Exoplanet detection and characterisation with high resolution spectroscopy

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Brown dwarf detection and characterisation with high resolution spectroscopy

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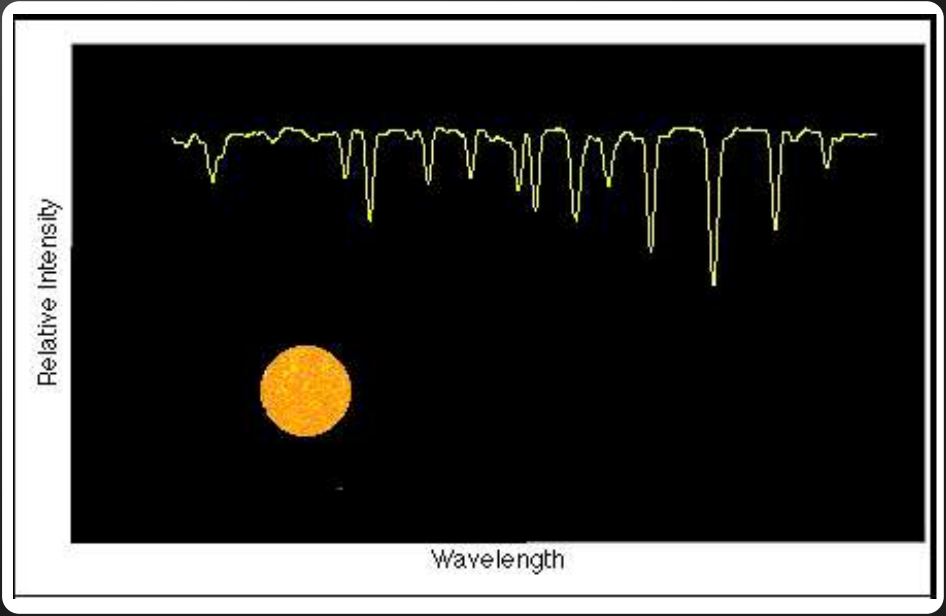
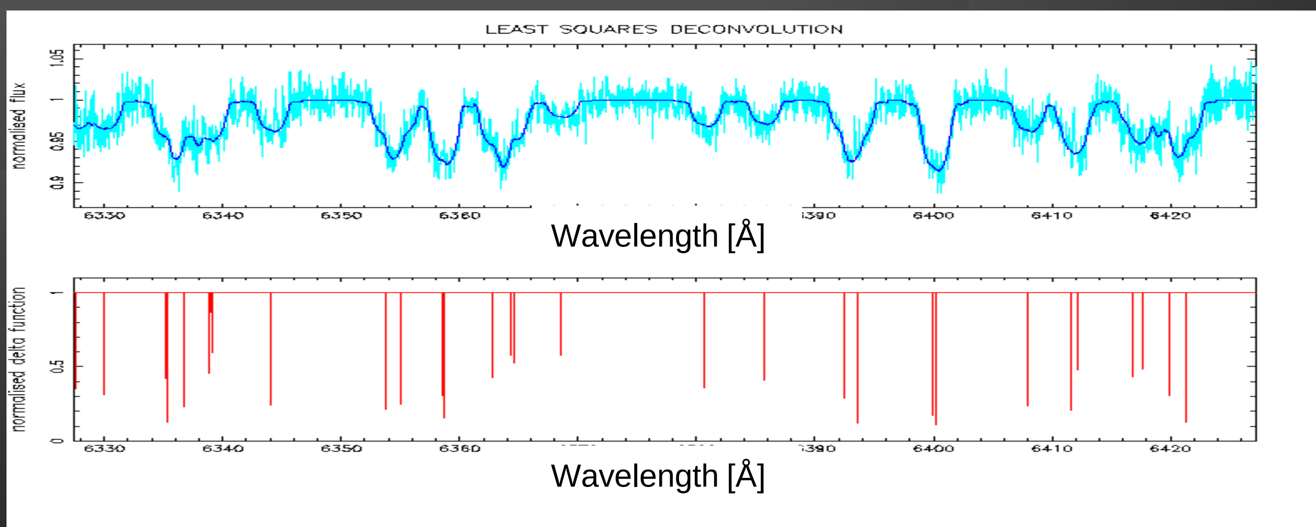
Direct near infrared spectroscopic planetary signal (high resolution)

