Finding Proto-spectroscopic binaries

Precise multi-epoch RV of 7 protostars in Ophiuchus

Pedro Viana Almeida (ESO, CAUP, DFA)

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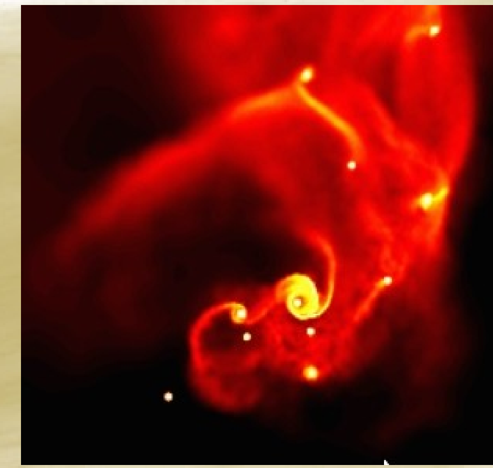
Claudio Melo (ESO)
Nuno Santos (CAUP)
Pedro Figueira (O. de Genéve)
Filipe Gameiro (CAUP, DFA)
Michael Sterzik (ESO)

Study of multiplicity in protostellar ages



Credits: M. Bate

- **~50% multiplicity solar-type MS** (*e.g.* Raghavan et al. 2010)

- **SFRs have diff. BF, initial conditions and dynamics during SF are relevant** (see *e.g.* Patience et al. 2002; Ratzka et al. 2005, *Gaspare talk*)

- **difficult modelling of SF process to account for the observed BF – Observe younger populations to understand how multiplicity evolves with time** (yesterday's talks)

- **Dynamical evolution occurs very early on, dynamical evolution has already taken place in Class I/II phase.**

Some open questions

- How fast is multiplicity defined and how is it connected to the SF process?

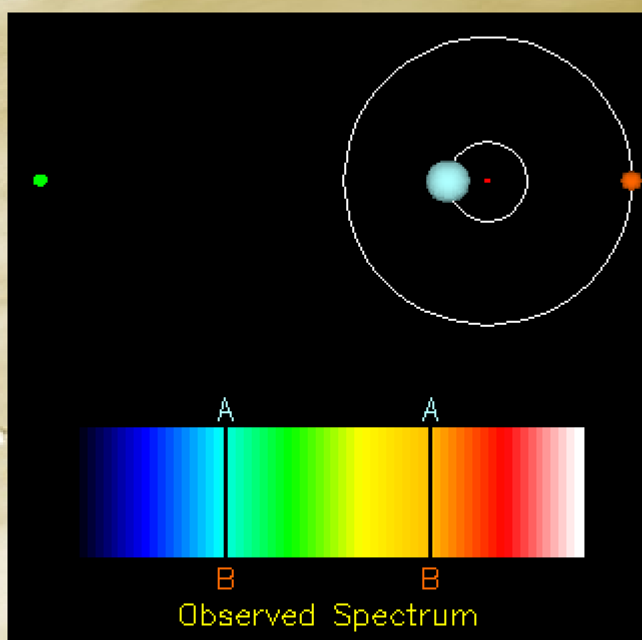
- Are spectroscopic companions formed during cloud fragmention or are they a product of dynamic interaction in pristine multiple systems?
(*e.g.* Tokovinin et al. 2006)

