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Thomas S. Rice
Harvard University

Sean D. Brittain
Clemson University, sbritt@clemson.edu

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A SPECTRO-ASTROMETRIC MEASUREMENT OF BRACKETT GAMMA EMISSION IN HERBIG Ae/Be STARS

Thomas S. Rice[1]
Department of Astronomy, Harvard University, Massachusetts, 02138

and

Sean Brittain
Department of Physics & Astronomy, Clemson University, South Carolina, 29631

ABSTRACT

In T Tauri stars, the Brackett γ line strength is a reliable indicator of accretion luminosity. Among intermediate mass young stars, Herbig Ae stars also show this correlation, but in Herbig Be stars the Brγ line flux significantly overpredicts accretion luminosity. This Brγ excess in Herbig Be stars is thought to arise from a spatially extended outflow. Using commissioning data from the LUCIFER spectrograph on the 8.4-meter Large Binocular Telescope (LBT), we present a spectro-astrometric study of two Herbig Ae/Be stars, the HAe star MWC480 and the HBe star HD 259431. In both stars, an extended Brγ source can be ruled out down to $0\farcs001$ at the 1σ level. Using currently accepted parallax values of 137 ± 25 pc and 173 ± 37 pc, this implies a lack of spatially extended structure beyond 0.131 ± 0.024 AU for MWC 480 and 0.166 ± 0.036 AU for HD 259431.

Spectro-astrometric precision depends on both the signal-to-noise and the angular resolution of an observation. To confidently rule out an extended Brγ source as the origin of the Brγ excess, either a repeat of these observations with the LBT's AO enabled, or an 81× increase in observing time, is needed.

Subject headings: stars: pre-main sequence – stars: Herbig Ae/Be – stars: individual (HD 259431, MWC 480) – protoplanetary disks – accretion – spectro-astrometry

1. INTRODUCTION

Mass accretion onto young, low-mass stars, known as T Tauri stars, is currently understood to occur through the magnetospheric accretion process (Hartmann et al. 1994; Bouvier et al. 2007, and references therein) in which large magnetic fields driven by a fully-convective young star channel gas and dust from its circumstellar disk into funnel flows that fall onto the stellar surface. However, mass accretion onto higher-mass young stars, known as Herbig Ae/Be stars, is not yet well-understood either quantitatively or qualitatively (Brittain et al. 2007; Donehew & Brittain 2011), and may occur via a number of mechanisms, such as boundary-layer accretion, magnetospheric accretion, or some other unknown process.

Herbig Ae/Be stars (HAeBes) were first identified as young stars by Herbig (1960) and are thought to span a mass range of 2 - 8 solar masses. They are the evolutionary precursors to A and B stars and display bright hydrogen emission lines; they also are often associated with obscured dark cloud regions, immediately surrounded by bright nebulosity, are photometrically variable, and show an infrared excess (The et al. 1994; Vieira et al. 2003).

In T Tauri stars, luminosity of the near-infrared Brackett γ (2.1661 μm) emission line has been found to correlate well with accretion luminosity (Muzerolle et al. 1998). Brackett γ is the name of the hydrogen emission line corresponding to an electronic transition from the $n = 7$ state to the $n = 4$ state, the third member of the Brackett spectral series. Previous studies of Brackett γ in HAeBes have shown that this relationship holds for Herbig Ae stars, but breaks down in Herbig Be stars; in HBes, Brγ often overpredicts the accretion luminosity (Donehew & Brittain 2011). Donehew & Brittain (2011) predict that this Brγ excess may come from a spatially extended emission region, such as an energetic outflow or hot stellar wind, and that this component becomes increasingly dominant from late-type to early-type stars. They indicate that interferometric or spectro-astrometric observations should be able to test this hypothesis.

The technique of spectro-astrometry, described by Whelan & Garcia (2008), can be used to obtain subseeing information about spatial structure. This method involves carefully measuring the center of light in a spectrum at each wavelength element, and comparing the center-of-light within emission features to the center-of-light of the continuum. With appropriate signal-to-noise, centroid shifts of just a small fraction of a pixel are discernible. Previous spectro-astrometry studies have been able to extract meaningful spatial information on angular scales down to 0.1 milliarcseconds, and on spatial scales as small as 0.1 AU (Whelan et al. 2004; Pontoppidan et al. 2008; Davies et al. 2010) and are especially well-suited to probe the inner environments around young stars.

