# Interpreting Near Infrared Hydrogen Lines in T Tauri Stars

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***Goal:*** Hydrogen line ratios are sensitive to density and temperature of circumstellar gas. We compare predictions for Case B recombination (1938) and local line excitation calculations of Kwan and Fischer (2011, 'KF') to IRTF *SpeX* Paschen, Brackett line ratio diagnostics of 16 T Tauri stars covering 3 orders of magnitude in disk accretion rate.

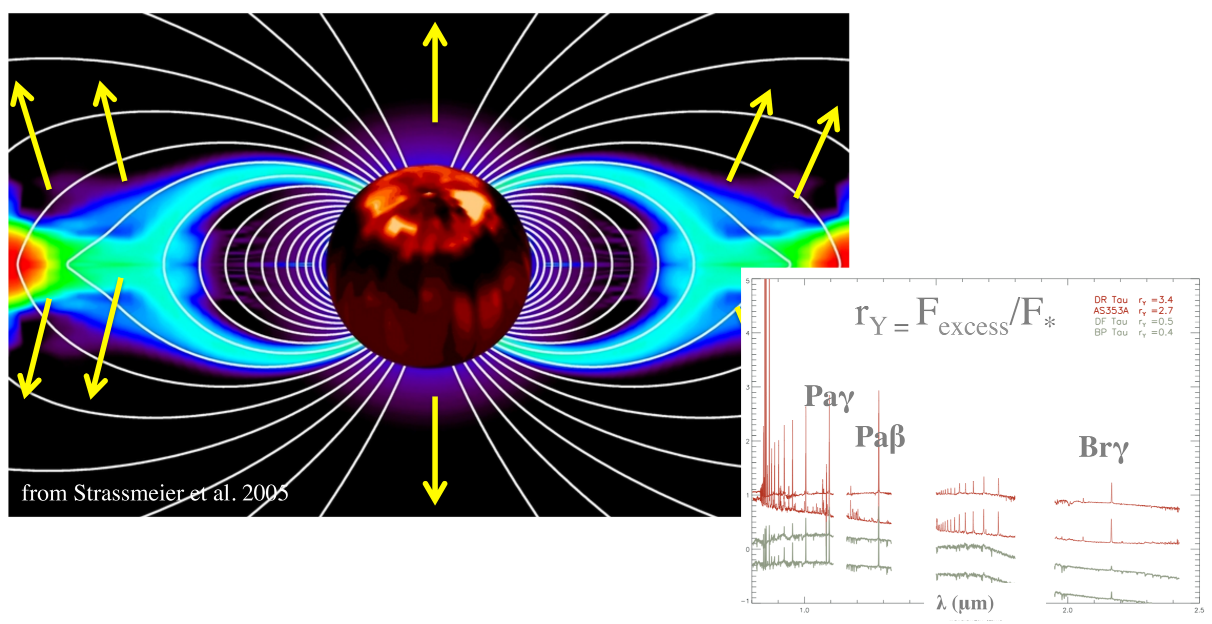
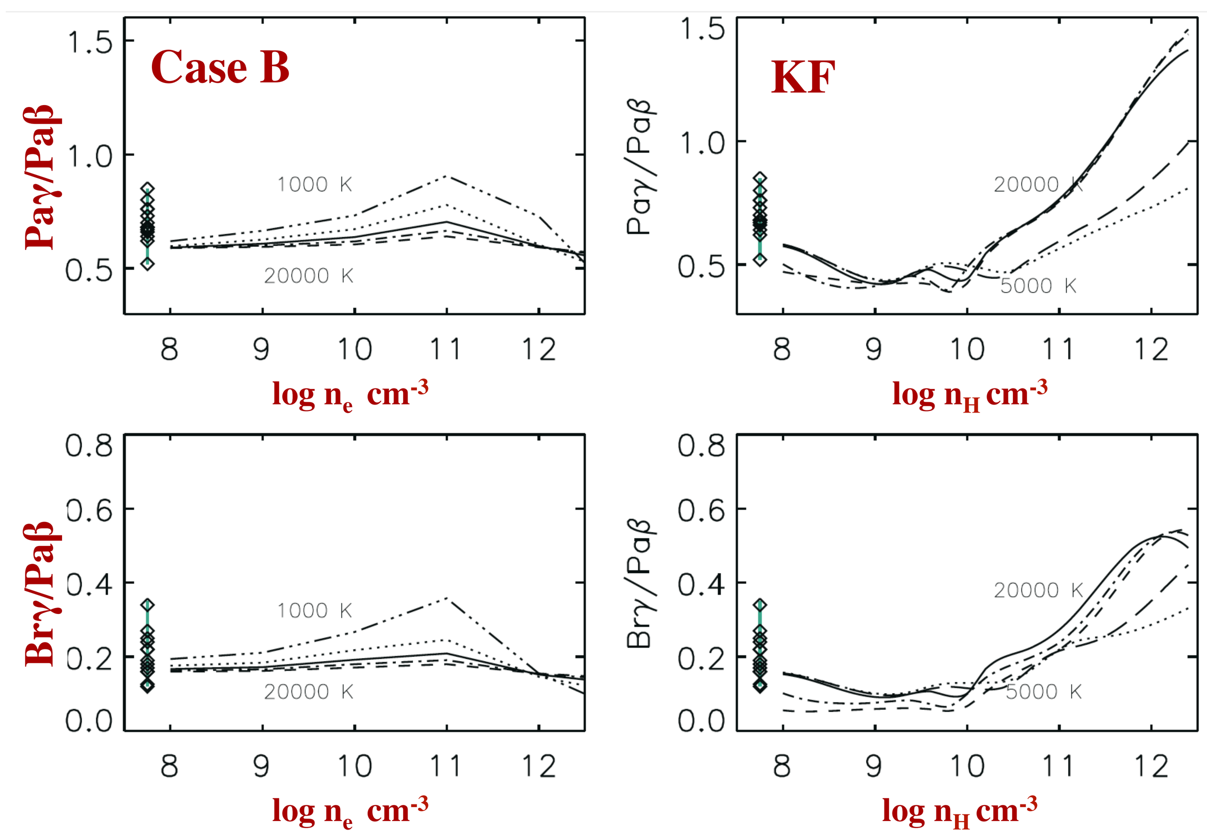



