# Observations of the inner regions of winds around young T Tauri type stars

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9th October 2009

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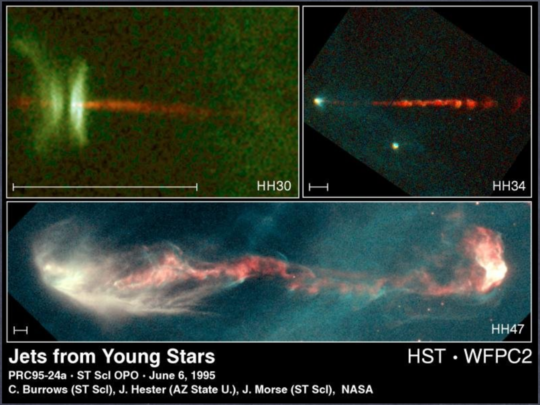
RTN FP6 (02/2005-02/2009)

# Outline

1. Introduction and thesis objectives
2. Technique: Integral Field Spectroscopy + AO
3. Jet properties in a T Tauri star with intermediate mass: RY Tau
4. Origin of the molecular $H_2$ emission: DG Tau
5. Conclusions and Perspectives

# Jets in young stars

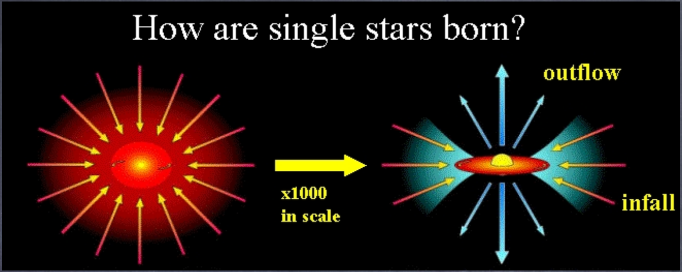


**Jets from Young Stars**

PRC95-24a · ST ScI OPO · June 6, 1995
C. Burrows (ST ScI), J. Hester (AZ State U.), J. Morse (ST ScI), NASA

- Collimated jets observed at all phases where active accretion occurs
- Important for the physics of the star-disk system.
  Jets remove angular momentum from the system?
- Jet-Accretion connexion in a large of Astrophysical domains
  (in particular, detected from Brown-Dwarf to massive stars)

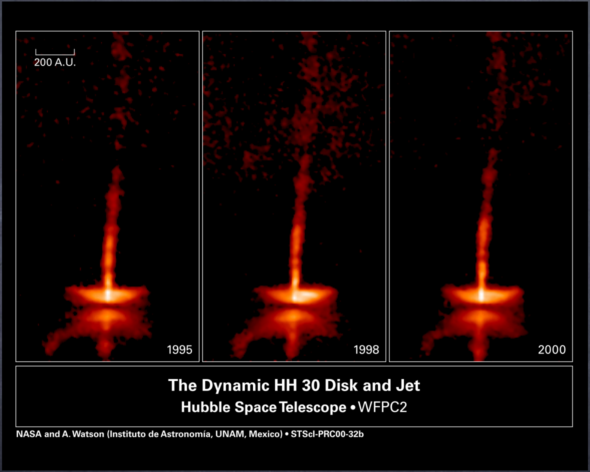
# T Tauri stars



*T Tauri stars*:

- Age $\sim 10^6$ years
- Strong UV/IR excess (produced by the accretion process)
- Outflow signatures: Strong Balmer emission lines, HeI, NaD, FeII lines and forbidden lines ([OI], [SII], [N II], [FeII])
- Jet launching and collimation at d $< 100$ AU ($0.1''$) $\Rightarrow$ HAR obs
- Kinematic $\Rightarrow$ high spectral resolution (R $> 3000$, $\Delta$v $< 100$ km/s)

# HAR observations



The Dynamic HH 30 Disk and Jet
Hubble Space Telescope • WFPC2

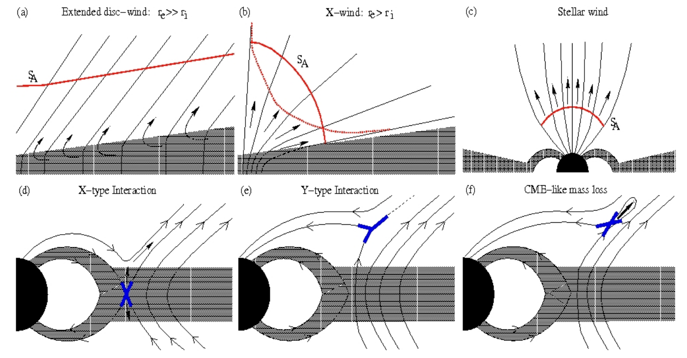
NASA and A. Watson (Instituto de Astronomía, UNAM, Mexico) • STScI-PRC00-32b

