SPATIALLY EXTENDED BRACKETT GAMMA EMISSION IN THE ENVIRONMENTS OF YOUNG STARS

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ABSTRACT

The majority of atomic hydrogen Brγ emission detected in the spectra of young stellar objects is believed to arise from the recombination regions associated with the magnetospheric accretion of circumstellar disk material onto the forming star. In this paper, we present the results of a K-band integral field unit spectroscopic study of Brγ emission in eight young protostars: CW Tau, DG Tau, Haro 6–10, HL Tau, HV Tau C, RW Aur, T Tau, and XZ Tau. We spatially resolve Brγ emission structures in half of these young stars and find that most of the extended emission is consistent with the location and velocities of the known Herbig–Haro flows associated with these systems. At some velocities through the Brγ line profile, the spatially extended emission comprises 20% or more of the integrated flux in that spectral channel. However, the total spatially extended Brγ is typically less than ~10% of the flux integrated over the full emission profile. For DG Tau and Haro 6–10 S, we estimate the mass outflow rate using simple assumptions about the hydrogen emission region and compare this to the derived mass accretion rate. We detect extended Brγ in the vicinity of the more obscured targets in our sample and conclude that spatially extended Brγ emission may exist toward other stars, but unattenuated photospheric flux probably limits its detectability.

Key words: stars: formation – stars: individual (CW Tau, DG Tau, Haro 6–10, HL Tau, HV Tau C, RW Aur, T Tau, XZ Tau) – stars: pre-main sequence – stars: winds, outflows

1. INTRODUCTION

H I emission lines are one of the defining characteristics of the classification of pre-main-sequence Sun-like sources known as T Tauri stars (TTSs). Still in the midst of formation, the less evolved TTS, known as classical TTS (CTTS), are surrounded by optically thick disks of gas and dust. In most cases, these young pre-main-sequence stars are still interacting with and accreting matter from the innermost regions of their disks via stellar magnetic fields. In this magnetospheric accretion paradigm, the stellar magnetosphere guides disk material from the inner disk onto the stellar surface through magnetic channels. The gas travels along these channels or so-called accretion columns near free-fall velocities, terminating in an accretion shock at the stellar surface. It is generally accepted that the gas is heated and ionized prior to and after reaching the stellar surface and that the characteristic H I emission lines result, in part, from recombing and accreting hydrogen gas confined to these magnetic channels (Lynden-Bell & Pringle 1974; Uchida & Shibata 1984; Bertout et al. 1988).

Balmer Hα emission is the dominant H I feature present in the optical spectra of CTTS, and the emission line strength (or line width) is often invoked as a measure of accretion rates for these sources (Muzerolle et al. 1998a). Spatially resolved observations of Hα emission lines in these young stellar objects (YSOs) also show it to be a strong component of the optical line emission from outflows, indicating that the underlying stimulation mechanisms for the H I lines are likely to be a combination of phenomena. Magnetospheric accretion models can successfully reproduce many aspects of the H I emission features detected in the spectra of young stars. However, they notably fail to account for the highest velocity gas in the H I line wings (Muzerolle et al. 1998a). Spectro-astrometric observations of the Paβ emission feature in the CTTS DG Tau show that the high-velocity blueshifted gas (v > ~200 km s⁻¹) is extended in the same direction as [Fe II] at 1.644 μm, a forbidden emission line feature that traces the known outflow in the DG Tau system. This illustrates why a model producing H I emission from accretion outflows does not account for high-velocity gas forming the H I line wings (Whelan et al. 2004). While the high-velocity gas is spatially shifted by as much as 0.5 around DG Tau (or ~70 AU at the distance of Taurus–Auriga), the majority of the Paβ emission remains coincident with the source. Although these results demonstrate that there are multiple processes for stimulating H I emission lines, the bulk of the emitting gas does seem to arise from radii within 14 AU of the central source constraining the emission to the magnetospheric accretion columns, inner gaseous disk, and the base of disk winds and outflows.

In the infrared, Brγ (2.16 μm) emission serves as a surrogate for Hα as a signpost for circumstellar disk accretion in TTS (Najita et al. 1996). Brγ line luminosities appear to correlate with mass accretion luminosity in brown dwarfs, CTTS, and Herbig Ae/Be stars (HAEBEs; Muzerolle et al. 1998a; Natta et al. 2004; Mohanty et al. 2003, 2005). Moreover, Brγ and other lines in the infrared are affected by different optical depth effects that have proven problematic for using Balmer series lines to infer temperatures, densities, and geometries of the emitting gas. Historically, the problem of predicting the spectra emerging from a recombing hydrogen gas has been divided into two distinct cases, A and B (Baker & Menzel 1938). Case A theory applies to very low density gases that are optically thin to all transitions of the hydrogen atom, including the ultraviolet photons associated with the Lyman series transitions. Case B theory, which applies to higher density gases which are

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optically thick to UV photons but optically thin to all $n \geq 2$ transitions, is often applied to the environments of TTSs. In a Case B model of a recombining atomic hydrogen gas, $\mathrm{Br}\gamma$ is $\sim$0.8%–1% of the flux of $\mathrm{H\alpha}$ for a wide range of densities and temperatures ($10^2 < n_e < 10^6 \, \text{cm}^{-3}, 5000 \, \text{K} < T < 20,000 \, \text{K}$). $\mathrm{H\alpha}$ is known to be a strong component in optical line emission from YSO outflows (Najita et al. 1996), it seems natural that a corresponding component of the $\mathrm{Br}\gamma$ emission would also arise from the outflows. Yet, to date, there has been little evidence in the literature for spatially resolved $\mathrm{Br}\gamma$ emission in the vicinity of YSOs, and hence nearly all $\mathrm{Br}\gamma$ emission is assumed to arise from magnetospheric processes within the inner accretion zone. In fact, infrared interferometric observations of HAeBe stars reveal that the $\mathrm{Br}\gamma$ emission component arises from very compact locations within the dust sublimation radius of the circumstellar disk (Eisner et al. 2009; Kraus et al. 2008). Though, a small extended $\mathrm{Br}\gamma$ emission component cannot be ruled out based on these observations. Further interferometric and spectro-astrometric programs that seek to reveal the inner $\sim$1 AU environments show that the compact $\mathrm{Br}\gamma$ is not always well modeled by disk emission alone (Eisner et al. 2010; Malbet et al. 2010). The analysis implies that a non-negligible component from outflowing gas needs to be incorporated into the models to explain the $\mathrm{Br}\gamma$ emission structure.