In this paper we present results from a spectro-astrometric observing campaign to measure any spatial extension of the Brackett γ line in two HAeBes: the Herbig Be star HD 259431 and the Herbig Ae star MWC 480. If a spectro-astrometric signature is detected, it may indicate that the Brackett γ emission does not entirely originate from the disk-star accretion interface but also comes from outflowing material, offering an explanation for the Brγ excess among Herbig Be stars noted by

Electronic address: trice@cfa.harvard.edu
[1] Southeastern Association for Research in Astronomy (SARA) NSF-REU Summer Intern

TABLE 1
Journal of Observations

Star	P.A.[a] (deg)	Observation Date	Seeing ($''$)
MWC 480	0	2010 December 9	0.6
MWC 480	45	2010 December 9	0.6
MWC 480	0	2010 December 11	0.6
MWC 480	90	2010 December 11	1.1
MWC 480	180	2010 December 11	0.6
MWC 480	270	2010 December 11	0.84
HD 259431	0	2010 December 12	0.84
HD 259431	90	2010 December 12	0.84
HD 259431	180	2010 December 12	0.84
HD 259431	270	2010 December 12	0.84
HD 259431	45	2010 December 12	0.84

Note. — Total integration time at each position angle was 4 minutes.

[a] Antiparallel spectra were observed for the purpose of pairwise combination, described in §3.

Donehew & Brittain (2011). However, a clear null result would be a strong indication that Herbig Be stars accrete via a qualitatively different mechanism than Herbig Ae stars.

2. OBSERVATIONS AND DATA REDUCTION

2.1. *LBT Observations*

Our targets were observed on the Large Binocular Telescope (Hill et al. 2006) using the near-infrared LUCIFER spectrograph (Ageorges et al. 2010; Seifert et al. 2010). The LBT is situated on Mount Graham in southeastern Arizona, and consists of a pair of 8.4-meter mirrors on a common mount. Using the N3.75 camera on LUCIFER, with its $0.''12$ pixel scale, we observed our two targets in non-AO mode, with spectral resolution R=8,600, covering the wavelength range $2.0 - 2.3$ μm.

Our observations were carried out on three nights in December 2010. Data for MWC 480 were taken on 2010 December 9 and 11, and data for HD 259431 were taken on 2010 December 12. Each star was observed at multiple slit position angles, and for each position angle our spectra were taken in an AABB nod sequence. In the nod sequence, the position of the star was separated by $15'$, and each exposure was 60 seconds long, for a total integration time of 4 minutes per position angle (Table 1). The stellar properties of our targets is given in Table 2.

2.2. *Spectroscopic Reduction*

Our data were reduced following standard procedures using scripts adopted from a NIRSPEC reduction package described extensively in Brittain et al. (2004). For each observation at each position angle, our spectra were combined by $(A{-}B{-}B{+}A)/2$ to correct for sky emission lines. Data were wavelength-calbrated by comparing atmospheric absorption features to lines in an atmospheric model.

3. SPECTRO-ASTROMETRIC ANALYSIS

To extract the spectro-astrometric signal from our data, we calculated the centroid of each wavelength element along the rectified two-dimensional spectrum. We use the following definition of the formal spatial centroid,