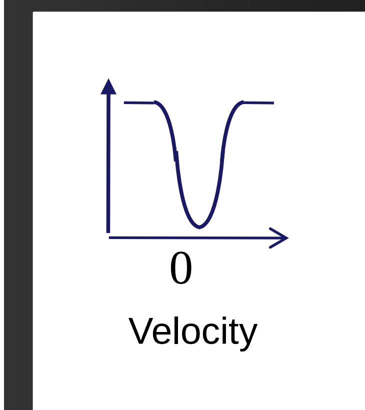
- F_p/F_* ~ 1/1,000 in the near infrared in the 2.2 μm K band
- Extract the signal from a high resolution spectral timeseries:
  - planetary signature is modeled as a phase dependent spectrum superimposed on an unvarying stellar spectrum
- Least squares deconvolution combines information from thousands of lines
  - Does not require transiting system
  - Contrast ratio determined
  - K_{planet}, hence orbital inclination and planet or BD mass determined
  - Test of model atomic/molecular linelists at high resolution
  - Split data into wavebands to obtain a local SED
  - Optimise the phase function fit to better constrain the energy distribution models



Deconvolution

- S/N in a single observed spectrum is typically a few hundred
- Several hundred to several thousand lines in a typical spectrum
  - Use *model spectrum linelist* to perform a least squares deconvolution of a *mean line profile* from the observed spectra ***after removal of stellar/telluric lines***
- Boosts the S/N ratio by a factor depending on the number of lines
  Gain factor of several up to a few x10 gain

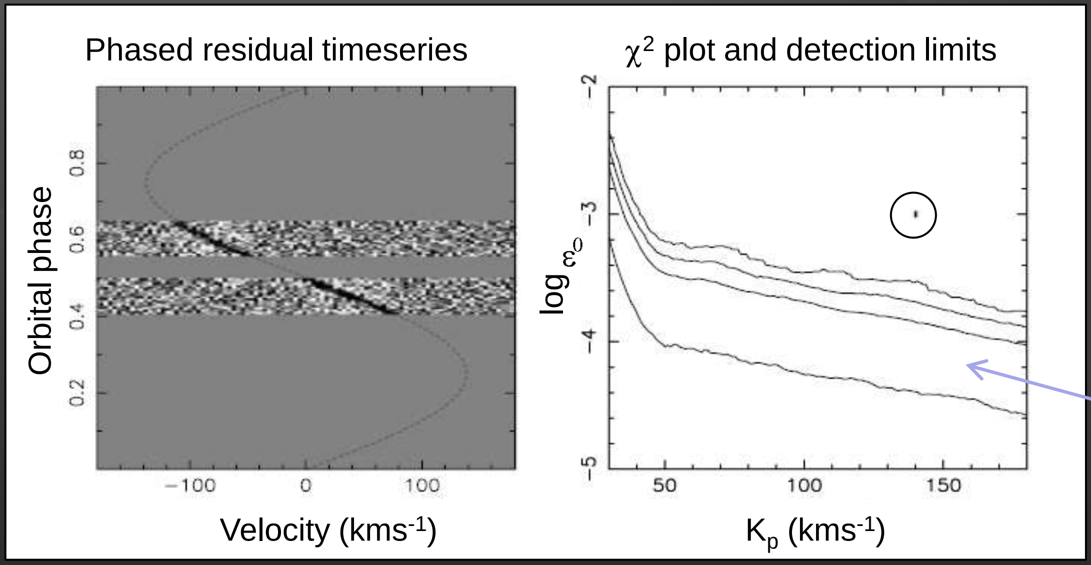




S/N ratios ~100s – 1000s can thus be achieved for a single spectrum, enabling search for planet signatures of similar contrast ratios

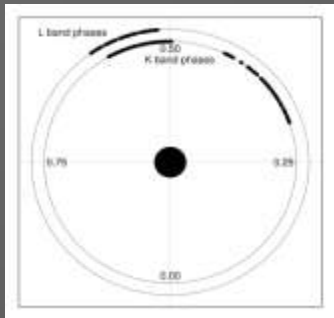
Modeling/detecting a planet

- Sinusoidal RV motion of the planet or faint secondary is modeled with model profile scaled according to orbital phase
- Since inclination is generally unknown run model for pairs of velocity amplitude, K_p, and maximum planet/star brightness, ε_0, and measure improvement in χ^2 for combination of ε_0 vs K_p