As an extension of the spectro-astrometric and interferometric studies mentioned above, imaging spectroscopy of these TTS can provide us with considerable insight into the geometric distribution of $\mathrm{H\upiota}$ emitting gas in accreting systems. Three-dimensional imaging spectroscopy techniques can help to disentangle the respective contributions to the $\mathrm{H\upiota}$ emission features. With just one pointing of a telescope, imaging spectroscopy with integral field units (IFUs) can provide three-dimensional $x$, $y$, $\lambda$ datacubes at high spatial resolution with simultaneous coverage of many emission lines of interest. There has recently been an increase in the capabilities for adaptive optics (AO) fed near-IR integral field spectroscopy at 8–10 m class observatories (Eisenhauer et al. 2000; McGregor et al. 2003; Larkin et al. 2006). IFUs optimized for AO spectroscopy have the power to spatially resolve emission line structures with less than 0′′1 extents over the full wavelength ranges sampled by typical IR spectrographs. As such, the new generation of IFUs provides the means to study the accretion and outflow environments in CTTSs.

In this paper, we present detections of spatially resolved $\mathrm{Br}\gamma$ emission in YSO environments from data acquired using the Near IR Integral Field Spectrograph (NIFS) at the Gemini North Observatory. We report on $\mathrm{Br}\gamma$ arising from eight CTTS systems and particularly highlight the spatially extended emission detected in four of these: DG Tau, Haro 6–10 (also known as GV Tau), HL Tau, and HV Tau C.

### 2. OBSERVATIONS

Observations of the eight CTTSs listed in Table 1 were obtained using the NIFS at the Frederick C. Gillette Gemini North Telescope on Mauna Kea, Hawaii. NIFS is an image slicing IFU fed by Gemini’s Near IR AO system, Altair, that is used to obtain integral field spectroscopy at spatial resolutions of $\lesssim$0′′1 with a spectral resolving power of $R \sim 5300$ at 2.2 $\mu\text{m}$ (as measured from arc and sky lines; McGregor et al. 2003). The NIFS field has a spatial extent of 3′′ × 3′′, and the individual IFU pixels are 0′′1 × 0′′04 on the sky. Data were obtained at the standard $K$-band wavelength setting for a spectral range of 2.003–2.447 $\mu\text{m}$. All observations were acquired in natural seeing of better than 0′′7 for excellent AO correction.

The data sets for this study were acquired for commissioning and system verification of NIFS in 2005 October and 2006 February, GTO time in 2006 December, and in queue mode in 2007 February (see Table 1). For each observation, a standard set of calibrations were acquired using the Gemini facility calibration unit, GCAL. The raw IFU frames were reduced into datacubes using the NIFS tasks in the Gemini IRAF package.4

Beck et al. (2008) discuss these NIFS data on DG Tau, HL Tau, HV Tau C, RW Aur, T Tau, and XZ Tau in the context of spatially resolved molecular hydrogen emission lines. Hence, the observational details, calibration, and data reduction information are described in great detail in that paper and excluded here. To study the $\mathrm{Br}\gamma$ emission in the young stars, the absorption features from the A0 stellar-type telluric calibration stars were removed by fitting and dividing Voigt absorption profiles in the 2.16 $\mu\text{m}$ spectral region and cleaning the calibration spectra for any small residuals. Observations of Haro 6–10 were acquired with the laser-fed AO system using the $R \sim 16.5$ mag southern component in this 1′′2 binary as the laser tip-tilt reference star. These data were obtained in excellent laser-quality weather, photometric with better than 0′′5 seeing. The CW Tau and Haro 6–10 data were processed in a similar manner to all other data, as described above and in Beck et al. (2008). All or part of the data for each source in this project were observed during photometric conditions and were flux calibrated using $K$-band magnitudes estimated by comparison to the brightness of the A0 standard star used for telluric correction. With the exception of Haro 6–10, the derived fluxes of the systems (combined in the case of multiples)

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4 Information on the Gemini IRAF package is available at [http://www.gemini.edu/sciops/data/dataIRAFIndex.html](http://www.gemini.edu/sciops/data/dataIRAFIndex.html).

### Table 1

| Star Name | HH No. | Obs. Date (UT) | P.A. of Obs. | Exp. Time/Co-adds | No. of Exp. | Total Exp. Time | Note on Obs. |
|-----------|--------|---------------|-------------|------------------|------------|-----------------|-------------|
| T Tau     | HH 255 | 2005 Oct 25   | 0″          | 5.3 s/24         | 36         | 4580 s          | AO Flexure Test |
| RW Aur   | HH 229 | 2005 Oct 22   | 221″        | 40 s/1           | 11         | 440 s           | AO Guide Test |
| XZ Tau   | HH 155 | 2005 Oct 25   | 0″          | 30 s/1           | 28         | 820 s           | AO+OIWFS* Flexure Test |
| DG Tau   | HH 158 | 2005 Oct 26   | 0″          | 20 s/6           | 101        | 12120 s         | AO+OIWFS* Flexure Test |
| HV Tau C | HH 233 | 2005 Oct 22   | 114″        | 900 s/1          | 3          | 2700 s          | System Sensitivity Test |
| HL Tau   | HH 150 | 2006 Feb 12   | 146″        | 900 s/1          | 3          | 2700 s          | 0′′2 Occulting Disk SV |
| CW Tau   | HH 150 | 2006 Dec 5    | 146″        | 900 s/1          | 3          | 2700 s          | NIFS PI GT   |
| Haro 6–10| HH 150 | 2007 Feb 7 and 8 | 0″   | 300 s/1          | 9          | 2700 s          | NIFS + LGS AO Queue |