Over 15 sources studied with high angular techniques
Only two with Integral Field Spectroscopy: DG Tau and RW Aur

# MHD Models

Stationary

Variable

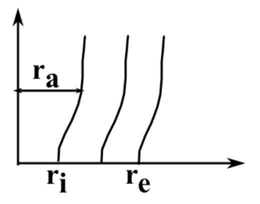


Ferreira et al., 2006

- Explain the link between ejection and accretion mechanisms
- Main different in the origin on the launching: star, large range of radii in the disc or at one annulus, at the co-rotation radius

# MHD Models - Self similar disk wind solution

(Ferreira et al., 1997, Casse & Ferreira, 2000)



## Eqs and relations (Ferreira et al., 2006):

$$v_p^{\infty} \sim v_k \sqrt{2\lambda - 3}$$

where $\lambda = (r_A/r_0)^2$, $v_k = \sqrt{GM_*/r_0}$

$$\xi = \frac{1}{2(\lambda - 1)} \qquad 2\frac{\dot{M}_j}{\dot{M}_{acc}} = \xi \ ln\left(\frac{r_e}{r_i}\right)$$

# Specific objectives of this thesis

Observational constrains of the launching mechanism ($d < 100$AU) increasing the number of sources studied in detail $\Rightarrow$ IFS + OA

- Morphology and Kinematics
- Gas excitation conditions
- Ejection/accretion rate
- Molecular component

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Observed objects:

*Star with intermediate mass:*
*RY Tau (Optical OASIS data)*

- Central mass star effect in jet properties

*Molecular component study:*
*DG Tau (NIR SINFONI data)*

- Deep study of the molecular component
- Comparison with atomic emission

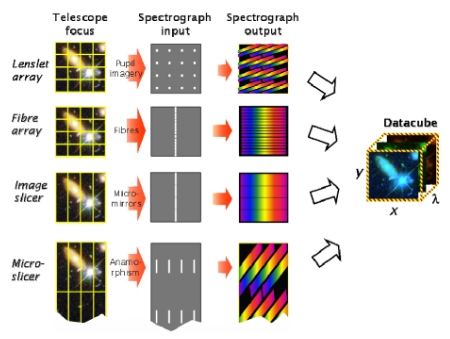
# Technique:

# Integral Field Spectroscopy + AO

# Integral Field Spectroscopy (IFS)

*3D spectroscopy*:

A spectrum for each 2D spatial element simultaneously



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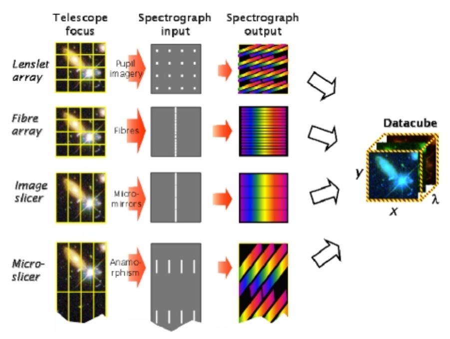
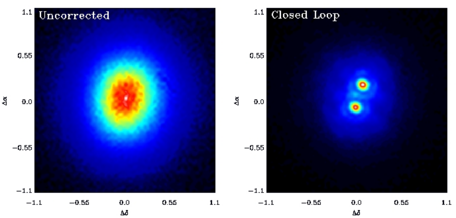


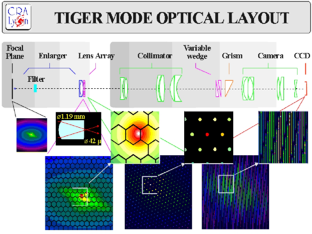
CFHT Adaptive optics system



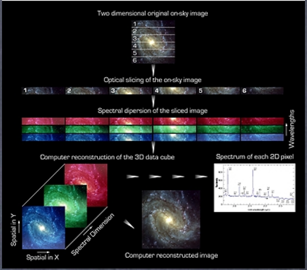
Advantages:

- Global velocity field
- Stellar continuum subtraction to isolate line emission close to the central source
- Deconvolution of channel maps

# IFS - Instruments used



OASIS (CFHT)



SINFONI (VLT)

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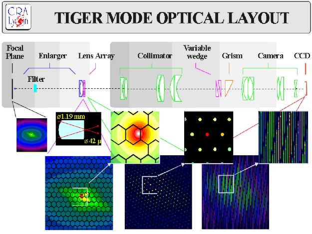