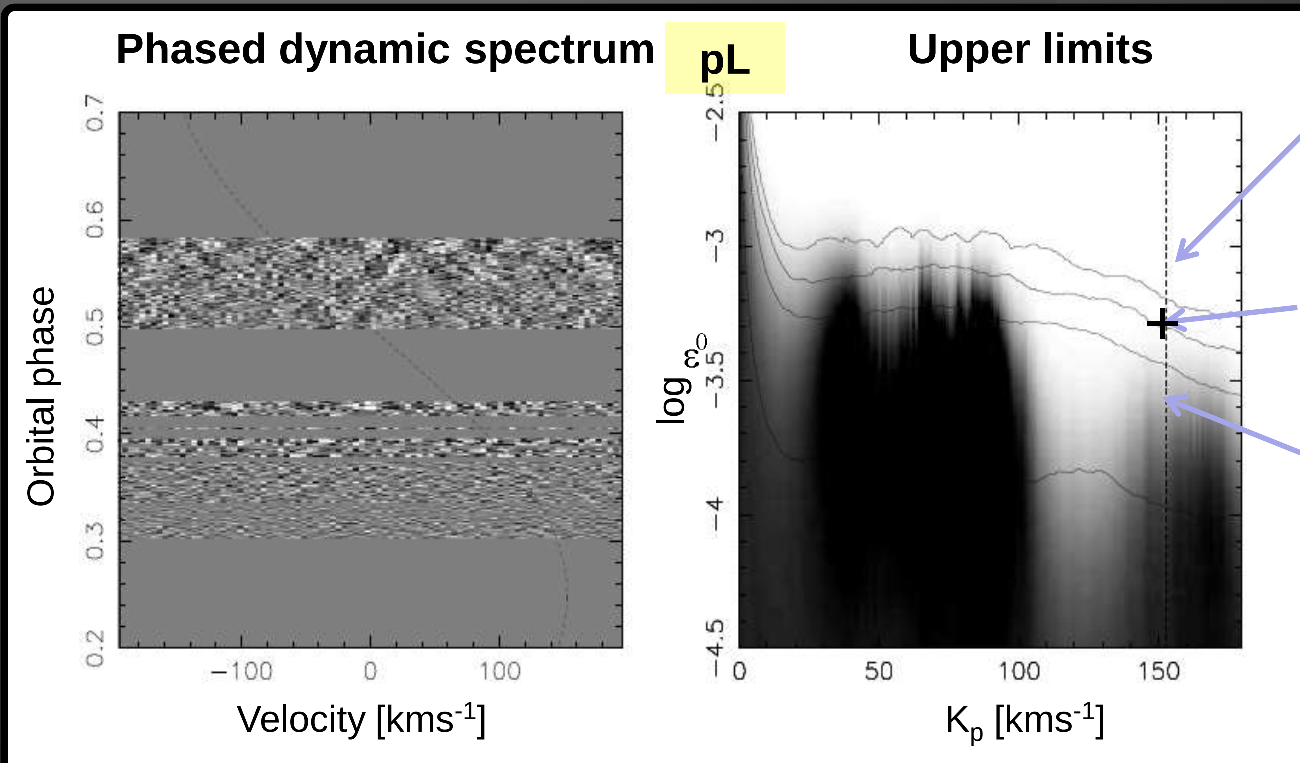
99.9%, 99%, 95.4%, 68.3% confidence levels

- Test significance of the result by randomising the order of spectra within each night and re-performing the search as above. By using several thousand randomised data sets, we can plot confidence levels for detected enhancements in χ^2.



2008 Results: HD 189733b
K band (enhanced CO_2)

15/06/08 & 22/06/08 - R ~ 25,000



Observed planet
log ε_0 = -3.286
(1/1930)

No planet detection

99% : log ε_0 = -3.301
(1/2000)

95.4% : log ε_0 = -3.441
(1/2760)

2006 data published in Barnes, Barman, Prato, Segransan, Jones, Leigh, Collier Cameron, Pinfield, 2007, MNRAS, 382, 473

