High resolution spectroscopy and spectro-astrometry of Herbig Ae/Be Stars

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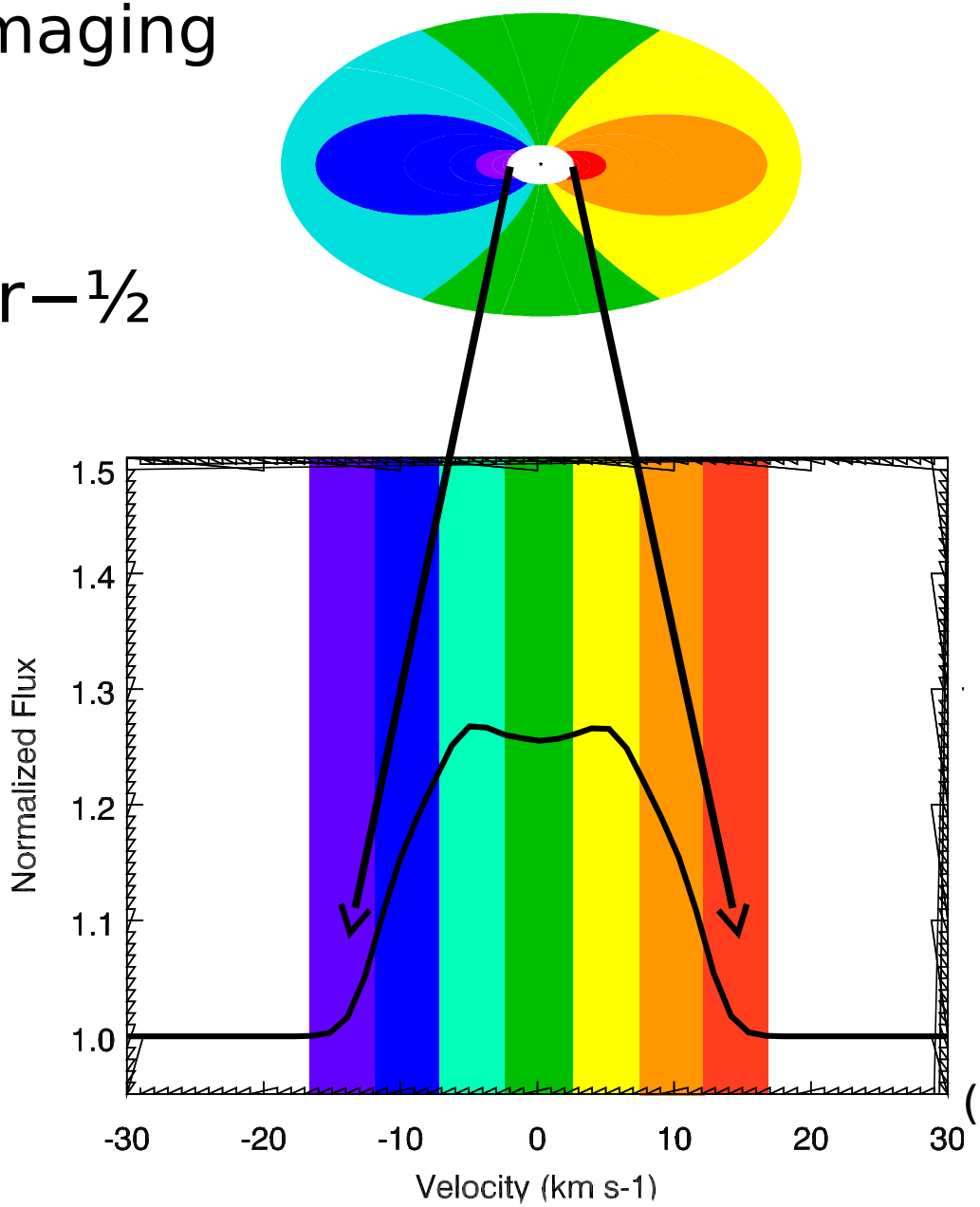
Clemson University

Supported by NSF AST-0954811

TECHNIQUE

Spectrally Resolved Lines as Surrogates for High Resolution Imaging

$v(M^*,i,r) \mu r^{-1/2}$



(See Smak 1981)

Spectrally Resolved Lines as Surrogates for High Resolution Imaging

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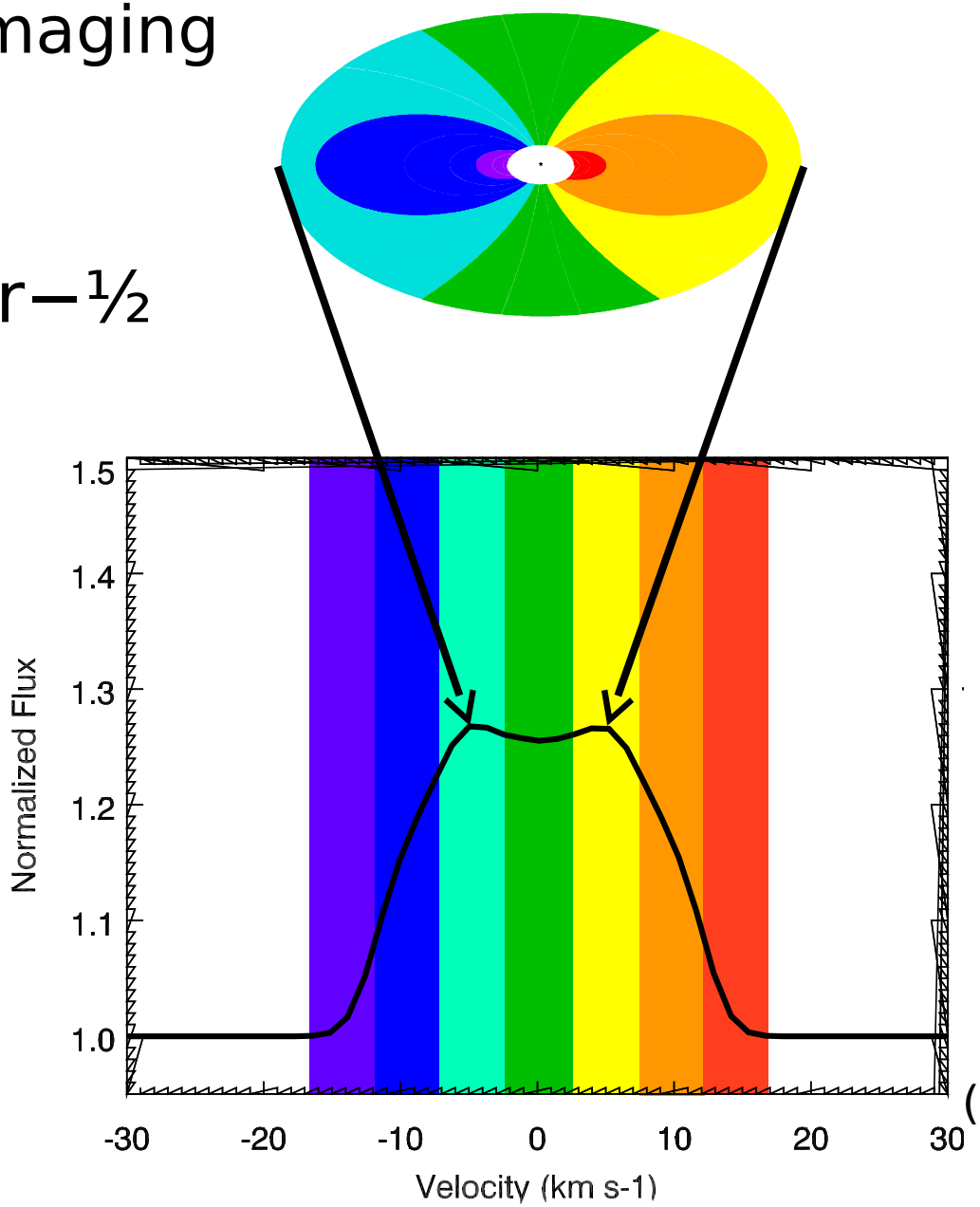
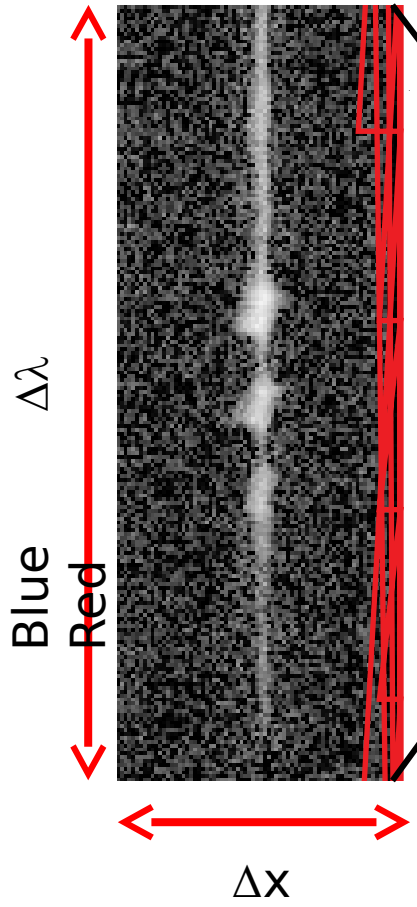
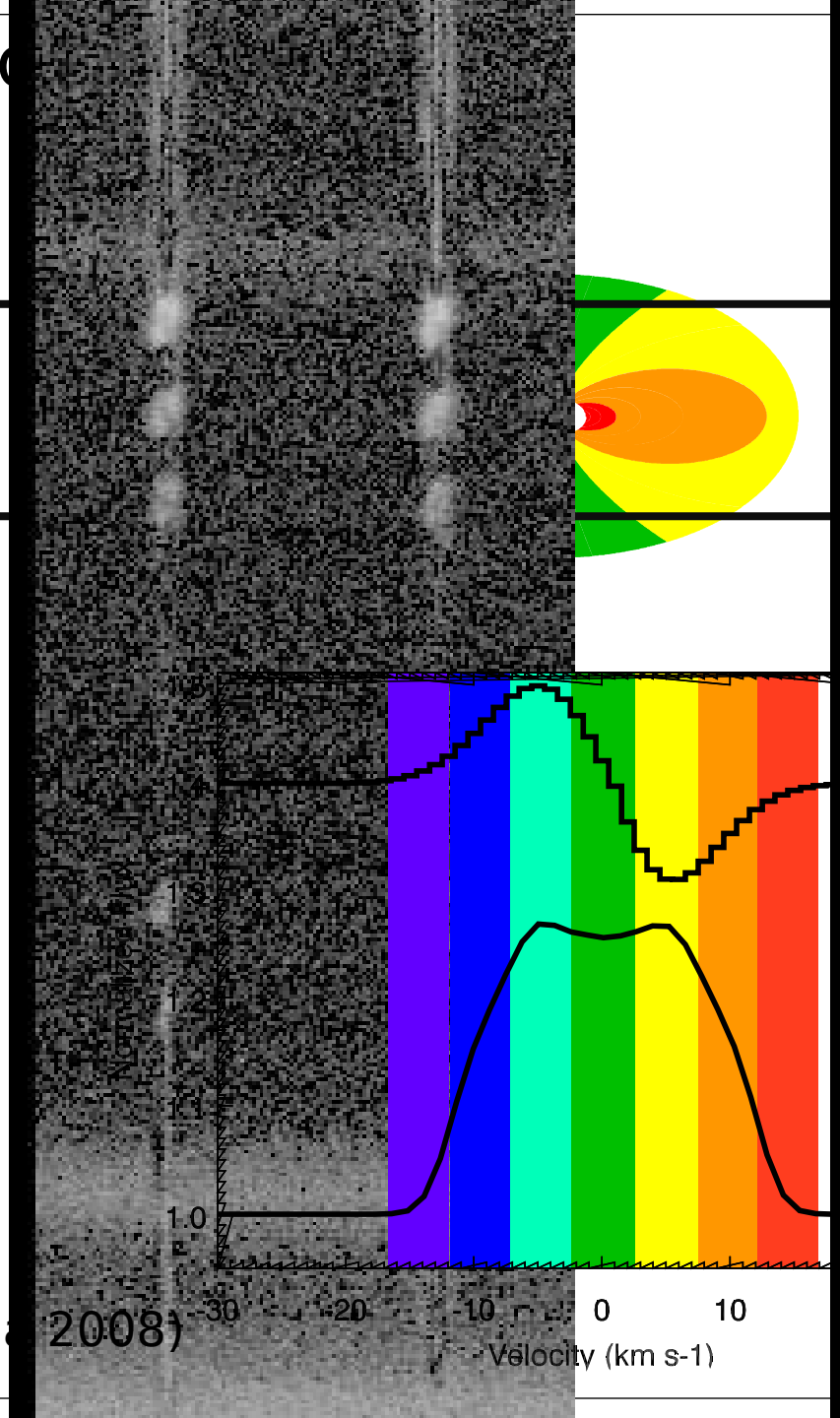


(See Smak 1981)

Spec

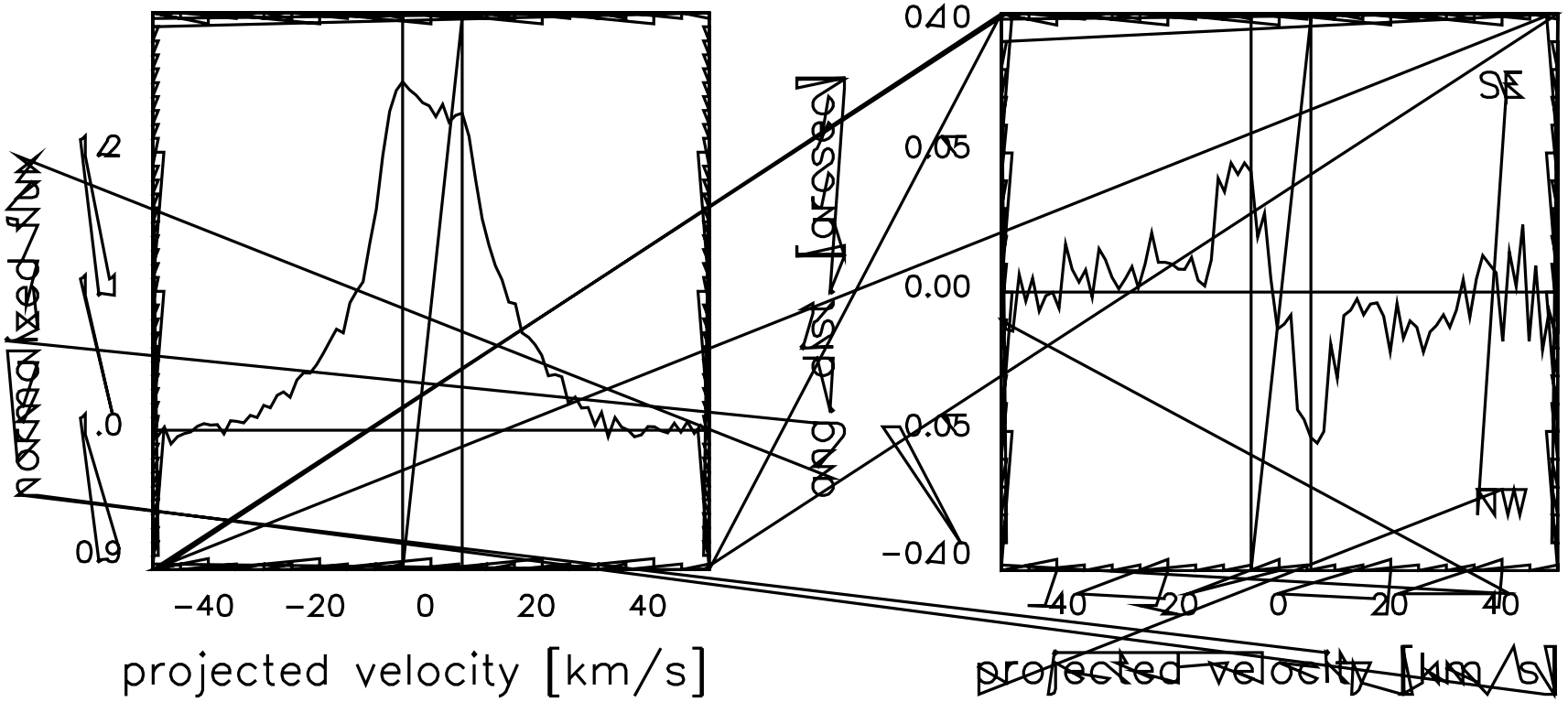




$v(M^*,i,r) \mu r^{-1/2}$?

(See Whelan & Garci 2008)

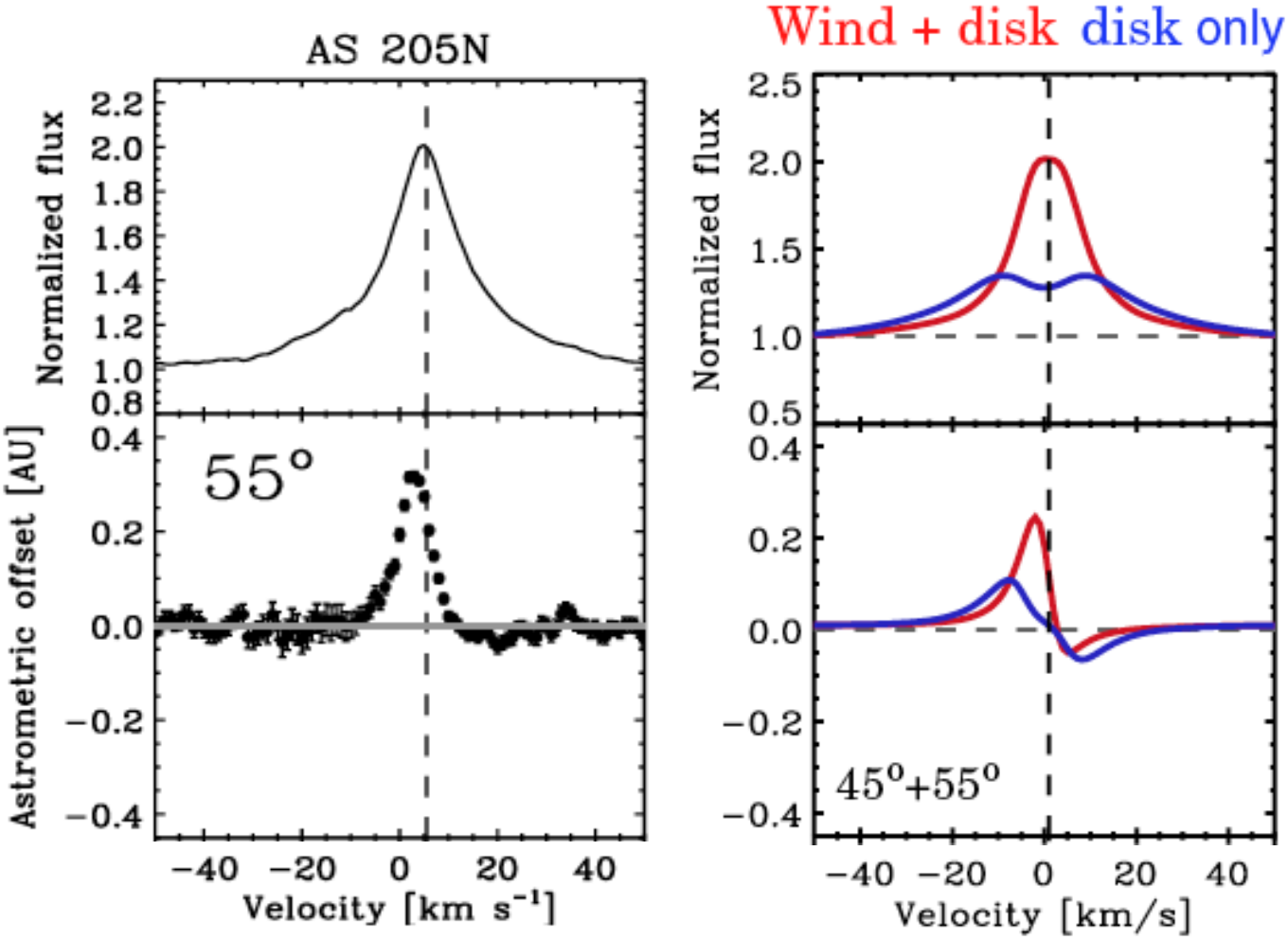
[OI] 6300Å Emission from Herbig Ae/Be Stars



$v(M^*,i,r) \mu r^{-1/2}$

Adapted from Acke & van den Ancker 2006

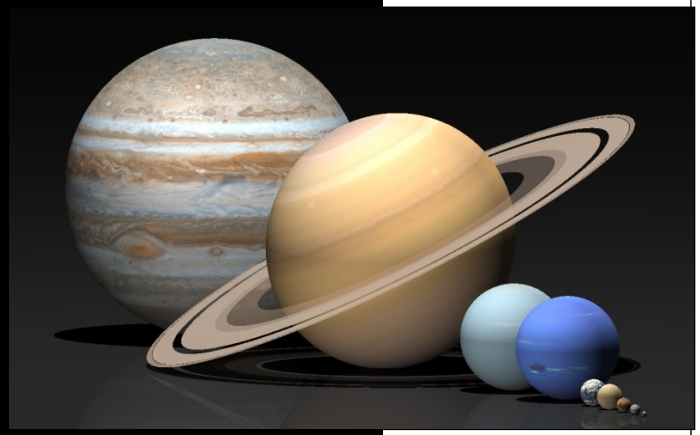
Non-Keplerian Signals



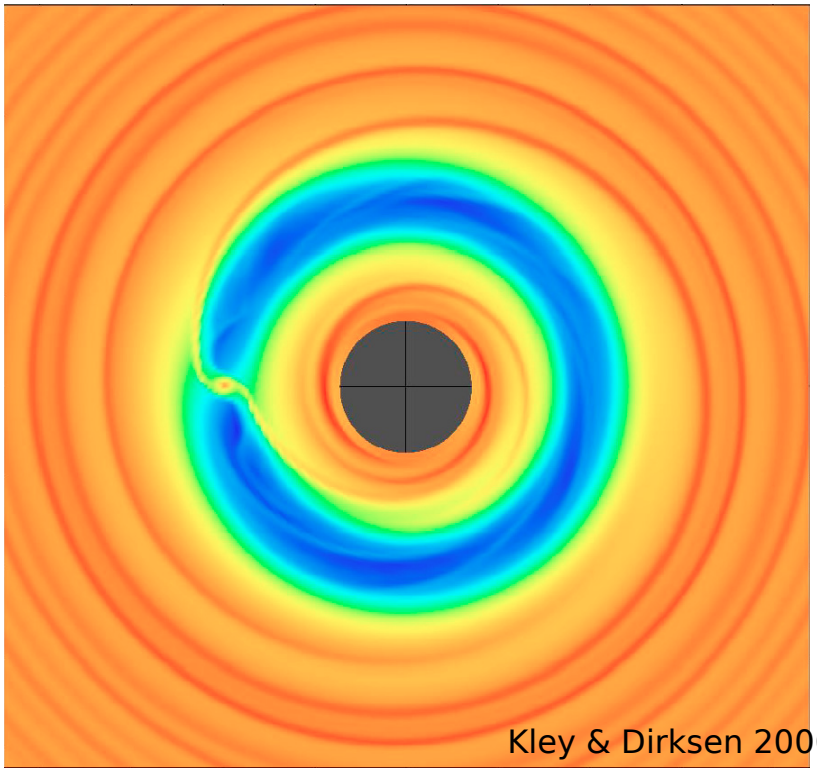
$v(M^*,i,r) \propto r^{-1/2}$

Pontoppidan et al. 2011 (see also Bast et al. 2011)

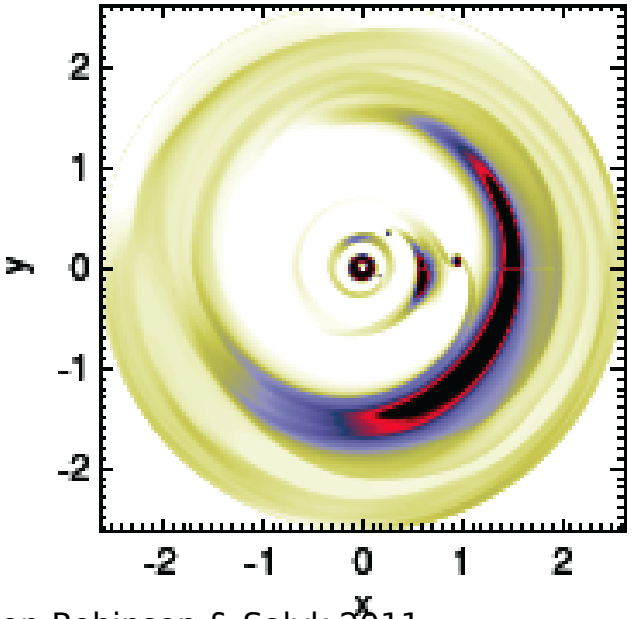
APPLICATIONS I.
Signposts of Planet Formation



"I think you should be more explicit here in step two."