**Note:** *The NIFS On-Instrument WaveFront Sensor (OIWFS) is used to correct spatial flexure in the observations.*

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were within 10%–15% of published or Two Micron All Sky Survey magnitudes. For Haro 6–10, the NIFS IFU spectra were compared to infrared K-band images acquired nearby in time for a complimentary project, the difference in flux was less than 0.2 mag between the two observations. We estimate that our overall data flux calibration is good to ±10%–15%. The data-cubes were interpolated onto a square pixel grid with 0.′05 spatial sampling, and the velocity channel steps through the IFU cubes are ∼29 km s⁻¹ pixels in extent at 2.20 μm (∼56 km s⁻¹ 2 pixel resolution). The final reduced, combined, telluric corrected, and flux-calibrated datacubes of the Brγ line emission for each target are discussed in detail in the following sections.

3. SPATIALLY EXTENDED Brγ EMISSION FROM YSO ENVIRONMENTS

The data acquired for this project, described in detail in the preceding section, were obtained with the goal of studying the K-band features of molecular hydrogen emission. The IFU spectral data were discussed by Beck et al. (2008) in this context. We never expected to detect spatially extended Brγ emission in any CTTS. This was a serendipitous discovery, revealed as we stepped through the raw velocity cube at Brγ wavelengths in the Haro 6–10 S data. The clear detection of spatially extended emission from the Haro 6–10 S jet prompted us to take a closer look at the Brγ emission in all TTS for which K-band IFU spectra had been obtained. As presented and discussed in the following, we have found significant spatially extended Brγ emission in four of the eight stars presented here: DG Tau, Haro 6–10, HL Tau, and HV Tau C. We do not find appreciable spatially extended Brγ in CW Tau, T Tau, XZ Tau, or RW Aur.

Figures 1–4 show the images of the spatially extended Brγ emission from DG Tau (Figure 1), Haro 6–10 (Figure 2), HL Tau (Figure 3), and HV Tau C (Figure 4). The panels in these figures show the following: (a) the continuum emission with contours of [Fe ii] emission overplotted to demonstrate the outflow position and geometry, (b) continuum-subtracted Brγ line emission maps with contours of the continuum overplotted, (c) “point-source subtracted” spatially extended maps of Brγ emission with the contours of the continuum subtracted, and (d) images of the integrated blueshifted Brγ emission only, with contours of the point-source-subtracted Brγ emission overplotted. At the right side of each image is the key correlating the image intensity to flux. The continuum images in panel (a) were constructed by fitting a straight line to the continuum around the Brγ emission feature and integrating the linear fit through the velocity channels that correspond to the Brγ emission. The images of the total Brγ emission presented in panel (b) were constructed by subtracting the linear fit to the continuum from the datacubes, then integrating in velocity over the Brγ emission feature. The “point-source-subtracted” Brγ images shown in panel (c) were derived by normalizing the
continuum (point-spread function, PSF) image to the peak flux in each velocity channel through the Brγ emission datacube, subtracting this scaled continuum image off of the Brγ cube, and integrating over the velocity extent to form an image of only the extended emission. The image of spatially extended blueshifted Brγ emission shown in panel (d) was made by integrating the “point-source-subtracted” image in 2–3 velocity channels of blueshifted emission only. Panel (d) shows that the spatially extended Brγ emission is stronger in the blueshifted velocity channels. Because of Poisson statistics associated with the subtraction process, detection of spatially extended Brγ emission is less robust at distances of \(<0.1''\) from the central point source. The Brγ emission in the vicinity of HV Tau C is quite weak, and all of the detected line emission is spatially extended. As a result, Figure 4 presents only panels (a) and (b) for HV Tau C.

For DG Tau and Haro 6–10 S, the majority of the Brγ emission that we detect, integrated over wavelength, is consistent with the stellar point-source image. For HL Tau and HV Tau C, the majority of the Brγ is not coincident with the central TTS. The integrated Brγ emission from DG Tau follows the point-source continuum contours with little deviation (Figure 1(b)). The spatially extended Brγ emission from DG Tau is detected in panel 1(c) and seen clearly in the blueshifted emission shown in panel 1(d). The blueshifted emission (Figure 1(d)) extends to the southwest of DG Tau, at an orientation and velocity consistent with the known, collimated blueshifted jet. Haro 6–10 also shows the bulk of the Brγ emission arising from the two stellar point sources. However, strong emission comes from the same location as the [Fe II] outflow emission from Haro 6–10 S (Figure 2(c)). In fact, for Haro 6–10 S, the Brγ arising from the outflow is \(\sim20\%\) of the total spatially integrated Brγ emission in some blueshifted velocity channels (Figure 2(d)). No spatially extended Brγ is detected toward the Haro 6–10 N component.