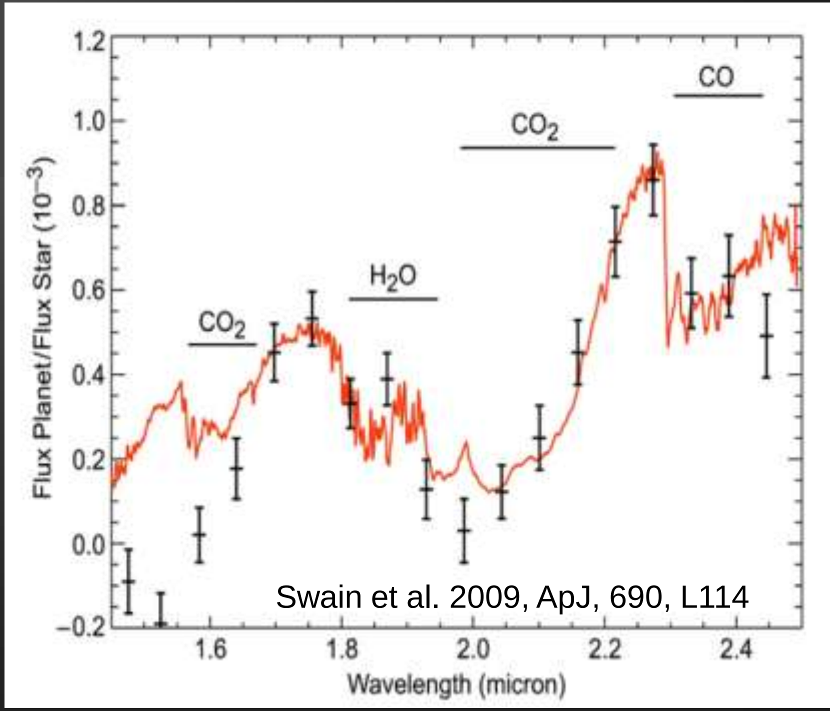
- Planet is not detected at a contrast which is 1.9 times (at 2σ – 95.4%) deeper than *observation shows* (less sensitive than no-CO_2 result)

Summary

For Hot Jupiter atmospheres at high resolution:

- HD 189733b: We can rule out the pL atmosphere where atomic species such as Ti and V have "rained out" resulting in an atmosphere dominated by H_2O, CO & CO_2 absorption

- What are the main Model uncertainties?
  - Relative line depths
  - Wavelength uncertainty
  - T_{planet}
  - Velocity fields/winds re-distribute heat → Jets, profile broadening
  - Ephemeris/phasing



Swain et al. 2009, ApJ, 690, L114

Conclusions (from Madrid talk)

- Prospects for ground based high resolution spectroscopic characterisation studies of M dwarfs looks promising

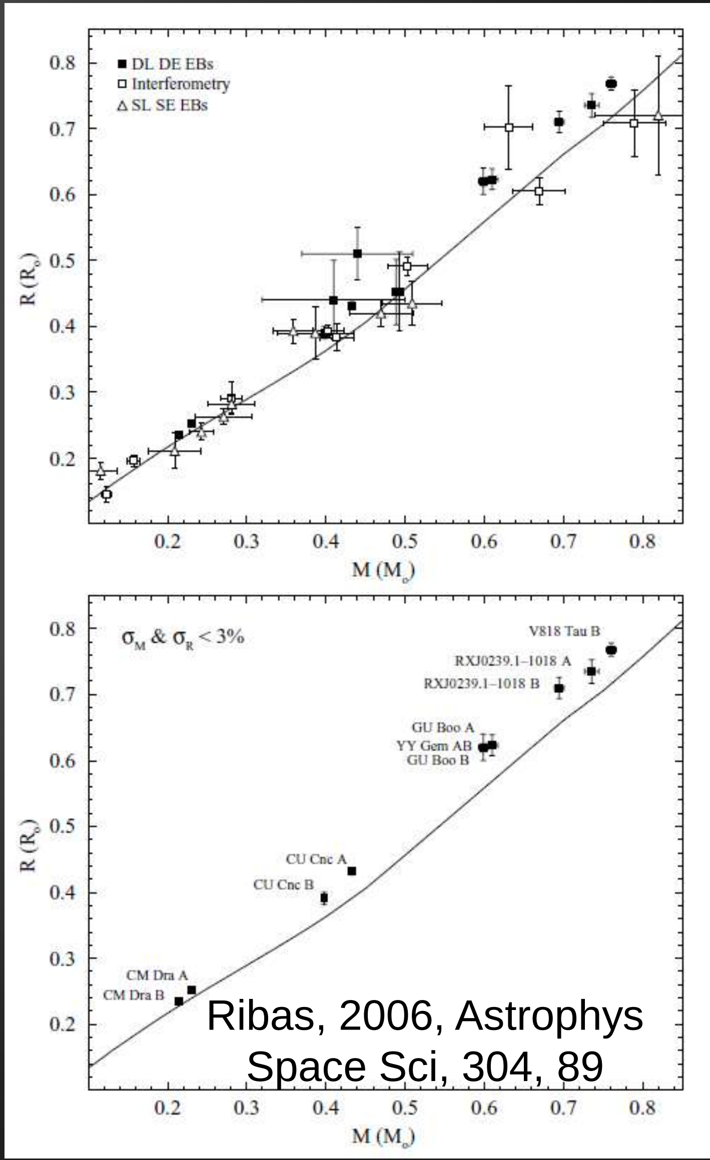
  - 42m E-ELT will give gain (over 8m tels.) of 3.6 mags for same time allocation enabling study of K~10 systems