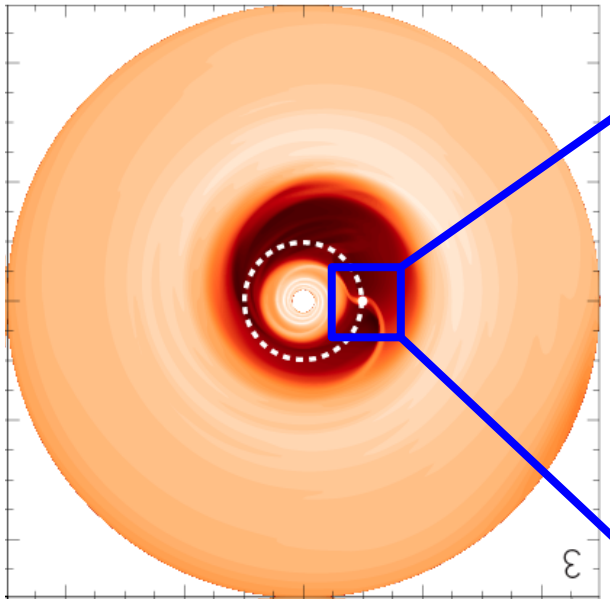


Kley & Dirksen 2006

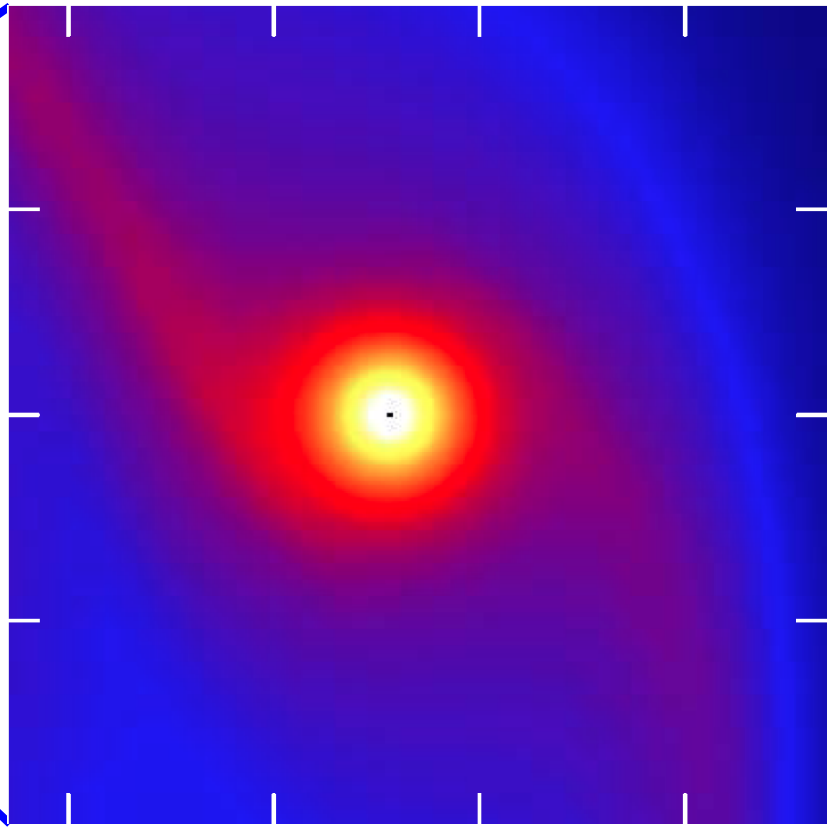


Dodson-Robinson & Salyk 2011

Spectroscopic Signposts of Giant Planet Formation

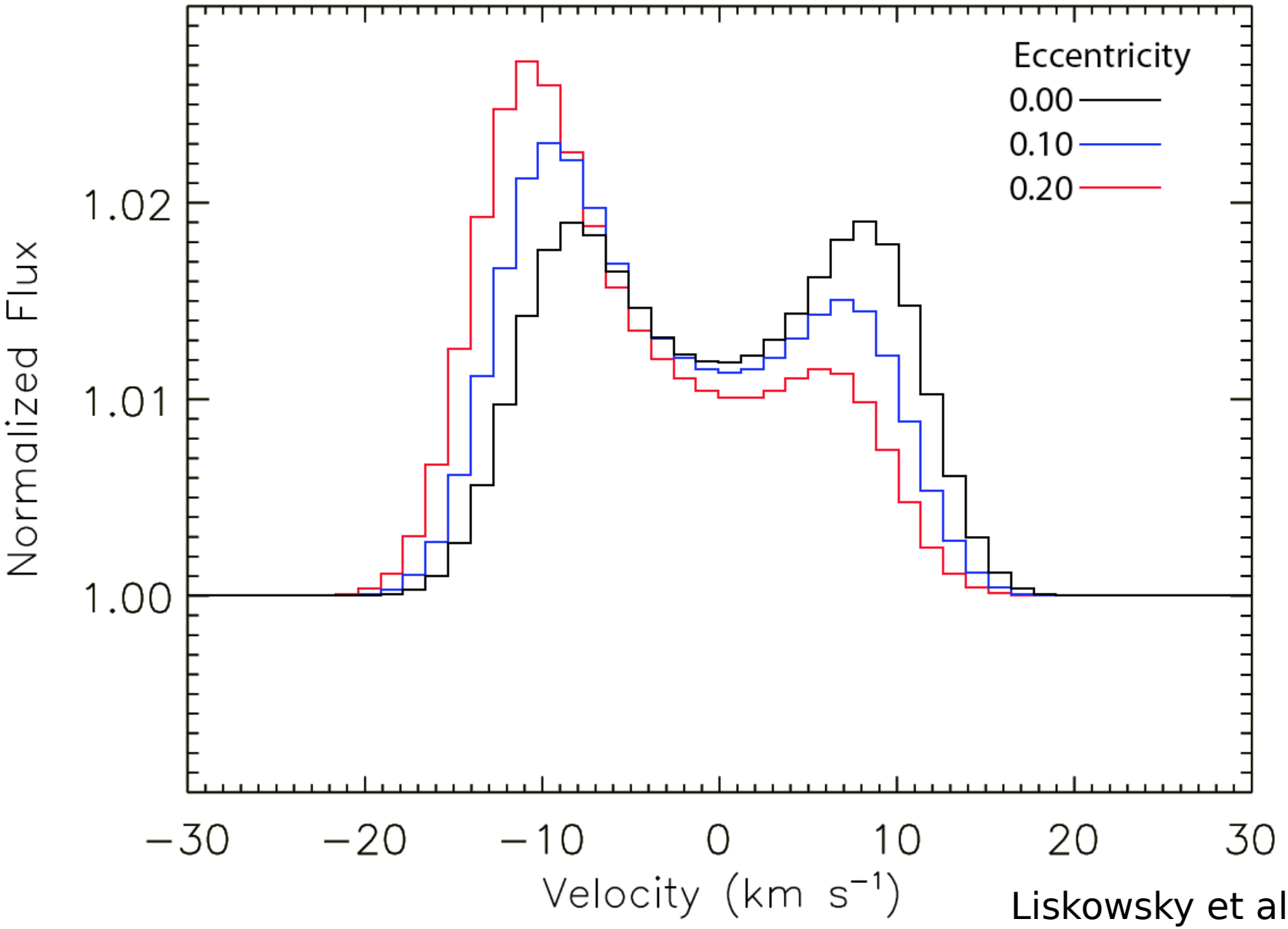


Regaly et al. 2010



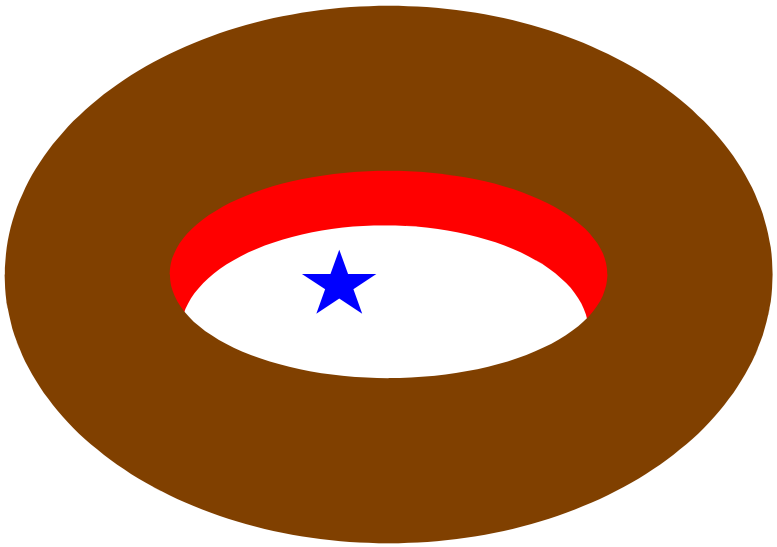
Ayliffe & Bate 2009

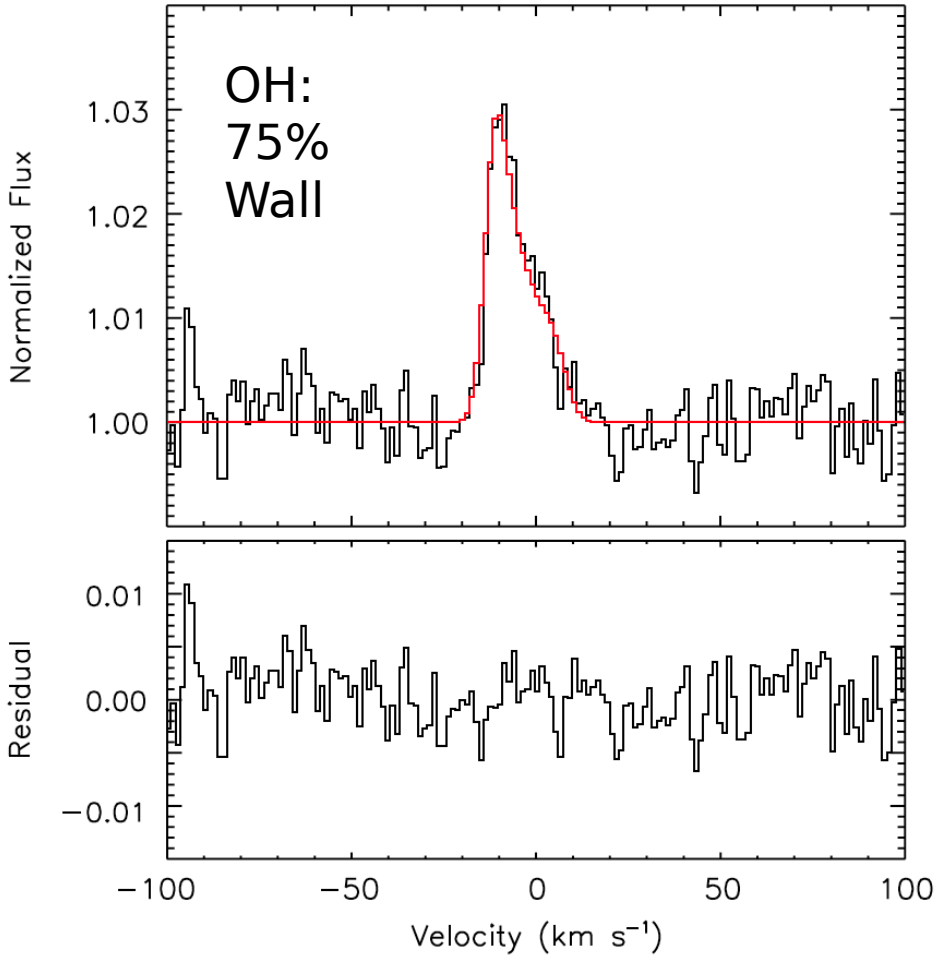
Emission from an Eccentric Ring



Liskowsky et al.

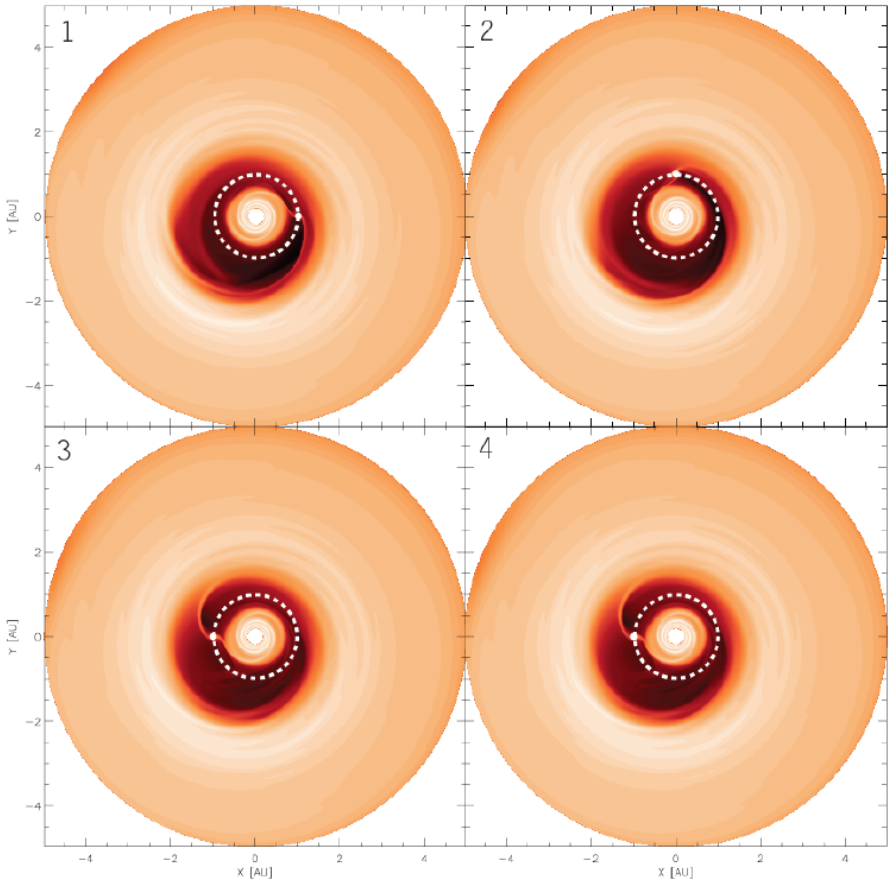
Companion in a Transitional Disk?



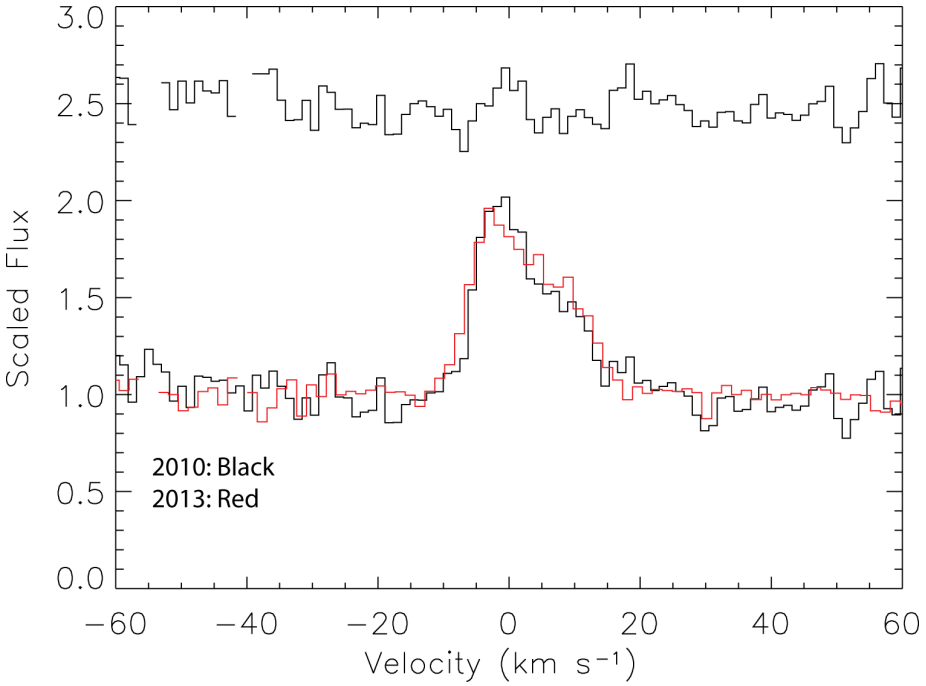


Liskowsky et al.

Confirmation?