$$X(v) = C\frac{\sum_i (x_i(v) - x_0)F_i(v)}{\sum_i F_i(v)}, \qquad (1)$$

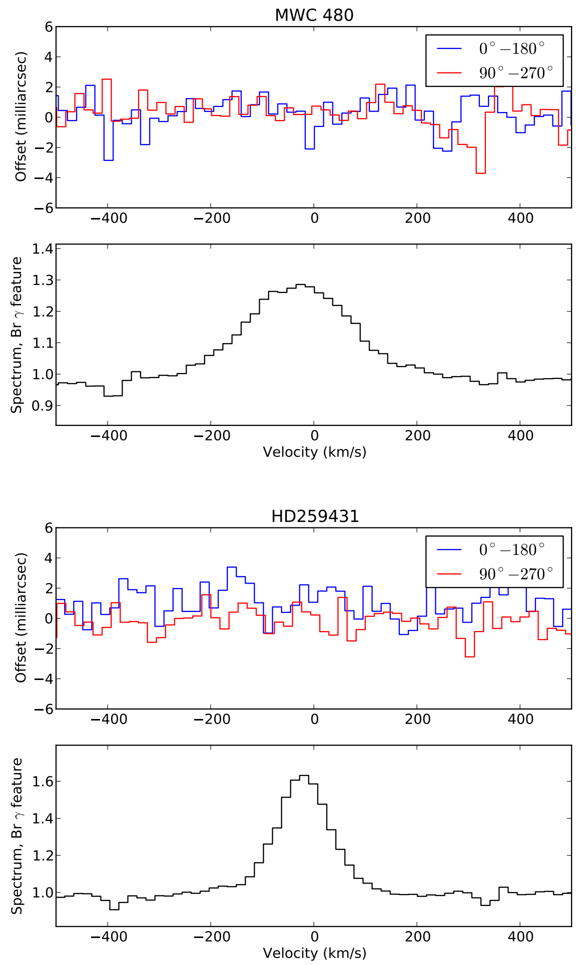

Fig. 1.— Spectro-astrometry for MWC 480 (top) and HD 259431 (bottom) of the Br γ emission line and surrounding continuum. In both stars, no spectro-astrometric signal is detected above the noise of 1 mas.

from Pontoppidan et al. (2008), Equation (1), where $x_i(v) - x_0$ is the center of the i^{th} pixel relative to the star's continuum centroid at velocity v in the spatial direction and $F_i(v)$ is the flux in that pixel. To minimize the rms of the centroid variations in the continuum, while also minimizing continuum contamination of any spectro-astrometric signal, we chose to sum over a spatial aperture of 360 milliarcseconds (mas), or the 3 pixels surrounding the peak of the PSF.

Each of our spectra are paired with an observation taken at an antiparallel slit position angle. Once we obtained the spectro-astrometric profile from each spectrum, we combined the centroids of antiparallel spectra to remove instrumentation artifacts while keeping real signal, i.e. $X(v) = (X_{0^\circ} - X_{180^\circ})/2$.

4. RESULTS

The spectro-astrometric analysis of our data show no significant deviation from the continuum's center of light within the Brγ emission feature. As seen in Figure 1, no signal within the Brγ line rises above the pixel-to-pixel variations seen in the neighboring continuum region.

By calculating the rms variation in spatial offset over a section of the continuum spanning 100 pixels, we

TABLE 2
Stellar Properties

Star	Spectral Type	Distance (pc)	Ks Magnitude (2MASS)	Mass ($M_\odot$)	Radius ($R_\odot$)
MWC 480	A3	137 ± 25	5.51	1.8	1.67
HD 259431	B6	173 ± 37	5.73	12.2	6.4

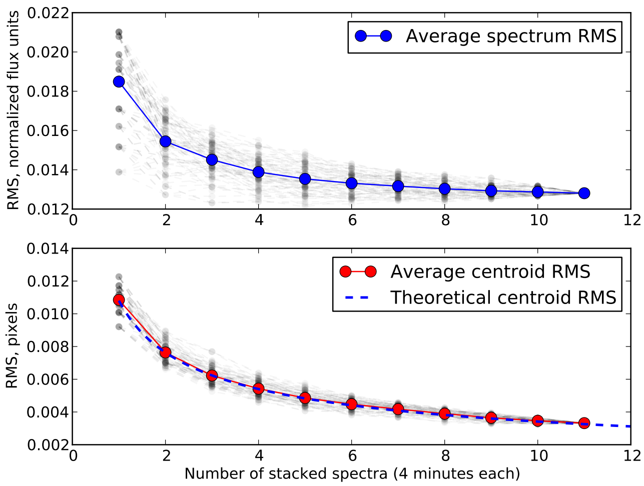

Fig. 2.— Sensitivity of our spectro-astrometric observations versus integration time. To produce this figure, all observations were stacked in order to investigate whether instrumental effects would dominate noise. The bottom panel shows that the noise falls off faithfully with $1/\sqrt{\text{integration time}}$, showing that our observations are still photon-limited.

can empirically estimate the sensitivity of our spectro-astrometric measurement. In each antiparallel pair of slit observations, we derive an uncertainty σ_{centroid} between 0.9 and 1.1 mas.

