-linewidth emission from the Brγ transition of hydrogen gas. We use the technique of spectro-astrometry to determine centroids of different velocity components of this gaseous emission at a precision orders of magnitude better than the angular resolution. In all sources, we find the gaseous emission to be more compact than or distributed on similar spatial scales to the dust emission. We attempt to fit the data with models including both dust and Brγ-emitting gas, and we consider both disk and infall/outflow morphologies for the gaseous matter. In most cases where we can distinguish between these two models, the data show a preference for infall/outflow models. In all cases, our data appear consistent with the presence of some gas at stellocentric radii of ~0.01 AU. Our findings support the hypothesis that Brγ emission generally traces magnetospherically driven accretion and/or outflows in young star/disk systems.

Key words: circumstellar matter – stars: individual (AS 205, AS 353, DG Tau, DK Tau, DR Tau, MWC 275, MWC 480, MWC 758, MWC 863, MWC 1080, RY Tau, RW Aur, V1057 Cyg, V1331 Cyg, V2508 Oph) – stars: pre-main-sequence – techniques: interferometric – techniques: spectroscopic

1. INTRODUCTION

Protoplanetary disks play an integral part in the formation of both stars and planets. Disks provide a reservoir from which stars and planets accrete material, and a knowledge of the structure of inner regions of disks is needed to understand the star/disk interface as well as planet formation in disk “terrestrial” regions.

Near-infrared interferometry enables spatially resolved observations of sub-AU-sized regions of protoplanetary disks in nearby star-forming regions (see Millan-Gabet et al. 2007, or Dullemond & Monnier 2010 for recent reviews). These observations have enabled direct constraints on the distribution and temperature of dust in terrestrial planet-forming regions, and have more recently begun to probe gaseous emission as well (Eisner et al. 2007a; Eisner 2007; Malbet et al. 2007; Tatulli et al. 2007, 2008; Tannirkulam et al. 2008; Isella et al. 2008; Kraus et al. 2008; Eisner et al. 2009). Spatially resolved observations remove ambiguities inherent in previous modeling of spatially unresolved spectral energy distributions (e.g., Bertout et al. 1988; Hillenbrand et al. 1992) or gaseous emission lines (e.g., Edwards et al. 1994; Najita et al. 1996), and allow critical tests of these models.

Spectrally and spatially resolved observations of hydrogen gas have the potential to constrain how inner disk material accretes onto the central star or leaves the system (carrying away angular momentum) in outflows. Because hydrogen in accretion flows or in the innermost regions of outflows can be ionized, it may emit via a number of electronic transitions as recently recombined atoms cascade down to the ground state. The Brγ transition, from the n = 7 → 4 electronic states, produces a spectral line at 2.1662 μm, and can be observed with infrared interferometers. This line has been shown to be strongly correlated with accretion onto young stars (Muzerolle et al. 1998). While Balmer series hydrogen lines often show P Cygni profiles associated with winds (or a combination of winds and infall; e.g., Kurosawa et al. 2006), Brγ line profiles are often more consistent with infall kinematics (e.g., Najita et al. 1996).

Accretion is thought to occur by magnetospheric accretion in low-mass stars (e.g., Königl 1991). Viscous accretion of gas brings material through the disk to the magnetospheric radius where stellar magnetic fields exert outward pressure to balance the inward pressure of accretion; gas is then funneled along magnetic field lines onto high-latitude regions of the star. The interaction of the stellar magnetic field and the disk may also lead to the launching of outflows near this magnetospheric radius (e.g., Shu et al. 1994) or from stellocentric radii of an AU or more (e.g., Königl & Pudritz 2000). An alternative to the magnetospheric accretion picture (that may operate in high-mass stars; e.g., Eisner et al. 2004) is disk/boundary layer accretion. Matter is accreted viscously through a disk all the way to the star, at which point a shock forms due to the large difference in velocities between the Keplerian disk and rotating stellar surface (e.g., Lynden-Bell & Pringle 1974).

Previous, spatially resolved observations of protoplanetary disks generally found Brγ emission to be more compactly distributed than continuum emission (Eisner 2007; Kraus et al. 2008; Eisner et al. 2009), although more extended distributions were seen in a few cases (Malbet et al. 2007; Tatulli et al. 2007). For the subset of observations where the Brγ line was spectrally resolved, Kraus et al. (2008) claimed that only one object appears compatible with a model where the Brγ emission arises in an infalling accretion flow. For the other four objects...
in their sample, Kraus et al. (2008) suggested that this emission may trace extended disk winds (as described in, e.g., Konigl & Pudritz 2000). However, this sample was limited to a few bright A and B stars, which may not be representative of most young stars.

Here we use the Keck Interferometer (KI) to spatially and spectrally resolve gas within 1 AU of a sample of 15 young stars spanning a mass range from $\sim0.5$ to $10\ M_\odot$. These observations expand the previous sample by a factor of 3 in number and by an order of magnitude in mass range. We determine the spatial distribution and velocity structure of the Br$\gamma$-emitting gas for this sample. We investigate how these properties depend on stellar mass or accretion rate, and compare our findings to models of accretion and outflow.

2. OBSERVATIONS AND DATA REDUCTION

2.1. Sample

We selected a sample of young stars (Table 1) known to be surrounded by protoplanetary disks, all of which have been observed previously at near-IR wavelengths with long-baseline interferometers (Millan-Gabet et al. 2001; Eisner et al. 2004, 2005, 2007b; Colavita et al. 2003; Monnier et al. 2005; Akeson et al. 2005a, 2005b). All targets have been previously spatially resolved in the near-IR.

Our sample (Table 1) includes seven T Tauri stars, pre-main-sequence analogs of solar-type stars like our own Sun; five Herbig Ae/Be stars, 2–10 $M_\odot$ pre-main-sequence stars; and three stars (AS 353, V1057 Cyg, and V1331 Cyg) with heavily veiled stellar photospheres whose spectral types are uncertain. Our experimental setup imposes limiting magnitudes of $K \sim 7$ at near-IR wavelengths and $V \sim 12$ at optical wavelengths. We also require that sources be at zenith angles of less than $\sim50^\circ$, which excludes from our sample any sources with $\delta \lesssim -35^\circ$.

The sample was selected to satisfy these criteria, and includes most T Tauri stars that could be observed, focusing on those that are known to emit Br$\gamma$ and/or CO overtone emission (e.g., Folha & Emerson 2001; Carr 1989; Najita et al. 1996, 2007). Two sources in our sample are actually fainter than the limiting system magnitudes at $K$ band: AS 353 and V1331 Cyg. We included these because of their strong, previously observed CO overtone emission (e.g., Carr 1989). However, as we discuss

| Source   | $\alpha$ (J2000) | $\delta$ (J2000) | $d$ (pc) | Spectral Type | $m_\gamma$ | $m_K$ | References |
|----------|-----------------|-----------------|--------|--------------|--------|------|------------|
| HD23642  | 03 47 29.453    | +24 17 18.04    | 110    | A0V          | 6.8    | 6.8  | DG Tau,DK Tau A,DR Tau,RW Aur A |
| HD23632  | 03 47 20.969    | +23 48 12.05    | 120    | A1V          | 7.0    | 7.0  | DG Tau,DK Tau A,DR Tau,RW Aur A |
| HD 23753 | 03 48 20.816    | +23 25 16.499   | 104    | B8V          | 5.4    | 5.7  | Ry Tau,MWC 480,MWC 758 |
| HD 27777 | 04 24 29.155    | +34 07 50.73    | 187    | B8V          | 5.7    | 6.0  | Ry Tau,MWC 480,MWC 758 |
| HD31464  | 04 57 06.426    | +24 45 07.90    | 45     | G5V          | 8.6    | 7.0  | DG Tau,DK Tau A,DR Tau,RW Aur A |
| HD139364 | 15 38 25.358    | −19 54 47.45    | 53     | F3V          | 6.7    | 5.7  | AS 205 A |
| HD14465  | 15 49 52.979    | −17 54 07.007   | 43     | F3V          | 6.8    | 5.9  | AS 205 A |
| HD144821 | 16 08 16.582    | −13 46 08.582   | 76     | G2V          | 7.5    | 6.0  | AS 205 A,V2508 Oph |
| HD148968 | 16 32 08.085    | −12 25 53.910   | 146    | A0V          | 7.0    | 7.0  | AS 205 A,V2508 Oph |
| HD 149013| 16 32 38.133    | −15 59 15.12    | 41     | F8V          | 7.0    | 5.7  | MWC 863 |
| HD 163955| 17 59 47.553    | −23 48 58.08    | 134    | B9V          | 4.7    | 4.9  | MWC 275 |
| HD 170657| 18 31 18.960    | −18 54 31.72    | 13     | K1V          | 6.8    | 4.7  | MWC 275 |
| HD183442 | 19 29 30.077    | +03 05 23.607   | 43     | B7V          | 8.1    | 8.4  | AS 353 A |
| HD192985 | 20 16 00.615    | +45 34 46.291   | 35     | F5V          | 5.9    | 4.8  | V1057 Cyg |
| HD195950 | 20 27 34.258    | +38 26 25.194   | 83     | A3V          | 5.6    | 5.5  | V1057 Cyg |
| HD198812 | 20 46 53.060    | +47 06 41.502   | 185    | A1V          | 7.8    | 7.8  | V1331 Cyg |
| HD19623  | 23 16 42.303    | +53 12 48.512   | 20     | F7V          | 5.6    | 4.3  | MWC 1080 |