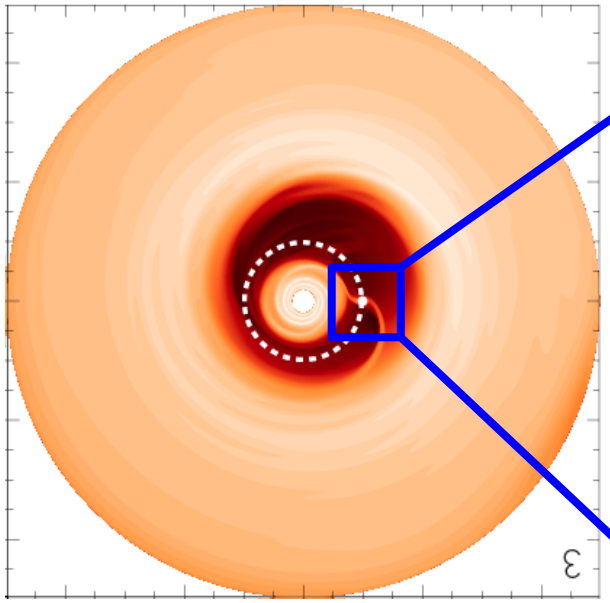


Regaly et al. 2011; also Kley & Dirksen 2006; Papaloizou et al. 2001)

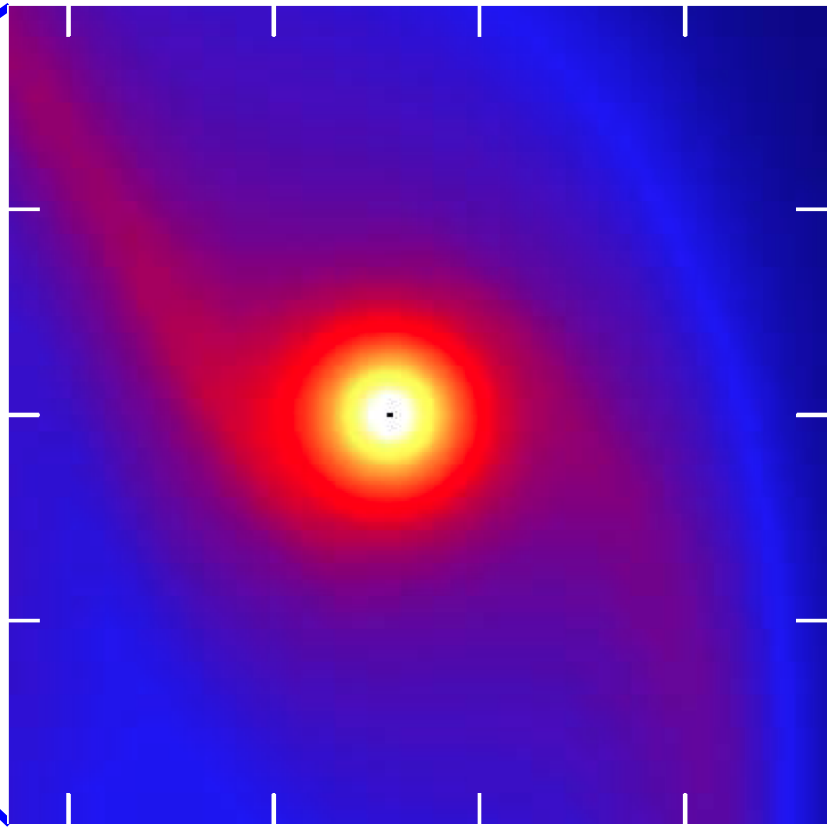


Brittain et al. 2014

Spectroscopic Signposts of Giant Planet Formation



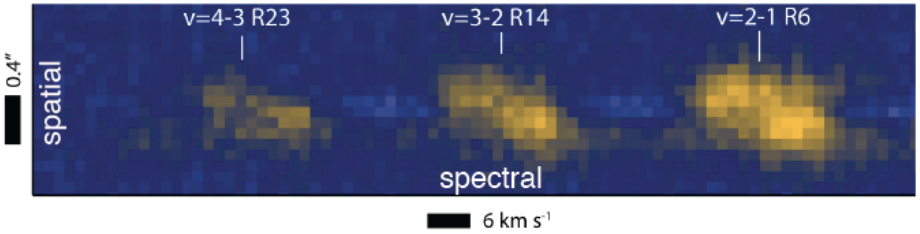
Regaly et al. 2010



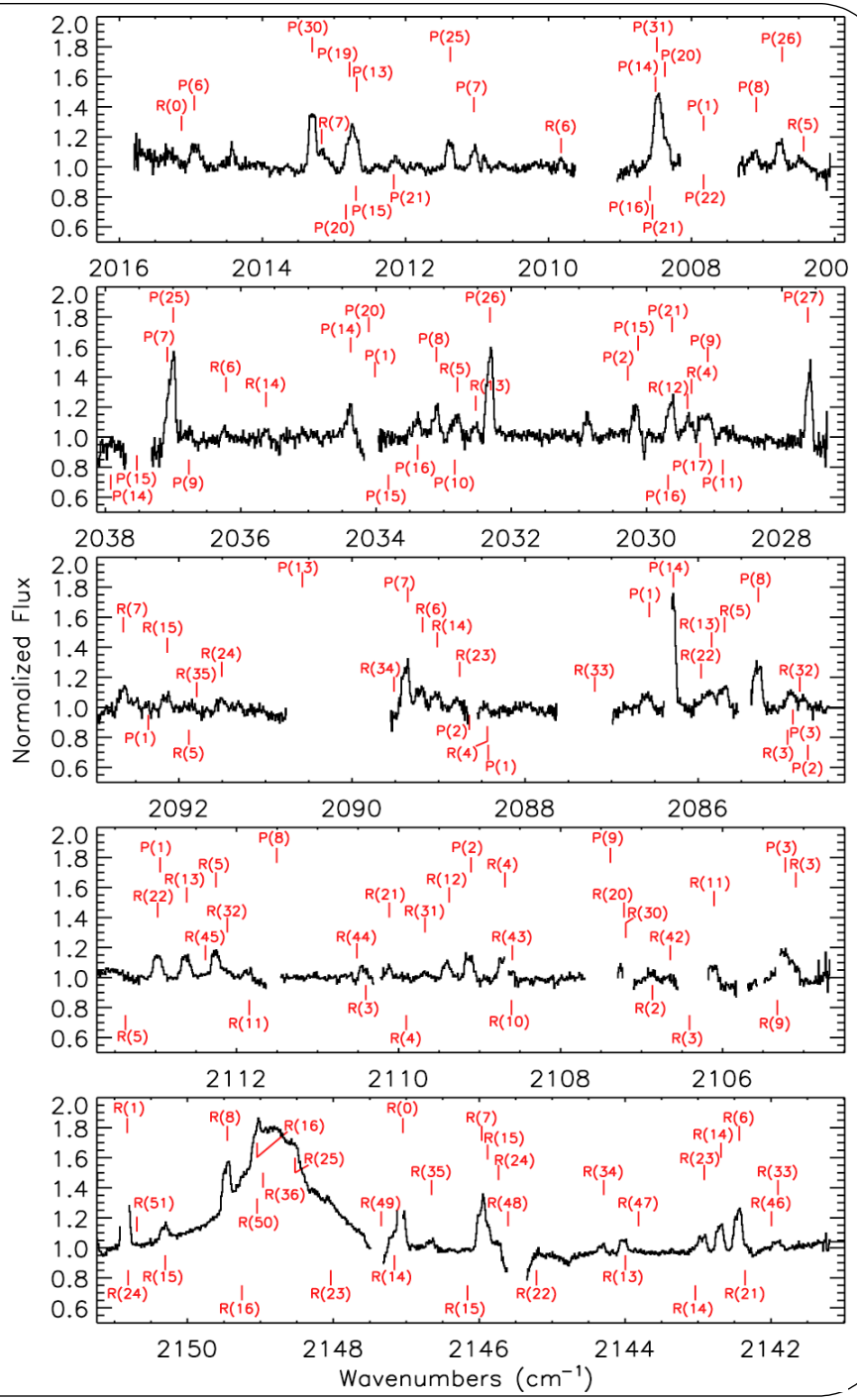
Ayliffe & Bate 2009

HD100546: rovib CO

- CO hot bands (dv = 1, $v_{low} > 0$) UV fluoresced
- CO v=1-0 also has thermal (excited by collisions)
- R(CO) =13 AU to ~100 AU



Brittain et al. 2009; See also van der Plas et al. 2009; Hein Bertelsen 2014; Talks by R. Hein Bertelsen and G. van der Plas on Wednesday.



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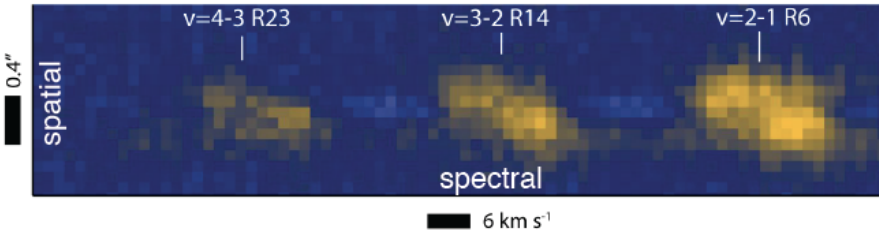
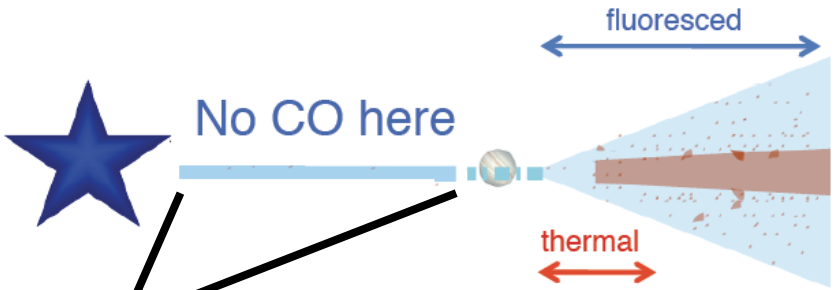
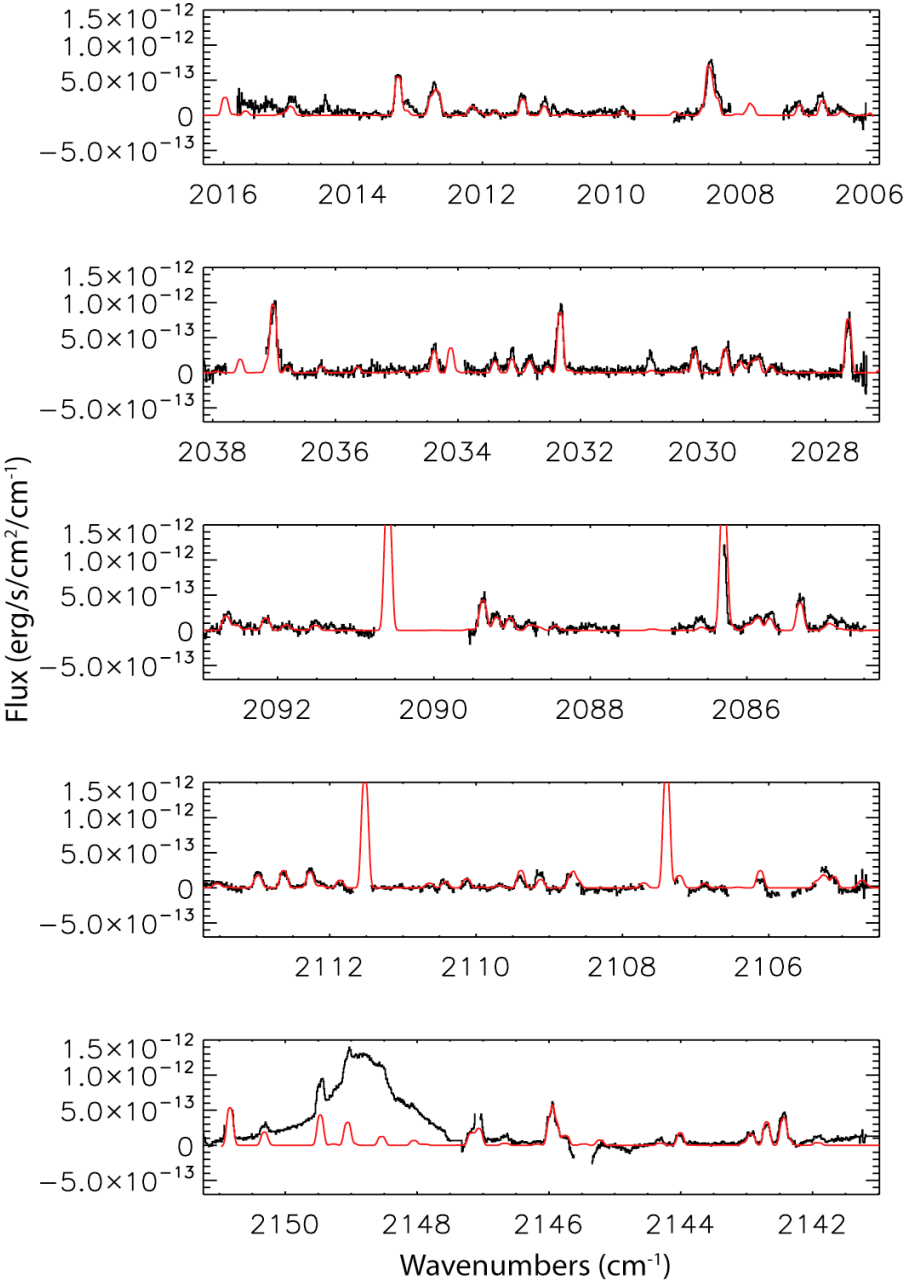
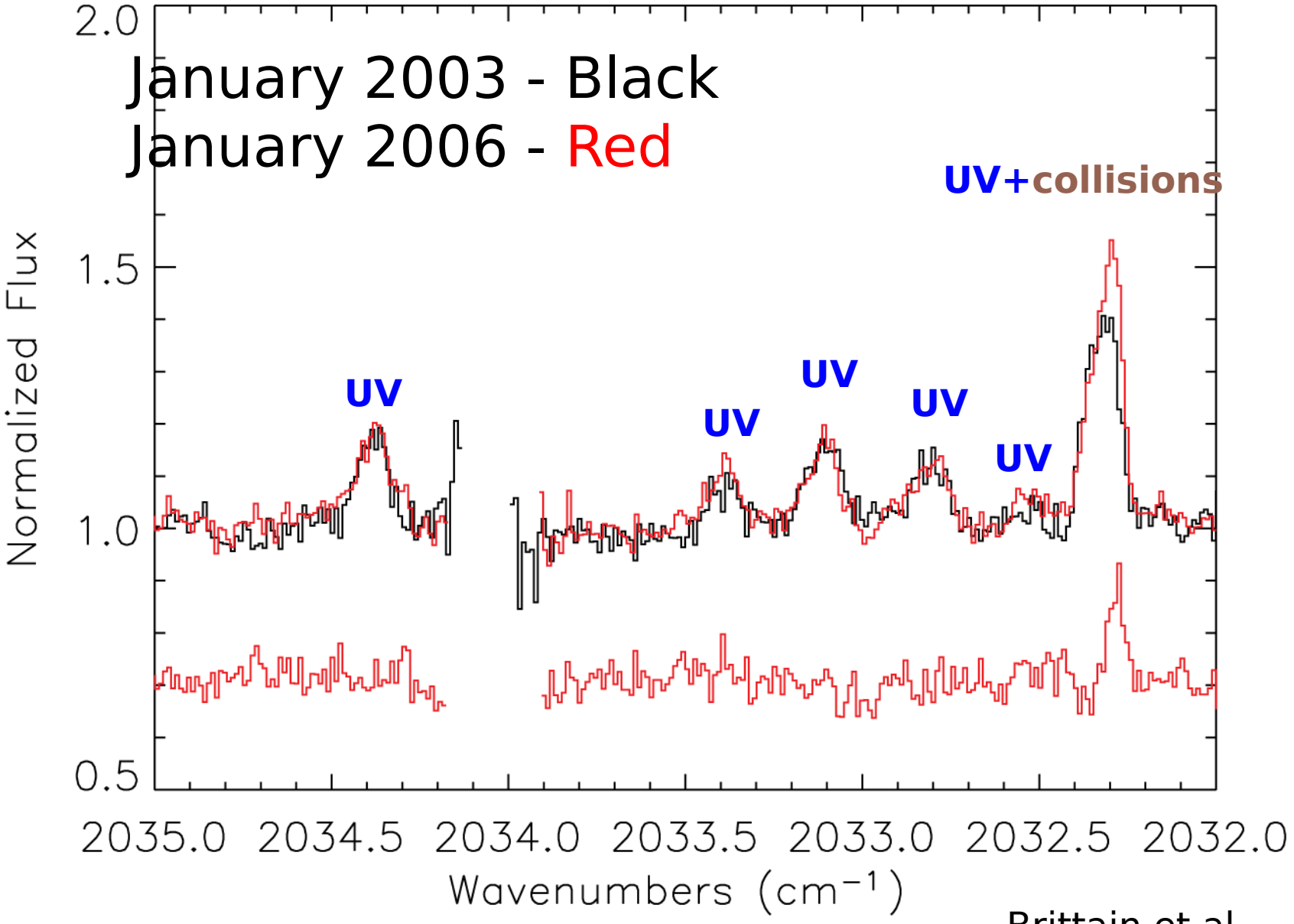




Free of molecules: Habart+ 2006; Brittain+ 2009; van der Plas+2009; Carmona+ 2011; Liskowsky+2012



The Circumplanetary Disk?



Brittain et al.

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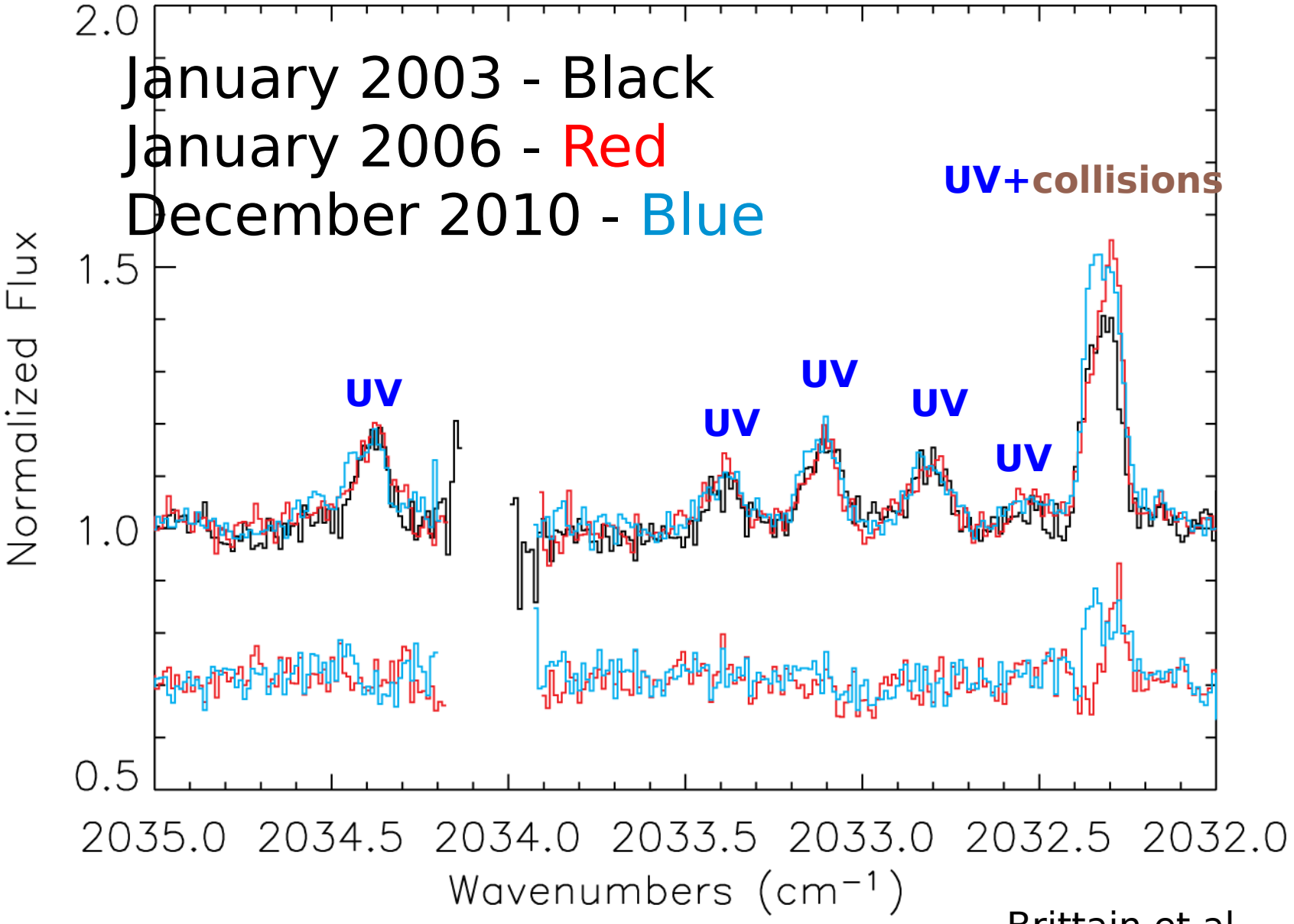
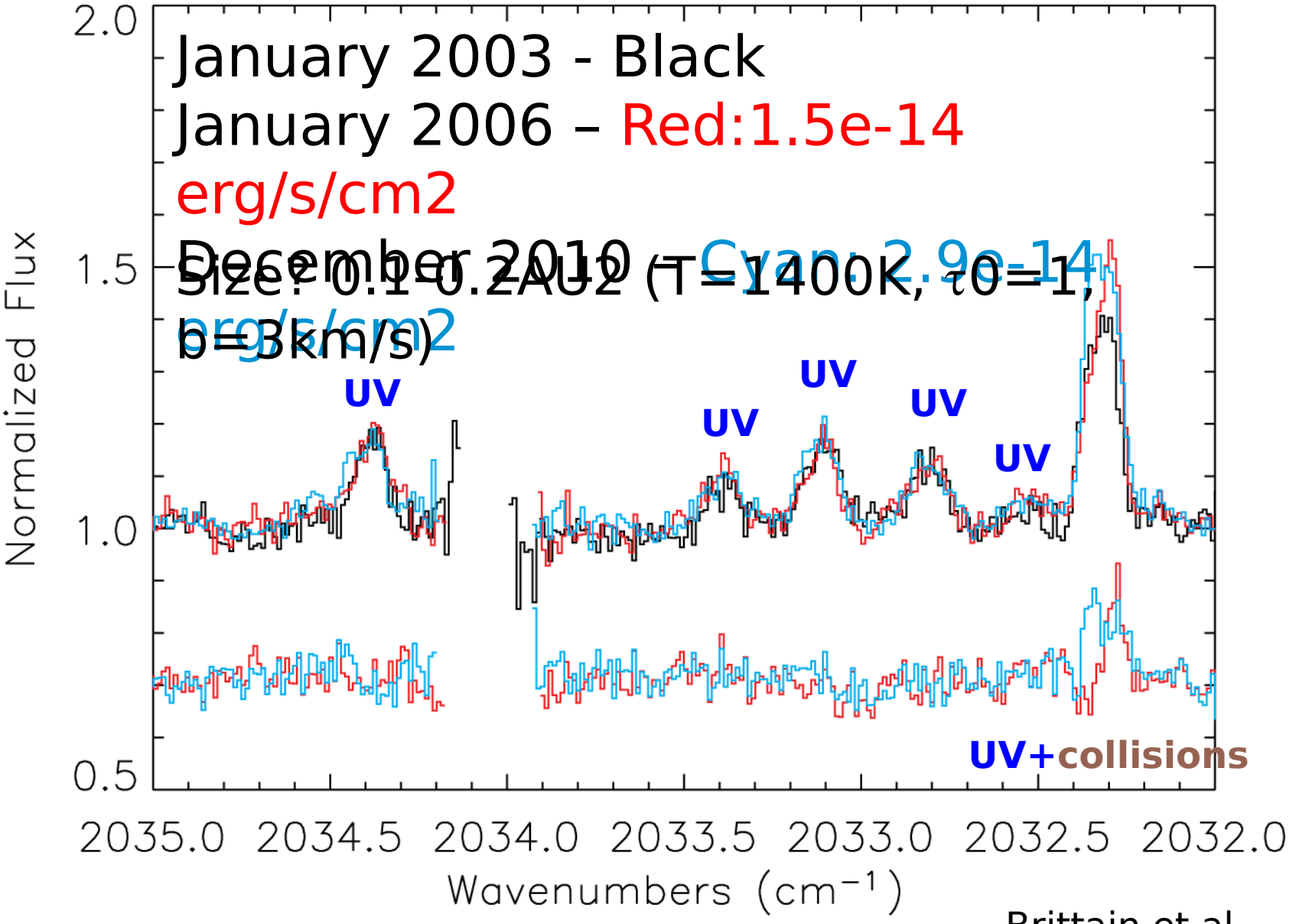