5. DISCUSSION

5.1. *Discussion of present results*

Our null-detection of an extended Brγ source in these observations allows us to place an upper limit on the origin of excess Brγ flux in Herbig Be stars identified by Donehew & Brittain (2011).

The inclusion of MWC 480, a type A3 star, in our observations was primarily as an experimental control. It is not expected to have any significant Brγ-emitting outflow, because as a late HAe star, it fits well within the Brγ − L_{acc} correlation for T Tauri stars and Herbig Ae stars.

HD 259431, on the other hand, is a type B6 star, and therefore an extended Brγ signature is expected. Using the Hipparcos distance of 173 ± 37 pc (van Leeuwen 2007), our observations constrain any extended Brγ emission around HD 259431 to a spatial scale smaller than 0.17 ± 0.037 AU with 1-σ confidence.

In his spectro-interferometric study of YSO inner accretion disks, Kraus (2008) identifies five primary sites of Brγ line emission: mass infall via magnetospheric accretion onto the star; hot, optically thin gas inside the dust-destruction radius; stellar winds; X-winds launched from the inner edge of the disk; and cooler winds launched further out from the disk. Our observations place strong constraints on which, if any, of these phenomena are responsible for the Brγ excess in HBe stars.

5.2. *Discussion of follow-up observations*

In order to identify precisely the nature of the extended Brγ emission, or rule out an extended origin altogether, further observations are necessary. Resolving spatial structure down to the disk co-rotation radius of 0.07 AU (van den Ancker et al. 1998; Kraus 2008) should settle the question. In order to successfully probe this region with 3-σ confidence, an improvement in sensitivity by a factor of 9 is necessary.

The theoretical sensitivity of the spectro-astrometric signal is described in Whelan & Garcia (2008) as

$$\sigma_{\text{centroid}} = \frac{\text{seeing(mas)}}{2.3548\sqrt{N_p}}. \quad (2)$$

where N_p is the number of collected photons, which is proportional to integration time.

Equation 2 ignores any instrumental defects (such as $1/f$ noise) which would strongly affect the outcome. Because the LUCIFER spectrograph on the LBT is a new instrument, its sources of error may not be well-calibrated. To investigate how the spectro-astrometric sensitivity would increase for observations longer than those in this study, we successively stacked all 11 spectra and empirically estimated the noise for each number of combined spectra. To ensure that our analysis was not adversely affected by a single anomalous observation, the order in which the spectra were stacked was randomized 100 times and averaged over runs.

The results of this analysis are displayed in Figure 2. The rms of the stacked centroids faithfully follows the $1/\sqrt{N_p}$ behavior predicted by Equation 2.

To achieve a 9× improvement in spatial sensitivity using the same observing setup, observations lasting 81× longer are needed. Practically, this translates to 321 minutes (5.4 hours) of integration per position angle. This would be feasible in an 8-night observing campaign with 4 position angles for each star.

In addition to longer observations, adaptive optics will greatly increase spatial sensitivity. The LBT's adaptive optics system has been shown to regularly achieve diffraction-limited angular resolution with Strehl ratio of above 80%. At Brγ's wavelength of 2.16 μm, the diffraction limit on an 8.4-meter telescope is $0\farcs06$, a full factor of 10 improvement on the seeing of this dataset's best observations. Repeating these observations when AO is enabled for LUCIFER should deliver the desired results.

6. CONCLUSION

In this study we investigated the spectro-astrometry of two Herbig Ae/Be stars in Brγ and found no spatial extension down to $0\farcs001$. This shows that any extended origin of Brγ in the HBe star HD 259431 is confined to within 0.17 ± 0.037 AU with 1-σ confidence, and places constraints on the nature of that extended emission.

In order to conclusively rule out an extended origin of Brγ in HBe stars, a $9\times$ improvement in spatial sensitivity is needed. This increase in sensitivity can be obtained either by increasing integration time by a factor of 81, taking advantage of the LBT's adaptive optics system and keeping integration time constant, or a combination of the two approaches.

Either a positive or a negative detection of extended Brγ emission will place important constraints on accretion processes in Herbig Ae/Be stars.

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