**Fig 1.** CTTS H lines likely form in magnetospheric accretion funnels, accretion shocks and/or inner winds. Case B line ratios are frequently used to infer physical conditions in the line formation region, but the requisite optically thin condition may not apply. KF local line excitation calculations offer a more realistic assessment of interpreting line ratios over a wide range of optical depths.

## Two Models for H Line Ratios: Behavior with Density, Temperature

**Case B: Dominant process is radiative ionization and recombination; implicitly assumes an ionization rate and emission length scale so NIR H lines are optically thin.**

**KF: Fully accounts for both recombination and collisional excitation for a given ionization rate and velocity gradient and covers a broad range of optical depths.**




- **KF**: large dynamic range, transition from low ratios through steep rise to a plateau as $n_H$ and line opacity increase.
- **Case B**: very small dynamic range for T > 5000 K, require orders of magnitude higher photoionization rates than KF, Line ratios increase with $n_e$ until collisional de-excitation and collisional ionization begin to dominate over radiative decay.
- **Observed ratios** (along left of each panel): many require T~1000 K for Case B (Bary et al. 2008), all consistent with intermediate optical depths and $n_H \sim 10^{11}$

**Fig 2**. Line ratios from a similar range of $n_e$ arise in very different physical regimes in the two models. The fundamental difference is the energy source for the line photons – continuum photons > 13.6 eV in the Case B recombination model and thermal kinetic energy in the KF model.