- Low resolution: transmission and direct spectroscopy studies:

  - 6.5m JWST will enable space based precision to probe K~10 systems

Characterising low-mass binary systems

- Mass and chemical composition of a star are the basic properties which we wish to learn and understand: i.e. mass, radius, temperature, luminosity and their variation with time
- M dwarfs: radii too high
  - Magnetic activity: Spots lead to lower surface temperature → star increases radius to conserve radiative flux (Spruit, 1986, A&A, 166, 167)
  - Effect removed by M ~ 0.2 $M_\odot$?

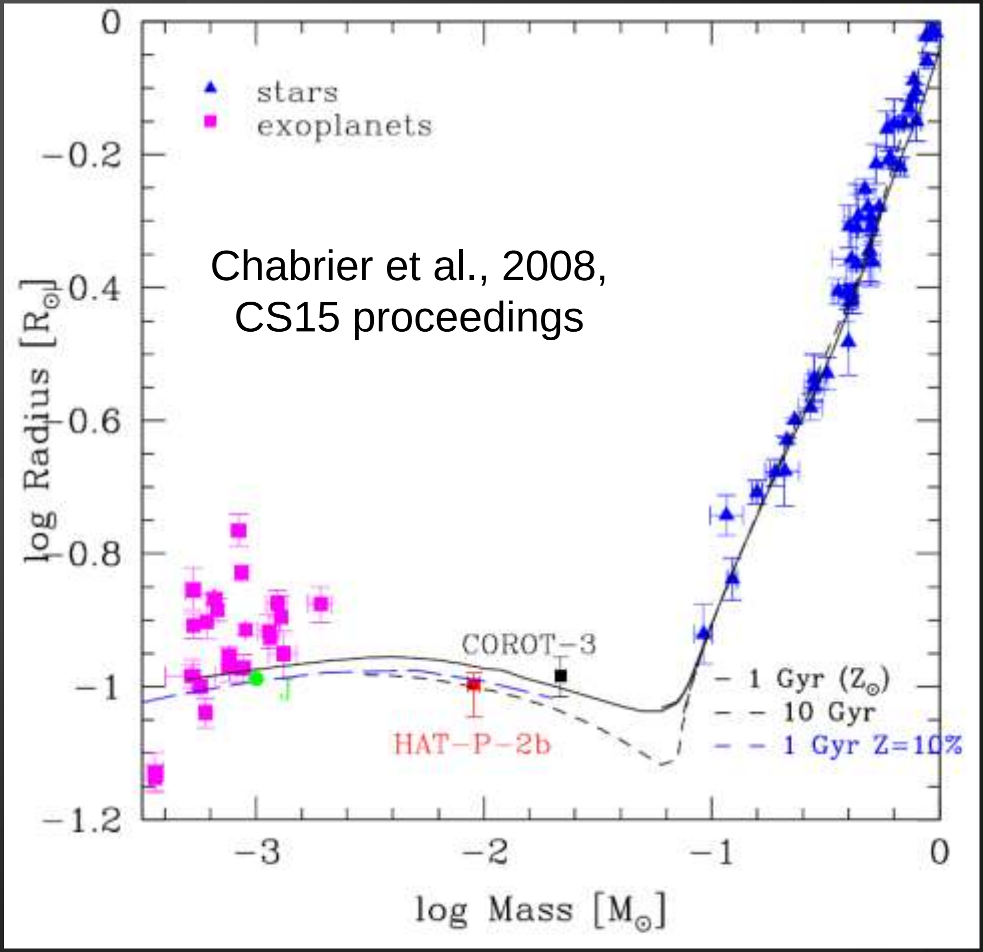


Ribas, 2006, Astrophys Space Sci, 304, 89

Mass-radius relationship

- Stellar to planetary mass

  Few or no objects in the 0.001-0.1 BD mass regime where MR relationship form is determined by partially degenerate electrons