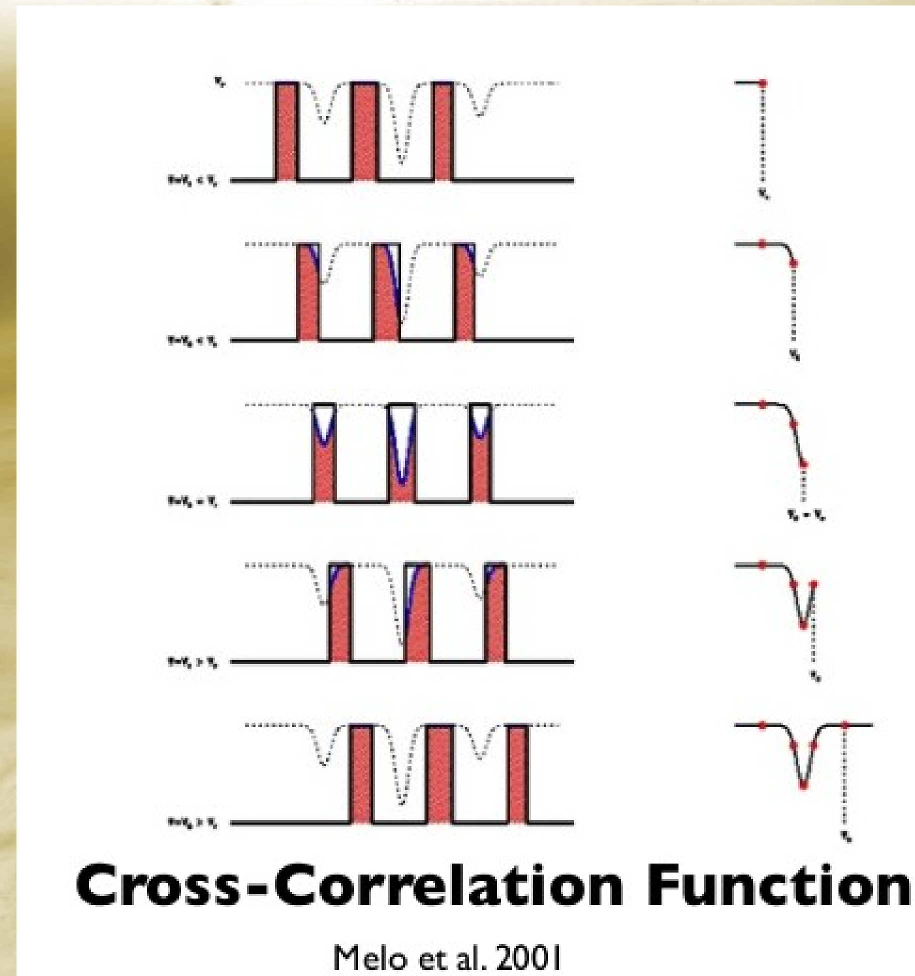
- What is then the MF at early stages and how does it depend on the period (separation) between the different system components?

- How do binary systems constraint planet formation?

Multi epoch RV survey

As a star moves in the direction of the line-of-sight, their spectral lines are shifted by Doppler Effect





Radial velocities with CRIRES: The near-IR

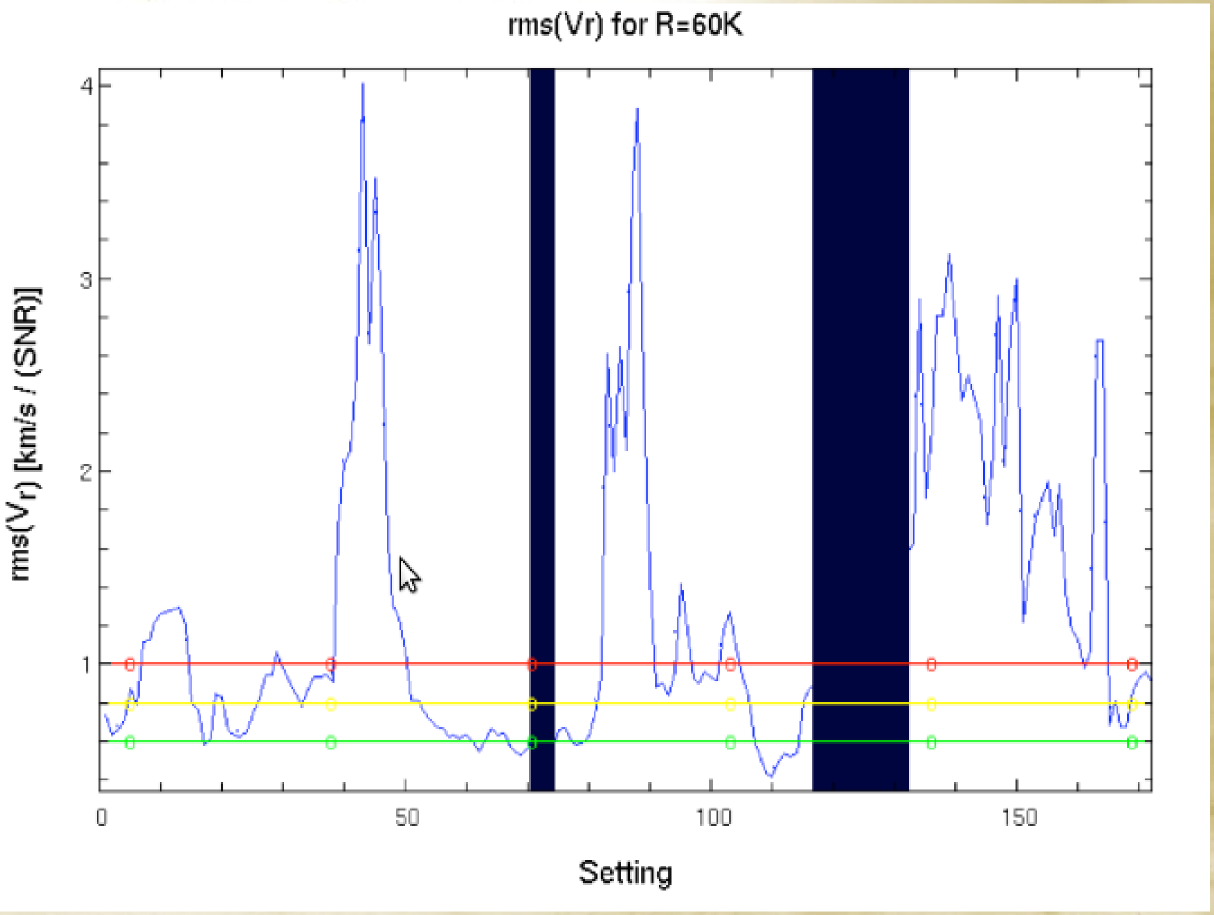
The CRyogenic high-resolution InfraRed Echelle Spectrograph was developed by ESO and mounted on VLT UT1