Data on HL Tau were acquired with the 0.2'' occulting disk blocking the central stellar point source, however, an appreciable amount of the detected Brγ emission is seen to deviate from the central stellar position. HL Tau shows strong spatially extended Brγ that follows the scattered light nebulosity revealed in the continuum emission (Figures 3(b) and (c); Takami et al. 2007; Close et al. 1997). The integrated blueshifted Brγ from HL Tau (Figure 2(d)) shows very weak emission detected at a 4σ level of significance that corresponds precisely with the spatial location of the [Fe II] emission. HV Tau C is a system with a known circumstellar disk viewed nearly edge-on (Stapelfeldt et al. 2003) and the stellar continuum flux is much fainter than

Figure 2. (a) 2.16 μm continuum flux level from Haro 6–10 with contours of [Fe II] emission overplotted, designating the outflow location, (b) the continuum-subtracted point-source Brγ flux, and (c) the continuum- and point-source-subtracted map of spatially extended Brγ from Haro 6–10 S. Also, included here is a continuum- and point-source-subtracted map of spatially extended Brγ, integrated over only three blueshifted velocity channels (d). Panel (d) shows that much of the spatially extended Brγ emission is blueshifted. The locations designated as “B” and “C” had one-dimensional spectral traces extracted, these are presented in Figure 5.
Figure 3. (a) 2.16 μm continuum flux level from HL Tau with the 0.2 occulting disk in the beam with contours of [Fe ii] emission overplotted, designating the outflow location, (b) the continuum-subtracted point-source Brγ flux, and (c) the continuum- and (d) point-source-subtracted map of spatially extended Brγ from HL Tau. Also, included here is a continuum- and point-source-subtracted map of spatially extended Brγ, integrated over only two blueshifted velocity channels (d). Panel (d) shows weak blueshifted Brγ emission that arises from the same spatial location as the [Fe ii] emission from the outflow. The locations designated as “B” and “C” had one-dimensional spectral traces extracted, these are presented in Figure 5.

Figure 4. (a) 2.16 μm continuum flux level from HV Tau C with contours of [Fe ii] emission overplotted, designating the outflow location and (b) the continuum-subtracted point-source Brγ flux. The locations designated as “B” and “C” had one-dimensional spectral traces extracted, these are presented in Figure 5.

The spatially extended Brγ emission revealed in Figures 1, 2, and 4 for DG Tau, Haro 6–10 S, and HV Tau C lies precisely along the outflow axis of the known Herbig–Haro energy flows associated with these young stars. For HL Tau, the detected (low signal-to-noise ratio (S/N)) Brγ emission in the blueshifted...
component of the emission (Figure 3(d)) arises from the same spatial location as the known blueshifted outflow (Takami et al. 2007). However, in HL Tau the majority of the spatially extended \( \text{Br} \gamma \) emission (Figure 3(c)) is not appreciably shifted in velocity from the nominal stellar radial velocity; it is detected at much higher S/N and appears to arise from \( \text{Br} \gamma \) emission from the central point source that has been scattered off of the wall of the outflow cavity (Close et al. 1997; Takami et al. 2007).

Figure 5 shows the velocity profiles of the \( \text{Br} \gamma \) flux associated with the central point source for DG Tau, Haro 6–10, HL Tau, and HV Tau C at the location of the peak continuum emission (upper panel) and the profiles of \( \text{Br} \gamma \) emission extracted in 0′′.2 diameter apertures at “Position B” and “Position C” as designated in Figures 1–4 for each star. The spatially extended \( \text{Br} \gamma \) from DG Tau and Haro 6–10 S is blueshifted in velocity by \( >100 \text{ km s}^{-1} \) with respect to the central point-source flux. HL Tau shows strong emission at the velocity of the point-source flux in “Position B” and very slight \( \sim 3 \sigma – 4 \sigma \) detection of flux from blueshifted (\( \sim –200 \text{ km s}^{-1} \)) emission from the outflow.

In DG Tau, Haro 6–10 S and HL Tau, the spatially extended \( \text{Br} \gamma \) emission that we detect from the outflows corresponds to the blueshifted regions of the jets. This is consistent with the fact that blueshifted jet components are flowing into our line of sight and are hence less obscured by intervening circumstellar disk material. HV Tau C is the only source where both blueshifted and redshifted \( \text{Br} \gamma \) are detected from opposite sides of the outflow with respect to the (estimated) position of the central star. The extended \( \text{Br} \gamma \) from HV Tau C is quite weak in some regions, it is detected at a low S/N but follows the location of the extended outflow. Curiously, we find that the blueshifted outflow lies to the northeast and the redshifted emission lies to the southwest, which (as predicted by Stapelfeldt et al. 2003) is at odds with the relative brightnesses of the lobes of the scattered light edge-on disk reflection nebula associated with this source. The southwestern lobe of the HV Tau C scattered light nebula is brighter, and was thus thought to be associated with the blueshifted (closer) lobe of the outflow. Our data reveal that this is not the case, and the northeastern, fainter lobe seems to be associated with more blueshifted outflow emission.

Figure 6 presents the standard deviation of continuum-subtracted \( \text{Br} \gamma \) flux with increasing distance from the central star (plotted as a solid line) for HL Tau (a), DG Tau (b), Haro
Figure 6. Standard deviation of the continuum-subtracted Brγ flux plotted vs. distance from the central continuum peak for HL Tau (a), DG Tau (b), Haro 6–10 S (c), and HV Tau C (d). The overplotted dashed line represents the level of spatially extended continuum- and point-source-subtracted Brγ flux. The ratio of the spatially extended flux to the standard deviation of point-source-subtracted emission (dashed line to solid line) represents a measure of the S/N of the spatially extended Brγ. The peak of the S/N for extended Brγ is ∼11 for HL Tau, ∼6 for DG Tau, ∼25 for Haro 6–10 S, and ∼11 for HV Tau C.

Figure 7 plots the same standard deviation of continuum-subtracted Brγ flux with increasing distance from CW Tau, T Tau, XZ Tau, and RW Aur, and a dashed line is also overplotted that presents the peak magnitude of the point-source-subtracted Brγ emission from the central star (in the case of the multiple systems, the central star is assumed to be the brightest stellar component). The stellar companion position locations are apparent in the plots for XZ Tau and T Tau, while RW Aur’s companion has a slightly greater separation than presented in Figure 7(d). For all four sources presented in Figure 7, no excess was seen in spatially extended Brγ emission at the location of the known Herbig–Haro outflows. For the cases of CW Tau, XZ Tau, and RW Aur, no strong evidence of extended Brγ emission beyond an S/N of ∼3 is found. Curiously, XZ Tau B showed weak Brγ emission associated with the position of the star, but XZ Tau A had no detectable Brγ. This result is seemingly at odds with the proposition that XZ Tau A is the more actively accreting star and the main driving source of the Herbig–Haro flow associated with this system (Krist et al. 2008). Although RW Aur exhibits very strong, centralized Brγ emission flux, RW Aur B showed no measurable Brγ emission associated with stellar mass accretion from its circumstellar disk.