References. (1) Muzerolle et al. 2003; (2) White & Ghez 2001; (3) Monin et al. 1998; (4) Eisner et al. 2004; (5) Monnier et al. 2006; (6) Eisner et al. 2005; (7) Prato et al. 2003; (8) Herbig et al. 2003; (9) Eisner et al. 2007b. Calibrator star distances are based on Hipparcos parallax measurements (Perryman et al. 1997).
below, we were unable to obtain high quality measurements for these fainter objects. Finally, we included several brighter Herbig Ae/Be stars that expanded the stellar mass range of the sample.

2.2. Experimental Setup

KI is a fringe-tracking long baseline near-IR Michelson interferometer combining light from the two 10 m Keck apertures (Colavita & Wizinowich 2003; Colavita et al. 2003). Each of the 10 m apertures is equipped with a natural guide star adaptive optics (NGS-AO) system that corrects phase errors caused by atmospheric turbulence across each telescope pupil, and thereby maintains spatial coherence of the light from the source across each aperture. The NGS-AO systems require sources with \( R \) magnitudes brighter than \( \sim 12 \). Optical beam trains transport the light from each Keck aperture down into a tunnel connecting the two Kecks and to a set of beam combination optics.

We used the “self-phase referencing” (SPR) mode of KI, implemented as part of the ASTRometric and phase-Referenced Astronomy (ASTRA) program (see Woillez et al. 2010). The SPR mode introduces a split in the beams from each aperture, immediately before the fast delay line optics. 55% of the light is passed down the “primary” channel, which consists of the normal KI optics used in the standard \( V^2 \) mode. Of the remaining 45%, 20% of the light is split off to the “secondary” fast delay lines (which are generally used as part of the KI Nuller), and ultimately sent to a second beam-combining table and detector. Each of the detectors consists of a HAWAII array.

For both primary and secondary sides, interferometric fringes are measured by modulating the relative delay of the two input beams and then measuring the modulated intensity level of the combined beams during four “ABCD” detector reads (Colavita 1999). Each read has an integration time of 2 ms. The measured intensities in these reads are used to determine atmosphere-induced fringe motions, and a servo loop removes these motions to keep the fringes centered near zero phase.

For the secondary side, a servo loop uses the phase information measured on the primary side to stabilize the atmospheric phase motions, and we can thus use longer modulation periods (and hence integration times). We use integration times between 0.5 and 2 s, approximately 1000 times longer than possible with the uncorrected primary side. While integrations longer than 2 s are possible, observations at wavelengths longer than 2 \( \mu \)m become background limited in this regime.

In front of the secondary detector is a grism. This grism consists of a prism made of S-FTM16 glass, with refractive index \( n = 1.56 \) and an apex angle of 36:8; and an epoxy grating with 150 grooves per \( \text{mm} \) and a blaze angle of 36:8. Used in first order, the grism passes the entire \( K \) band with a dispersion of \( \lambda/\Delta\lambda \approx 2000 \). This spectral resolution is confirmed with measurements of a neon lamp spectrum. Note, however, that the lines are not fully Nyquist sampled with our detector; spectra are Nyquist sampled at a resolution of \( \approx 1000 \). Neon lamp spectra and/or Fourier Transform Spectroscopy are also used to determine the wavelength scale for each night of observed data. While the entire \( K \) band falls on the detector, vignetting in the camera leads to lower throughput toward the band edges. The effective bandpass of our observations is approximately 2.05 to 2.35 \( \mu \)m.

8 This beamsplitting optic was designed to split \( K \)- and \( N \)-band light for the Nuller, and is not perfect as a \( K \)-band beamsplitter.

| Source        | Date     | \( u \) (m) | \( v \) (m) |
|---------------|----------|-------------|-------------|
| RY Tau        | 2008 Nov 18 | 56,56,56,46,46,45 | 57,57,58,58,71,71 |
| DG Tau        | 2008 Nov 17 | 55,55,56,56,74,77,30,30 | 51,51,54,54,70,70,77,77 |
| DK Tau        | 2008 Nov 17 | 56,56 | 56,56 |
| DR Tau        | 2008 Nov 17 | 56,56,41,40 | 60,61,72,72 |
| MWC 480       | 2008 Nov 18 | 56,56,41,40 | 60,61,72,72 |
| RW Aur        | 2008 Nov 17 | 56,56,56,56,33,32 | 55,55,58,58,79,77,78 |
| MWC 758       | 2008 Nov 18 | 56,56 | 58,59 |
| AS 205a       | 2009 Jul 15 | 32,32,31,53,53,53,51,50 | 45,45,45,54,54,52,52 |
| MWC 863       | 2009 Jul 15 | 44,44 | 44,43 |
| V2508 Oph     | 2008 Apr 25 | 35,34,31 | 50,50,49 |
| MWC 275       | 2009 Jul 15 | 52,52,50,50,54,54,50,49 | 51,51,49,49,53,52,49,48 |
| AS 353        | 2009 Jul 15 | 52 | 66 |
| V1057 Cyg     | 2009 Jul 15 | 54,54,52,51,51,49,49 | 56,57,60,61,61,64,64 |
| V1331 Cyg     | 2009 Jul 15 | 44,43,40,39 | 67,67,71,71 |
| MWC 1080      | 2009 Jul 15 | 48,48,45,44 | 55,56,60,61 |

In this paper, we focus on Br\( \gamma \) emission, which fills only a small portion of the \( K \) band. Our measurements actually cover other interesting spectral regions that include significant opacity from H\(_2\)O and CO transitions. We defer discussion of these spectral regions to a later paper.

2.3. Observations

We obtained KI observations of our sample on UT 2008 April 25, 2008 November 17, 2008 November 18, and 2009 July 15 (see Table 2). The first of these nights was actually the commissioning night of the SPR mode, and so we observed a number of unresolved calibrator stars and known, strong Br\( \gamma \) emitters, to use for system characterization. The analysis of these initial data is presented in separate papers (Woillez et al. 2010; Pott et al. 2010). When observing our sample, targets were interleaved with calibrators every 10–15 minutes.

2.4. \( V^2 \) Calibration

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). The system visibility (i.e., the point source response of the interferometer) was measured using observations of these calibrators, whose angular sizes were estimated by fitting blackbodies to literature photometry. These size estimates are not crucial since the calibrators are unresolved (i.e., their angular sizes are much smaller than the interferometric fringe spacing) in almost all cases. HD 163955, a calibrator for MWC 275, is mildly resolved; we account for this when computing the system visibility.

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 calibrators 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 the analysis that follows.

Source and calibrator data were corrected for standard detection biases as described by Colavita (1999) and averaged into 5 s
blocks. Calibrated $V^2$ were then computed by dividing the average measured $V^2$ over 130 s scans (consisting of 5 s sub-blocks) for targets by the average system visibility. Uncertainties are given by the quadrature addition of the internal scatter in the target data and the uncertainty in the system visibility. We average together all of the calibrated data for a given source to produce a single measurement of $V^2$ in each spectral channel. The observations of our targets typically spanned $\lesssim$ 1 hr, and the averaging therefore has a small effect on the uv coverage.

