Constraining Temperature and Density of Accretion Flows in T Tauri Stars from Brackett Line Ratios

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1. Motivation

Low-mass Young Stellar Objects (YSOs) actively accreting from a protoplanetary disk are classified as T Tauri Stars (TTSs). Hydrogen Brackett (Br) emission in TTSs has been shown to originate predominantly in shocks caused by gas accreting onto the stellar surface (Najita et al. 1996; Muzerolle et al. 1998). These shocks arise as gas in the accretion disk becomes entrained by the star's magnetic field, following field lines until impacting the star in a process known as magnetospheric accretion (e.g., Shu et al. 1994; Hartmann et al. 2016). Bary et al. (2008) analyzed the Hydrogen Paschen and Brackett lines in 104 low-resolution spectra of 16 TTSs that were collected using the CORMASS spectrograph ($R \simeq 300$). Using a recombination model for which the gas is optically thick to Lyman series and continuum photons (Case B), the physical conditions that best fit the observed line ratios were $T \leq 2000$ K and a tightly constrained density of 10^{10} cm^{-3}. This result was in contrast to magnetospheric accretion models that predict temperatures between 6000 K and 12,000 K (Muzerolle et al. 2001). These high temperatures are also supported by near-UV spectra of accreting systems (e.g., Ingleby et al. 2013). With more recent studies finding higher temperatures and densities using Balmer and Paschen line decrements (e.g., Antoniucci et al. 2017), we revisit the analysis of Bary et al. with 614 high-resolution spectra from the Immersion Grating Infrared Spectrometer (IGRINS) for 165 TTSs in the Taurus star-forming region.

2. Methods

IGRINS provides simultaneous wavelength coverage of H and K bands (1.45–2.5μm) at a spectral resolution of $R \simeq 45{,}000$ (Mace et al. 2016, 2018). The H and K band spectra of 165 TTSs were collected over multiple epochs (between 1 and 10) and combined, weighted by their signal-to-noise. Each spectrum was accompanied by an adjacent A0V observation for telluric correction and relative flux calibration. Due to a relative flux offset between *H* and *K* orders in the combined spectra, we focus our analysis on *H*-band Brackett lines. The spectra were analyzed using a custom Python script that corrected for extinction values found in the literature (Herczeg & Hillenbrand 2014; White & Ghez 2001), continuum normalized the spectra, searched for an emission line in the expected wavelength range for 10 Brackett lines (Br10–Br19), and measured the properties of detected emission lines. The measurements were the peak relative flux, full width at half maximum, full width at zero intensity (FWZI), and equivalent width of the emission lines. Finally, the endpoint used to calculate FWZI were used to to integrate each line's total flux. These line parameter calculations were based off of the procedure outlined by Folha (1998).

A bootstrap Monte Carlo simulation was run to determine the uncertainties of the line measurements. In each simulation Gaussian noise was added to each flux value as the photon noise from the combined SNR of the IGRINS spectrum. Error distributions are generally symmetric, but we conservatively adopted the larger of the 68% confidence intervals as our uncertainty.

Line ratios relative to Br10 were calculated using a weighted arithmetic mean. Only YSO's with at least three ratios were included in the weighted mean (Figure 1; left), winnowing our sample to 7 sources (5 of which overlap with the sample used in Bary et al. 2008). The nine line ratios calculated and their associated errors were fit against a grid of pre-computed line ratios from a hydrogenic Case B recombination model provided by Storey & Hummer (1995) for which the system density and temperature are free parameters. The fit was evaluated using a reduced χ^2 statistic presented in Figure 1 (right).

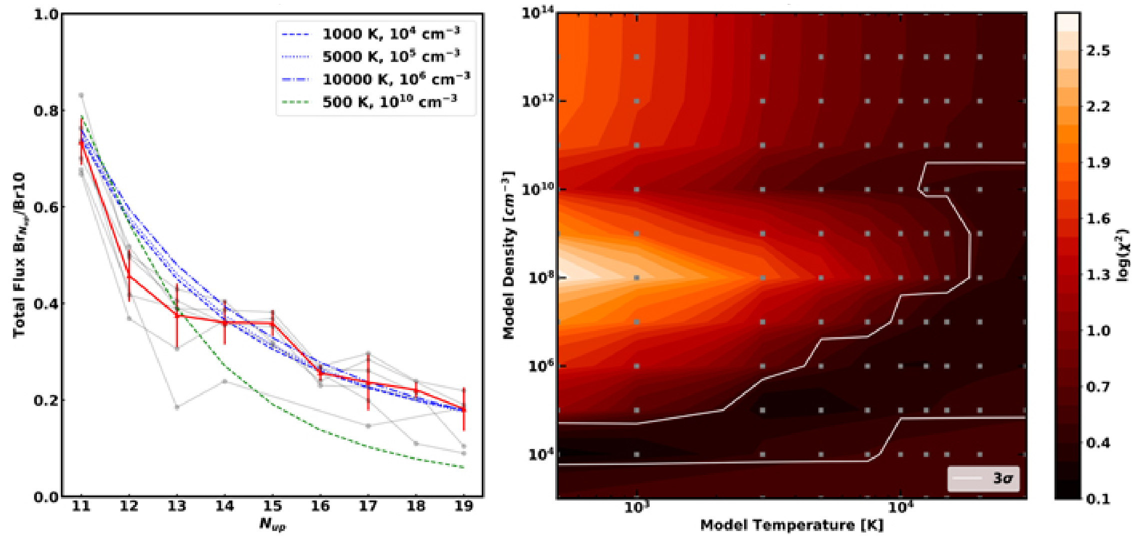

Figure 1. Left: Br10 line ratio decrement curves for YSO's with valid BrN_{up}/Br10 ratios (gray), and the weighted arithmetic mean for each ratio (red). Blue lines mark three well-fitting models described in the figure legend. The green line represents one of the best fit conditions from Bary et al. (2008). Right: reduced χ^2 contour as a function of temperature and density of the mean decrement curve to a Case B recombination model. Gray squares represent the model grid points. The white contour encloses the reduced χ^2 values that fall within 99.7% of the reduced χ^2 distribution.

3. Conclusion

Using *H*-band Brackett line ratios alone, we are only able to place loose constraints on the density and temperature of accretion flows (assuming Case B recombination), favoring models that correlate in density and temperature between ~10^3–10^8 cm^{-3} and ~500–13,000 K. While broad, this range of physical conditions includes those predicted by magnetospheric accretion models. Interestingly, we exclude the exact regions favored by Bary et al. (2008). This discrepancy may result from the higher resolution of our spectra, which enable us to detect low-amplitude and broad emission that may be missed in low-resolution spectra. Additionally, we have used combined spectra which may be capturing T Tauri stars accreting at different rates or modes (stable versus unstable accretion; Romanova et al. 2008), and we have used a different subset of lines for our comparison with models. In future work, we will investigate the individual epochs, which will include Brγ, providing a more direct comparison with previous studies and a larger, more diverse sample.

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