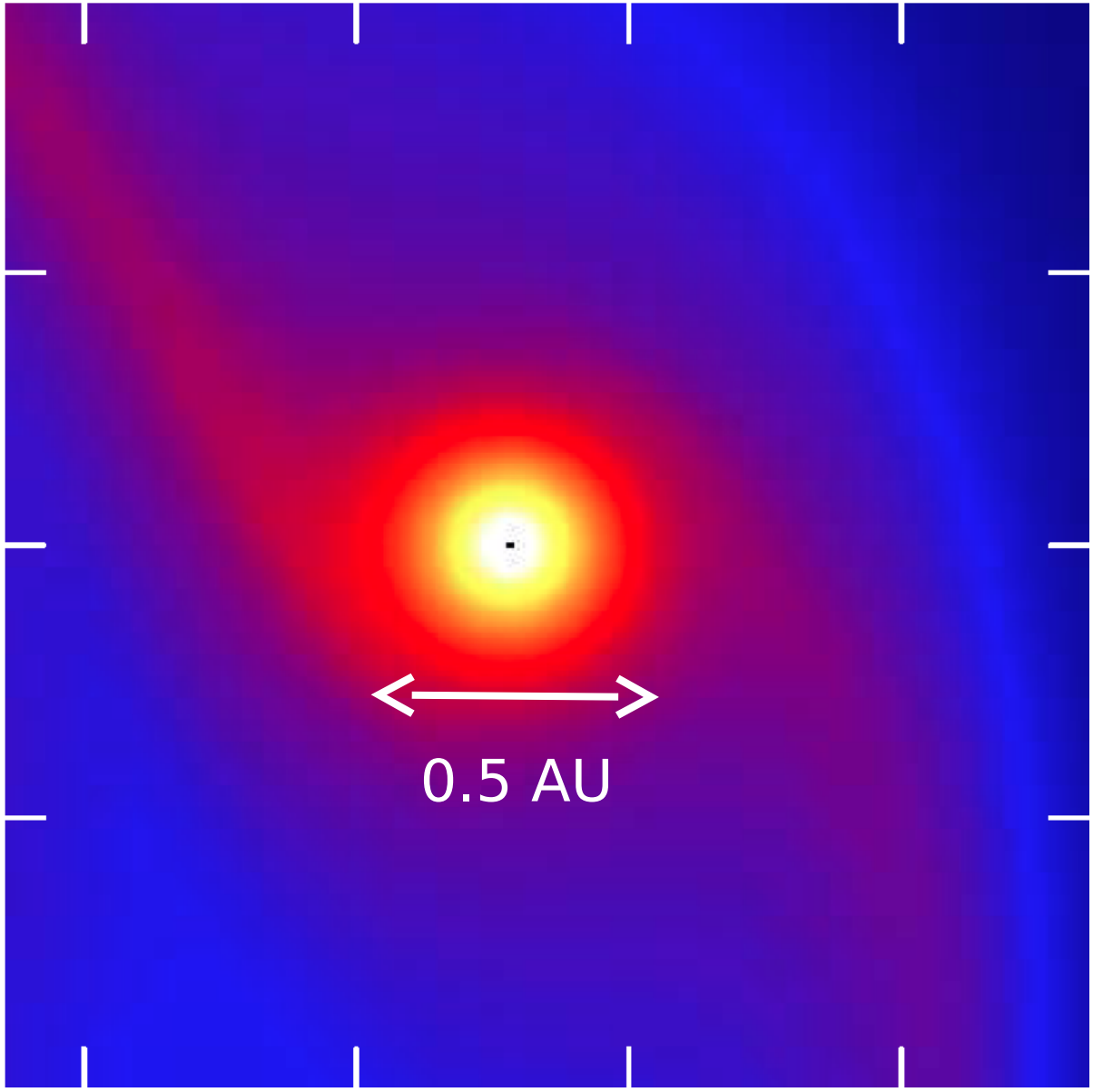
Brittain et al. 2013

The Circumplanetary Disk?



Brittain et al.

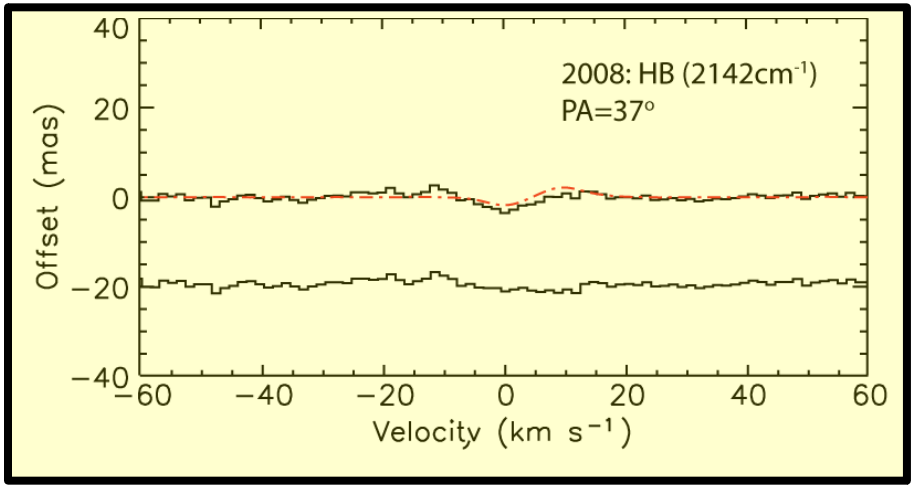
Signposts of Planet formation: Circumplanetary Disks?

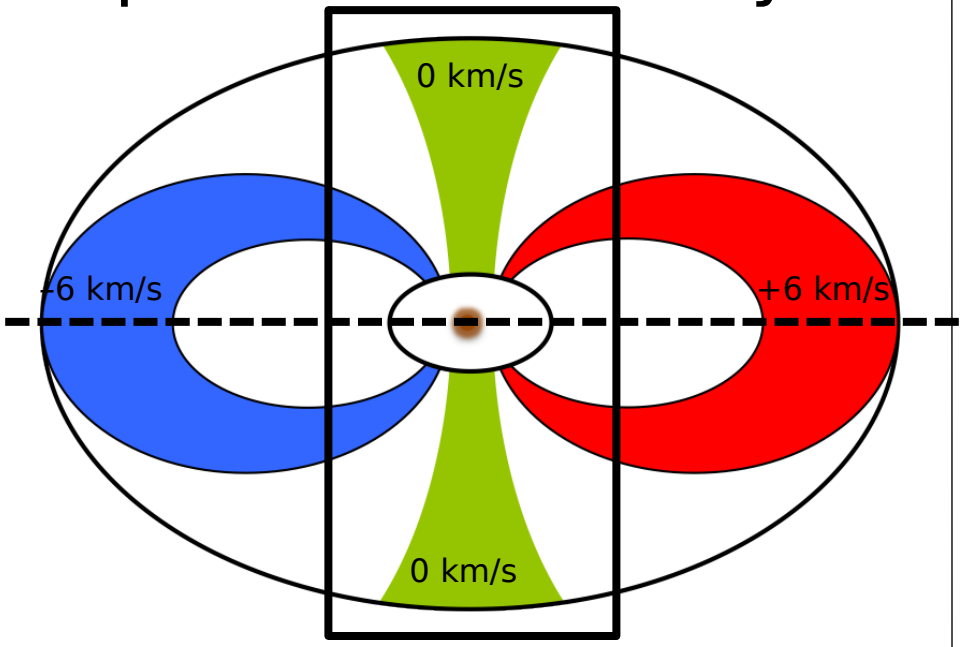


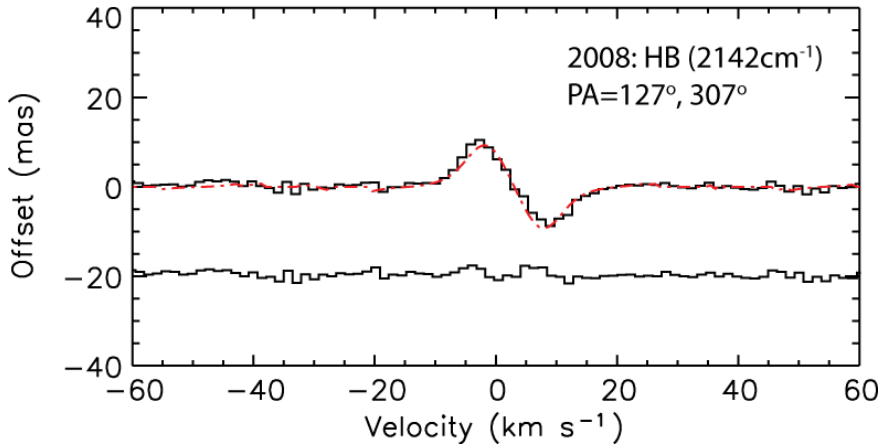
Emission lines from a circumplanetary disk will be Doppler shifted relative to the star.

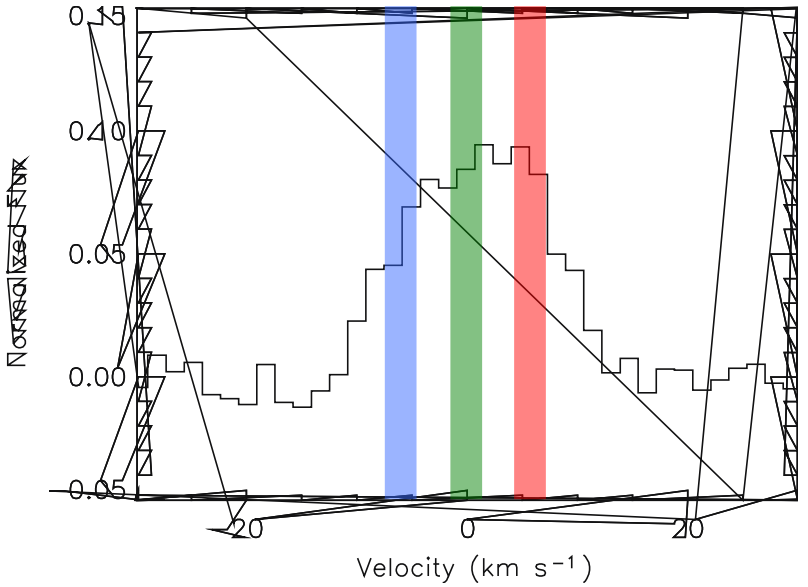
Ayliffe & Bate 2009, 2012 (see also Quillen & Trilling 1998; Lubow et al. 2011; Tanigawa et al. 2012; Gressel et al. 2013).