As seen in previous observations with a lower-dispersion grism at K1 (Eisner et al. 2007c), we find channel-to-channel uncertainties of a few percent or less in our data. Here we estimate these uncertainties by computing the standard deviation of $V^2$ measured in a spectral region spanning 2.2–2.25 $\mu$m. This region typically has good signal to noise, and does not contain signal from Brγ emission or absorption.

The “ABCD” reads are used to calculate the phase of interference fringes recorded in both the primary channel (as described in Section 2.2) and in the secondary channel. Infrared interferometers generally do not measure phase information that is intrinsic to the target, because rapid atmospheric phase distortions scramble the phase of the “pristine” wave fronts emitted by the source (e.g., Monnier 2007). However, with our SPR observations the atmospheric phase distortions are measured by the primary fringe tracker, and these phase motions are subtracted from the secondary side. Furthermore, for the dispersed fringes on the secondary side, any residual atmospheric phase motions would affect the fringes in each channel (approximately) the same way, and so the differential phase ($\Delta \phi$) across the observed spectrum is intrinsic to the source.

Raw phases are measured in the same “ABCD” reads 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 180° jumps. 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 air masses, 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. Since we are focused on a small spectral region around the Brγ feature, we are largely insensitive to errors in these calibrations.

We estimate the uncertainty on the differential phase measurements by taking the standard deviation of measurements in a spectral region between 2.2 and 2.25 $\mu$m (as we did for $V^2$ above). The errors derived from the data are typically $\lesssim 1^\circ$, although the faintest objects in our sample exhibit somewhat larger uncertainties.

2.6. Flux Calibration

We used the count rates in each channel observed during “foreground integrations” (Colavita 1999) to recover crude spectra for our targets. These spectra are measured when no fringes are present, and include all flux measured within the $\sim$50 mas diameter of the instrumental field of view. 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 template spectra suitable for the spectral types of the calibrators.

We used Nextgen stellar atmosphere models (Hauschildt et al. 1999) as templates. These model spectra are computed at a resolution of 2 Å (more than five times finer than the resolution of our data) for stars with effective temperatures up to 10,000 K. They are thus suitable templates to be used with our calibrator stars (see Table 1).

Tests of our calibration procedure for main-sequence stars of known spectral type, calibrated using other calibrator stars, indicate channel-to-channel uncertainties of a few percent. Similar uncertainties are found by calculating the standard deviation in a spectral region adjacent to Brγ; we adopt these uncertainties for the analysis presented below. While we also see evidence for uncertainties in the spectral slope across the $K$ band (the slope varies from one observation to the next), we ignore these here since they do not affect the narrow-band data in the Brγ spectral region.

2.7. Separating Stellar and Circumstellar Components

The fluxes, squared visibilities, and differential phases described above contain contributions from both circumstellar material and central stars. Since our interest here is in the circumstellar matter, we remove the stellar component of the measurements before proceeding.

Decomposition of the spectrum into stellar and circumstellar components is straightforward as long as the ratio of circumstellar-to-stellar flux is known at each observed wavelength. We estimate the circumstellar-to-stellar flux ratio at each observed wavelength following Eisner et al. (2009). We use stellar radii, effective temperatures, distances, and extinctions (assuming the reddening law of Steenman & Thé 1991) from the literature (Hessman & Guenther 1997; Monin et al. 1998; White & Ghez 2001; Muzerolle et al. 2003; Eisner et al. 2004, 2005; Monnier et al. 2005, 2006; Bertout et al. 2007) to fit the stellar photosphere. The Nextgen models described in Section 2.6 are then used to determine the stellar fluxes at each of our observed wavelengths. These models are suitable for all of our stars except MWC 1080, whose effective temperature is substantially higher than the 10,000 K maximum of the Nextgen models. 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 spectrum may underestimate the true line-to-continuum ratio ($L/C$).

For AS 353A, V1331 Cyg, and V1057 Cyg, whose stellar photospheres are effectively invisible, we cannot reliably estimate the circumstellar-to-stellar flux ratios. For these objects we assume that 100% of the $K$-band flux arises from the circumstellar environment. This assumption is consistent with previous spectroscopic observations of these objects (Eisloeffel et al. 1990; Herbig & Jones 1983; Eisner et al. 2007b; Hartmann et al. 2004).

To estimate the circumstellar components of the $V^2$ and $\Delta \phi$, we consider the contribution of the star to the complex visibilities:

\[
V_{\text{meas}} e^{i \Delta \phi_{\text{meas}}} = \frac{F_\ast V_\ast e^{i \Delta \phi} + F_{\text{disk}} V_{\text{disk}} e^{i \Delta \phi_{\text{disk}}}}{F_\ast + F_{\text{disk}}}. \tag{1}
\]
Here, $V_{\text{meas}} = \sqrt{V_{\text{meas}}^2 + F_\ast}$, and $F_{\text{disk}}$ are the stellar and circumstellar fluxes (determined above), and $V_\ast$ and $V_{\text{disk}}$ are the stellar and circumstellar components contributing to the measured visibilities. Assuming the central star is unresolved and at the photo-center of the continuum emission, this can be simplified to
\[
V_{\text{meas}} e^{i \Delta \phi_{\text{meas}}} = \frac{F_\ast + F_{\text{disk}}}{F_\ast + F_{\text{disk}}} e^{i \Delta \phi_{\text{disk}}}.
\] (2)

The real and imaginary parts of Equation (2) provide two equations, which can be solved for the two unknown quantities $V_{\text{disk}}$ and $\Delta \phi_{\text{disk}}$:
\[
\Delta \phi_{\text{disk}} = \tan^{-1} \left[ \frac{V_{\text{meas}} \sin(\Delta \phi_{\text{meas}})(F_\ast + F_{\text{disk}})}{V_{\text{meas}} \cos(\Delta \phi_{\text{meas}})(F_\ast + F_{\text{disk}}) - F_\ast} \right],
\] (3)
\[
V_{\text{disk}} = \frac{V_{\text{meas}} \sin(\Delta \phi_{\text{meas}})}{\sin(\Delta \phi_{\text{disk}})} \left( \frac{F_\ast + F_{\text{disk}}}{F_{\text{disk}}} \right).
\] (4)

We use Equations (3) and (4) to compute the squared visibilities and differential phases corresponding to the circumstellar matter. However, we note that if the differential phases are small ($\ll 1$ rad), we can simplify these equations to somewhat more intuitive forms using the small angle approximation:
\[
V_{\text{disk}} = \frac{V_{\text{meas}}(1 + F_{\text{disk}}/F_\ast) - 1}{F_{\text{disk}}/F_\ast},
\] (5)
\[
\Delta \phi_{\text{disk}} = \frac{\Delta \phi_{\text{meas}} (1 + V_{\text{disk}} F_{\text{disk}}/F_\ast)}{V_{\text{disk}} F_{\text{disk}}/F_\ast}.
\] (6)

This assumption is equivalent to assuming that the differential phase is linearly related to the centroid offset, which is true for unresolved or marginally resolved structures:
\[
\Delta \theta = \Delta \phi \frac{\lambda}{2 \pi B},
\] (7)
where $\lambda$ is the observed wavelength and $B$ is the projected baseline length.

The uncertainties on $V_{\text{disk}}^2$ and $\Delta \phi_{\text{disk}}$ are computed from the uncertainties in $V_{\text{meas}}^2$ or $\Delta \phi_{\text{meas}}$ and an assumed uncertainty of 20% on the circumstellar-to-stellar flux ratio. We fit our models for the circumstellar emission to $F_{\text{disk}}$, $V_{\text{disk}}^2$, and $\Delta \phi_{\text{disk}}$ below.

2.8. General Features of Calibrated Data

Figure 1 shows the fluxes in the Brγ spectral region, calibrated with the procedure outlined in Section 2.6. Since many of our targets are early-type stars, which exhibit photospheric Brγ absorption, we also plot in Figure 1 spectra from which the stellar contribution has been removed (Section 2.7). All of our targets except one show evidence of circumstellar Brγ emission; in V1057 Cyg, Brγ appears in absorption. In the analysis presented below we will focus on the remaining 14 objects that exhibit Brγ emission.