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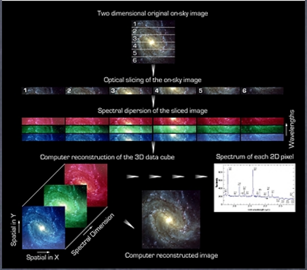


SINFONI (VLT)

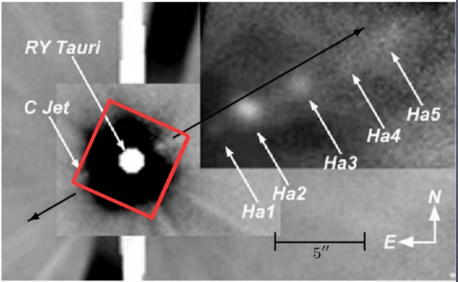
| Instrument | Object | Wavelength domain | Sky sampling | FOV | Spec res. |
|---|---|---|---|---|---|
| OASIS | RY Tau | 6209-6549 Å | 160 mas | $6.2'' \times 5.0''$ | 3000 |
| SINFONI | DG Tau | 1.45-1.85 $\mu$m (H Band) | 100 mas | $3'' \times 3''$ | 3000 |
| SINFONI | DG Tau | 1.95-2.45 $\mu$m (K Band) | 100 mas | $3'' \times 3''$ | 4000 |

| Instrument | Object | Spatial res. |
|---|---|---|
| OASIS | RY Tau | $0.4''$ |
| SINFONI | DG Tau | $0.15''$ |

# Jet properties in a T Tauri star with intermediate mass:

## RY TAU

# RY Tau - the jet

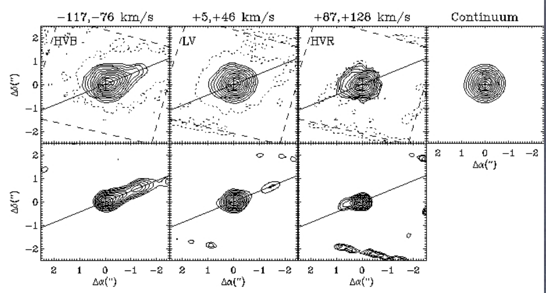


$H_\alpha$ obs by St-Onge & Bastien, 2008

- F8-G1 star located in the Tarurus-Auriga cloud, at 140 pc
- Mass= 2 $M_\odot$

- Jet suggested by Cabrit et al, 1990 and Hartigan et al, 1995
- Confirmed by St-Onge & Bastien, 2008

# RY Tau - Morphology - [OI]6300Å



- Blue jet detection ($\sim$ -70 km/s)
- PA=294°= PA of the large scale jet in $H_\alpha$
- Knot at 1.2″ in the deconvolved images
- Red counter-jet

Agra-Amboage, V. et al, 2009, A&A, 493, 1029

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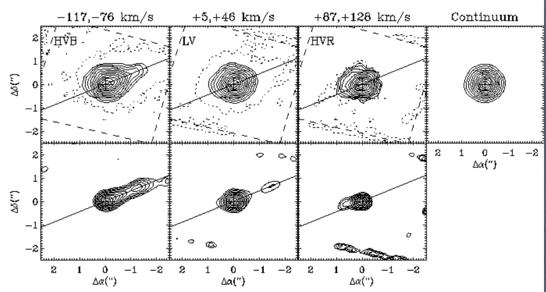
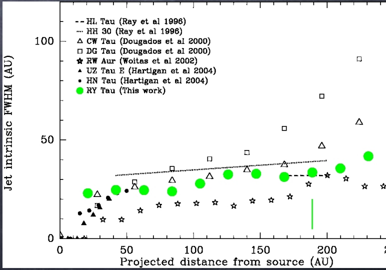


- Blue jet detection (~ -70 km/s)
- PA=294°= PA of the large scale jet in $H_\alpha$
- Knot at 1.2″ in the deconvolved images
- Red counter-jet

- Opening Angle ~5°
- No significant change of the width at the knot position
- Similar to other T Tauri microjets



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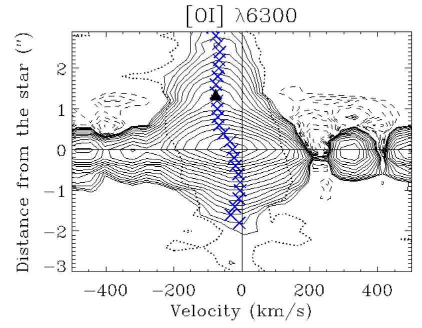
# RY Tau - Kinematics - [OI]6300Å



- LV component dominates near the source (d≤0.5″)
- Terminal velocity reached at distances ≤ 0.4″
- 45°≤i≤ 77°⇒$V_j$=100-300km/s
- Most probable value at 165km/s