Spectral range from ***0.95 to 5.4 μm*** with a simultaneous wavelength coverage of *λ/70* and provides a ***R*** of up to ***100 000***

The detectors are four Aladdin III InSb arrays. A MACAO system for optimizing the *SNR* and the spatial resolution

For **m/s** precision, we need a ***simultaneous*** wavelength calibration technique *(e.g. Figueira et al. 2010)*.

Set-up selection - Photon noise error prediction



Photon noise error using CCF
(Queloz et al. 1995)

$$\epsilon(V_r) = 0.5 \times \frac{R}{(SNR)\bar{I}n_l^{1/2}}$$

Additional systematic errors
- zero-point instabilities
- drift correction errors
- centering errors

- Final SNR ~ 30

final RV accuracy of ~100 m/s

Good enough to detect protostellar companions!!

Observation of Class I/II Protostars - 1

- 38 Class I/II sources, half of them multiple, from 3 SFRs (Haisch et al. 2004, 2006)

- *K* magnitude < 12

- slit width ~ 0.3'', R~60.000, no-AO, 2 nodding cycles (ABBA)

- good seeing (~ 0.8'')

- set-up 2287.1nm, around the CO bandhead 2-0

- 3 RV standard stars were followed in the same period to check for stability

The reduction pipeline

Reduction using a custom pipeline, programmed in IRAF:

- dark subtraction;
- linearity correction;
- flat-fielding, corrected by spectrograph blaze function variation;
- nodding subtraction to correct for artifacts.

The data products were analysed by a Geneva-inspired pipeline which:

- fitted a wavelength solution on each individual frame;
- performed a correlation with a stellar template mask, cleaned from telluric pollution;
- corrected for earth movement around the Sun, delivering heliocentric RV's.

Only 7 Class I/II Protostars multi-epoch

- 15 YSO with one epoch

- Multi-epoch available only for 7 Class I/II sources!!!

- Non detectability presented no correlation with extinction, magnitude, spectral index, observation airmass or seeing.

- T_{exp} not sufficient or Magnitudes wrong? Variable extinction???