To better illustrate the behavior of $V^2$ versus wavelength, we fit the $V^2$ data for each source, in each channel, with a simple uniform ring model (e.g., Eisner et al. 2004). The results, shown in Figure 2, give the “spectral size distribution” of the emission, illustrating how the spatial scale of the near-IR emission depends on wavelength. Figure 2 also shows the estimated angular size of only the circumstellar emission, calculated as described in Section 2.7.

\begin{table}[h]
\centering
\caption{Inferred Sizes of Brγ Emission Regions}
\begin{tabular}{|c|c|c|}
\hline
Source & $\theta_{\text{Brγ}}$ (mas) & $R_{\text{Brγ}}$ (AU) \\
\hline
RY Tau & <0.12 & <0.01 \ 
DG Tau & 1.85 ± 0.04 & 0.13 ± 0.01 \ 
DK Tau & 1.26 ± 0.07 & 0.09 ± 0.01 \ 
RW Aur & <0.10 & <0.01 \ 
MWC 480 & <0.10 & <0.01 \ 
MWC 758 & <0.01 & <0.02 \ 
AS 205 A & <0.01 & <0.02 \ 
MWC 863 & 0.97 ± 0.19 & 0.07 ± 0.01 \ 
V2508 Oph & 0.56 ± 0.42 & 0.04 ± 0.03 \ 
MCW 275 & 0.45 ± 0.40 & 0.03 ± 0.02 \ 
AS 353 & 1.68 ± 0.05 & 0.13 ± 0.01 \ 
V1057 Cyg & <5.00 & <1.50 \ 
V1331 Cyg & 0.80 ± 0.13 & 0.28 ± 0.05 \ 
MWC 1080 & 0.42 ± 0.44 & 0.21 ± 0.22 \ 
\hline
\end{tabular}
\end{table}

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

Figure 2 shows that the angular diameter of the near-IR emission changes across the spectral region of Brγ emission in most of our target objects. While more compact sizes of Brγ emission relative to continuum emission have been previously reported for a number of these objects (Eisner 2007; Eisner et al. 2009), here we resolve the size versus wavelength spectrally across the Brγ feature. This augments the small number of existing measurements of this kind, since our sample only has an overlap of one with previous observations at similar spectral resolution (Kraus et al. 2008).

In all of our targets, the Brγ emission appears either more compactly distributed than the surrounding continuum emission, or distributed on similar spatial scales. Using Equations (3) and (4), but with the line-to-continuum flux ratio in each spectral channel in lieu of the circumstellar-to-stellar flux ratios, we can compute the $V^2$ for the Brγ-emitting gas. Fitting this $V^2$ with a uniform ring model, we can derive simple size estimates. In particular, we fit a uniform ring model to the peak channel; since this is the lowest velocity material, it should also be the most extended and should thus approximately trace the full extent of the Brγ-emitting gas.

In Table 3, we compare the derived uniform ring sizes for the Brγ-emitting region with those of the continuum. Table 3 confirms the suggestion, based on Figure 2, that the Brγ emission is more compact than, or distributed on similar scales to, the continuum emission for all objects in our sample. Furthermore, we see that in a number of cases, the inferred size of the Brγ emission is $\lesssim 0.1$ mas, corresponding to radii $\lesssim 0.01$ AU for our targets.

To facilitate interpretation of the differential phase data, we convert the $\Delta \phi$ values into centroid offsets (Equation (7)). Since K1 consists of a single baseline, and we observe our targets with a limited $uv$ range, the derived centroid offsets are essentially projections onto a single position angle (P.A.) on the sky for a given object. The centroid offsets versus wavelength for our sample are plotted in Figure 3.

In most cases, no clear signals are seen in the differential phase data above the uncertainty level. However, a few objects display deviations from the mean phase at the wavelength of the Brγ transition. Objects with clear signals are generally the brightest objects in our sample (RY Tau, MWC 480, MWC 275, and MWC 1080). The differential phase data are noisier and less...
Figure 1. Spectra of our sample in the spectral region around Br\textsubscript{γ}. Observed fluxes are plotted with solid black histograms. Circumstellar fluxes, determined using the procedure described in Section 2.7, are shown with gray histograms. For AS 353, V1057 Cyg, and V1331 Cyg, we assume that all of the near-IR flux arises from the circumstellar environment. 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 gray lines indicate the central (rest) wavelength of the Br\textsubscript{γ} transition, 2.1662 μm.

reliable for fainter sources. For example, while AS 205 exhibits features in the differential phases (not at the Br\textsubscript{γ} wavelength) that appear significant, these may be spurious signals for this fainter object.

3. MODELING

In this section we use our flux, V\textsuperscript{2}, and differential phase measurements, after removal of the stellar components (Section 2.7) to constrain the distribution of dust and gas around our sample stars. In Section 3.1, we consider a Keplerian disk model with a rotating, gaseous disk extending from some inner radius out to the dust sublimation radius, where a ring of continuum emission resides. In Section 3.2, we replace the rotating, gaseous disk with a compact, bipolar infall/outflow structure.

In these models we make the simple assumption that continuum emission is confined to a ring whose annular width is 20% of its inner radius. This assumption makes sense if the continuum emission traces dust, since most of the emission will come
Figure 2. 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 the procedure described in Section 2.7, are shown with gray histograms.

from radii near the sublimation point of silicate dust (Dullemond et al. 2001; Isella & Natta 2005). However, previous work has shown that inner disk gas or highly refractory dust, on smaller scales than the bulk of the dust emission, also produces continuum emission (e.g., Tannirkulam et al. 2008; Eisner et al. 2009; Benisty et al. 2010). This compact continuum emission can lead to underestimated sizes for the (bulk) dust distribution. However, since we are focused on the line emission, we are not concerned with such potential errors. The assumption that continuum emission lies in a single ring should not affect inferred constraints on the Brγ emission morphology.

The properties of the continuum emission can be constrained directly from the observations of spectral regions free of Brγ emission. The inner ring radius is determined directly from a fit of a uniform ring model to V2 data in spectral regions adjacent to those where Brγ emission is observed. We determine the ring radius for all P.A.s and inclinations considered for our gaseous disk model (below). With R_{ring} determined from the V2 data, the
temperature of the ring is set so that the continuum flux level matches the observed continuum fluxes. Neither \( R_{\text{ring}} \) nor \( T_{\text{ring}} \) are free parameters in the models discussed below.

### 3.1. Keplerian Disks

We begin with a model that assumes all of the observed emission, including both continuum and Br\( \gamma \), lies in a common disk plane. The gaseous disk extends from \( R_{\text{in}} \) to \( R_{\text{out}} = R_{\text{ring}} \). While gaseous emission may exist at stellocentric radii larger than \( R_{\text{ring}} \), we make the simple assumption that any such emission is hidden by the optically thick dust disk (we ignore any potential emission from hot gas in outer disk surface layers). Both the disk and the ring of continuum emission have a common inclination, \( i \), and position angle, P.A., that are free parameters.

The brightness profile of the gaseous disk is parameterized with a power law,

\[
B_{\text{disk}}(R) = B_{\text{in}} \left( \frac{R}{R_{\text{in}}} \right)^{-\alpha}.
\]

(8)
The value of $\alpha$ is difficult to determine analytically since it depends on the temperature profile and surface density profile of the disk. We therefore leave $\alpha$ as a free parameter in our modeling.

The normalization of the brightness profile is chosen so that the resulting spectrum has a specified $L/C$. $L/C$ is defined as the ratio of the total flux of the gaseous emission, integrated over space and velocity, to the total flux of the continuum component.

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

$$v_{\text{orb}}(R) = \sqrt{\frac{GM_\ast}{R}} \cos(\text{P.A.}) \sin(i).$$

Here, $M_\ast$ is the stellar mass, P.A. is the disk position angle, and $i$ is the disk inclination. For simplicity, we do not enter exact values of $M_\ast$ 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 star MWC 1080.

Using the power-law brightness profile and (assumed) Keplerian velocity profile, we generate channel maps of the model. Each modeled channel is centered on the central wavelength of a channel in our data. Channel maps are generated and saved for a grid of parameter values.