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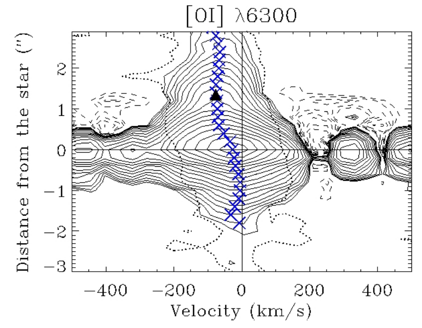

**Eqs and relations (Ferreira et al., 2006)**

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- LV component dominates near the source ($d \leq 0.5''$)
- Terminal velocity reached at distances $\leq 0.4''$
- $45° \leq i \leq 77° \Rightarrow V_j = 100\text{-}300$km/s
- Most probable value at 165km/s

- X-wind predictions: v∼300-500 km/s, compatibles with i∼77° ($\lambda \sim 3\text{-}6$, $r_0 = r_{co}$)
- Disk-wind compatible with the observed range of velocity ($\lambda \sim 2\text{-}15$, $r_0 = 0.05\text{-}1$AU)

Agra-Amboage, V. et al, 2009, A&A, 493, 1029

# RY Tau - Mass loss rate

- [OI] line optically thin ⇒ $L_{[OI]} \propto$ total mass of emitting atoms

**Volume emission**

$$\dot{M}_J = 9.61 \times 10^{-6} \left(\frac{1}{1 - x_{\rm e}}\right)\left(1 + \frac{n_{\rm cr}}{n_{\rm e}}\right)\left(\frac{L_{[OI]6300}}{L_\odot}\right)\left(V_\perp / l_\perp\right) \quad M_\odot / yr$$

Method assuming uniform physical conditions on the emitting gas inside the jet

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Method assuming uniform physical conditions on the emitting gas inside the jet

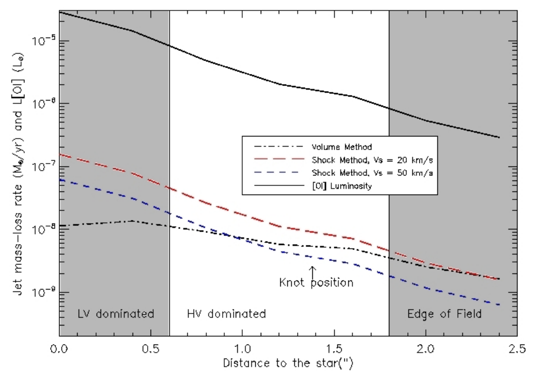
**Shocks**

$$\dot{M}_J = 6.616 \times 10^{-4} \left(\frac{V_{\rm jet}}{V_{\rm shock}}\right) \left(\frac{L_{[OI]6300}}{L_\odot}\right) \left(\frac{\cos\theta}{N_{\rm shock}}\right) \quad M_\odot/yr$$

Method assuming emission in a shock front

Agra-Amboage, V. et al, 2009, A&A, 493, 1029

# RY Tau - Mass loss rate



- $\dot{M}$= 0.16-2.6×$10^{-8}$ $M_\odot$/yr
- $\dot{M}$ 4 times higher than Hartigan et al., 95, using long-slit spectroscopy
- $\dot{M}_{acc}$=6.4-9.1×$10^{-8}$ $M_\odot$/yr Calvet et al., 04
- $\dot{M}/\dot{M}_{acc}$=0.02-0.4
- Compatible with the average ratio ≃0.1 Cabrit et al., 2007

Agra-Amboage, V. et al, 2009, A&A, 493, 1029

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  ⇒ More stars with different masses must be studied
- Red counter-jet marginally detected
- Global properties: collimation, terminal velocity, mass-loss rate are well reproduced by extended MHD disk wind model
- X-wind model is not excluded

# Origin of the molecular $H_2$ emission:

## DG TAU

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- Clarify the nature of the molecular emission in $H_2$ at $2.12\mu$m:
  - $H_2\lambda2.12\mu$m observed in jets in more embedded phases
  - Seen in only 6 TTCs associated with outflowing gas: 1 case clear identified with a HV jet (RW Aur), the other show LV (Beck et al, 2008)
  - $H_2\lambda2.12\mu$m thermalized at ∼2000K in these sources

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Excitation of the gas:

- UV fluorescence (FUV or Ly$\alpha$)
- Stellar UV/X-ray irradiation
- Shocks

Origin of the emission:

- Material on the disk
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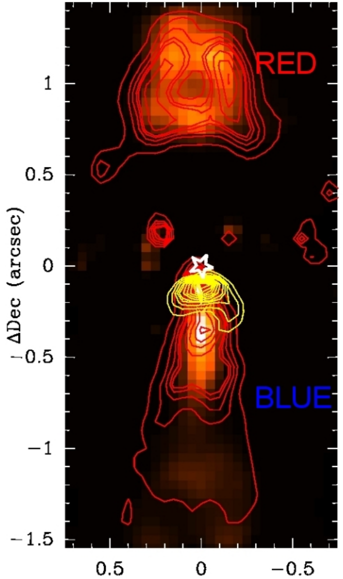
Takami et al., 2004; Beck, 2008: gas excited by shocks in a wide-angle wind component, but none of the possibilities is really excluded

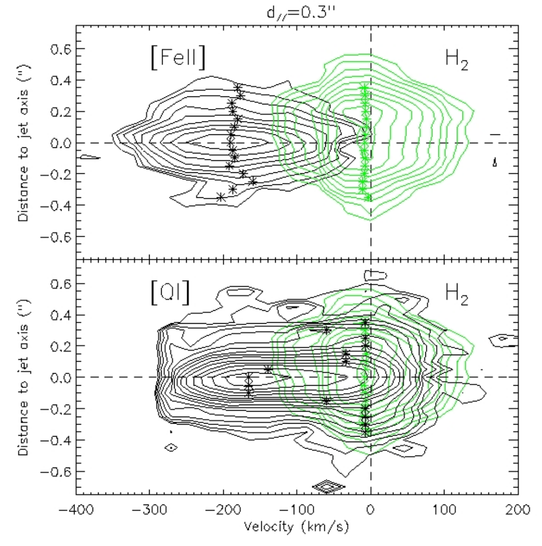
# DG Tau - Atomic/molecular comparison



- Background: [FeII]$\lambda 1.64 \mu$m at $> 150$ km/s
- Red Cont: [FeII]$\lambda 1.64 \mu$m at $< 150$ km/s
- Yellow Cont: $H_2 \lambda 2.12 \mu$m v=[-50,50] km/s

- [FeII] more collimated at high velocities
- Red emission hidden by the disk
- Molecular emission broader than atomic
- Molecular emission stopped at the -0.4″ atomic knot and encloses it
- Constrains on the launching radius:
  $r_0$([FeII]) $< 6$ AU
  $r_0(H_2) < 14$ AU

# DG Tau - Kinematics across the jet



[OI] HST obs by Coffey et al., 2008

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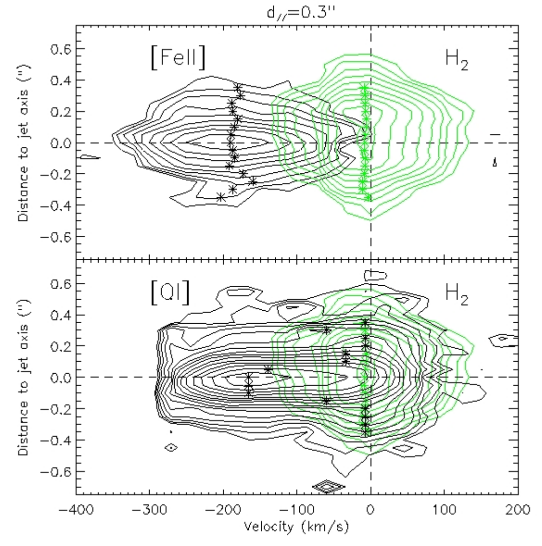


[OI] HST obs by Coffey et al., 2008

- [OI] "wide angle" flow surrounding [FeII] and filling the $H_2$ cavity
- Very slow [OI] could be a different component ("Halo" observed by Lavalley et al., 1997?)

# DG Tau - Mass loss rate from the Iron - Methods

## Cross section and density

$$\dot{M} = \mu m_H n_H V_j \Rightarrow \dot{M} = 1.23 \times 10^{-9} \left(\frac{n_H}{10^5 cm^{-3}}\right) \left(\frac{FWHM}{14AU}\right)^2 \left(\frac{V_j}{100km/s}\right) \qquad (M_\odot/yr)$$