Spectro-Astrometry

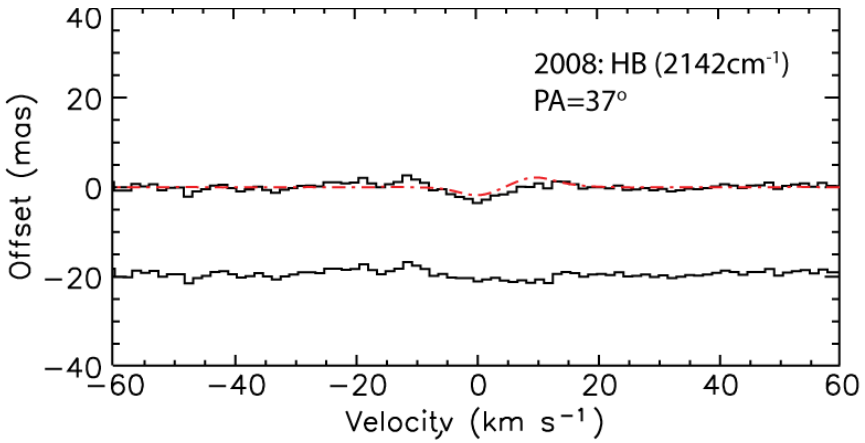


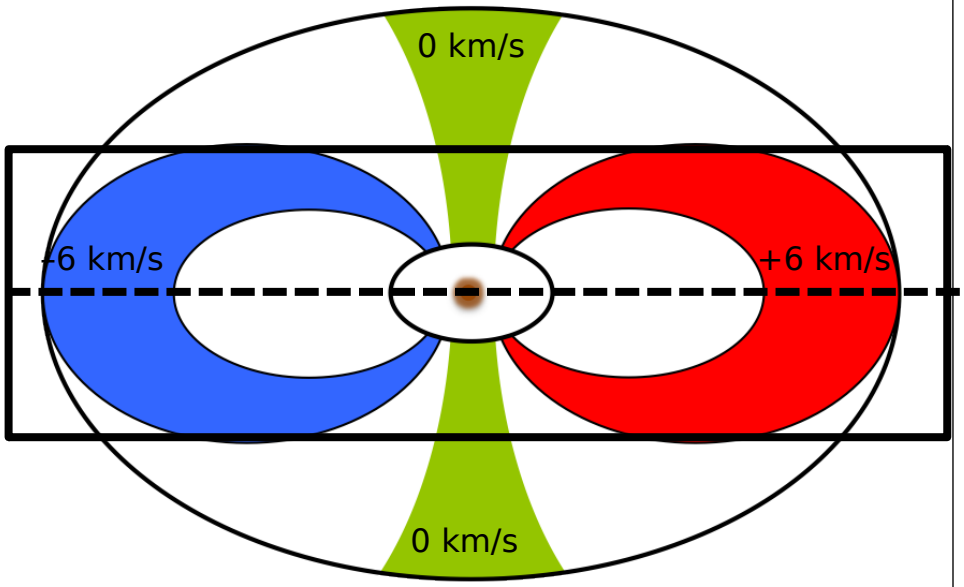


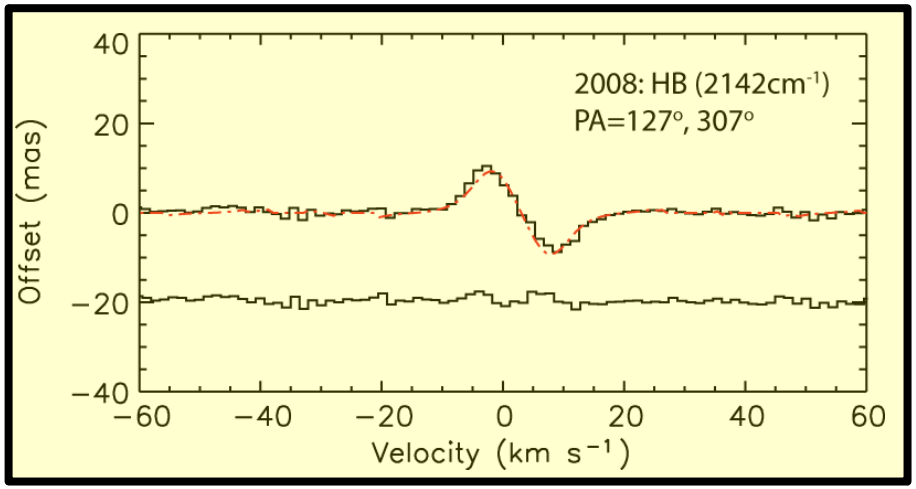


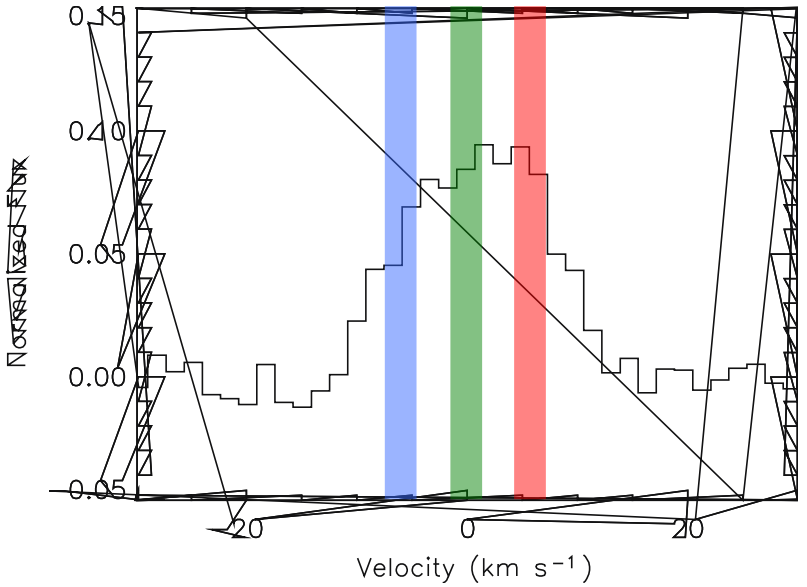


Spectro-Astrometry

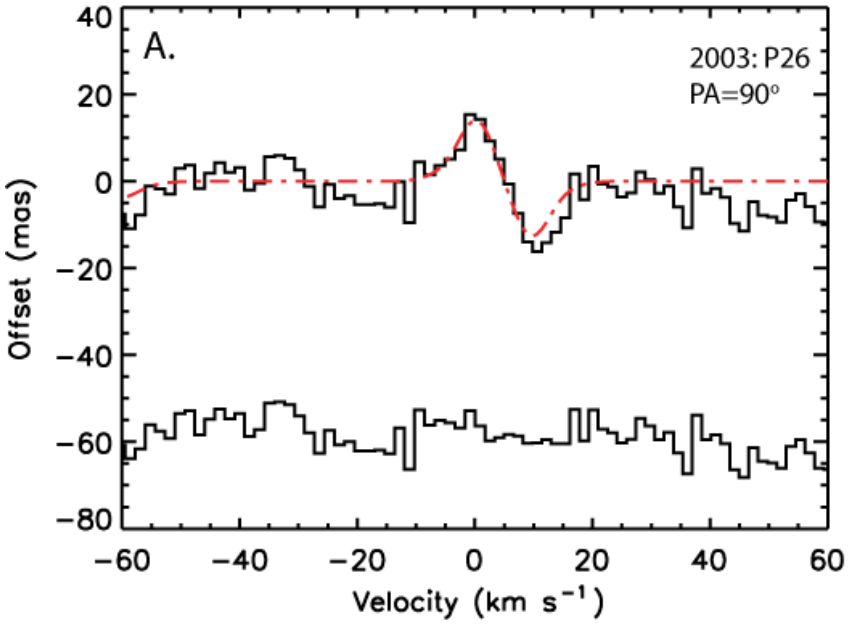


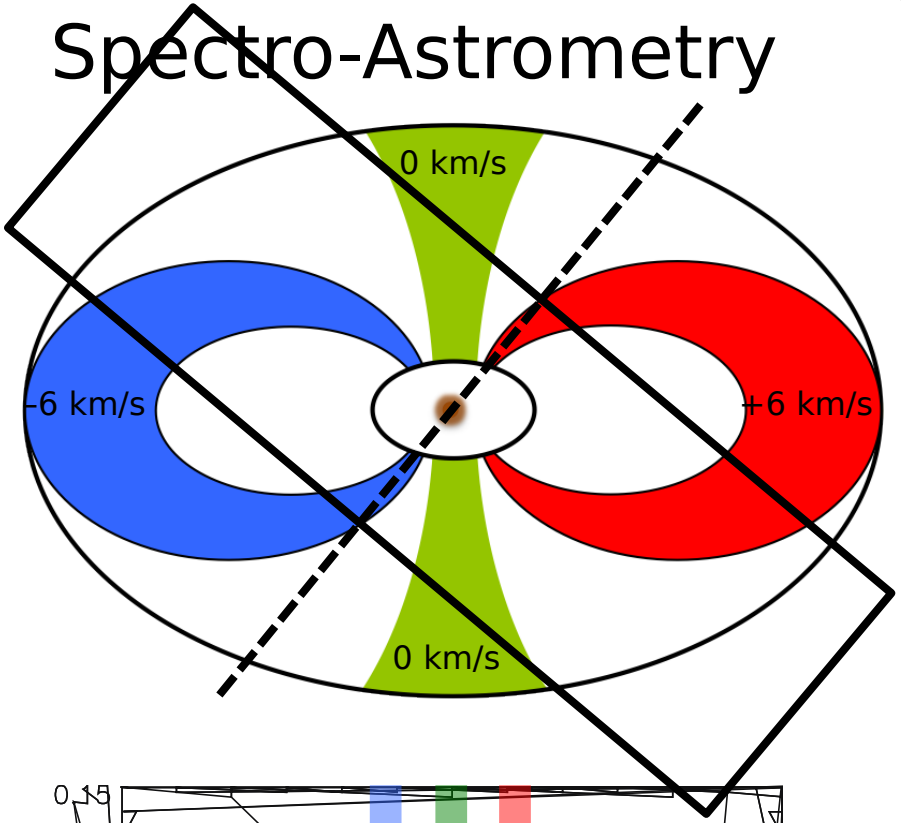


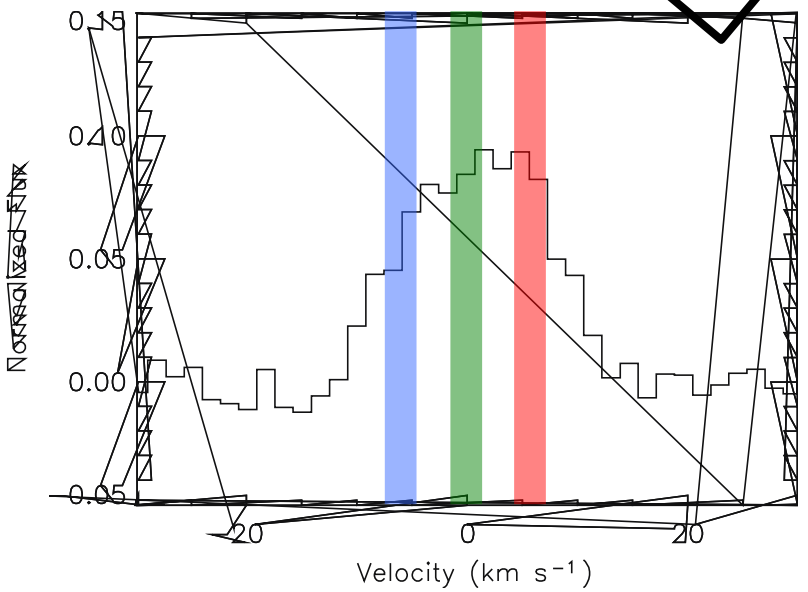




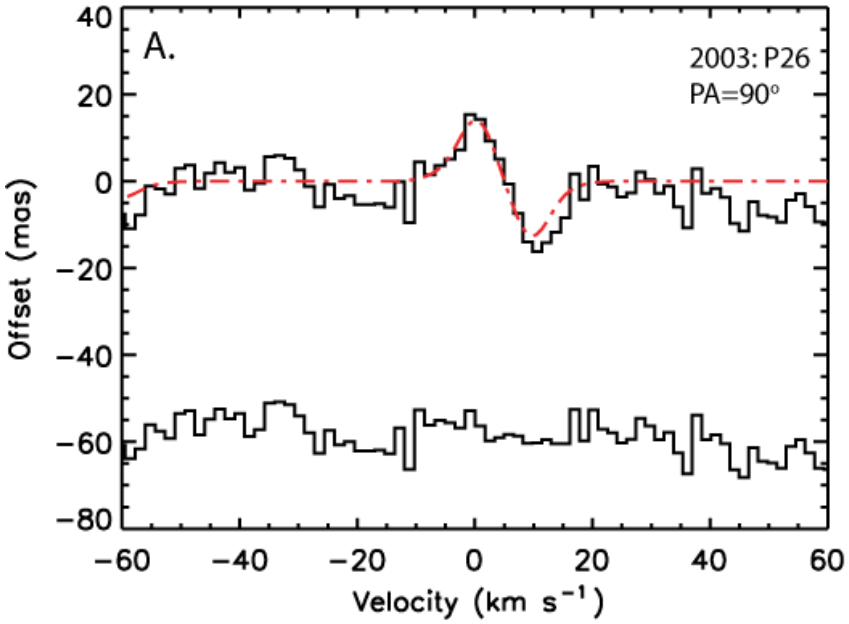
Spectro-Astrometry

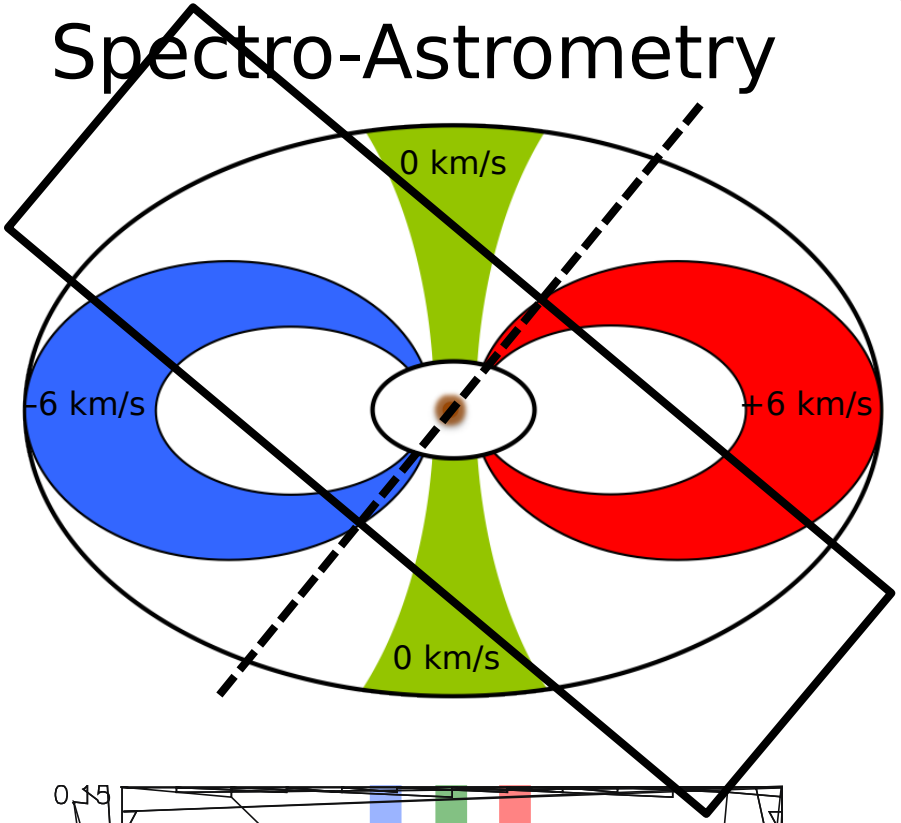


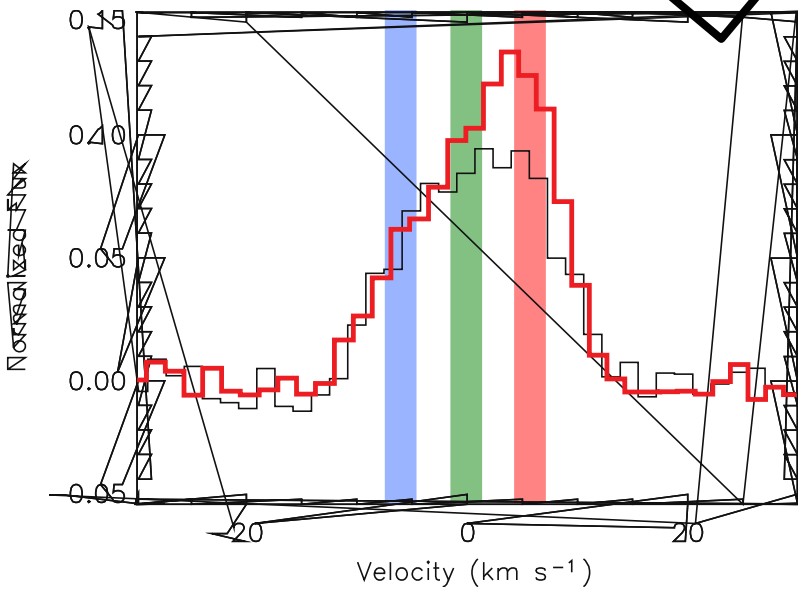




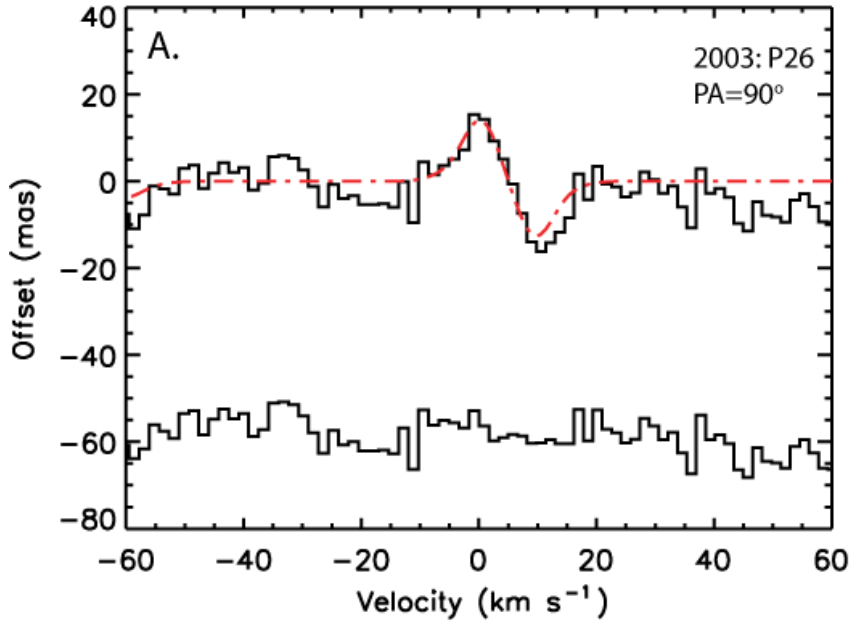
Spectro-Astrometry

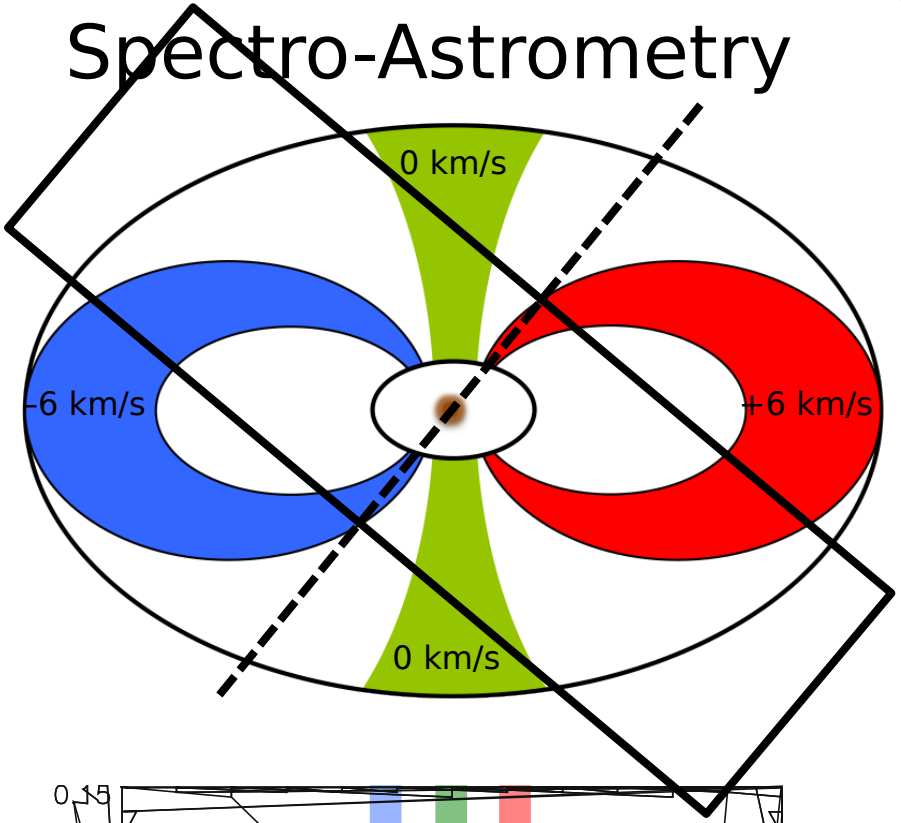


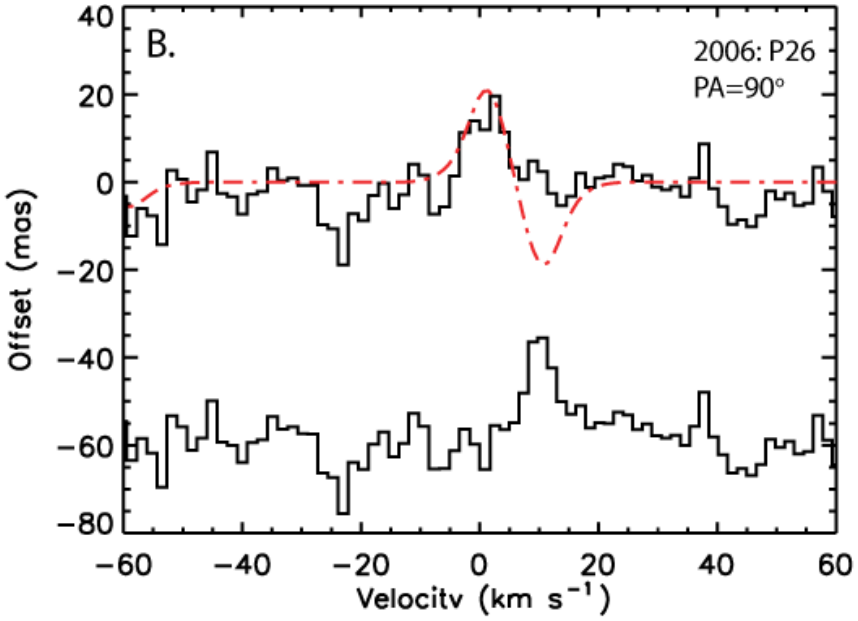


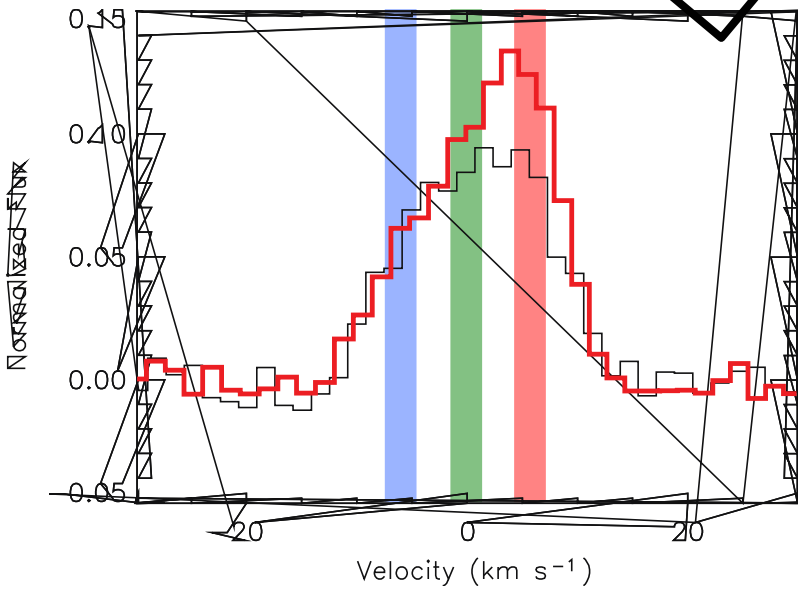


Spectro-Astrometry









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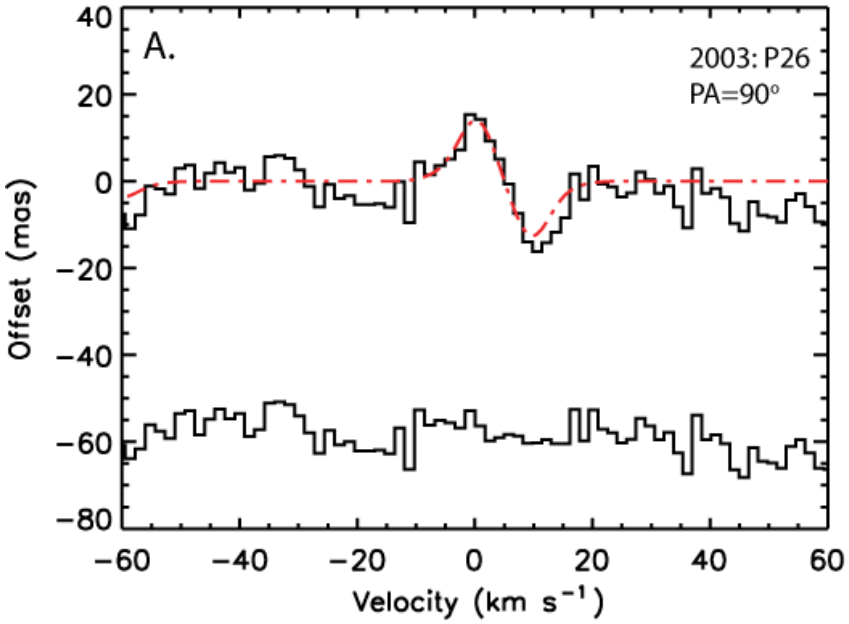
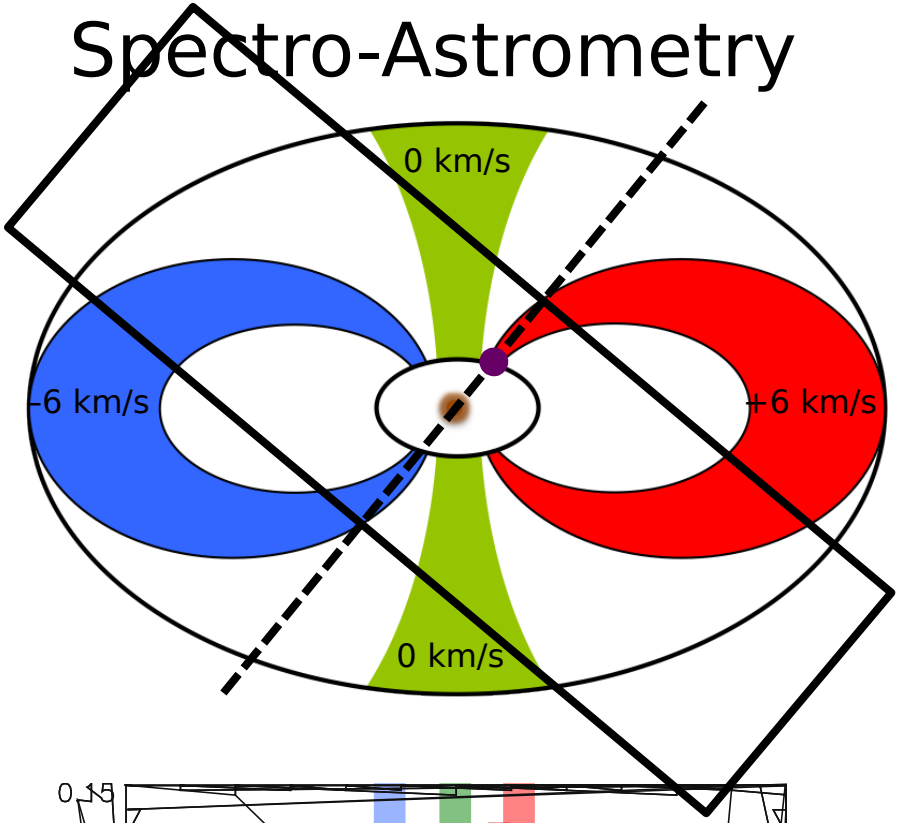
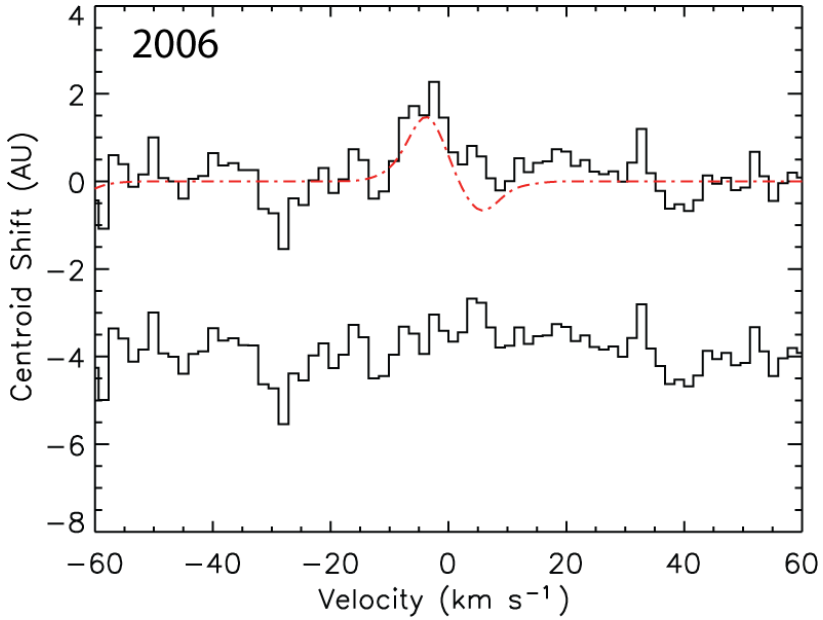
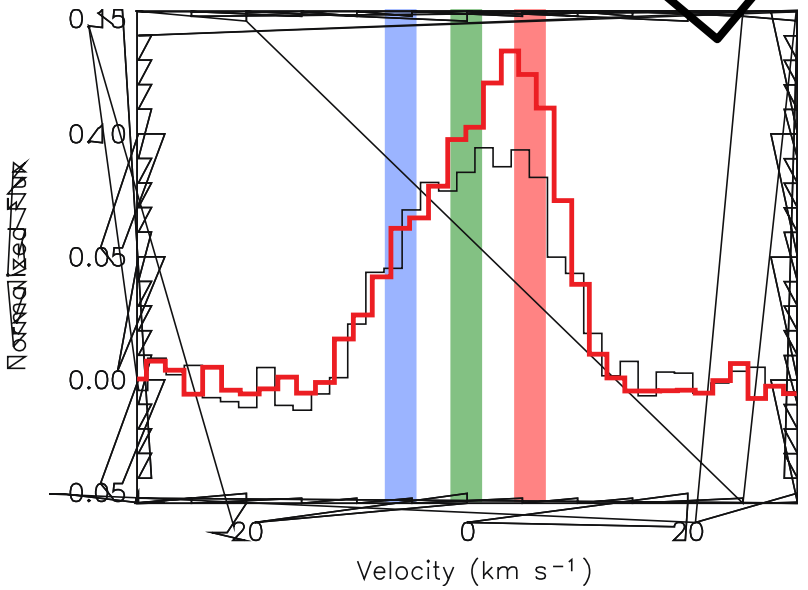
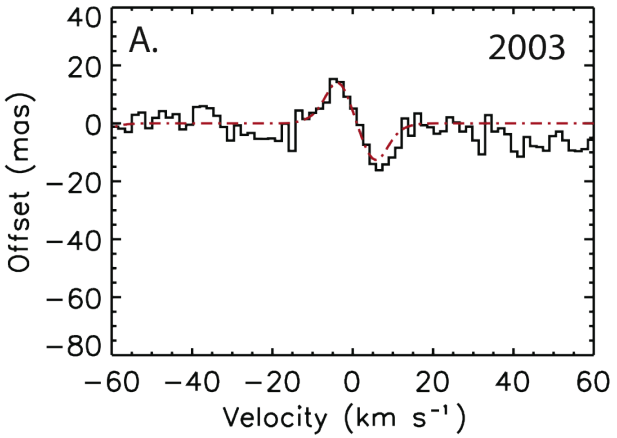