To fit this model to the data for a given source, we must first convert the model channel maps into spectra, squared visibilities, and differential phases. The model spectra are computed by summing the flux in each channel map. We then calculate a discrete Fourier transform of each channel map to determine the complex visibilities we would “observe”:

$$V_{\text{model}}(u, v) = \sum_x \sum_y A(x, y) e^{-2\pi i (ux + vy)/\lambda}.$$  

Here, $A(x, y)$ is the brightness distribution of a given channel map, $u$ and $v$ are the projected east–west and north–south baseline lengths, and the sums are taken over the spatial dimensions $x$ and $y$. The model $V^2$ and $\Delta\phi$ are the squared amplitude and phase of these complex visibilities:

$$V^2_{\text{model}} = \text{Real}[V_{\text{model}}(u, v)]^2 + \text{Imaginary}[V_{\text{model}}(u, v)]^2,$$

$$\Delta\phi_{\text{model}} = \tan^{-1}\left(\frac{\text{Imaginary}[V_{\text{model}}(u, v)]}{\text{Real}[V_{\text{model}}(u, v)]}\right).$$

An example disk model is shown in Figure 4. Different disk morphologies can be obtained by adjusting the free parameters described above. These parameters can be considered in three groups: disk geometry, described by $R_{\text{in}}$ and $R_{\text{ring}}$; the disk brightness profile, parameterized by $\alpha$ and $L/C$; and the viewing geometry, described by P.A. and $i$. Before describing the results of fitting these disk models to data, we start with brief discussion of how model parameters affect synthetic fluxes, $V^2$, and differential phases. These effects are illustrated in Figures 5–7, and described in the following sections.

### 3.1.1. Disk Geometry

Here we consider the effects of $R_{\text{in}}$ and $R_{\text{ring}}$ on fluxes, $V^2$, and differential phases predicted by disk models. A smaller value of $R_{\text{in}}$ means that while there is emission from smaller radii, there will also be less emission from gas at larger radii (for a given $L/C$). Thus the line profile becomes broader as more flux is distributed to the higher-velocity material at small radii. The system becomes less spatially resolved at high velocities (i.e., in the line wings) since the $L/C$ of the compact emission has increased. The emission becomes more resolved for lower velocities as the $L/C$ of this emission decreases (and the mean size thus shifts out toward the continuum ring). Smaller values of $R_{\text{in}}$ drive centroid offsets closer to zero, and hence lead to smaller $\Delta\phi$.

Values of $R_{\text{in}}$ larger than those shown in Figure 5 lead to even narrower profiles of flux and $V^2$ versus wavelength, and larger differential phase signatures. For very large $R_{\text{in}}$, the line may become completely spectrally unresolved, in which case the $\Delta\phi$ would become zero. Since observed spectra for all targets show spectrally resolved Br$\gamma$ line profiles (Figure 1), we do not consider values of $R_{\text{in}}$ larger than 0.05 AU in this modeling.

Because $R_{\text{ring}}$ is also taken to be the outer radius of the gaseous disk, it does have an impact on the observables beyond the normalization of the continuum. Larger values of $R_{\text{ring}}$ lead to larger centroid offsets between the red and blue sides of the gaseous disk. Moreover, larger values of $R_{\text{ring}}$ lead to a lower correlated continuum flux ($V_{\text{cont}}F_{\text{cont}}$), meaning that the contribution of the symmetric continuum component to the total measured differential phase signal is decreased (see Equation (6)). Thus, a larger radius of the continuum emission helps to amplify any differential phase signal arising from the gaseous emission. Note that $R_{\text{ring}}$ is determined directly from a fit of a ring model to continuum data, and so is not actually a free parameter in the models.

### 3.1.2. Disk Brightness Profile

The disk brightness profile depends on the $L/C$, which determines the normalization, and on $\alpha$, which describes the radial profile. Both have prominent effects on the synthetic data (Figure 6).
we vary No. 2, 2010 SPATIALLY AND SPECTRALLY RESOLVED HYDROGEN GAS 783

Figure 5. Synthetic fluxes, $V^2$, and differential phases ($\Delta \phi$) computed for the disk model described in Section 3.1. We assume a fiducial model with $R_0 = 0.01$ AU, $P.A. = 0, i = 45^\circ, \alpha = 3$, an L/C of 0.5, $d = 140$ pc, and $M_s = 3 M_\odot$. Here, we vary $R_{\text{in}}$ (top) and $R_{\text{out}}$ (bottom), and illustrate the effects of these variations on the synthetic data.

Figure 6. Synthetic fluxes, $V^2$, and differential phases ($\Delta \phi$) computed for the disk model described in Section 3.1. Assuming the fiducial model described in Figure 5, we vary $\alpha$ (top) and L/C (bottom) and illustrate the effects of changing these parameters on the synthetic data.

Steeper brightness profiles, corresponding to higher values of $\alpha$, result in a higher proportion of flux in the extreme velocities. Hence large values of $\alpha$ result in double-peaked profiles, while $\alpha$ values closer to zero result in single-peaked profiles. Models with shallower flux profiles will be more spatially resolved, since more flux is found at larger radii. Similarly, differential phases deviate from zero more strongly for shallower flux profiles. Note that the effects of increasing $\alpha$ are similar to the effects of decreasing $R_{\text{in}}$.

Higher L/Cs produce brighter lines in model spectra (by definition). Because of the higher proportion of flux in the compact gaseous component relative to the continuum ring, models with higher L/Cs also produce less resolved (higher) $V^2$ within the emission line. Higher L/Cs mean that the centroid offsets between different velocity components of the gaseous disk have less dilution from the continuum ring (which has no centroid offset versus wavelength). Thus we find larger differential phase signatures for L/Cs.

3.1.3. Disk Viewing Geometry

The P.A. has no effect on the total flux emitted, although it may impact the modeled $V^2$ and $\Delta \phi$, since models (and data)
are only “observed” over a limited range of baseline P.A.s. If the baseline P.A. is aligned with the disk P.A., then the system will appear more resolved, and differential phase signals will be larger. If the baseline P.A. is orthogonal to the disk P.A., the system will be less resolved, and we will observe no differential phase deviations from zero.

Face-on disks show no radial velocity gradients, and near-to-face-on disks show narrow emission features. For sufficiently low inclinations, all of the disk emission fits into a single spectral channel in our synthetic spectra. While the emission in this channel will be more compact (higher $V^2$) than the surrounding continuum, such a model produces no differential phase signature since the average centroid offset of the entire disk is zero. In contrast, higher inclinations mean broader emission lines, which lead to $V^2$ and $\Delta \phi$ signatures in multiple channels. The magnitude of these signatures depends on whether the disk P.A. is aligned with the baseline P.A., and on the inclination. In Figure 7, the gaseous disk becomes less resolved with increasing inclination, since the system P.A. is not perfectly aligned with the baseline P.A.

With a single baseline, we do not claim that we can constrain the P.A. or inclination of the disk. However, we allow these parameters to vary in the models to reflect potential misalignments between the baseline P.A. and the disk.

### 3.2. Magnetospheric Infall/Outflow Models

We also consider models that include gaseous outflows or inflows interior to the dust sublimation front. We allow these outflows to extend to scales larger than the dust sublimation radii. As with the disk model considered in Section 3.1, we include a ring of continuum emission. For simplicity here, we assume the P.A. and inclination of the ring are zero. Note that the ring geometry is not coupled to the morphology of the gas.

We assume an infall/outflow cone with an opening angle of $5^\circ$. The cone has a position angle, P.A., 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 disk 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:

$$v_{\text{obs}}(R) = v_{\text{in}} \left( \frac{R}{R_{\text{in}}} \right)^{-\beta} \sin \phi.$$  \hfill (13)

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,

$$\Delta v = v_{\text{in}} \sin \phi.$$  \hfill (14)

Examination of Equations (13) and (14) shows that the velocity profile depends on $\Delta v, R_{\text{in}},$ and $\beta$, but not directly on $\phi$. The geometry of the outflow of the sky depends on P.A., 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 $-1$. Thus, the model includes a bipolar infall/outflow structure within the dust sublimation radius.