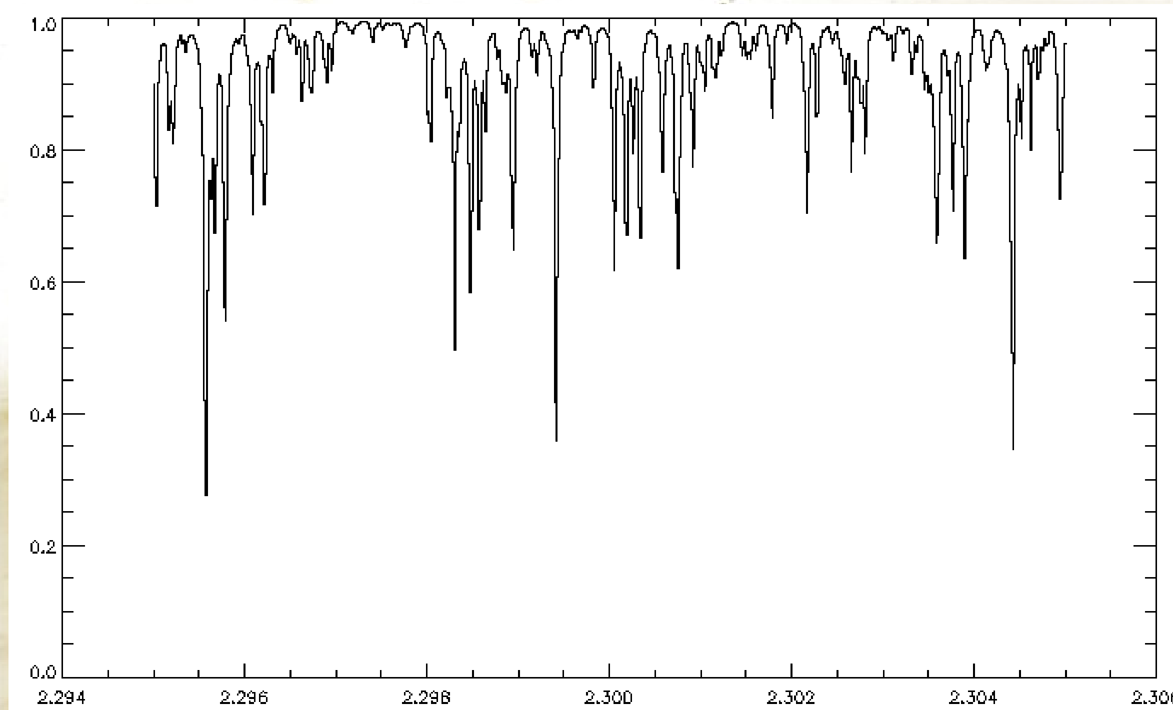
The remaining multi-epoch: 7 protostars

Source	Date Observed	DIT [s]	K (mag)	Nodding cycles	S/N*	SED
GSS 26	28 apr 2008				25	
	9 may 2008	120.0	9.4	2	35	Class I
	21 aug 2008				30	
GY 23	28 apr 2008				30	
	9 may 2008	30.0	7.4	2	30	Class II
	1 sept 2008				25	
GY 51	28 apr 2008				30	
	9 may 2008	180.0	10.2	2	30	Class I
	11 may 2008				35	
	1 sept 2008				25	
WL 17	11 may 2008	180.0	10.3	2	25	Class I
	24 may 2008				20	
IRS 34	11 may 2008				30	
	26 may 2008	180.0	9.2	2	25	Flat Spectrum
	3 sept 2008				25	
VSSG 18	11 may 2008				30	
	26 may 2008	120.0	9.2	2	30	Flat Spectrum
	24 sept 2008				30	
L1689 SNO2 N	21 aug 2008				30	
	11 feb 2009	45.0	8.3	2	20	Flat Spectrum
	22 feb 2009				25	
Radial velocity standards						
HD 129642	28 apr 2008				110	
	9 may 2008	120.0	6.2	3	120	
	18 aug 2008				130	
	3 sept 2008				120	
HD105671	28 dec 2008	60.0	5.8	2	150	
Gl406	28 feb 2009	60.0	6.1	2	120	

Evolutionary state from SED characteristics

Haisch et al. (2004)

Wavelength calibration - 1



Detector 4 in our setting

Atmospheric lines in the nIR are very stable, down to 2 m/s!!
(*e.g.* Figueira et al. 2010)

A wealth of CH4 lines: sharp, deep and easy to identify
(see also Blake et al. 2007, 2010)

HITRAN 2004 database ~50 m/s precision in spectral line position

CH4 lines provide a reliable atmospheric frame for wavelength calibration!