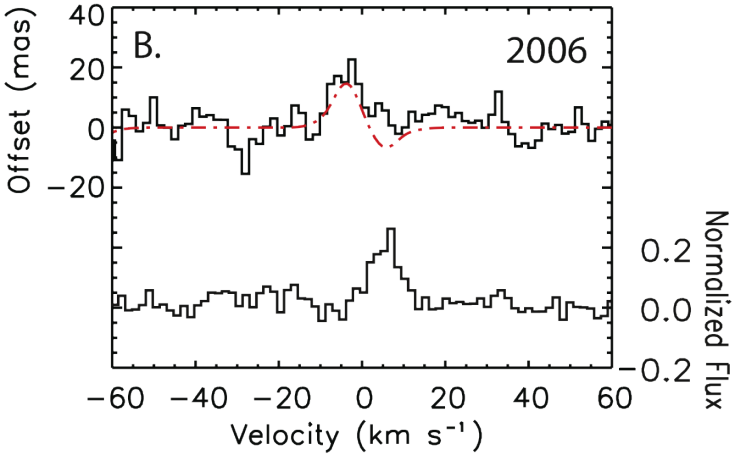


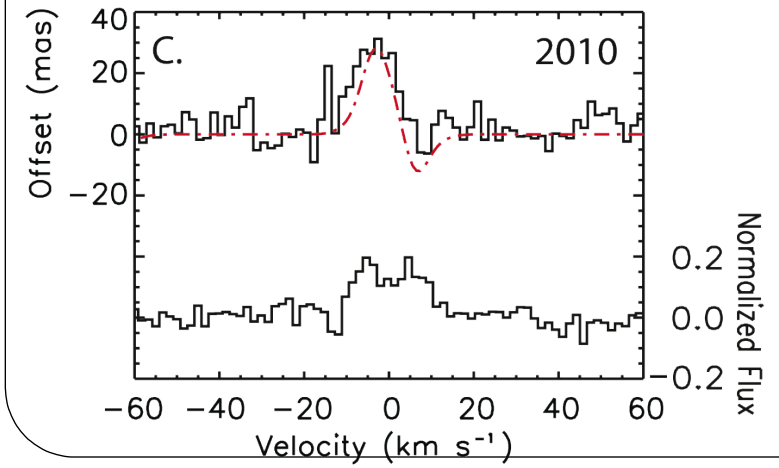


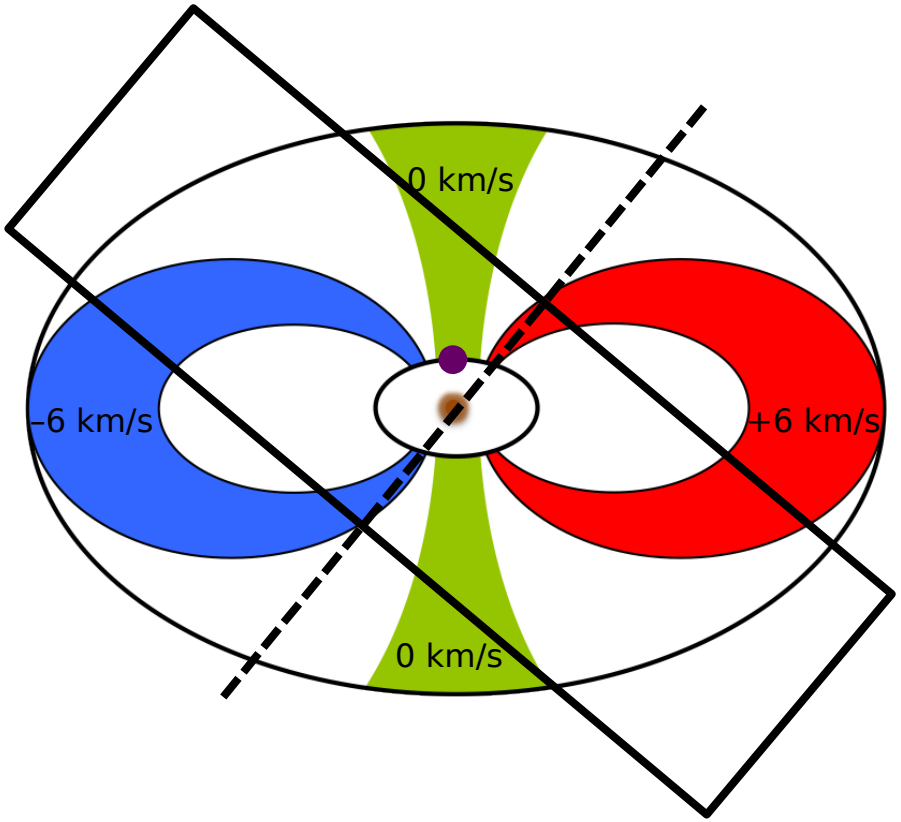


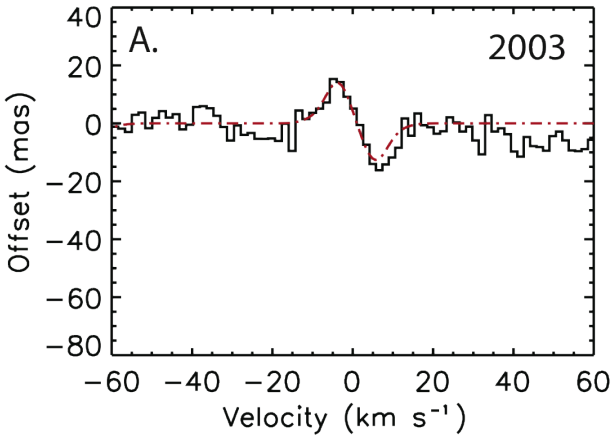
Line Evolution

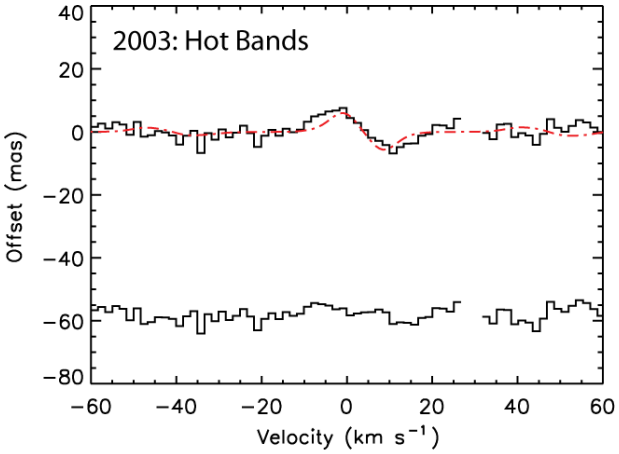


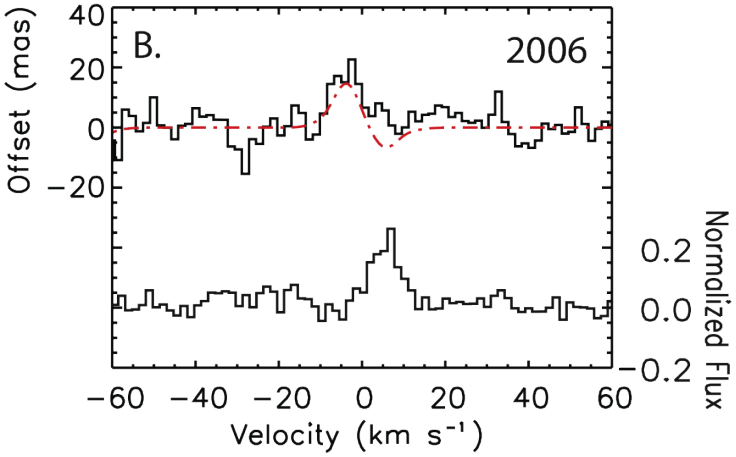


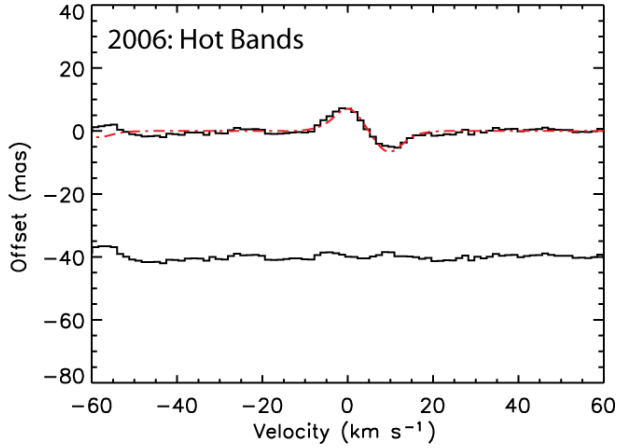


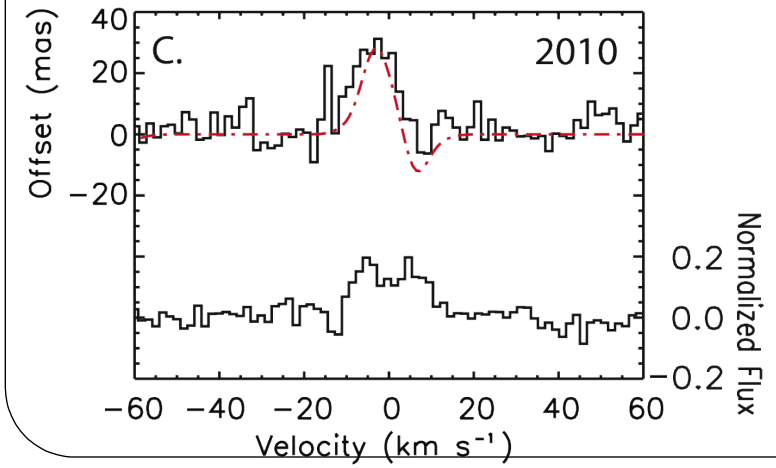


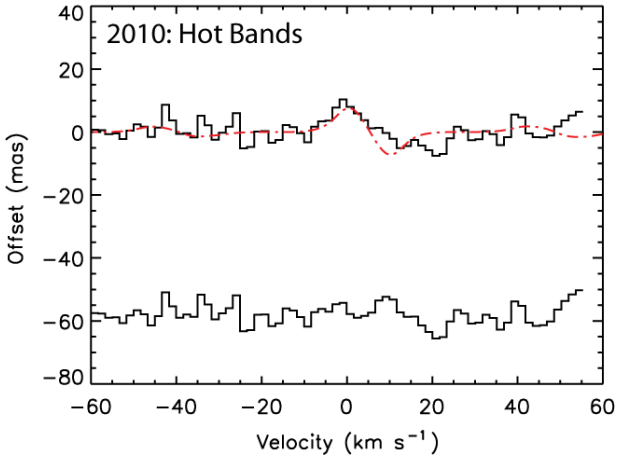

A.
2003
Offset (mas)
Velocity (km s⁻¹)

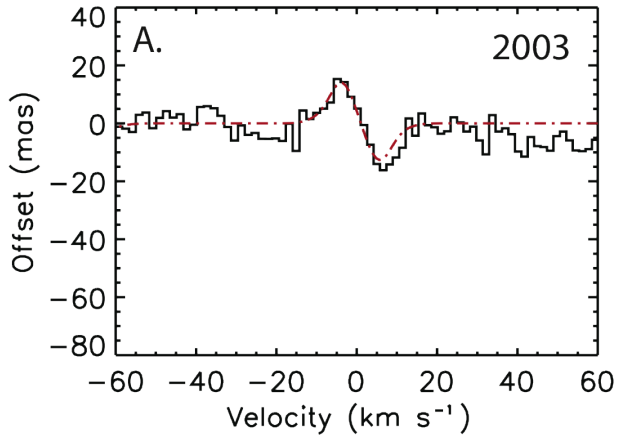

2003: Hot Bands
Offset (mas)
Velocity (km s⁻¹)

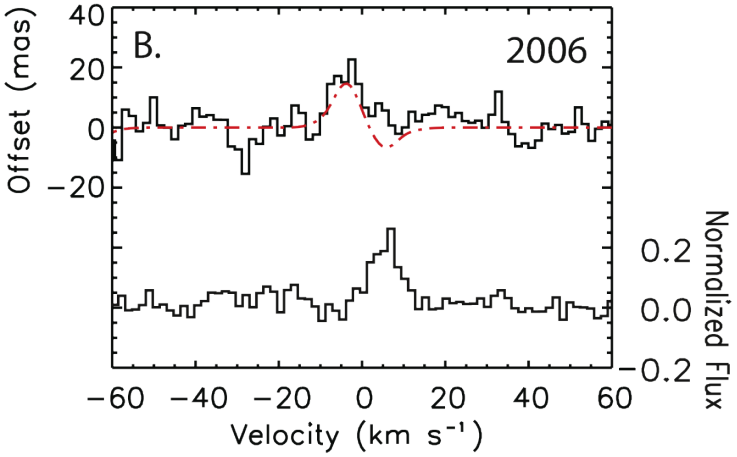

B.
2006
Offset (mas)
Normalized Flux
Velocity (km s⁻¹)

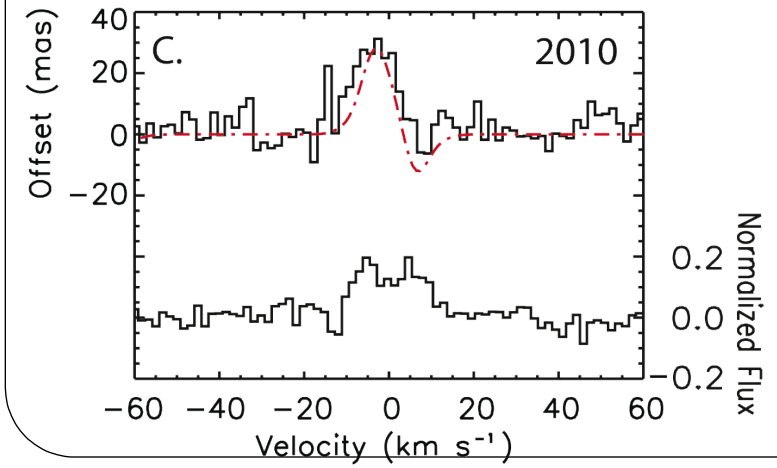

2006: Hot Bands
Offset (mas)
Velocity (km s⁻¹)


C.
2010
Offset (mas)
Normalized Flux
Velocity (km s⁻¹)

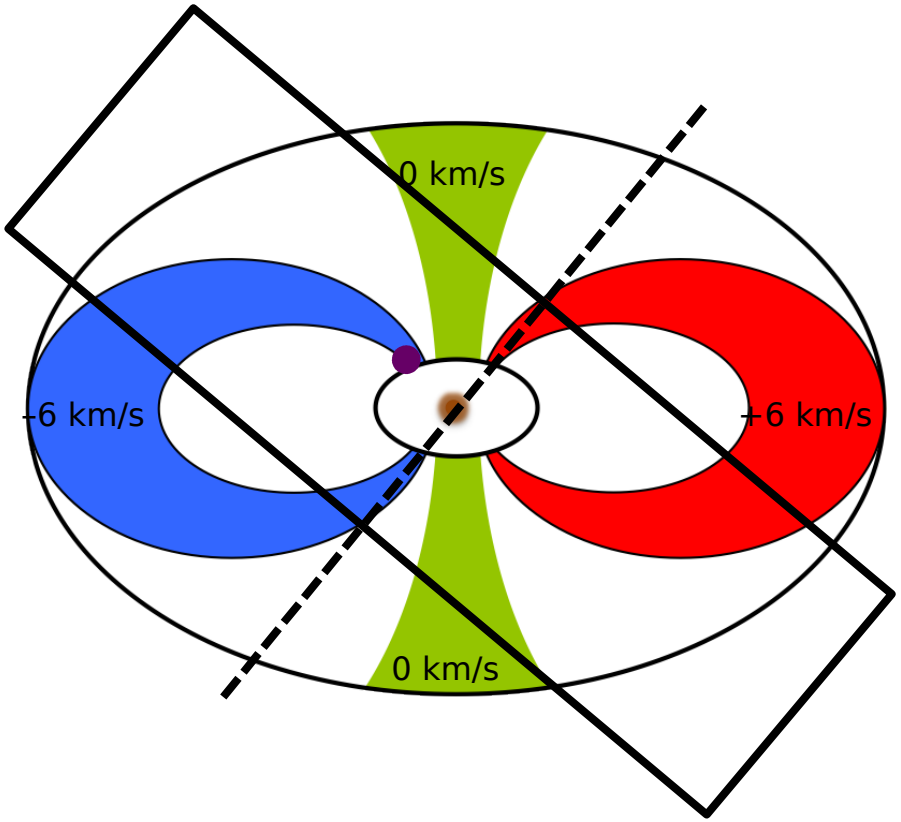

2010: Hot Bands
Offset (mas)
Velocity (km s⁻¹)