The brightness distribution of the infall/outflow cones is

$$B_{\text{infall/outflow}}(R) = B_{\text{in}} \left( \frac{R}{R_{\text{in}}} \right)^{-\alpha},$$  \hfill (15)

where $B_{\text{in}}$ is chosen to reproduce a specified L/C. As above, $L/C$ is defined as the total, integrated flux of the gaseous emission over the total flux of the continuum. Note that $\alpha$ rolls all information about 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” or the infall/outflow may be scaled. We denote this factor as $f_\alpha$, since it represents an asymmetry in the model.

An image of an example infall/outflow model is shown in Figure 8. Different models may be generated by varying the
free parameters $R_{in}$, $R_{out}$, P.A., $\alpha$, $\beta$, $\Delta v$, $L/C$, and $f_\nu$. We now summarize the effects of each of these parameters on synthetic fluxes, $V^2$, and differential phases, and illustrate these effects in Figures 9–12.

3.2.1. Infall/Outflow Geometry

The inner and outer radii of the infall/outflow structure have small effects on modeled fluxes and $V^2$, but can have a larger effect on the differential phases. The larger effects on $\Delta\phi$ stem from the greater sensitivity of differential phases to compact structure. Since centroiding accuracy is better than the angular resolution (by a factor of the signal-to-noise ratio, S/N), smaller source structure can be constrained.

A larger inner radius means that the highest velocity material is located farther from the star, and so covers more area. The relative amount of flux in the high-velocity component of the outflow is thus increased, which leads to a flatter line profile. Since the $L/C$ is increased for high-velocity material, but decreased for low-velocity gas, the $V^2$ versus wavelength also flattens. Larger values of $R_{in}$ drive larger centroid offsets, and hence lead to larger $\Delta\phi$. Similarly, larger values of $R_{out}$ lead to (some-what) more extended emission, and hence to larger centroid offsets.

As for the disk model considered above, a larger value of $R_{ring}$ leads to less correlated flux from the continuum component. This

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As for the disk model considered above, a larger value of $R_{ring}$ leads to less correlated flux from the continuum component. This
Figure 10. Synthetic fluxes, $V_{\lambda}$, and differential phases ($\Delta \phi$) computed for the infall/outflow model described in Section 3.2. The fiducial model is as described in Figure 9, and we vary $\alpha$, L/C, and $f_c$ here.

Figure 11. Synthetic fluxes, $V_{\lambda}$, and differential phases ($\Delta \phi$) computed for the infall/outflow model described in Section 3.2. The fiducial model is as described in Figure 9, and we vary $\beta$ and $\Delta \nu$ here.
decreases the contribution of the continuum to the observed differential phases, and will amplify any differential phase signatures coming from the infall/outflow component.

3.2.2. Infall/Outflow Brightness Profile

The effect of $\alpha$ on the observables is similar to the effects described above in the context of disk models. The line profile becomes less peaked, the $V^2$ versus wavelength also becomes less peaked, and the differential phase signatures get smaller as the brightness profile of the model is steepened. The dependence of the synthetic data on $L/C$ for the infall/outflow model is the same as for the disk model described above.

Decreasing $f_a$ increases the flux ratio between the blue and red sides of the infall/outflow structure. This manifests itself through slight asymmetries in the synthetic flux and $V^2$ versus wavelength. The effect on synthetic differential phases is more pronounced, since these are more sensitive to the differences in emission on such compact scales.

3.2.3. Infall/Outflow Velocity Structure

The effect of $\beta$ on the observables is similar to, but not degenerate with, the effects of $\alpha$. A steeper velocity profile means that more of the low-velocity gas is found at smaller stellocentric radii, where the emission is stronger. Thus, a higher value of $\beta$ is similar to a smaller value of $\alpha$. However, comparison of Figures 10 and 11 demonstrates that the effects on the synthetic data are sufficiently different so as to be distinguishable.

As $\Delta v$ is increased the line profile becomes broader and flatter (flatter because the $L/C$ is held fixed for a given parameter study). The $V^2$ versus wavelength also becomes broader and flatter. Examination of Equations (13) and (14) shows that the physical effect of increasing $\Delta v$ is to increase the radial velocity at the inner edge of the infall/outflow structure. This, in turn, causes the radius where the infall/outflow reaches systemic velocity to move outward. A larger offset of the near-zero velocity material leads to a larger differential phase signature.

3.2.4. Infall/Outflow Viewing Geometry

The effect of P.A. on the observables is similar to the effects described above in the context of disk models. Since the differential phases are sensitive to structure on smaller scales than the $V^2$, and the infall/outflow model generates most of its flux on compact scales, it is not surprising that the $\Delta \phi$ is more sensitive than $V^2$ to P.A. changes. For the definition of our model, $\phi$ has no direct effect on the synthetic data.

3.3. Model Fitting

We compute grids of models using the parameter values shown in Figures 5–12. Grids with more finely sampled parameter values are not possible given the computational time needed to compute these models. Our disk model grid requires one to two weeks, while our infall/outflow model grid (which has more free parameters) requires over three weeks to run on a fast desktop computer.

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

$$\chi^2_{\text{tot}} = \chi^2_{\text{flux}} + \chi^2_{V^2} + \chi^2_{\Delta \phi}. \quad (16)$$

Finally, we minimize $\chi^2_{\text{tot}}$ to determine the “best-fit” model. With such a sparse grid of models, we cannot claim that our “best-fit” model is the true, absolute minimum of the $\chi^2$ surface, as opposed to a deep local minimum. Furthermore, we cannot give rigorous error intervals on the fitted parameters, since we have not adequately sampled the $\chi^2$ surface.

The best-fit models are illustrated in Figure 13. Reduced $\chi^2$ values, and parameters of the best-fitting models, are listed in Table 4.

4. RESULTS AND ANALYSIS

4.1. Accretion Properties Inferred from Brγ Spectra

Before discussing the distribution of circumstellar matter for our sample, we begin by analyzing our Brγ spectra and estimating accretion luminosities using tools that have been developed and used previously. These accretion luminosities will provide some basis for comparison against the circumstellar properties.

In Table 5, we list the equivalent widths (EWs) of the Brγ lines measured for our sample, after removal of the stellar components of the spectra using the procedure described in Section 2.7. Following Eisner et al. (2007b), we use these EWs in conjunction with literature photometry and extinction estimates to determine the Brγ line luminosities.

These line luminosities are then converted into accretion luminosities using an empirically determined relationship from Muzerolle et al. (1998, 2001). This relationship is determined by comparing Brγ line luminosities to accretion luminosities determined by fitting shock models to UV data. Note, however, that this relationship was determined for mostly solar-type T Tauri stars. While the relationship has been extended to $\sim 3 M_\odot$.
stars (Calvet et al. 2004), it has not been calibrated at high stellar masses and may break down for targets like MWC 1080. In fact, we argue below and elsewhere (e.g., Eisner et al. 2004) that this object may not undergo magnetospheric accretion, in which case the relationship from Muzerolle et al. (1998, 2001) is almost certainly invalid.

The accretion luminosity can be converted into an accretion rate: \( M \approx L_{\text{acc}} R_* / GM_* \). Since Brγ is in absorption for V1057 Cyg, neither \( L_{\text{acc}} \) nor \( M \) is meaningful in this case. For AS 353 and V1331 Cyg, we do not have reliable estimates of stellar parameters, and so we cannot estimate \( M \).

Table 5 shows that our sample spans a wide range in Brγ luminosity, and hence in accretion luminosity and mass accretion rate. Measured EWs (and accretion luminosities and mass accretion rates) are generally within a factor of 2 of previous measurements (Najita et al. 1996; Folha & Emerson...
Given the large variations in Brγ EW over multiple epochs observed by previous investigators (e.g., Najita et al. 1996; Eisner et al. 2007b), our measurements seem compatible with the previous results.

4.2. Distribution of Brγ Emission

For many objects in our sample, both the disk and infall/outflow models considered above provide reasonable fits to the data (Table 4), and so we cannot distinguish between the two models, at least based on the available data. However, there are several sources for which we can distinguish. For MWC 480, MWC 863, and MWC 275, the $\chi^2$ values for fits of the disk model are substantially higher than those of infall/outflow model fits. These objects all show strong Brγ emission, and have been observed at high S/N. It seems likely that higher S/N observations of some fainter targets in our sample—especially those exhibiting bright Brγ emission—would also show them to be better described by infall/outflow models.
However, this produces differential phase signals larger than expected, contradicting the observations. To ensure single-peaked line profiles, the brightness profiles of disk models must be shallow. For example, if one posits an infall pointed nearly toward the observer, a lot of flux could come from near-systemic velocities without creating a large centroid offset (on the sky) of different velocity components.