Optical surveys vs Infrared surveys

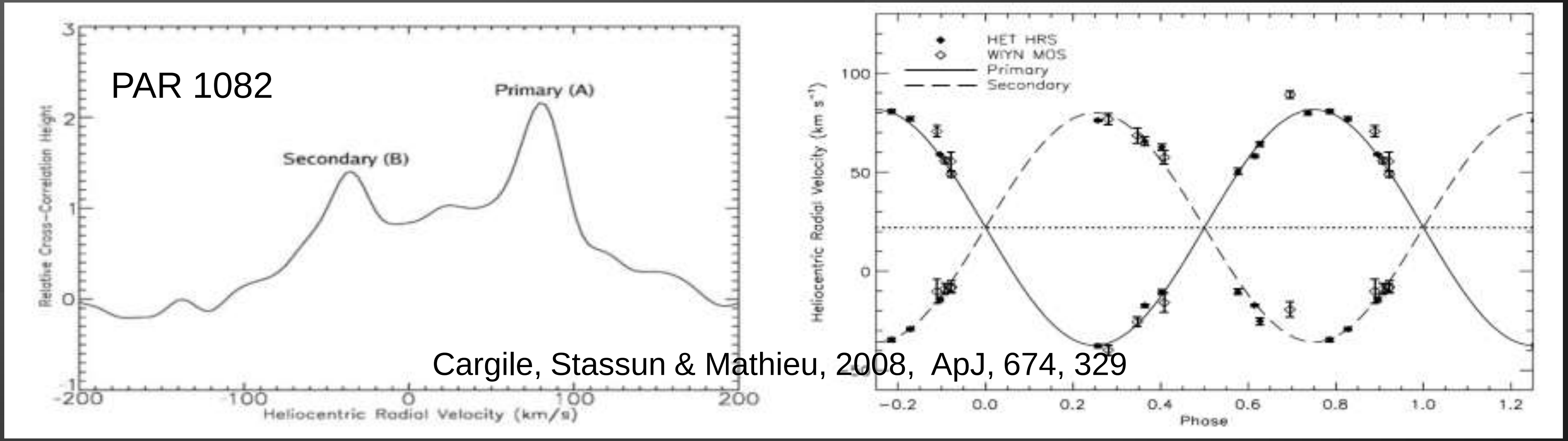
- Optical transit surveys target mostly F-K stars and turn up low mass secondaries in the M dwarf regime

  (SuperWASP-N followup program PI L. Hebb, St Andrews)

- Infrared surveys targeting low mass stars might be expected to detect substellar companions
- Application of high resolution spectroscopic signature to detection and characterisation of low-mass binary secondary components

Measuring stellar masses

- Cross correlation function enables stellar mass ratio to be determined from RV curve. For eclipsing systems, inclination can be determined and hence mass of components.



Cargile, Stassun & Mathieu, 2008, ApJ, 674, 329

$$f(m) = \frac{[m_2 \sin(i)]^3}{(m_1+m_2)^2} = 1.0361\times10^{-7}(1-e^2)^{3/2} K_1^3 P \quad M_\odot, \quad q = \frac{K_1}{K_2} = \frac{m_2}{m_1}$$

- PAR 1082: Pair of Orion pre-main-sequence stars with masses of 0.414 and 0.406 $M_\odot$ with 10% uncertainty (Stassun et al., 2008, Nature, 453. 1079) P = 4.7 d

Characterising substellar systems

- A number of ***resolved*** substellar systems have been imaged with spectral types estimated from low resolution spectroscopy
- Measurement of mass difficult as typically wide binary systems – may take many years or decades