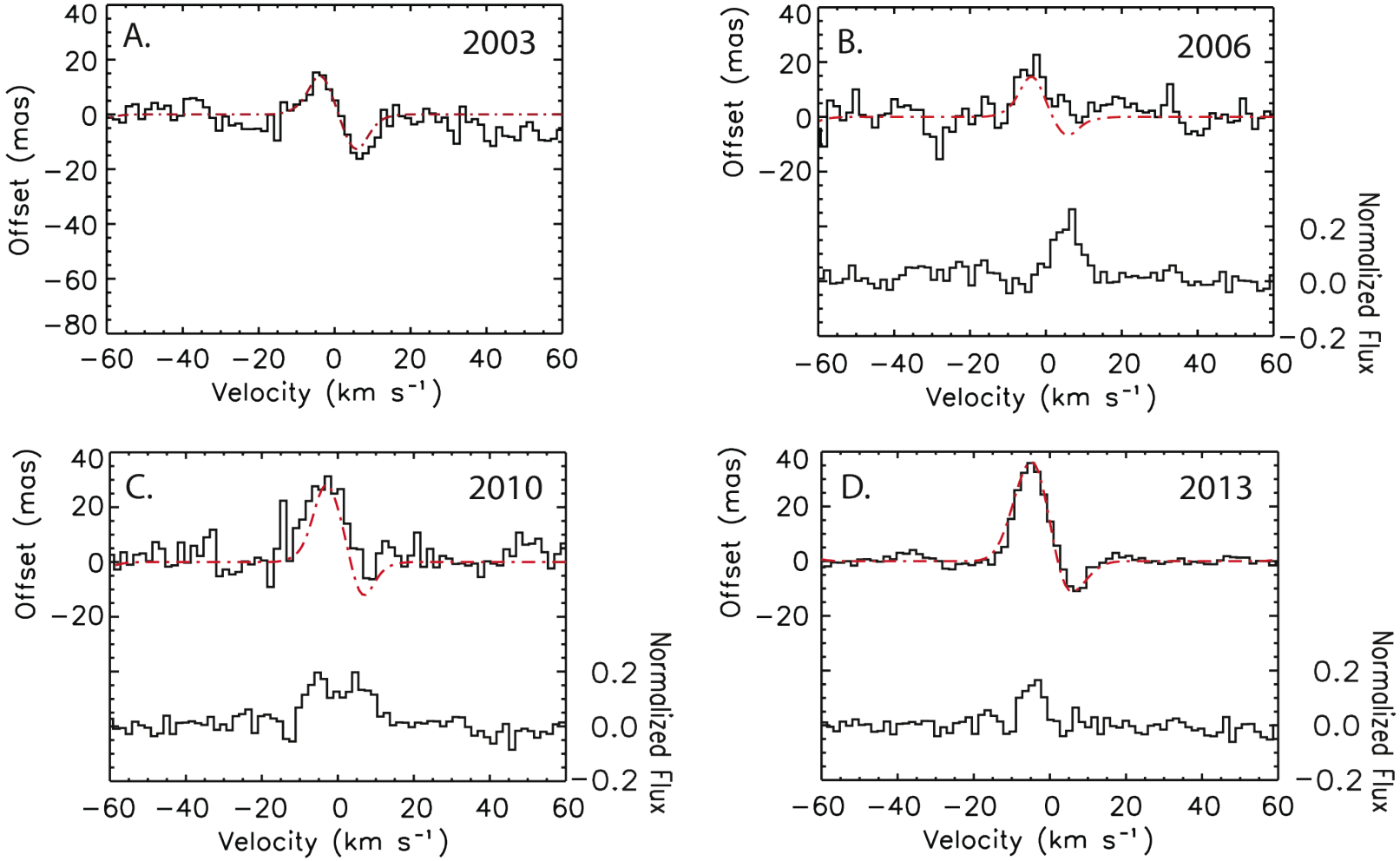




Line Evolution

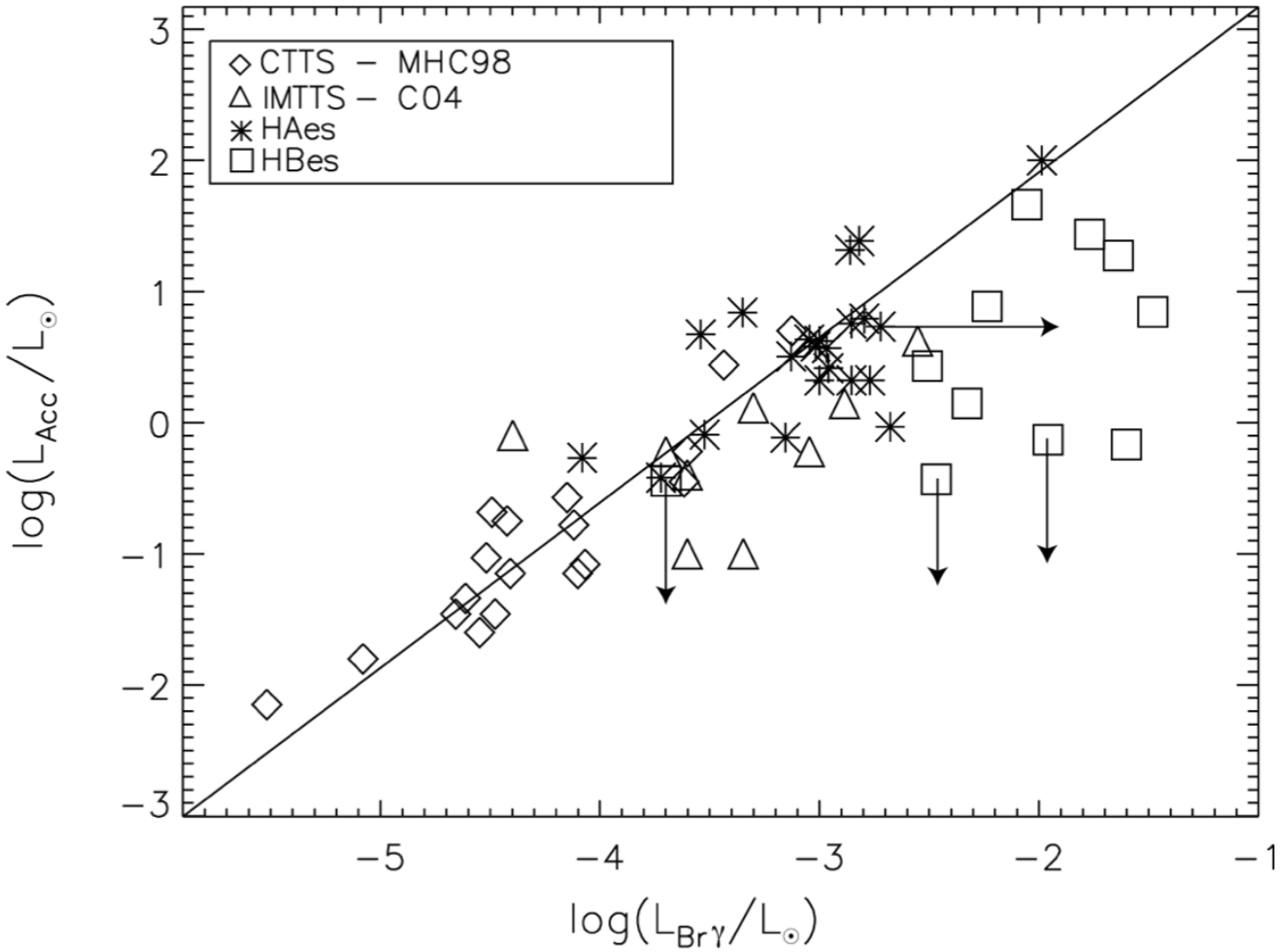


Line Evolution



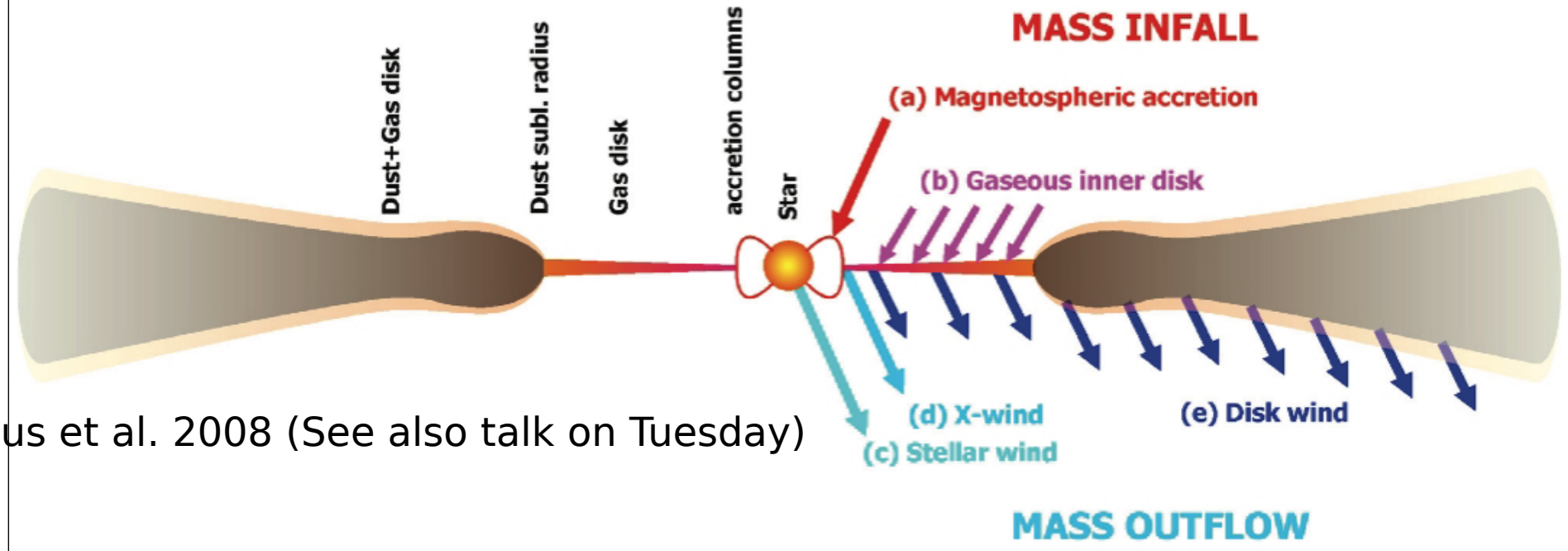
APPLICATIONS II.
The Origin of the HI Lines

Accretion on to Herbig Ae/Be Stars



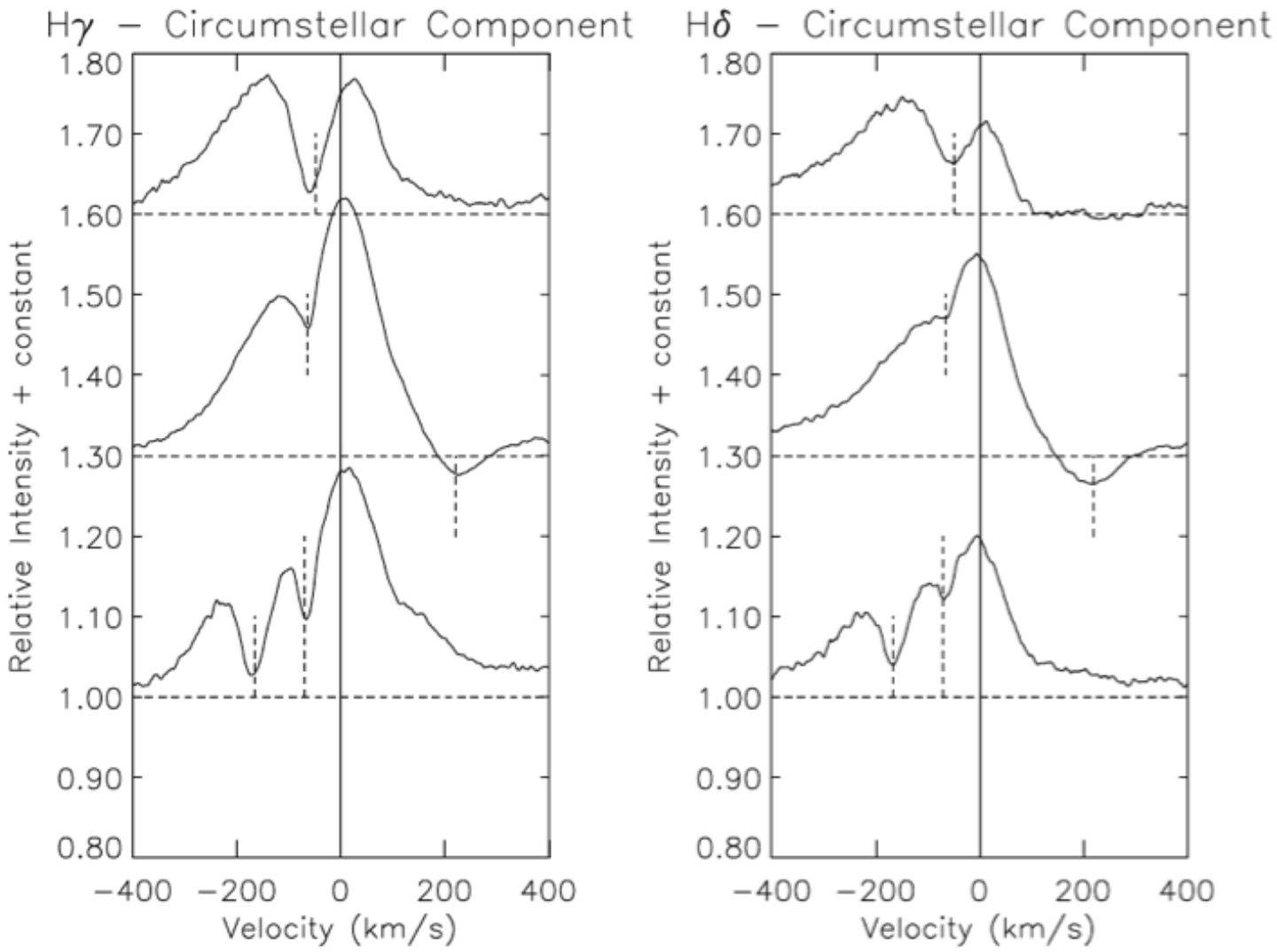
Donehew & Brittain 2011 (see also Vink et al. 2005; Mottram et al. 2007; Costigan et al. 2014; talk by C. Dougados today and J. Vink Tuesday)

Accretion on to Herbig Ae/Be Stars



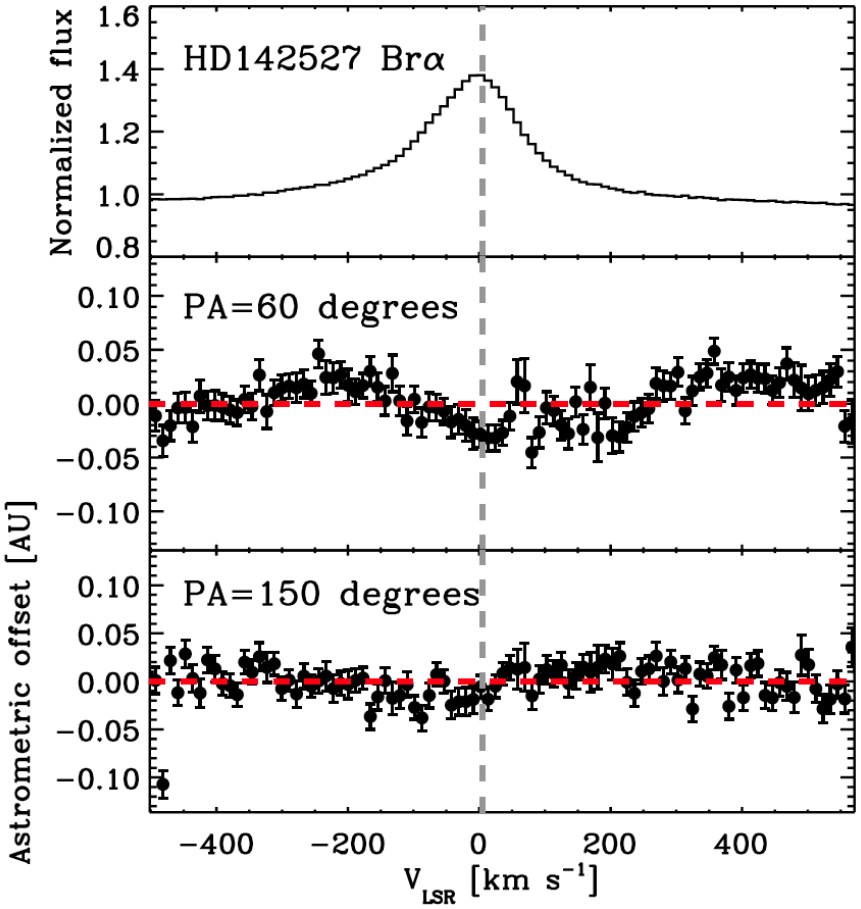
us et al. 2008 (See also talk on Tuesday)

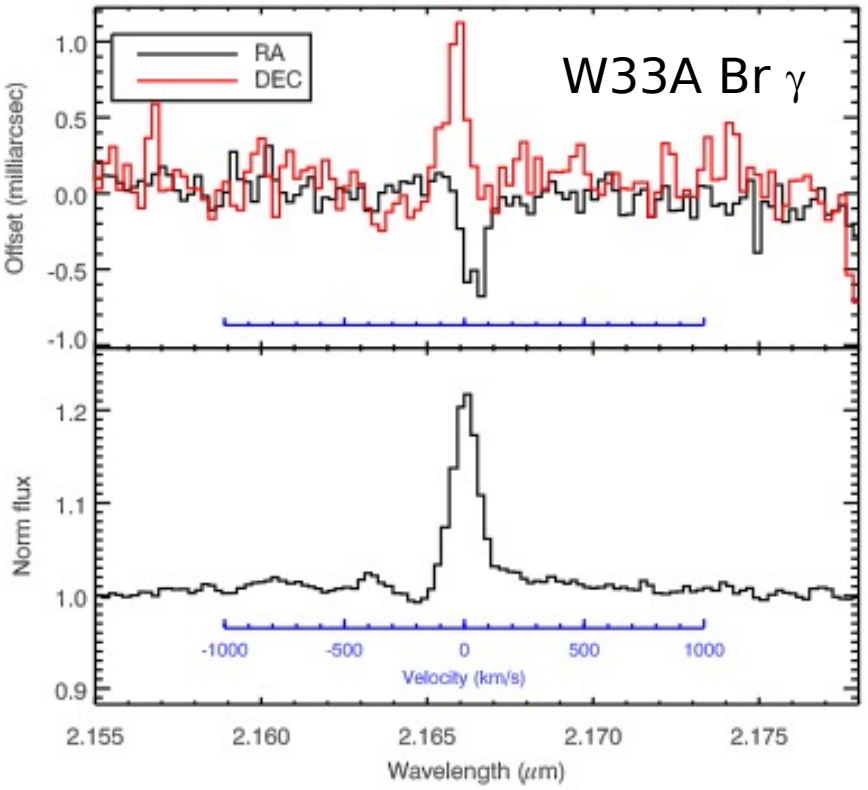
Accretion on to Herbig Ae/Be Stars



Guimarães et al. 2006

HI in Herbig Ae/Be Stars



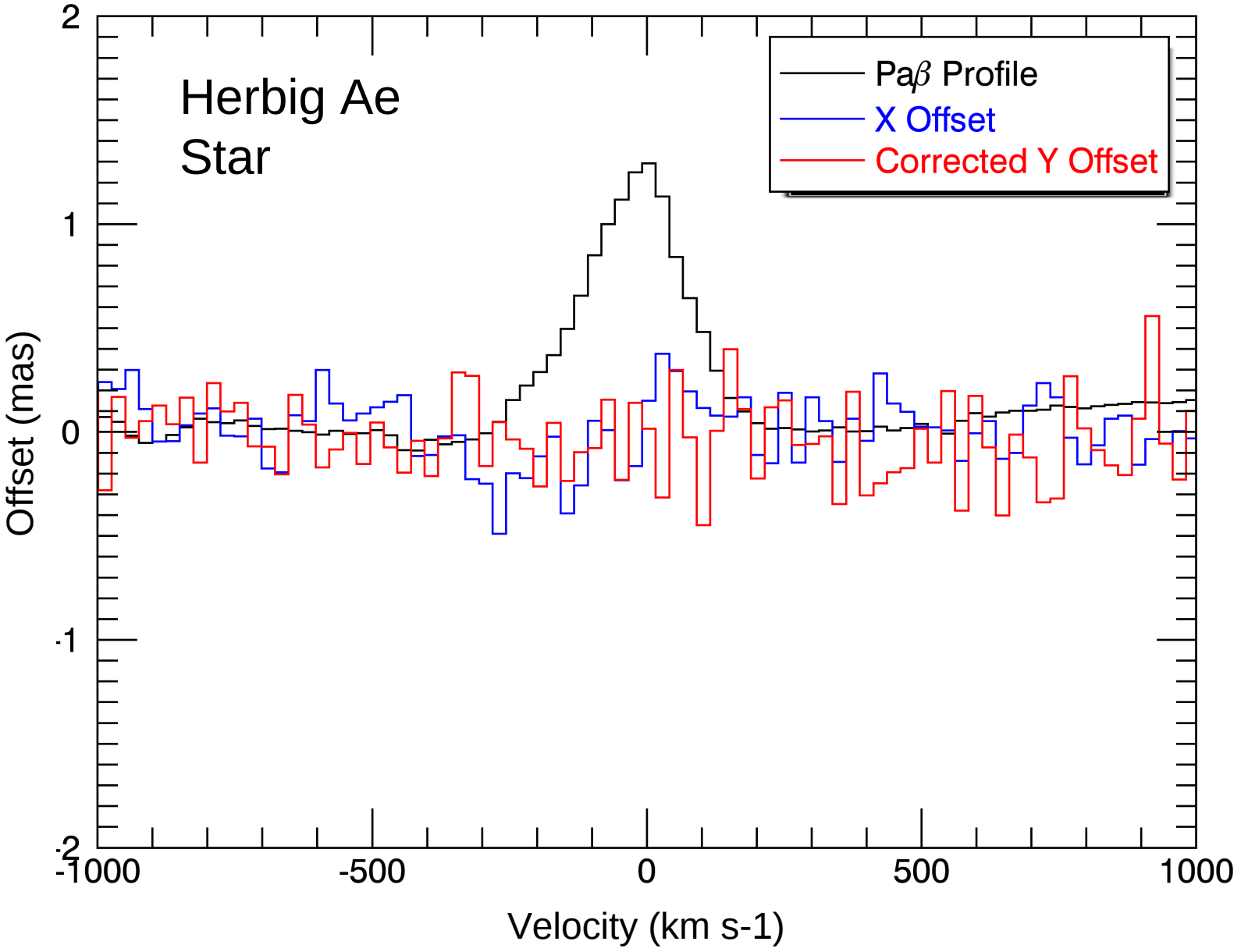


Davies et al. 2010

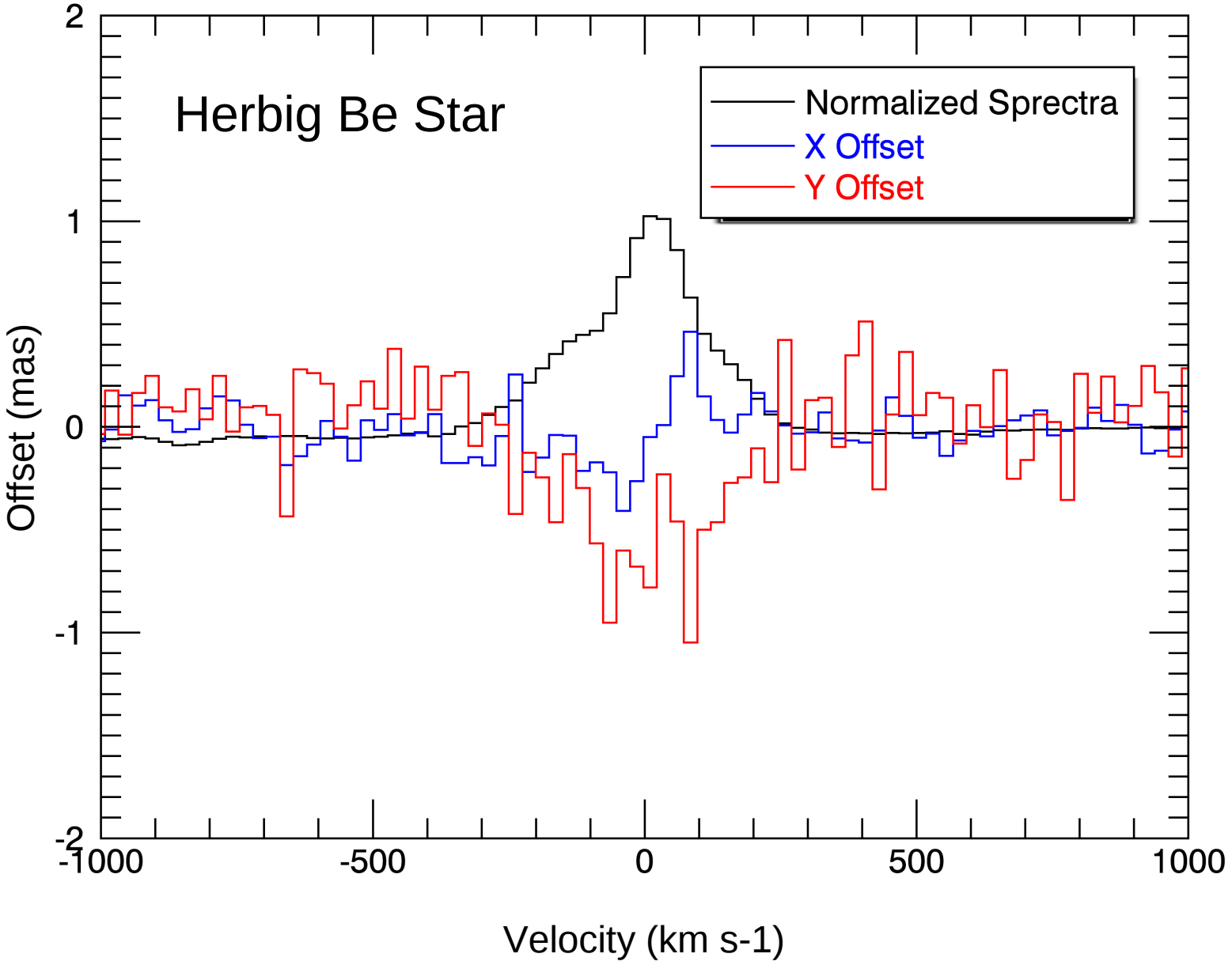
ppidan et al. 2011 (see also talk by R. Ramírez on Tues)