For fainter sources, it is difficult to apply this argument, because of the lower signal to noise in both flux and differential phase measurements. Noisier fluxes make it harder to rule out models predicting spectrally unresolved emission (which also
predict no $\Delta \phi$ signature), while noisy $\Delta \phi$ measurements make it harder to rule out large centroid offsets with wavelength of the model emission. However, it is likely that observations of (some of) these fainter sources with higher S/N would find a preference for infall/outflow models.

We note that the orientation of the KI baseline with respect to the disk P.A. can be estimated in a few cases. For MWC 275, MWC 480, and MWC 758, estimated disk P.A.s (Tannirkulam et al. 2008; Eisner et al. 2004) are nearly orthogonal to the baseline P.A. This supports our interpretation of the data for MWC 480 and MWC 758 in terms of outflow models. In contrast, for MWC 1080, the estimated disk P.A. (Eisner et al. 2004) is nearly aligned with the KI baseline, suggesting that the $\mathrm{Br}\gamma$ observations may be sensitive to rotating gas in this source.

5. DISCUSSION

5.1. $\mathrm{Br}\gamma$ as a Tracer of Magnetospheric Accretion

In Section 4.2, we argued that the spectra, $V^2$, and differential phases measured for our sample are more compatible with infall/outflow models than with disk models, at least in some cases. Somewhat less direct evidence also argues against disk models for some of our targets. Low-mass young stars are thought to accrete material not via a boundary layer between star and accretion disk, but rather through funnel flows originating near the magnetospheric radius and then following stellar magnetic field lines to high-latitude regions of the star (e.g., Königl 1991; Hartmann 1998). This magnetospheric accretion picture provides a natural mechanism for truncating circumstellar disks and hence allowing direct illumination of the inner edge. This, in turn, would lead to the puffed-up inner disk walls evinced by continuum measurements of the inner regions of disks around T Tauri and Herbig Ae stars (Millan-Gabet et al. 2007, and references therein).

While our data are often fitted better with infall/outflow models, we cannot distinguish between infall and outflow models directly with the spatial and kinematic constraints provided by our observations. However, we can compare our results with size scales of gaseous emission predicted by various physical infall or outflow models. Matter falling in along stellar magnetic field lines will glow brightly near the stellar surface, where it converts most of its gravitational potential energy to radiation, and so we would expect to see $\mathrm{Br}\gamma$ emission from very close to the stellar surface in this case (e.g., Muzerolle et al. 1998). For models where the $\mathrm{Br}\gamma$ emission arises in hot, magnetically launched winds, we might see emission close to the magnetospheric radius at hundredths to tenths of an AU (as in the X-wind model; e.g., Konigl & Pudritz 2000).

Our modeling suggests that the $\mathrm{Br}\gamma$ emission in most objects arises in material that extends very close to the central star ($\lesssim 0.01$ AU; Table 4), consistent with expectations of magnetospheric infall models. This conclusion is supported for most sources by the very small average sizes of the $\mathrm{Br}\gamma$ emission found from simple geometric fits to the data (Table 3).

However, for some targets, we infer somewhat larger inner radii and/or shallow brightness profiles for the $\mathrm{Br}\gamma$ emission. Somewhat larger sizes are also inferred for the average $\mathrm{Br}\gamma$ emission from these targets ($\sim 0.05$–0.2 AU; Table 3). Evidently, much of the $\mathrm{Br}\gamma$ emission from these objects is found on scales larger than expected from accretion columns. X-wind or disk wind models predict more $\mathrm{Br}\gamma$ emission from larger radii, potentially consistent with the inferred size scales and brightness profiles for these sources.

### Table 4

| Source | Disk models | Infall/outflow models |
|--------|-------------|-----------------------|
|        | $x^2/\chi$ | $R_{\text{in}}$ | $R_{\text{out}}$ | P.A. | $\beta$ | $\Delta v$ | L/C | $f_\delta$ | $\alpha$ |
| RYTau  | 0.09 0.03  | 45 70 0.1 4 | 0.08 0.03 0.10 90 1 | 0.15 0.01 0.50 0 1 | 350 0.1 | 1.0 1 |
| DG Tau | 0.14 0.05  | 45 70 0.1 2 | 0.26 0.03 0.10 45 1 | 0.25 0.01 0.50 45 2 | 250 0.5 | 1.0 3 |
| DK Tau | 0.27 0.05  | 45 70 0.1 2 | 0.40 0.01 0.50 45 2 | 250 0.5 | 0.1 3 |
| DR Tau | 0.39 0.01  | 90 45 0.5 2 | 0.51 0.03 0.10 0 2 | 250 0.5 | 0.1 3 |
| MWC480 | 0.86 0.03  | 90 45 0.5 2 | 0.62 0.01 0.10 0 2 | 250 0.1 | 1.0 1 |
| RW Aur | 0.59 0.01  | 45 5 0.1 4 | 0.20 0.01 0.05 45 2 | 250 0.1 | 1.0 3 |
| MWC758 | 0.20 0.03  | 0 45 0.1 4 | 0.54 0.03 0.10 0 2 | 350 0.1 | 1.0 2 |
| AS205A | 0.52 0.05  | 0 45 0.1 4 | 0.35 0.01 0.05 0 1 | 250 0.5 | 0.1 1 |
| MWC863 | 0.44 0.03  | 0 45 0.5 2 | 0.76 0.01 0.50 0 2 | 250 0.5 | 1.0 1 |
| V2508Oph | 0.72 0.05 | 45 5 0.5 2 | 0.30 0.01 0.05 90 2 | 250 0.5 | 0.5 3 |
| MWC275 | 0.54 0.01  | 0 45 0.5 4 | 0.73 0.03 0.50 0 1 | 250 1.0 1.0 2 |
| AS353  | 0.77 0.05  | 0 5 1.0 2 | 0.47 0.03 0.05 0 1 | 500 0.1 1.0 3 |
| V1057Cyg | 0.54 0.01 | 90 70 0.1 4 | 0.49 0.01 0.50 90 1 | 350 1.0 | 1.0 1 |
| V1331Cyg | 0.56 0.05 | 90 5 0.5 2 | 0.26 0.03 0.10 45 2 | 500 0.5 | 1.0 1 |
| MWC1080 | 0.28 0.03 | 90 45 0.5 2 | 0.26 0.03 0.10 45 2 | 500 0.5 | 1.0 1 |

### Table 5

| Source | EW ($\mathrm{\AA}$) | $L_{\mathrm{Br}\gamma}/(10^{-4} L_{\odot})$ | $L_{\text{acc}}/L_{\odot}$ | $L_{\text{H}/L_{\gamma}}$ | $M/(10^{-8} M_{\odot} \, \text{yr}^{-1})$ |
|--------|------------------|-------------------|-----------------|-----------------|------------------|
| RYTau  | -1.0             | 1.9               | 0.5             | 0.1             | 6.4              |
| DG Tau | -8.1             | 3.8               | 1.3             | 1.5             | 7.6              |
| DK Tau | -2.2             | 0.8               | 0.2             | 0.2             | 1.2              |
| DR Tau | -7.1             | 3.1               | 1.0             | 1.1             | 5.7              |
| MWC480 | -7.7             | 9.8               | 4.4             | 0.2             | 9.3              |
| RW Aur | -7.2             | 2.7               | 0.9             | 0.5             | 4.8              |
| MWC758 | -1.4             | 1.9               | 0.6             | 0.1             | 1.1              |
| AS205A | -2.6             | 3.7               | 1.3             | 1.0             | 8.1              |
| MWC863 | -5.5             | 7.3               | 3.0             | 0.2             | 6.4              |
| V2508Oph | -5.8 | 4.2               | 1.5             | 0.5             | 17.2             |
| MWC275 | -6.1             | 14.7              | 7.3             | 0.2             | 17.5             |
| AS353  | -12.6            | 1.5               | 0.4             | ...             | ...              |
| V1057Cyg | 0.9           | ...               | ...             | ...             | ...              |
| V1331Cyg | -13.5          | 30.7              | 18.4            | ...             | ...              |
| MWC1080 | -5.1            | 1181.4            | 1824.8          | 0.1             | 4374.6           |
Based on these arguments it seems likely that in the sample of objects with steeper brightness profiles, \( \text{Br}\gamma \) emission traces magnetospheric accretion. For sources with shallower brightness profiles, \( \text{Br}\gamma \) emission traces infalling material that has a shallow radial brightness profile, outflowing material that is magnetospherically launched from small radii, or a combination of both infalling and outflowing material. In the latter case, the infalling material could produce very compact emission while more extended winds could “fill in” the emission profile at larger radii.