The central region of Brγ emission for T Tau N was saturated in the data, making a proper measurement of the continuum-subtracted Brγ flux and point-source-subtracted flux difficult. The surrounding spatial and spectral regions nearby are not saturated, and were used to estimate the 2.16 μm flux level based on the shape of the PSF. A cursory fitting analysis done at velocities on and off of the emission line using the A0 spectral-type telluric calibrator as a PSF reference showed that the Brγ
emission associated with T Tau N is not appreciably extended compared to the point-source continuum emission. The line emission is asymmetric around the T Tau S PSF and is brighter to the northwest at the location of T Tau Sb. Hence, the Brγ line emission associated with the nearby 0′′.1 T Tau S a+b binary seems to arise preferentially from the b component, and it is stronger than the continuum flux (i.e., the T Tau Sb/Sc flux ratio is greater in Brγ). This causes the apparent enhancement in Brγ emission at the position of the companion in Figure 7(b). Extraction of the individual spectra of the blended components was not done because of the saturation of T Tau N, which would need to serve as a PSF calibrator.

4. Brγ ESTIMATES OF YSO MASS ACCRETION AND MASS OUTFLOW RATES

Muzerolle et al. (1998b) showed that the Brγ line luminosity from young stars correlates with the mass accretion rate, as determined from UV excess emission. Hence, we now use our detected Brγ line fluxes to derive mass accretion rate for the observed targets. Table 2 presents the total Brγ emission line fluxes of velocity channels for each of the young stars in this study. The relation from Muzerolle et al. (1998b) assumed that all detected Brγ emission was associated with the stellar point sources, so the line fluxes that we have included in Table 2 are the total integrated flux values, including emission detected in the outflowing gas. Also, included in Table 2 are the adopted stellar parameters used to derive the mass accretion rates: the stellar mass, temperature, luminosity, and visual extinction (Kenyon & Hartmann 1995; White & Ghez 2001; Hartigan & Kenyon 2003; Doppmann et al. 2008). The stellar parameters seem consistent with our K-band spectra, so we do not rederive them from our data.

XZ Tau B, T Tau S, and Haro 6–10 N are “infrared luminous companions” (IRCs) to their respective primaries, and the stellar parameters for these sources are much less certain (Koresko et al. 1997; White & Ghez 2001). The accretion activity and line-of-sight visual extinction toward the IRCs could also be variable (Ghez et al. 1991; Beck et al. 2001, 2004; Leinert et al. 2001). Moreover, T Tau S is itself a binary, and the bulk of the Brγ emission that we detect arises not from the IRC but from the ∼M-type T Tau Sb companion (Duchène et al. 2005). Haro 6–10 N was found by Doppmann et al. (2008) to have weak evidence of photospheric Na absorption features at 2.20 μm, with a late spectral type and an infrared veiling value estimated to be in the range of 12–15. Similarly, XZ Tau B also has strong infrared veiling and a poorly determined spectral type. As a result, we do not try to estimate mass accretion rates for T Tau S, Haro...
6–10 N, or XZ Tau B. Column 7 of Table 2 presents the mass accretion rates ($\dot{M}_{acc}$) derived for all of the other stars, using the relation from Muzerolle et al. (1998b) for the Br$\gamma$ line luminosity to accretion luminosity and the virial theorem treatment put forth by Gullbring et al. (1998).

The mass accretion rates derived for the eight stars in this study that have well-determined stellar parameters lie in the range from less than $4 \times 10^{-10} M_\odot$ for RW Aur B to $1.5 \times 10^{-7} M_\odot$ for T Tau N, with most sources in the range of $10^{-8}$ to $10^{-7} M_\odot$. These values lie within the overall range of mass accretion rates derived for CTTSs (Muzerolle et al. 1998b; Gullbring et al. 1998). For the most part, the mass accretion rates that we derive here are similar to $\dot{M}_{acc}$ values for these stars that have been derived from previous studies, within the associated uncertainties (e.g., Hartigan et al. 1995; Muzerolle et al. 1998b; White & Hillenbrand 2004). However, direct comparisons between mass accretion values for DG Tau, particularly, show a large discrepancy in our study. DG Tau has in the past exhibited a mass accretion value on the high side of the range for TTSs, around or just under $10^{-6} M_\odot$ yr$^{-1}$. Our derived mass accretion rate is an order of magnitude less than many previously published estimates (Hartigan et al. 1995; Muzerolle et al. 1998b).

DG Tau is known to vary in flux and spectral characteristics on short timescales (Biscaya et al. 1997; Hessman & Menzel 1938; Brocklehurst 1971; Hummer & Storey 1987; Storey & Hummer 1995), we use a simple analysis to measure the mass outflow rate from these stars. Using the H$\alpha$ emission coefficients from Osterbrock (1989), the expression for the detected Br$\gamma$ flux can be described as

$$F_{\text{Br}\gamma} = 1.2 \times 10^{-28} (N_e V_{\text{H}i}/D^2),$$  

where $D$ is the distance to the emitting region in centimeters, $N_e$ is the electron density, and $V_{\text{H}i}$ is the volume of the emitting region (MKS units). The electron temperature is assumed to be $\sim 10^4$ K, which is a reasonable estimate for the inner regions of YSO outflows. The mass of the emitting hydrogen in the spatially resolved regions of the outflow can be estimated as $M_{\text{H}i} = m_p N_e V_{\text{H}i}$. Merging this equation for the mass with the above equation for the flux gives

$$M_{\text{H}i} = 1.5 \times 10^{-13} (F_{\text{Br}\gamma} V_{\text{H}i})^{1/2}/D.$$  

We can thus solve for the mass of emitting hydrogen gas using the parameters of our measured Br$\gamma$ flux, the selected emission volume, and the assumed 140 pc distance to the stars, which is based on distances derived toward TTS within the Taurus star-forming complex (Torres et al. 2009). For DG Tau, an H$\alpha$ mass of $1.2 \times 10^{-8} M_\odot$ is derived, and for Haro 6–10 S this value is $1.4 \times 10^{-8} M_\odot$. The flux extraction volumes were chosen to be the same, so the difference in the atomic hydrogen outflow masses between the two stars is determined by the difference in their detected Br$\gamma$ flux values. Having chosen the flux extraction volumes to correspond to the average annual proper motions of these jets, these estimates approximate the mass outflow rates for DG Tau and Haro 6–10 S in solar masses per year.