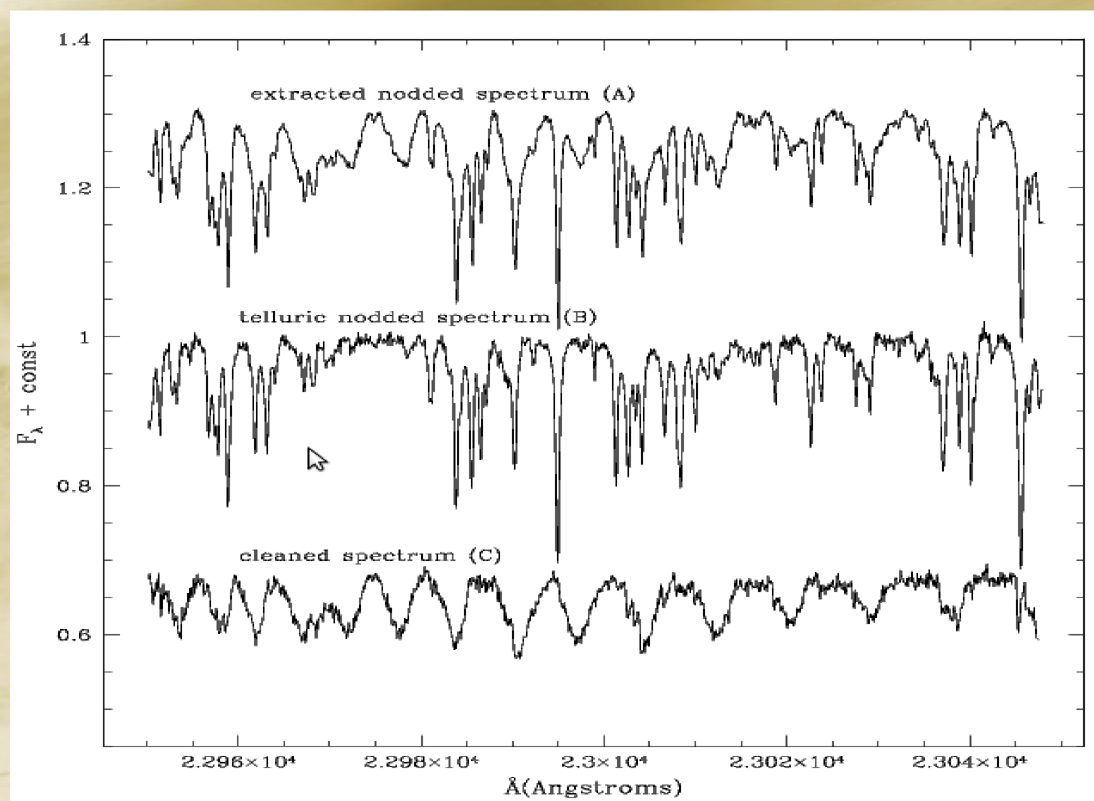
Wavelength calibration - 2

- No gas cell, so no systematic error introduced to ΔRV. Atmospheric lines and science spectral have same optical path.

- The wavelength calibration is calculated independently for each spectrum, i.e., each nodding position.

The drawback, telluric removal - 1

- Instrumental and atmospheric features were removed by dividing wavelength-calibrated object spectra by spectra of early-type stars observed at similar air mass at each slit position.



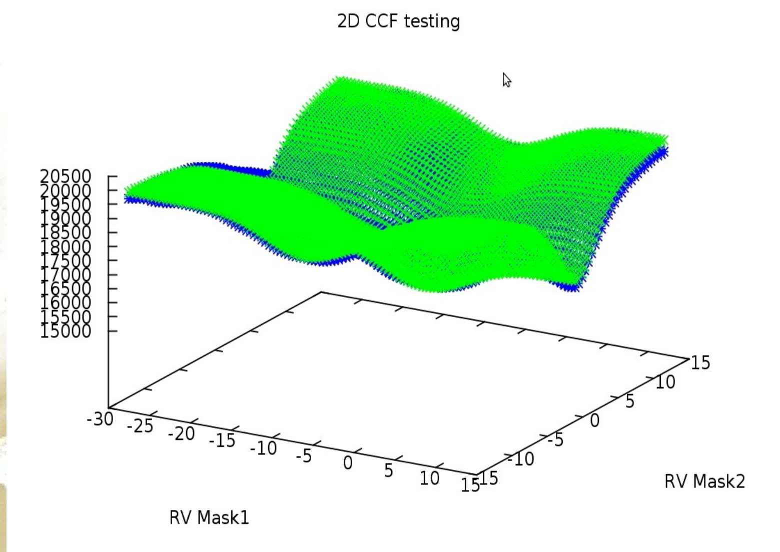
The drawback, telluric removal - 2

- Telluric STDs not as good as radiative transfer codes in reproducing tel. conditions (*e.g.* Seifhart et al. 2010)

- airmass scaling sometimes difficult -> telluric contamination

- Time consuming

Cross Correlation in the near-IR



Cross-correlation with a template mask creates an average stellar line, the CCF

The CCF is fitted with a gaussian in order to determine its center

<u>NEED OF A PRECISE WAVELENGTH REF.</u>

Cross-correlation with these PHOENIX LTE atmospheric models and with template spectra