Further support for magnetospheric accretion as the origin for (some of) the \( \text{Br}\gamma \) emission comes from analysis of line profiles observed at higher spectral (but lower spatial) resolution. While most of our targets exhibit H\( \alpha \) emission showing P Cygni profiles of winds (e.g., Acke et al. 2005; Najita et al. 1996, and references therein), the \( \text{Br}\gamma \) line profiles are more symmetric and/or blueshifted, and often show a “blue shoulder” (Najita et al. 1996; Folha & Emerson 2001; Eisner et al. 2007b). These properties are all consistent with infalling material rather than winds (Najita et al. 1996).

**5.2. Trends with Stellar Properties**

While magnetospheric accretion is favored for low-mass stars, previous investigators have argued that disk accretion may be a better description in Herbig Be stars (e.g., Eisner et al. 2004). Thus, for MWC 1080, the one Herbig Be star in our sample, one might expect the disk model considered above to fit the data well. Note that the gaseous disk described in Section 3.1 could correspond physically to the inner accretion disk expected for a boundary layer accretion scenario where disk material in Keplerian rotation shocks when it hits the slower-rotating stellar equator (e.g., Lynden-Bell & Pringle 1974).

Disk models fit the data for this source approximately as well as outflow models. Furthermore, the orientation of the KI baseline along the disk major axis lends credence to the hypothesis that the \( \text{Br}\gamma \) we observe traces disk rotation. Thus, our current study supports the idea that Herbig Be stars may accrete material through geometrically thin disks rather than magnetospheric accretion columns.

**5.3. Trends with \( \text{Br}\gamma \) Line Luminosities**

Our sample clearly exhibits a range in \( \text{Br}\gamma \) line strength (Figure 1), which correlates with \( \text{Br}\gamma \) line luminosity and accretion luminosity (Table 5). We are thus in a position to explore whether the circumstellar properties of the \( \text{Br}\gamma \) emission depend on the overall strength of the emission.

Beyond stronger L/Cs, it is unclear what we would expect the effects of stronger \( \text{Br}\gamma \) emission (and by extension accretion luminosity or rate) to be on the observed data and models. If \( \text{Br}\gamma \) emission strength was correlated with the emission morphology—e.g., if stronger \( \text{Br}\gamma \) emission tended to trace infall while weaker emission traced outflow from larger stellocentric radii—then we might expect trends in the data.

The simplest way to search for trends is to look at inferred size of the \( \text{Br}\gamma \) emission versus the accretion luminosity. Figure 14 shows no obvious correlation between the two. Similarly, a comparison of Tables 4 and 5 shows no clear correlation between \( L_{\text{acc}} \) and \( \alpha \). Thus, there is no strong indication that \( \text{Br}\gamma \) emission strength determines the overall morphology.

We do, however, see some (inverse) correlation between the inferred inner radius of the \( \text{Br}\gamma \) emission and the accretion luminosity. Considering best-fit parameters for infall/outflow model fits, and excluding MWC 1080, which appears to be better fitted with a disk model, we plot the inner radius of the infall/outflow inferred from our modeling against \( L_{\text{acc}} \) in Figure 15. This may indicate that sources that convert more gravitational energy into \( \text{Br}\gamma \) luminosity do so at preferentially smaller stellocentric radii. For example, sources where \( \text{Br}\gamma \) traces accreting flows will exhibit the most compact emission, and may also produce higher \( \text{Br}\gamma \) luminosities. Alternatively, the trend seen in Figure 15 could fit in with an X-wind scenario where \( \text{Br}\gamma \) emission traces the innermost regions of an outflow: higher accretion rates—which mean more gravitational energy release—push the “X-point” to smaller stellocentric radii as accretion pressure pushes in against stellar magnetic pressure.

**5.4. Comparison with Previous Results**

As discussed in Section 1, Kraus et al. (2008) observed five Herbig Ae/Be sources with the VLTI interferometer, and
obtained spatially and spectrally resolved data indicating that the Brγ emission arose on scales larger than expected for magnetospheric accretion models. Their derived sizes of the gaseous emission were a few tenths of an AU for the Herbig Ae sources and a few AU for the Herbig Be objects.

Fitting ring models to the Brγ emission, as done by Kraus et al. (2008), we typically find substantially smaller sizes (Table 3). For MWC 275, the size we infer for the Brγ emission is ~10 times smaller than that found by Kraus et al. (2008). We note that the components of the MWC 275 visibilities attributed to Brγ by Kraus et al. (2008) are all consistent with unity, and we would therefore argue that their data are consistent with the compact size for this object determined here. Given the greater angular resolution of KI relative to VLTI, we are more sensitive to emission on compact scales, and so it is not overly surprising that we are able to better constrain Brγ emission at small stellocentric radii.

The modeling presented here suggests emission over a range of radii. While some objects have average Brγ emission sizes as large as ~0.1 AU (Table 3), the combination of spectrally resolved flux and V2 profiles and small differential phases for these targets indicates some Brγ-emitting gas on ~0.01 scales (Table 4). Thus, all of our targets where Brγ emission is observed appear to have some gas on very compact scales.

While Kraus et al. (2008) argued that the Brγ emission appeared to trace more extended disk winds, our results and modeling belie this conclusion. Rather, we suggest that the Brγ emission traces accreting material in many, if not most, sources. In others, Brγ emission may trace a combination of accretion and outflow, or perhaps compact (≤0.05 AU) wind-launching regions.

6. CONCLUSIONS AND FUTURE WORK

We presented observations capable of resolving hydrogen gas on scales as small as 0.01 AU around young stars. These were the first such observations of solar-type T Tauri stars, and extended the mass range and sample size of previous studies at similar spectral (but somewhat lesser spatial) resolution.

We showed that Brγ emission is typically more compactly distributed than the continuum emission around young stars. In several objects, the bulk of the Brγ emission is found on scales ≤0.01 AU. In others, the average size of the Brγ emission is ~0.1 AU, although modeling of our combined data set shows evidence for some Brγ emission extending in to within a few hundredths of an AU of the central stars. For sources with very small average sizes of the Brγ emission, an origin of the Brγ emission in accretion flows appears to be the best explanation. For objects with somewhat more extended Brγ distributions, the emission probably traces the innermost regions of magnetospherically launched winds, or perhaps some combination of infall and outflow.

No obvious trends are seen in the average size of the Brγ emission versus accretion luminosity. However, there appears to be some inverse correlation between the inner radius for our best-fit models and the Brγ emission strength. Such a correlation may indicate a relationship between the physical origin of the Brγ emission and its luminosity.

While all of our observations are compatible with infall/outflow models, the data for the most massive star in our sample, MWC 1080, appear equally consistent with a Keplerian disk model. Previous investigators have argued that this object may have a dense, gaseous, inner disk that prevents direct stellar irradiation of dust near the sublimation radius. Our modeling of this source is consistent with a disk origin of the Brγ emission.

While we observed V1057 Cyg, we did not discuss it at length here. V1057 Cyg is the one target in our sample where Brγ appears in absorption, rather than emission. As an FU Ori star, the luminosity of this source is dominated by accretion energy released in the disk midplane (e.g., Hartmann et al. 2004), and so most lines should appear in absorption (e.g., Calvet et al. 1991). We plan to discuss this source in detail in a future paper targeting FU Ori sources.

We also plan to extend the analysis presented above to other spectral regions. Although we focused on Brγ here, our experimental setup included the CO overtone bandheads as well as regions of significant opacity from water vapor. In fact, several objects discussed here also show interesting spectral features in the region of the CO bandheads. Because the currently observed V2 and Δφ signatures associated with these features are marginal, we postpone discussion to future work, when we hope to have higher S/N data.

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