Based on this analysis, we derive average electron densities on the order of a few $10^4$ cm$^{-3}$ for the DG Tau and Haro 6–10 S outflows. These densities are consistent with the large values of $10^5$–$10^6$ cm$^{-3}$ for $N_e$ that are often found within the inner 100 AU regions of young star outflows derived by inspecting

| Star   | Mass ($M_\odot$) | Luminosity ($L_\odot$) | $T_{eff}$ (K) | $\lambda_b$ (mag) | Integrated Br$\gamma$ Flux (W m$^{-2}$) | $M_{acc}$ ($M_\odot$ yr$^{-1}$) | $M_{out}$ ($M_\odot$ yr$^{-1}$) | Reference          |
|--------|-----------------|------------------------|--------------|------------------|----------------------------------------|-------------------------------|----------------------|------------------|
| CW Tau | 1.1             | 0.7                    | 4700         | 2.2              | $1.5 \times 10^{-16}$                 | $1.3 \times 10^{-8}$          | ...                  | ...              |
| DG Tau | 2.2             | 7.7                    | 4775         | 3.3              | $4.5 \times 10^{-16}$                 | $9.6 \times 10^{-8}$          | > $1.2 \times 10^{-8}$ | Dopmann et al. (2008) |
| Haro 6–10 S | 0.7       | 1.8                    | 4000         | 12.1             | $7.2 \times 10^{-17}$                 | $6.7 \times 10^{-8}$          | > $1.4 \times 10^{-8}$ | ...              |
| HL Tau | 1.2             | 3.0                    | 4400         | 7.4              | $2.1 \times 10^{-16}$                 | $8.7 \times 10^{-8}$          | ...                  | ...              |
| RW Aur A | 2.8           | 12.9                   | 5000         | 0.16             | $7.2 \times 10^{-16}$                 | $1.4 \times 10^{-7}$          | ...                  | ...              |
| RW Aur B | 1.2           | 3.0                    | 4200         | 1.6              | < $5.1 \times 10^{-18}$               | < $4.1 \times 10^{-10}$       | ...                  | ...              |
| T Tau N | 2.1             | 7.2                    | 5250         | 1.5              | $8.4 \times 10^{-16}$                 | $1.5 \times 10^{-7}$          | ...                  | ...              |
| XZ Tau A | 0.45           | 0.4                    | 3400         | 1.4              | < $7.7 \times 10^{-18}$               | < $1.9 \times 10^{-9}$       | ...                  | ...              |
| XZ Tau B | 0.6            | 0.8                    | 4100         | 29.0             | $1.7 \times 10^{-17}$                 | $4.6 \times 10^{-8}$          | ...                  | ...              |
| Haro 6–10 N | 0.6          | 0.8                    | 4100         | 29.0             | $1.7 \times 10^{-17}$                 | $4.6 \times 10^{-8}$          | ...                  | ...              |

6–10 N, or XZ Tau B. Column 7 of Table 2 presents the mass accretion rates ($\dot{M}_{acc}$) derived for all of the other stars, using the relation from Muzerolle et al. (1998b) for the Br$\gamma$ line luminosity to accretion luminosity and the virial theorem treatment put forth by Gullbring et al. (1998).
[Fe II] and other forbidden emission species (Hartigan et al. 1995; Bacciotti & Eisloeffel 1999; Hartigan & Morse 2007; Hartigan & Hillenbrand 2009). These electron densities are also very consistent with past values found in the inner DG Tau high-velocity blueshifted jet (Bacciotti & Eisloeffel 1999; Coffey et al. 2008).

The hydrogen outflow rates of $1.2 \times 10^{-8} \ M_\odot$ yr$^{-1}$ for DG Tau and $1.4 \times 10^{-8} \ M_\odot$ yr$^{-1}$ for Haro 6–10 S represent lower limits for the true mass outflow levels derived in this manner. These mass outflow rates are underestimates of the true mass flow because only the fraction of the gas that has recently been heated by the shock radiates in the emission species that is studied. We also only detect the gas in the high-velocity component (HVC) of the outflow, not in lower velocity flow surrounding the jet axis (Bacciotti et al. 2000; Pyo et al. 2003). Moreover, the derived Brγ flux in the outflowing volume was not corrected for any line-of-sight extinction effects which might further serve to increase the derived mass outflow rate, particularly in the obscured Class I star, Haro 6–10 S. Thus, we predict that the true $M_{\text{out}}$ values are greater than $1.2 \times 10^{-8} \ M_\odot$ yr$^{-1}$ for DG Tau and more than $1.4 \times 10^{-8} \ M_\odot$ yr$^{-1}$ for Haro 6–10 S.

5. DISCUSSION

This study shows that not all H I Brγ emission from CTTS arises from magnetospheric accretion processes within a few radii from the central star. We detect spatially resolved Brγ from DG Tau, Haro 6–10 S, HL Tau, and HV Tau C, which represents 50% of the TTTS systems in our sample. We do not spatially resolve Brγ line emission in the environments of XZ Tau, RW Aur, T Tau, and CW Tau. Two stars within these latter systems, RW Aur B and XZ Tau A, exhibit no Brγ emission at all.