## Observed Relations

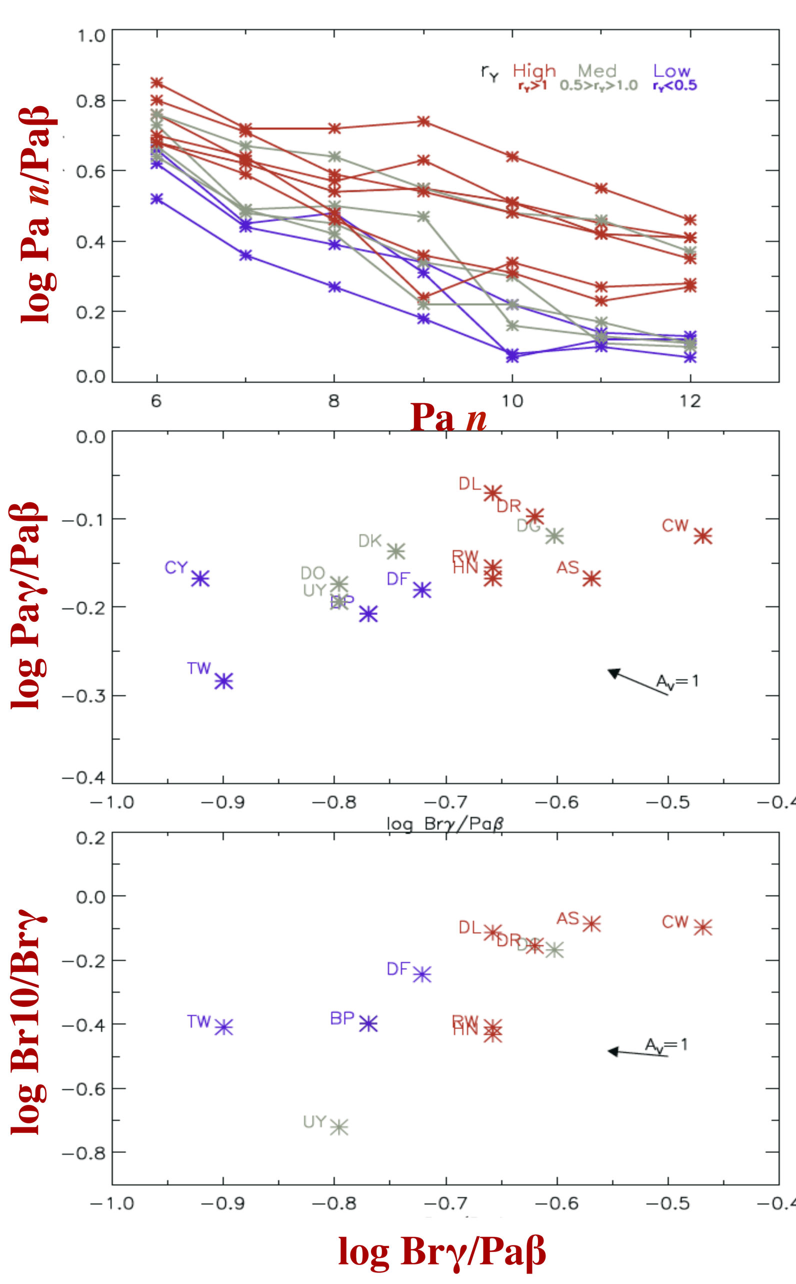



**Fig 3.** Observed relations of 16 CTTS. Stars with higher 1 μm veiling, $r_Y$, tend to have larger line ratios. $A_v$ from Fischer et al. 2011 (FEHK) are used here; extinction uncertainty dominates the error.