- **stellar mask (SM)**
- **atmospheric mask (AM)**

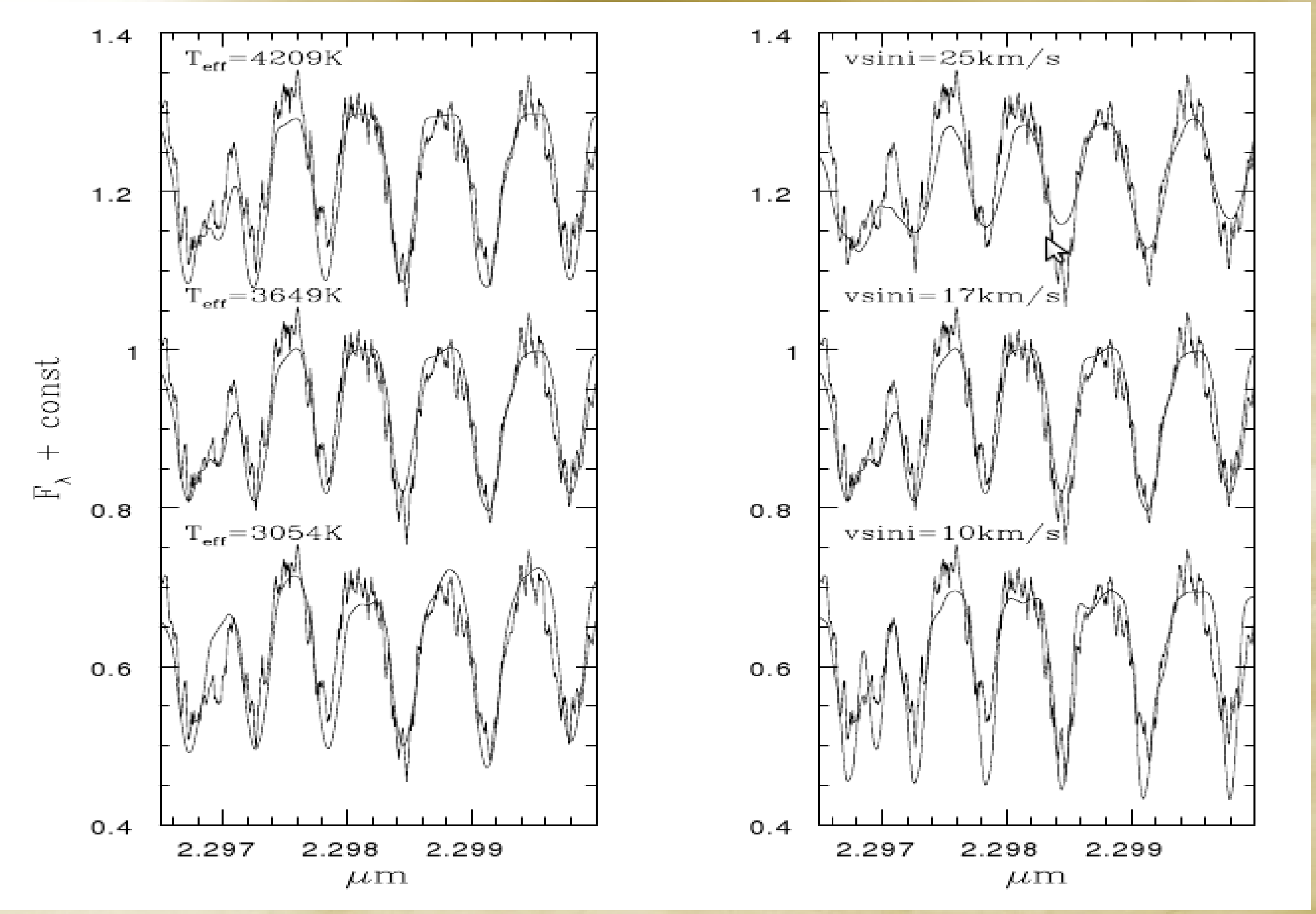
RV of the target relative to the zero-point established by the atmosphere

RV derived by the peak of the CCF.

Standard deviation from the weigthed mean.

CO: photospheric or circumstellar?

CO <u>is</u> photospheric! Reproducible by PHOENIX stellar profiles (Hauschild et al. 1999)