In two of the blueshifted velocity channels, the spatially extended Brγ from Haro 6–10 S makes up ~20% of the total spatially integrated line flux. Integrated over the whole velocity width, about 10% ± 2% of the Brγ emission from Haro 6–10 S is spatially resolved at distances of greater than $0^\prime.1$ (14 AU) in the extended outflow (entirely from the blueshifted velocity component). The spatially extended Brγ emission makes up ~2% of the total line flux for DG Tau. All of the detected Brγ flux seems to arise from the outflow for HV Tau C, but the star is not seen directly because the continuum flux is measured only from the scattered light nebula. The inner magnetospheric accretion region of HV Tau C may be shielded by the inner rim of the central circumstellar dust disk in our edge-on viewing orientation, hence in this case we might not see the strong central Brγ component in the scattered light nebula. HL Tau has considerable Brγ emission scattered off of its surrounding outflow cavity walls, and the fraction of spatially extended Brγ emission is estimated to be $18% \pm 7%$ of the line flux from the central position. Observations of HL Tau were acquired with an occulting disk in the beam, so the total point-source flux is estimated from the PSF shape in the target acquisition setup images and the resulting value is significantly less certain.

The majority of the integrated Brγ flux that we measure is spatially unresolved from the position of the central stellar sources in our data, with the noted exception of the edge-on disk system HV Tau C. NIFS data can spatially resolve the bright Brγ emission beyond $0^\prime.1$ from the star or about ~14 AU. Additional Brγ emission likely arises from the outflows in regions closer than our resolution limit, where it cannot be detected. Overall, the extended Brγ line emission that we detect beyond ~14 AU distances from the parent stars comprises anywhere from a few percent (DG Tau) to all of the detected line flux from these systems (HV Tau C).

All of the sources that we have studied here are known to drive Herbig–Haro outflows. It is not clear why some stars exhibit extended Brγ emission, while other sources with strong and collimated outflows do not. However, from information presented in Table 2, we see that the stars that have appreciable spatially extended Brγ emission also have stronger estimated levels of optical visual extinction, $A_v$, toward the stellar photosphere. The stars where we do not find extended Brγ emission all have lower estimated optical obscurations. In the systems where extended Brγ emission is seen, the stronger levels of stellar continuum flux attenuation from the high visual extinction may make the weak spatially extended emission easier to detect. The stars that do not exhibit extended Brγ emission have brighter stellar continuum flux, which may be a result of less obscuration by natal material because of a slightly older evolutionary state, or perhaps a more inclined viewing geometry that directly reveals more of the central photosphere of the star. Thus, spatially extended Brγ emission may exist toward the other stars, but the bright continuum flux might prevent us from detecting it.

Several recent spectro-astrometric and interferometric investigations of inner YSO disks have sought to spatially resolve the atomic hydrogen associated with the magnetospheric recombination regions within 1 AU from the target stars (Whelan et al. 2004; Eisner et al. 2009; Kraus et al. 2008). The spectro-astrometric study of Whelan et al. (2004) revealed that an appreciable amount of Paβ emission from the blueshifted and redshifted velocity profiles arises from spatially extended distances from a TTS. Three of their four targets exhibited spatially resolved Paβ emission, two revealed evidence for spatially extended bi-polar redshifted and blueshifted components. This is an important finding, since the broadened emission line wings seen in the H I profiles from CTTS have never been well explained by magnetospheric accretion models. Evidence from this Paβ study and now our Brγ project suggest that the H I emission from TTTS does have non-negligible components from the outflow on spatial scales that were unresolvable prior to the current generation of sensitive instrumentation on 8–10 m class telescopes.

Thus far, spectro-interferometric studies of Brγ that can spatially resolve the inner magnetospheric accretion region have largely concentrated on the brighter HAEBEs (Eisner et al. 2009; Kraus et al. 2008; Malbet et al. 2007). Interestingly, most interferometric data reveal that the Brγ emission surrounding the HAEBEs arises from a centralized location that is spatially more compact than the infrared continuum emission, with perhaps some contribution from an outflowing wind (Malbet et al. 2007). The compact H I likely arises predominantly from the accretion-driven processes within the star-disk boundary; either from the central stellar mass accretion engine or from a stellar or disk wind (Kraus et al. 2008; Malbet et al. 2007; Eisner et al. 2010). Further work is warranted to better reveal the central emission location of H I from TTTSs, and the fraction of H I emission that is truly spatially extended from the parent star in comparison to the higher mass HAEBEs.

Although we do detect spatially extended Brγ emission from 50% of our sample targets, the bulk of the line emission from most stars does arise within ~14 AU from the central unresolved point sources. While the spatially extended H I seems to affect the wings of the velocity line profile shapes (Whelan et al.
be derived from other observations. Additionally, the \( \dot{M}_{\text{out}} \) rates we find are lower limits, as discussed in Section 5. However, the uncertainties in the derivation of both the \( \dot{M}_{\text{out}} \) and \( \dot{M}_{\text{acc}} \) values can be very large. Our lower limit for the value of \( \dot{M}_{\text{out}} \) in DG Tau and Haro 6–10 S is derived from straightforward assumptions on the physics of LTE atomic hydrogen in recombination regions. As noted above, the hydrogen recombination emission area very close to the central star is possibly excited by non-thermal processes in the inner magnetospheric region (Bary et al. 2008). Hence, it seems feasible that these non-LTE conditions may extend into the inner regions of the outflow, making our H\textsc{ii}-like analysis of hydrogen emitting mass correspondingly uncertain. This is likely one of the largest sources of uncertainty in our analysis, but it is also difficult to characterize. We also estimate an additional source of error in our selection of the emission volume that was chosen to represent one year worth of jet motion. Moreover, the correlation of integrated B\textsc{r}\gamma line luminosity with stellar mass accretion luminosity has an intrinsic scatter (Muzerolle et al. 1998b), and deviation in \( \dot{M}_{\text{out}}/\dot{M}_{\text{acc}} \) by a factor of several for a given target can result from using this method to derive the stellar mass accretion rate. Multiple observations of accretion indicators from large sample of TTS demonstrate the highly variable nature of accretion activity in these young stars (e.g., Bary et al. 2008; Nguyen et al. 2009). However, the effects from intrinsic time variation in the accretion and outflow properties are not an issue in our study because the mass outflow and mass accretion rates are derived simultaneously from the same data set.