## Luminosity of uniform slab

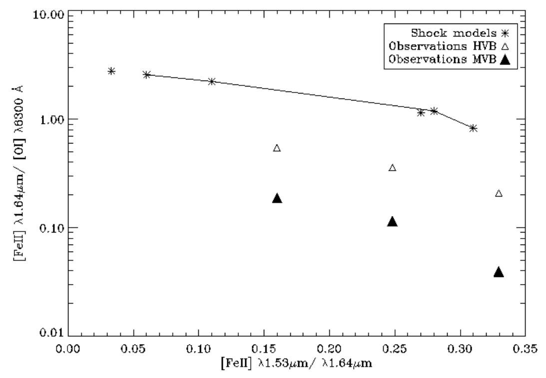
$$\dot{M} = 1.45 \times 10^{-8} \left(1 + \frac{3.5 \times 10^4}{n_e(cm^{-3})}\right) \left(\frac{L_{[FeII]1.64}}{10^{-4} L_\odot}\right) \left(\frac{V_t}{150km/s}\right) \left(\frac{l_t}{2 \times 10^{15} cm}\right)^{-1} \left(\frac{[Fe/H]}{[Fe/H]_\odot}\right)^{-1}$$

## Shocks

$$\dot{M}_s = 6.86 \times 10^{-17} \left(\frac{L_{1.64}}{L_\odot}\right) \left(\frac{n_H \times V_s}{F_{1.64}}\right) = 6.504 \times 10^{-4} \frac{L_{1.64}}{L_\odot} \left(\frac{[Fe/H]}{[Fe/H]_\odot}\right)^{-1} \qquad (M_\odot/yr)$$

Term $\left(\frac{n_H \times V_s}{F_{1.64}}\right)$ from fitting the values from the model

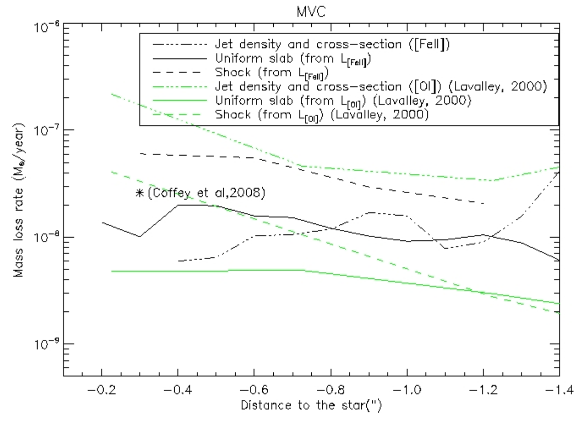
# DG Tau - Mass loss rate from the Iron - Iron depletion



- Models from Hartigan et al., 2004
- [OI] luminosities from Lavalley-Fouquet et al., 2000
- MVB is 10 times lower than predicted by models
- HVB is 4 times lower

- Depletion higher at lower velocities: Consistent with disk wind expectations (low velocities come from larger distances)
- Simultaneous obs in [OI] and [FeII] are required to better constrain these values

# DG Tau - Mass loss rate from the Iron



**Eqs and relations** (Ferreira et al., 2006)

$$\xi = \frac{1}{2(\lambda - 1)}$$

$$2\frac{\dot{M}_j}{\dot{M}_{acc}} = \xi \; ln\left(\frac{r_e}{r_i}\right)$$

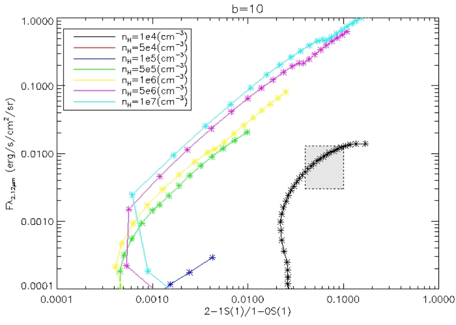
$$\text{Obs: } r_e < 6AU$$

$$\text{Exp: } r_i \sim 0.05 - 0.1AU$$

- Similar values to previous estimations within a factor 5
- $\dot{M}_{tot}$=4×$10^{-8}$ $M_\odot$/yr ⇒ 0.08<$\dot{M}_{ej}/\dot{M}_{acc}$<0.4
- For MHD disc wind with $\lambda$=13 (reproducing the optical obs (Cabrit, 2007)) ⇒ $r_e/r_i$>45 (compatible with expectations from obs)

# DG Tau - Origin of the $H_2$ emission

## Excitation by shocks



C-shock models by

Kristensen et al, 2008 ($n_H$,$v_s$,$b=B/\sqrt{n_H}$)

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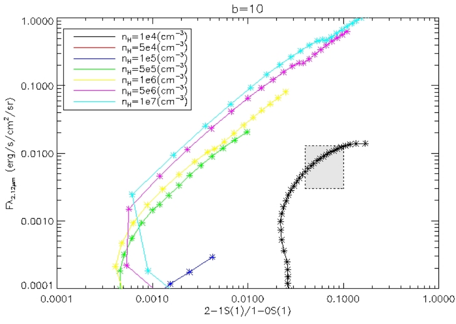