Finding the best AM and SM mask

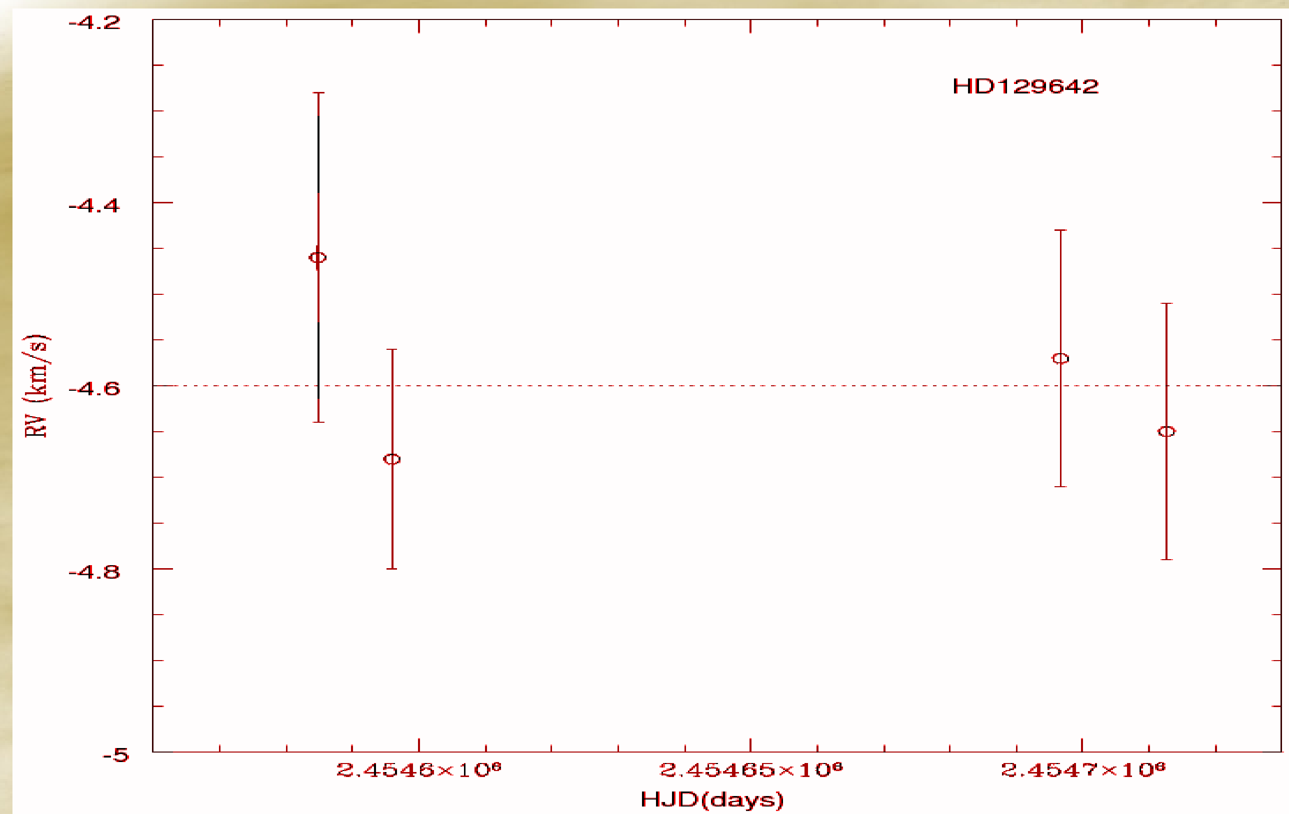
- Stellar masks were computed by rotationally-broadening the PHOENIX models and standards' spectra of different T_{eff} and then comparing them with our observations.

- In each successive comparison, we varied the *vsini* introduced to the different synthetic models and computed the residuals.

- The best mask for each spectrum was selected through the minimization of the average deviation yielded in this subtraction.

RV standard case: HD129642

Probatory stduy with Standards stars: Gl699, HD129642, HD105769



RV Standard HD129642 (~ -4.6km/s) was followed over 6 months!!

Our nIR RV was of ~ -4.59km/s

r.m.s. ~ 80 m/s!!