The blueshifted jet emerging from DG Tau is arguably one of the best studied outflows associated with a young star. It was among the first CTTSs for which a collimated jet-like outflow was discovered (Mundt & Fried 1983). Since its discovery, the HH 158 outflow from DG Tau has been investigated with high spatial resolution imaging and spectroscopy with \textit{Hubble Space Telescope} (HST), ground-based AO systems, and spectro-imaging techniques (Lavalley et al. 1997; Lavalley-Fouquet et al. 2000; Bacciotti et al. 2000, 2003; Dougados et al. 2002; Pyo et al. 2003; Takami et al. 2004; Coffey et al. 2008). This outflow has observationally revealed the structure of collimated YSO jets in great spatial detail; they are typically comprised of an on-axis HVC at radial velocities greater than \( \sim 50 \) km s\(^{-1} \) that can extend to spatial distances of hundreds of AU from the star and an encompassing shell of lower velocity gas that extends only about \( \sim 100 \) AU away from the central star (Bacciotti et al. 2000; Pyo et al. 2003; Takami et al. 2004). Although

[5] Bary et al. (2008) found the most likely temperature and density ranges of \( T < 2000 \) K and \( 10^9 \text{ cm}^{-3} < n_e \lesssim 10^{10} \text{ cm}^{-3} \).
He i 10830 emission is commonly attributed only to stellar winds in the inner \(\sim10\) AU environments of CTTSs, Takami et al. (2002) detect He i 10830 emission from DG Tau at the jet velocity, spatially extended over 0\(''\)5 (\(\sim70\) AU) of the jet, though their spectroastrometry did not find extension in the low-velocity He i 10830 emission. Bacciotti et al. (2000) and Pyo et al. (2003) described the blueshifted HH 158 jet as having an “onion-skin” structure, with high-velocity low density gas on-axis, surrounded by successive layers of lower velocity, higher density gas. Integrated over the width of the jet axis, the \(M_{\text{out}}/M_{\text{acc}}\) values derived for the DG Tau jet from past studies lie in the range of 0.05–0.1 (Lavalley et al. 1997; Bacciotti et al. 2000; et al. (2002) detect He i emission from these jets to further test the configuration, and all three of these systems have very strong CTTSs with circumstellar disks viewed in a nearly edge-on perspective. The detected Br \(\gamma\) emission environments.

6. SUMMARY

We have presented the results of our K-band integral field spectroscopy study of the Br \(\gamma\) line emission from eight TTS systems. The key points of our study are the following.

1. Using AO fed integral field spectroscopy, we have spatially resolved Br \(\gamma\) line emission in the circumstellar environments around four of our eight survey target stars: DG Tau, Haro 6–10 S, HL Tau, and HV Tau C.

2. The spatially extended Br \(\gamma\) emission arises predominantly from the hydrogen recombination regions associated with the inner Herbig–Haro outflows from these young stars. Only HL Tau shows a significant contribution of stellar Br \(\gamma\) emission scattered into our line of sight off of the outflow cavity walls. This emission from HL Tau has a similar morphology to the scattered light continuum flux, and it likely originated from the inner magnetospheric accretion region around the star.

3. At some blueshifted velocities, the spatially extended Br \(\gamma\) emission comprises \(\sim20\)% of the detected Br \(\gamma\) (e.g., Haro 6–10). Although we spatially resolve Br \(\gamma\) emission from outflows in our high-contrast measurements, the majority of the integrated Br \(\gamma\) from most systems is spatially unresolved and may arise from the magnetospheric accretion processes at the location of the central stellar source (with the exception of HV Tau C).

4. All of the Br \(\gamma\) emission that we detect above the continuum flux from HV Tau C is from the spatially extended emission, consistent with the location of the known Herbig–Haro outflow. HV Tau C is seen in continuum light as a scattered light edge-on disk nebulosity. The inner magnetospheric component of Br \(\gamma\) flux may be shielded from our line of sight by material in the inner edge of the circumstellar disk.

5. Derivation of the stellar mass accretion rates from the relationship between Br \(\gamma\) line luminosity and mass accretion reveals \(M_{\text{acc}}\) values that are typical of CTTSs.

6. Detection of the spatially extended Br \(\gamma\) emission from the outflows in the DG Tau and Haro 6–10 S systems has allowed us to derive a value for the emitting hydrogen mass outflow rate using simple arguments applicable to hydrogen recombination regions. The corresponding values for \(M_{\text{out}}/M_{\text{acc}}\) that we derive are on the order of \(\sim10\%–15\%\), consistent with many prediction from accretion-driven stellar winds and disk winds, while on the high side in comparison to observationally derived mass outflow to accretion rate ratios from past studies.

7. We find that in some young protostars, Br \(\gamma\) emission extended on spatial scales of greater than 0'1 (14 AU) can contribute \(\sim10\%\) of the flux to the detected integrated line emission (or more, as in the case of HL Tau and HV Tau C).

Several NIFS data sets presented in this study were acquired during the early stages of instrument integration at Gemini North Observatory, and we are extremely grateful for the support of the NIFS teams at the Australian National University, Auspace, and Gemini Observatory for their tireless efforts during the instrument commissioning and system verification. This study is based on data from the Gemini Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., on behalf of the international Gemini partnership of Argentina, Australia, Brazil, Canada, Chile, the United Kingdom, and the United States of America.

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