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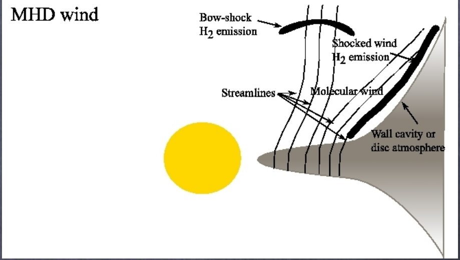
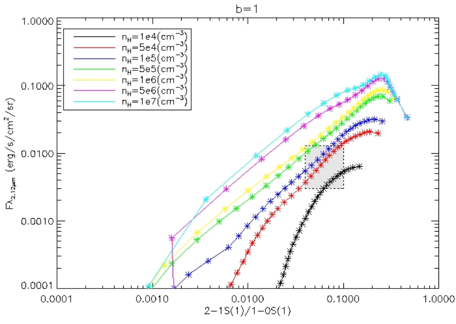


- If shock in a MHD wind:
  - For the used solution, the derived $\dot{M}_{ej}/\dot{M}_{acc}$ gives $r_e/r_i \geq 90$ (expected ~10)
  - A strong b is needed ⇒ $v_s \sim 90$ km/s ⇒ too fast for disk wind predictions
  - Fast X-Wind? shock morphology at 45° ⇒ $v_{obs} \sim v_s \sim$90 km/s!

# DG Tau - Origin of the $H_2$ emission

## Shocked disk atmosphere



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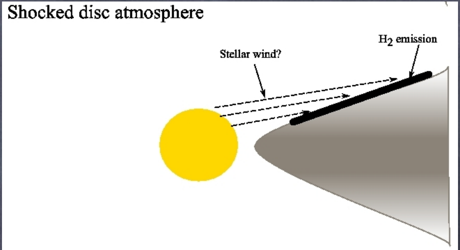

**Shocked disc atmosphere**

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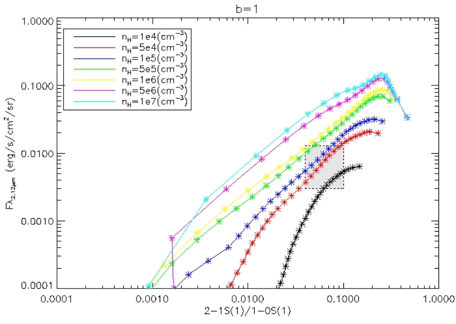
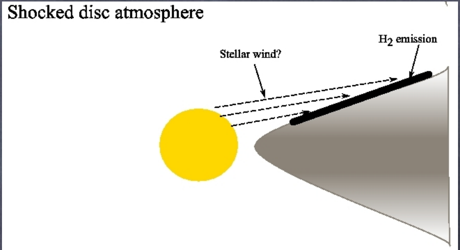
## Shocked disk atmosphere



C-shock models by

Kristensen et al, 2008 ($n_H$,$v_s$,b=B/$\sqrt{n_H}$)

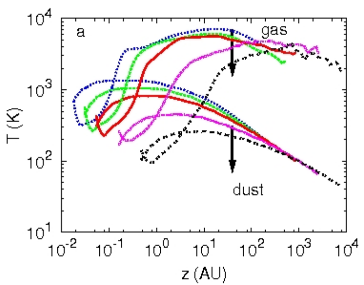

Shocked disc atmosphere

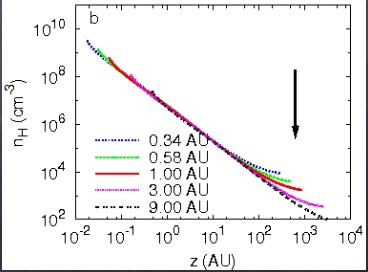
- If shock in disk atmosphere:
  - Low $v_s$ ⇒ low b and $n_H$=$10^5$-$10^6$ cm$^{-3}$ (Kristensen et al, 2008 models)
  - Agree with disk atmosphere models Nomura et al., 2007
  - BUT redshifted emission?
  - BUT expansion of the cavity in small time scales (∼20yr)?