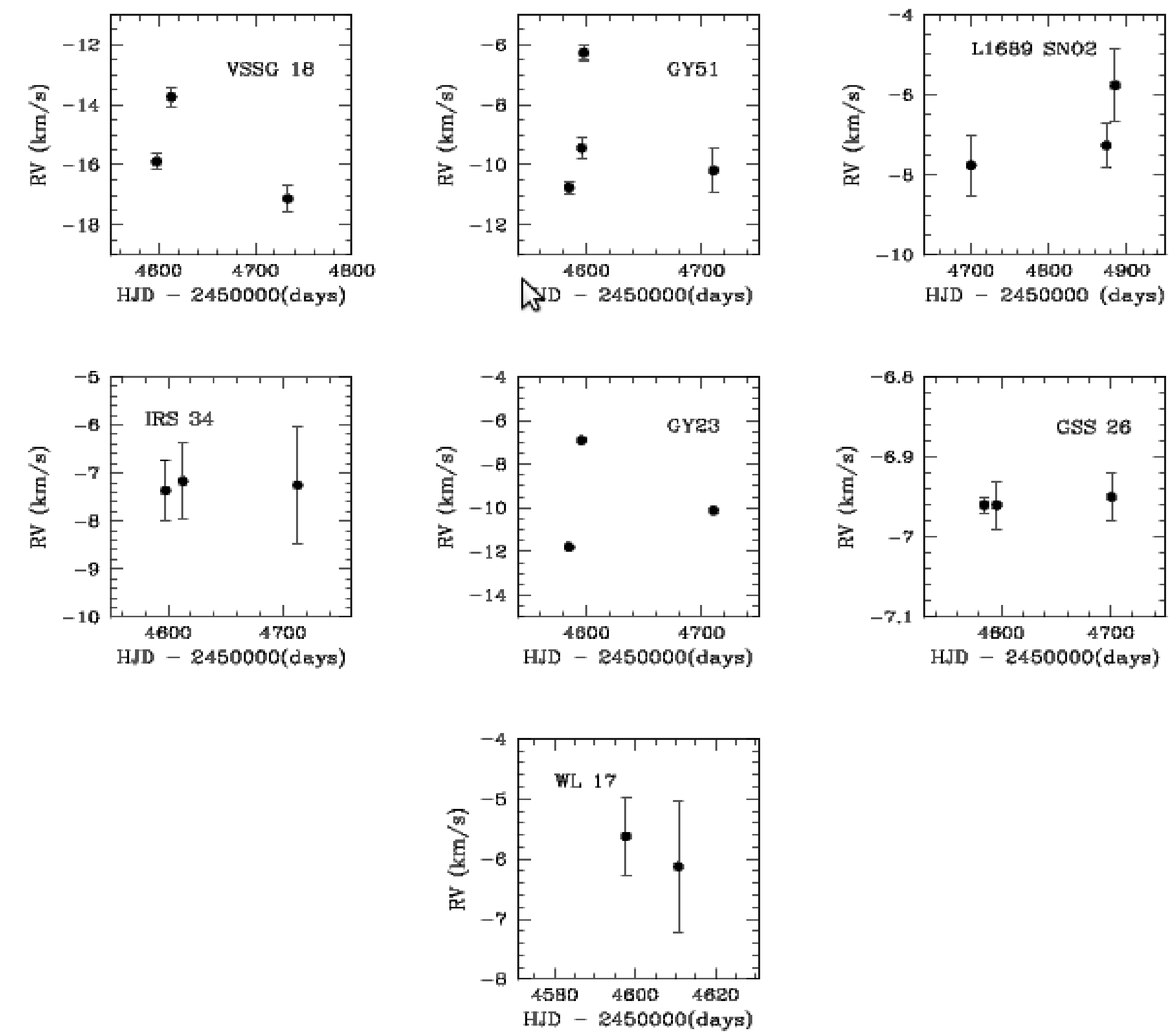
Our results 3-epoch RVs

- RV variations up to 4 km/s

- Precision from 0.05 km/s to 1.22 km/s

- Ophiuchus cloud RV=-6.3 ± 1.0 km/s (Kurosawa et al. 2006)

- YSO due to accretion may mimic RV variations max. 2-3 km/s (*e.g.* Alencar et al. 2006)



An aside:
Understanding telluric removal errors

PHOENIX stellar models
(e.g., Hauschild et al. 1999)

→ Rotational broadening kernel with *vsini* from 15 to 25 km/s

→ shifting it by derived RV

↓ multiplying it by the telluric transmission model of that setup

← Matched S/N of the simulated spectra to that of the protostars data and added Poisson noise to simulate photon noise

↓ Performed our standard telluric removal

→ delta RV max. ~ 30m/s!!

Multiplicity final bill

7 protostars (Class I/II):

2 single systems, 3 binaries, 1 spectroscopic binary + 1visual companion, 1 spectroscopic binary + 3 visual companions.
(M. Bate's talk – a whole fauna of PSBs)

- **GY23 (visual + spectroscopic) – evolved or primeval system?**
- **GY51 (spectroscopic + 3 visual) – hierarchic system evolving?**
- **VSSG18 (isolated spectroscopic binary)**

New questions – never ending story

- Is our sample representative of the multiplicity (10^5 years)? Low number statistics? Need to extend this study to a higher sample. Proposed for P89!

- N-body simulations predict primordial multiplicity to be disrupted within 10^5 years (*e.g.* Reipurth and Clarke 2001)

Some conclusions

- merging multilplicity with Haisch et al. (2004, 2006) we obtain a multiplicity fraction (ms/ts) of ~71%

- Spectroscopic binaries may well exist as soon as ~10^5 years

- Method works and is being refined with radiative transfer models instead of telluric spectra

- Precision (~100 m/s) makes us dream with the detection of low-mass proto-companions