## Comparing Observations to Theoretical Predictions: Role of Extinction

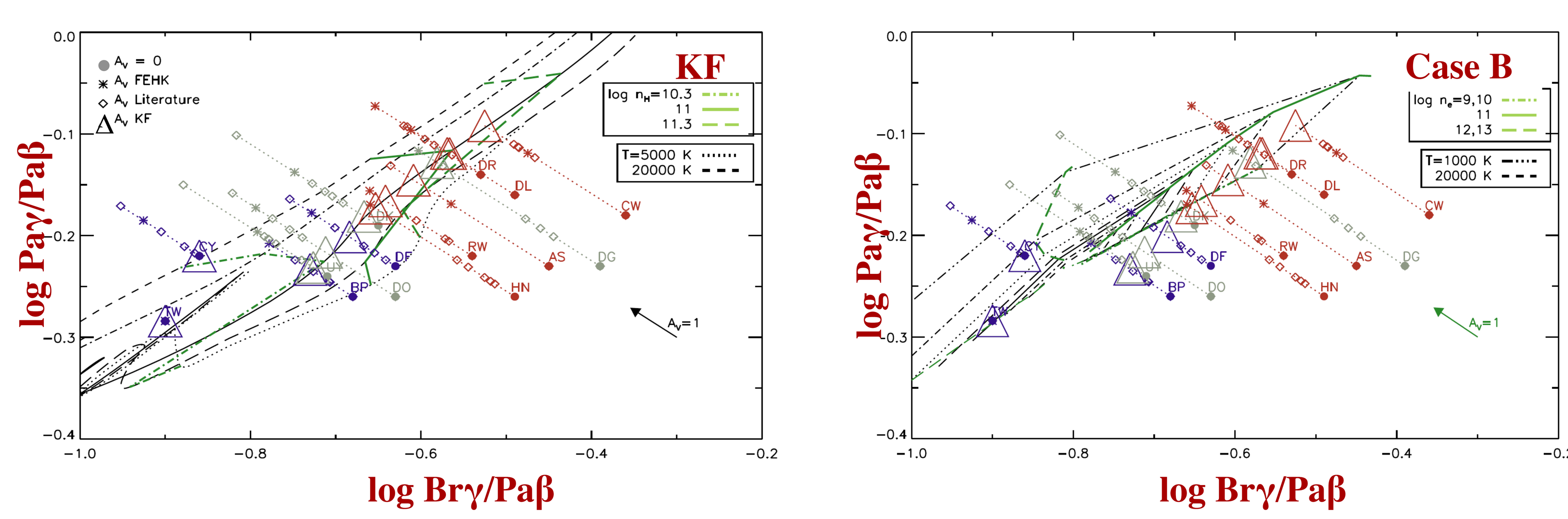



**Fig. 4:** Example of ratio-ratio relations for Paγ/Paβ vs. Brγ/Paβ for KF and Case B compared with observations for a variety of choices of $A_V$ (FEHK, up to 7 values from the literature, Av=0). Large open triangles are for $A_V$ derived under the assumption T = 10,000 K and KF conditions.

**KF:**

- $n_H = 2\times10^{10} - 2\times10^{11}$ cm$^{-3}$, consistent in multiple relations
  - Higher veiling stars = higher $n_H$
- Extinction uncertainties compromise T, but allow common T for all CTTS.

**CASE B:**

- Wide range of T ( 10× )
- Wide range of $n_e$ ( > 100× )
- Inconsistent across relations
- Extinction uncertainties compromise both $n_e$, T.

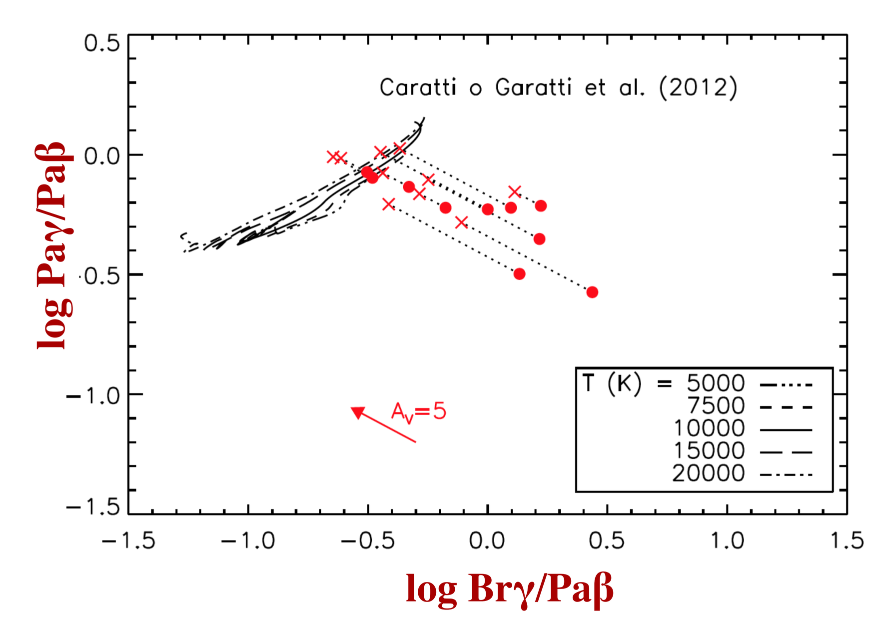



**Fig. 5**: In KF relations the ratio-ratio contours are more sensitive to density than temperature and both extinction and density can be inferred. For 10 sources in L 1641 we show both directly observed and extinction corrected values from Carotti o Garatti et al. (2012). The KF relations suggest the more embedded sources may have extinctions that are underestimated.

***Conclusions:*** KF local line excitation models give consistent results across multiple diagnostics, in contrast to Case *B.* The inferred density in the hydrogen line formation region is an order of magnitude lower than typical models for magnetospheric accretion. The local line excitation ratios offer a new approach to determining extinction to TTS and embedded sources in addition to determining $n_H$ in the H line formation region.

**A number of H line ratio versus density files from the KF local line excitation calculations will be available online following acceptance of the paper by the Astrophysical Journal.**