# DG Tau - Origin of the $H_2$ emission

## Molecular MHD wind - Ambipolar diffusion

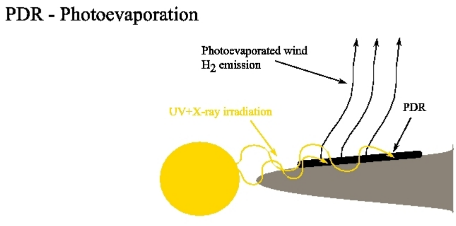
- Ambipolar diffusion (Panoglou et al, 2009):
  - Predicts $H_2$ wind for $r_0 > 1$AU
  - $\dot{M}_{H_2} \sim 1.4{\times}10^{-9}$ $M_\odot$/yr (volume method) $\Rightarrow \dot{M}_{ej}/\dot{M}_{acc}(H_2) \geq 0.014$
  - For $r_e \leq$10 AU (jet width measurements) $\Rightarrow r_i \leq$ 5AU (compatible with atomic $r_e$ from rotation studies (Pesenti et al., 2004)
  - The temperature at 2000 K is also well reproduced
  - BUT $n_H$=$10^4$-$10^5$cm$^{-3}$, too low to have $H_2$ in LTE?





# DG Tau - Origin of the $H_2$ emission

## Photo-dissociation region



FUV photos heat the disk and if $v_{th} > v_{esc} \Rightarrow$ wind

Characteristics radius for thermal evaporation (Dullemond et al., 2007):

$$r_{cr} \sim 15AU \left(\frac{T}{1000K}\right)^{-1} \left(\frac{M_*}{M_\odot}\right)$$

- Le Petit et al., 2006 PDR model fits well flux ratios for $n_H = 10^{6-7}$ cm$^{-3}$
- It reproduces also the observed temperature
- PDR model predicts [OI] and $H_2$ at same temperature
- BUT It fails to reproduce the $H_2 \lambda 2.12 \mu m$ brightness by a factor 3-5

- $r_{cr} > 5$ AU ($H_2$) et 1 AU ([OI])
- Predicted terminal velocities of ~15km/s (Font et al., 2004)

# DG Tau - Conclusions

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- Atomic emission:
  - MHD disk wind model reproduces the global jet properties, both in the optical and in the NIR
- Molecular emission:
  - Kinematical connexion with the [OI] emission at very low velocities
  - As test of MHD disk wind model ⇒ inconclusive
  - Emission difficult to explain by excitation by shocks, contrary to previous works
  - PDR, with a photo-evaporated wind, is a promising scenario, contrary to previous works

# Thesis Conclusions

# Conclusions and Perspectives

- Are the ejection mechanism universal for different properties of the central source? What is a "typical T Tauri star jets"?

| Atomic | | Molecular<br>(NIR $H_2$) | Radio/mm<br>(CO, PdBI) |
|---|---|---|---|
| Optique | NIR | | |
| $2 \longrightarrow 5$<br>$\sim$10 long-slit HAR | $0 \longrightarrow 1$<br>$\sim$10 long-slit HAR | $0 \longrightarrow 6$ | HH 30 (Class I)<br>HH 212 (Class 0) |

Class II: $0.5 < M_* < 2M_\odot$

$\dot{M}_{acc} \sim 10^{-7}\text{-}10^{-8}\ M_\odot/\mathrm{yr}$

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- What is the origin of the molecular emission? Which is the relationship with the atomic component?
  - Analysis of more T Tauri showing $H_2$ emission
  - Models of disk atmosphere adapted to the source conditions
  - Thorough study of the parameters space in MHD disk wind models
  - Include shocks in MHD wind model
  - Line fluxes and ratios predictions: maps, PV (OpenSESAMe by Jetset)

# Conclusions and Perspectives

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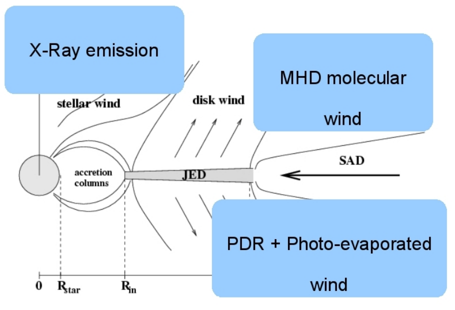

X-Ray emission

MHD molecular wind

PDR + Photo-evaporated wind

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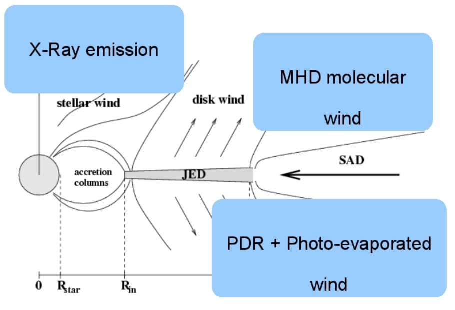
X-Ray emission

MHD molecular wind

PDR + Photo-evaporated wind

- State of the art techniques: interferometry/spectro-astrometry
- State of the art instruments: ALMA, MUSE (VLT), NIRSPEC (JWST)

Thank you!

Merci!

Gracias!