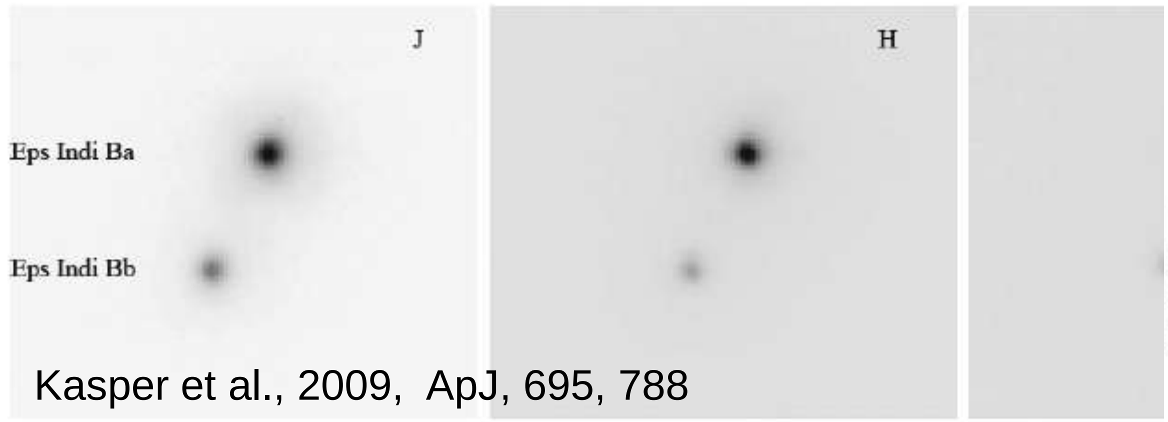
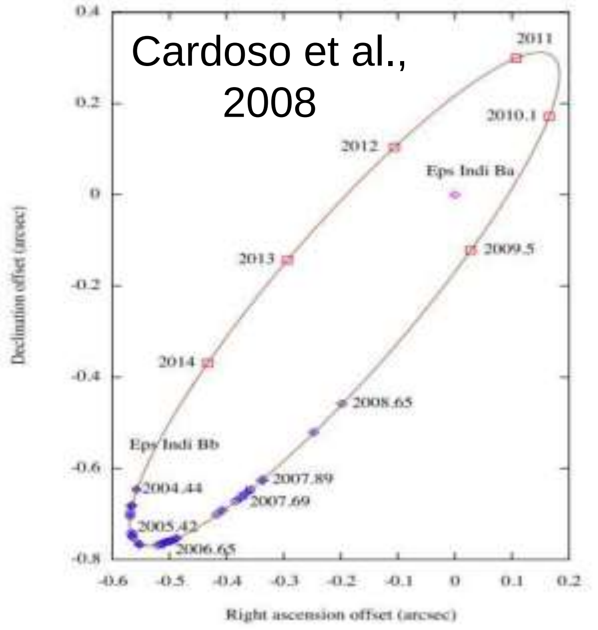


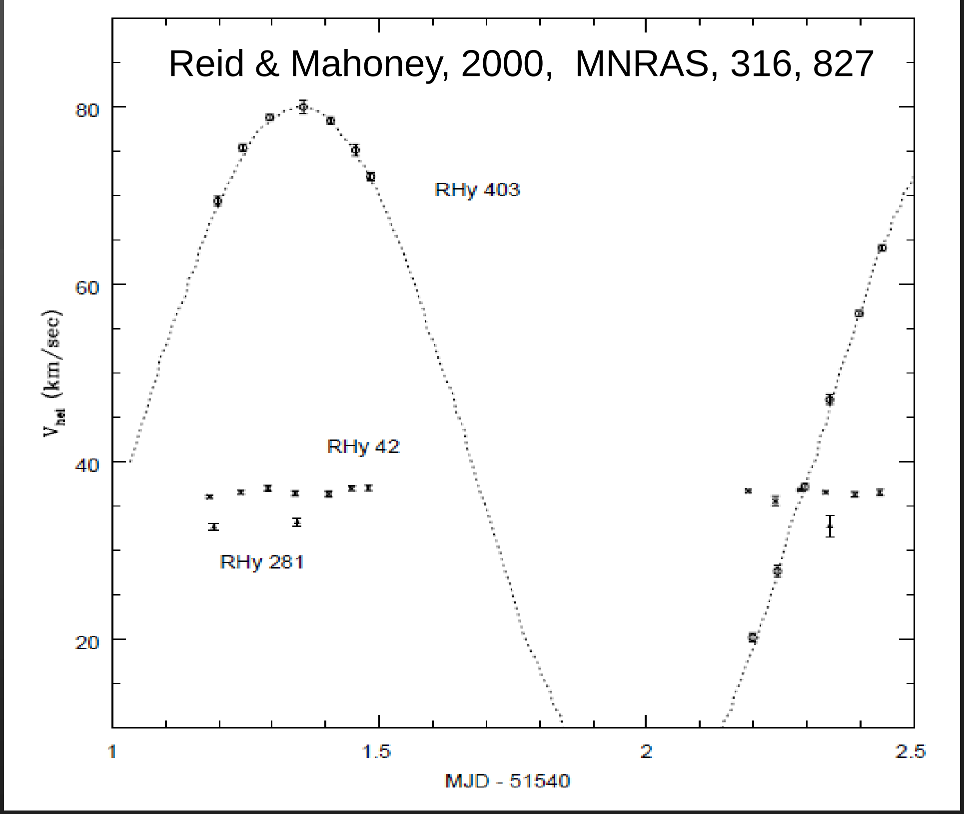
Figure 1. NACO broad band JHK images of the 0.″583 binary Eps Indi Bb. North is up, east is left