(See also Whelan+2004)

HI in Herbig Ae/Be Stars

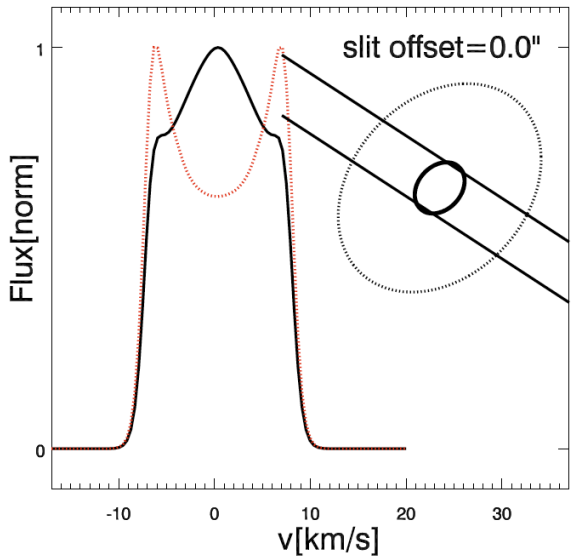


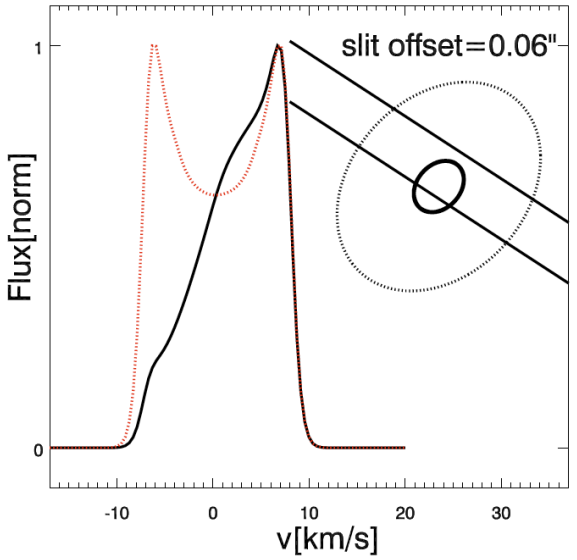
HI in Herbig Ae/Be Stars

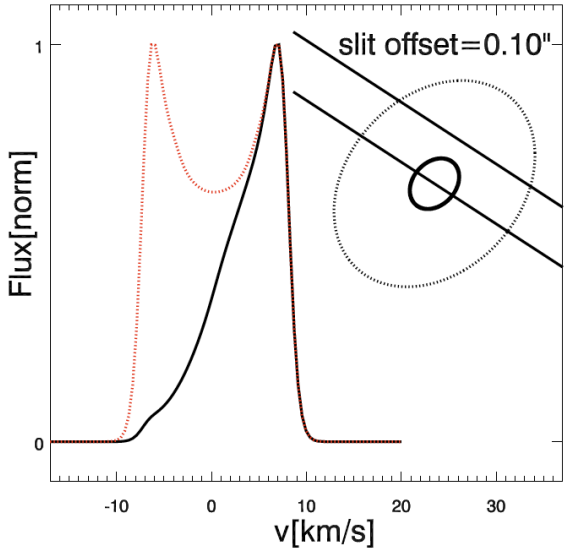


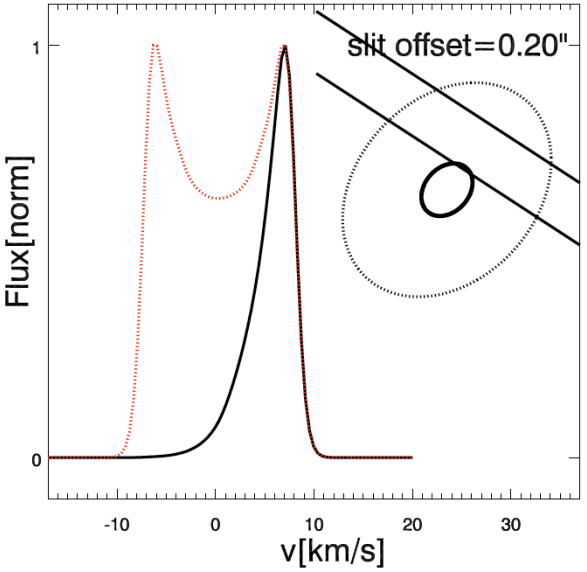
PITFALLS

Artifacts?



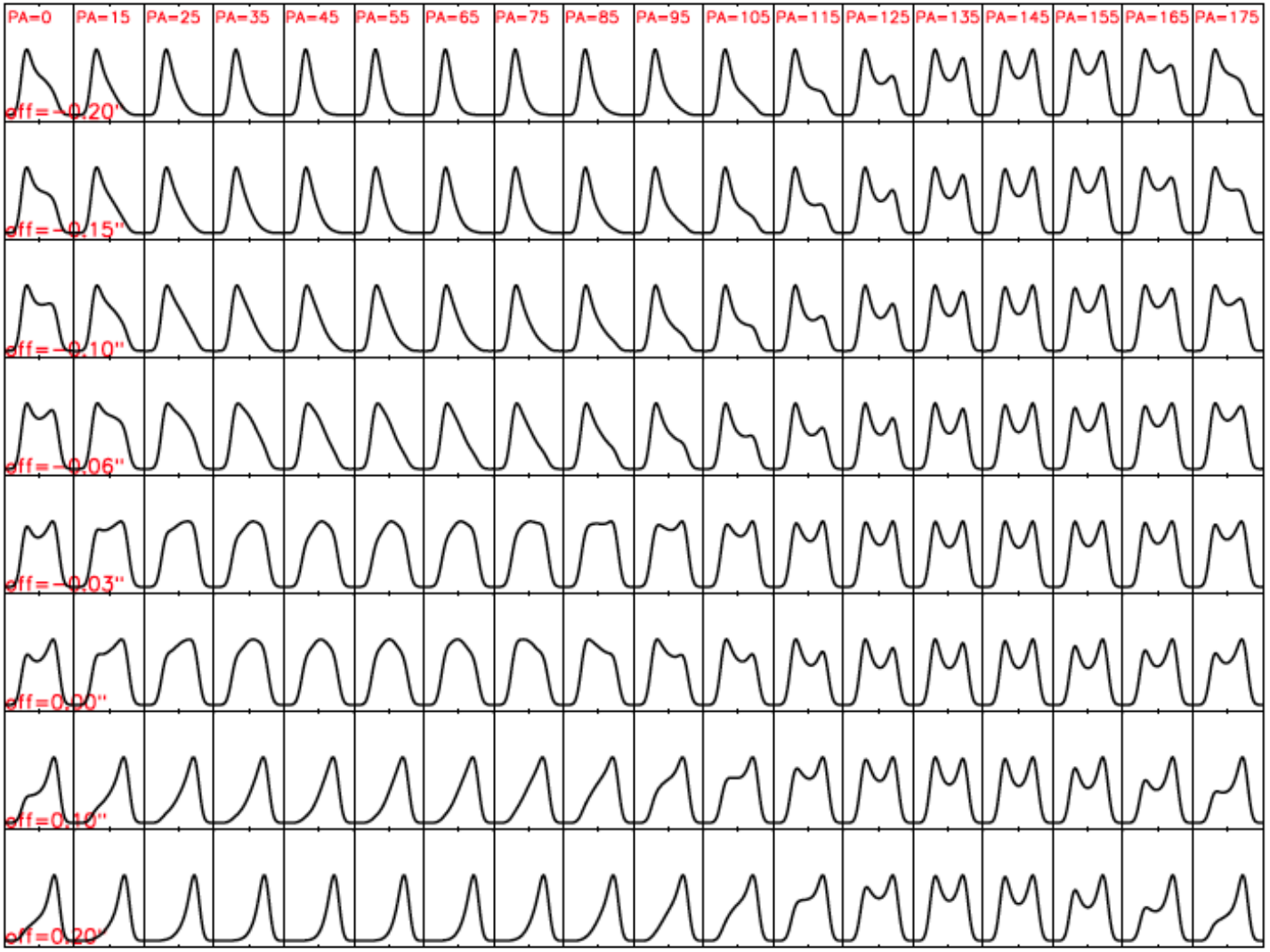






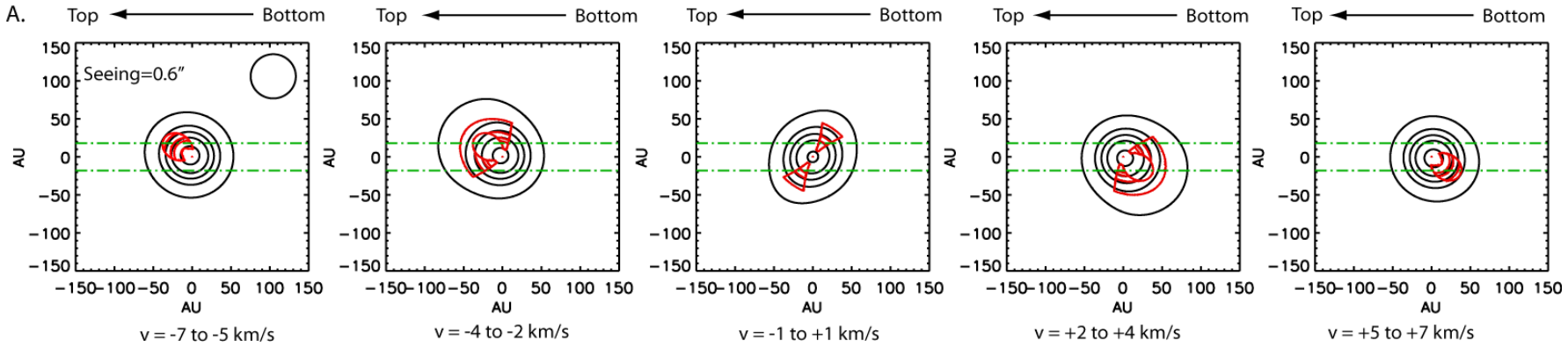
Hein Bertelsen+ 2014

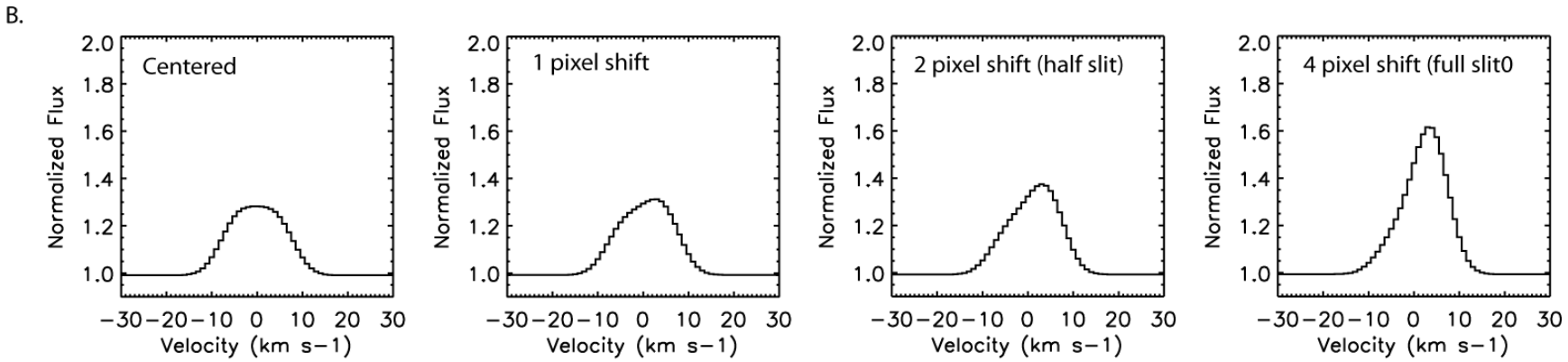
Artifacts?

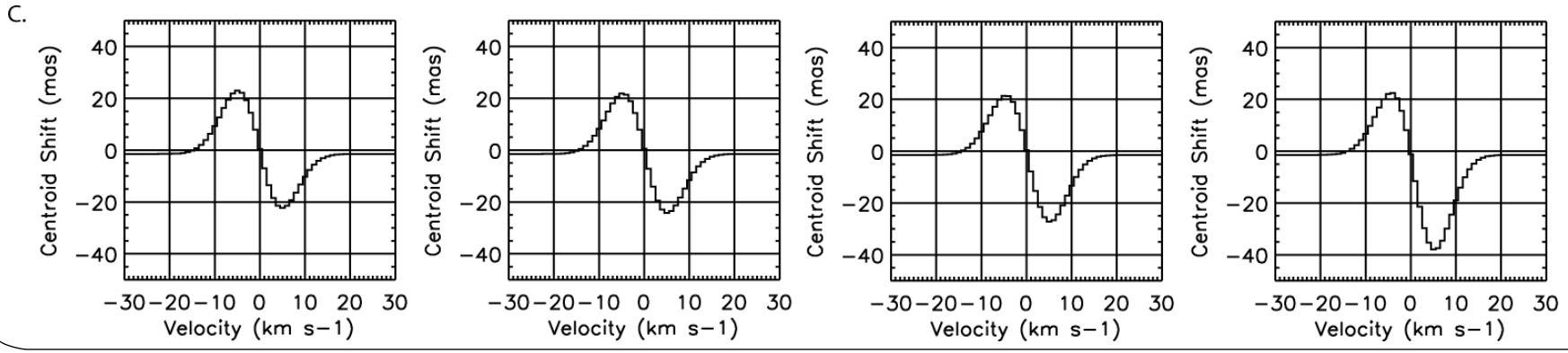


Hein Bertelsen+ 2014

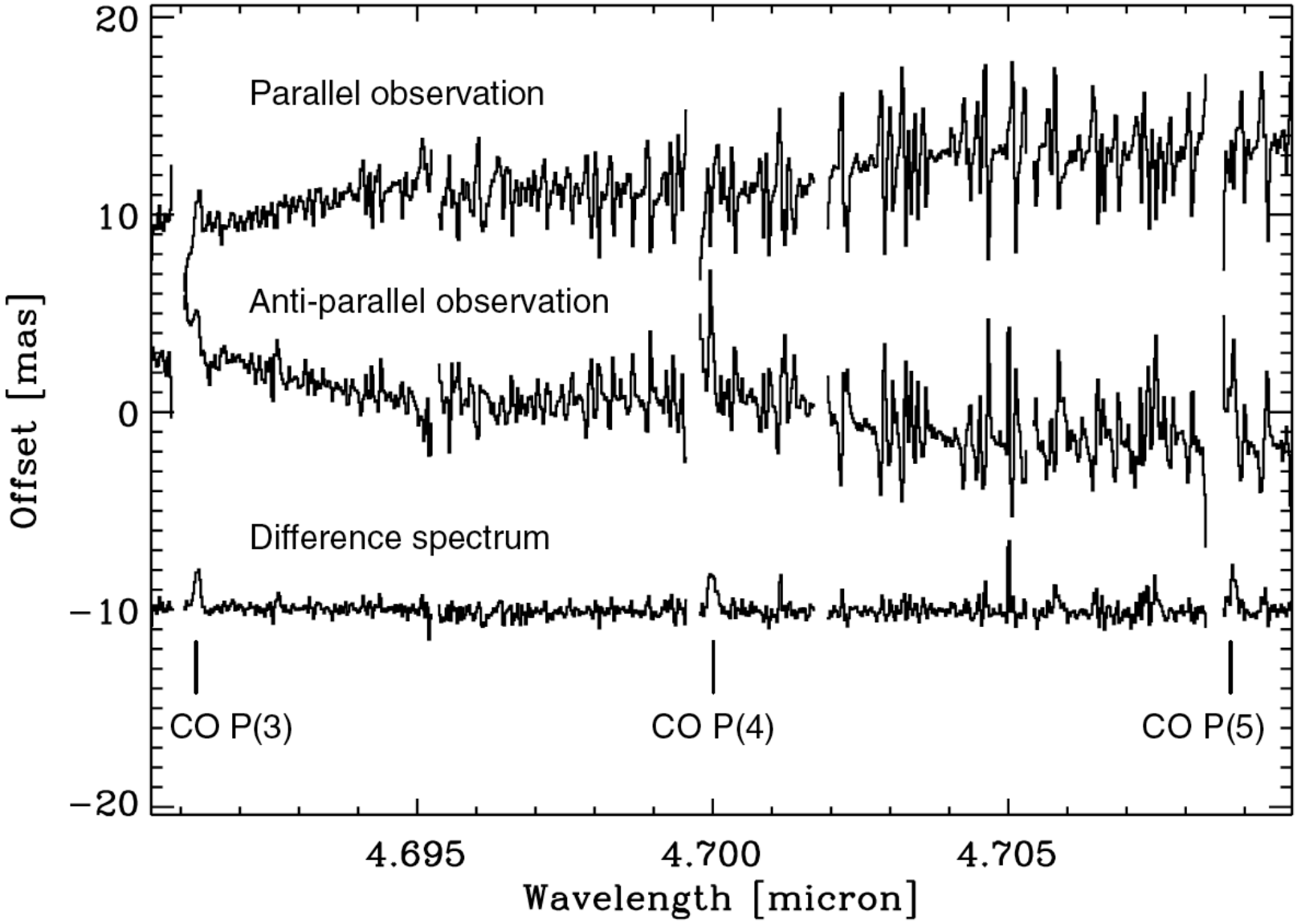
Artifacts?


A.
Top
Bottom
Seeing=0.6″
AU
v = -7 to -5 km/s
v = -4 to -2 km/s
v = -1 to +1 km/s
v = +2 to +4 km/s
v = +5 to +7 km/s


B.
Centered
1 pixel shift
2 pixel shift (half slit)
4 pixel shift (full slit0
Normalized Flux
Velocity (km s−1)

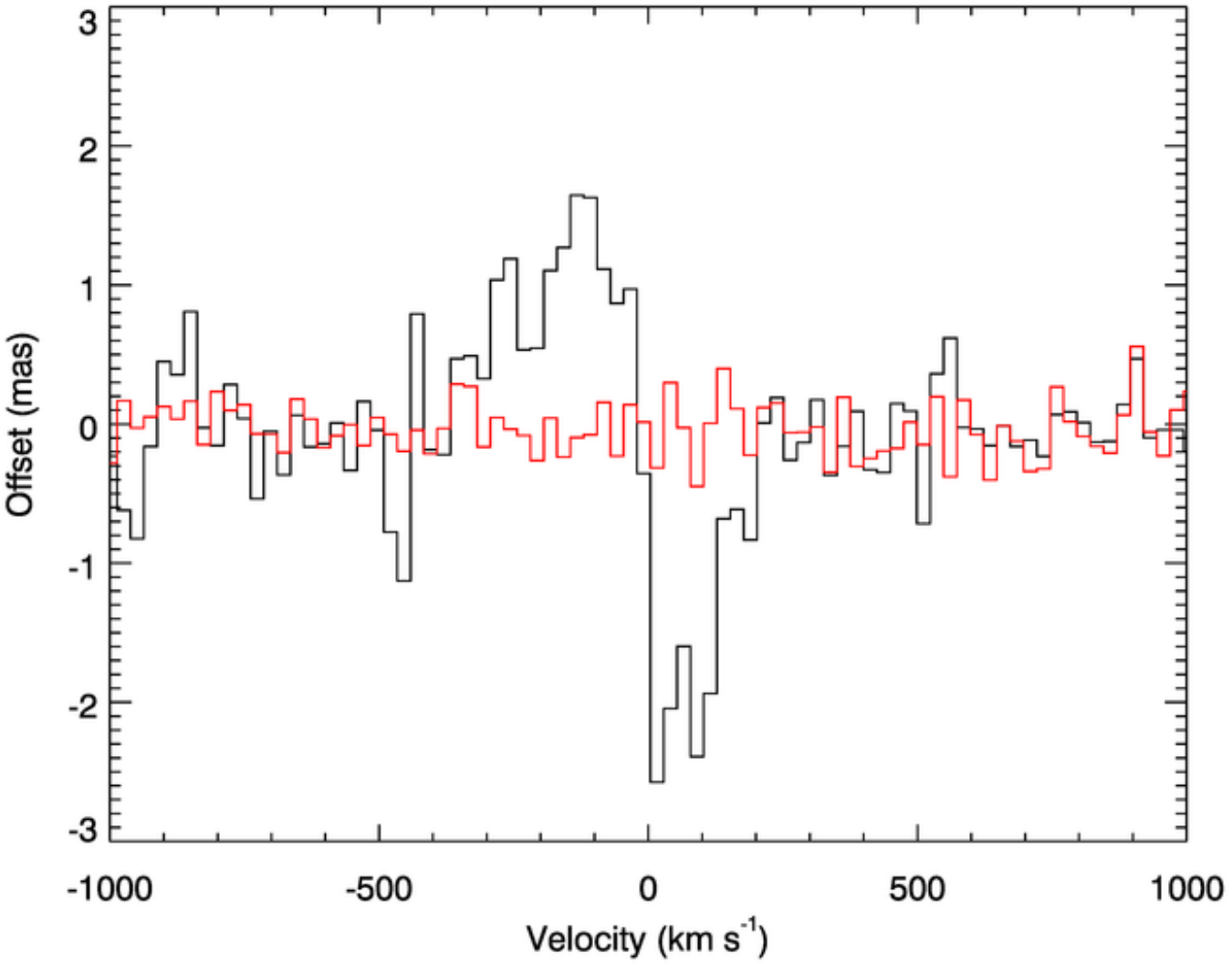

C.
Centroid Shift (mas)
Velocity (km s−1)

Artifacts?



Pontoppidan et al. 2011

Spectro-Astrometry with IFUs



CONCLUSIONS

- Technique
  - High resolution spectroscopy
  - Spectro-astrometry
- Applications
  - Dynamical markers of planet formation
  - Star/Disk interface of Herbig Ae/Bes
- Pitfalls
  - Sampling artifacts
  - Instrumental artifacts
- Promise
  - Stability
  - Longevity