ε Ind Ba, Bb are a pair of T1.5 and T6 dwarfs @ 3.63 pc. P = 11.2 yrs. Astrometric mass solution 47 ± 10 and 28 ± 7 M_{Jup}

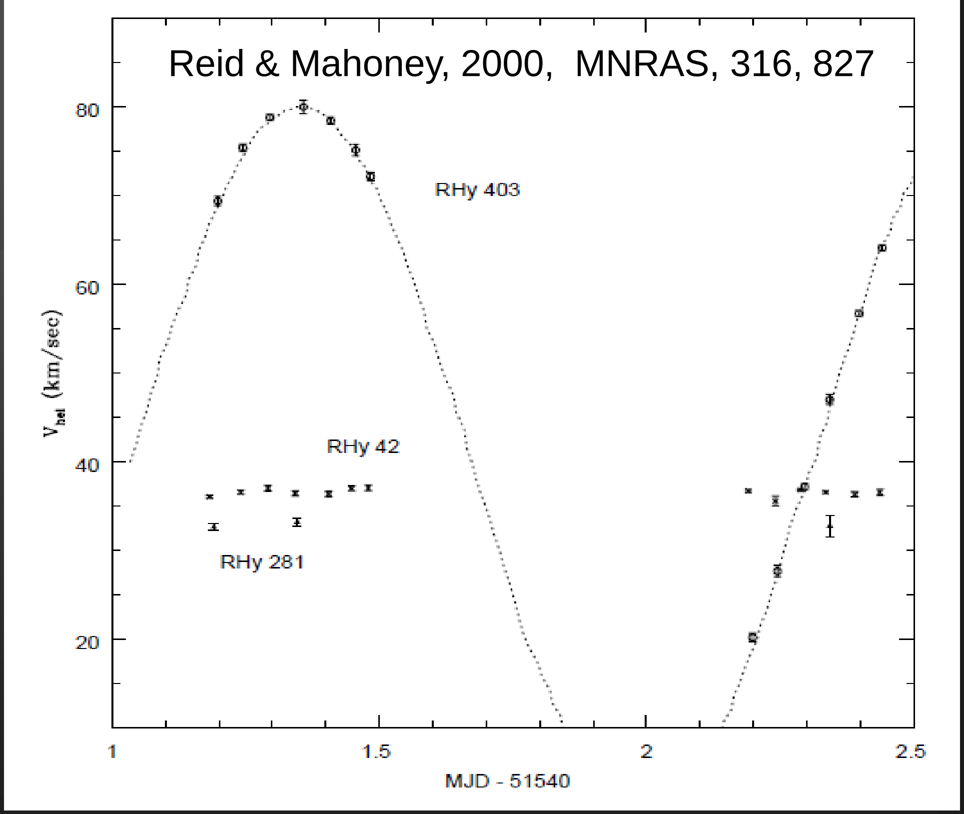
Measuring stellar masses

- *Short period* systems are most likely to be detected by transit surveys but measuring system masses may be difficult if the secondary signature is faint (single lined binaries) – i.e. can't measure m_2, hence only $f(m)$ measured
- e.g. Hyades: RHy 403
- P = 1.276 d
  - Only primary cross-correlation peak measured



RHy 403

- P = 1.276 d, circular orbit, K_p = 40 kms^{-1} , $a \sin i$ = 0.0047 au
- **K = 11.7**
- $f(m)$ = 0.0085 M_{bol} ~ 11 → 600 Myr model → m_1 ~ 0.15 $M_{\odot}$



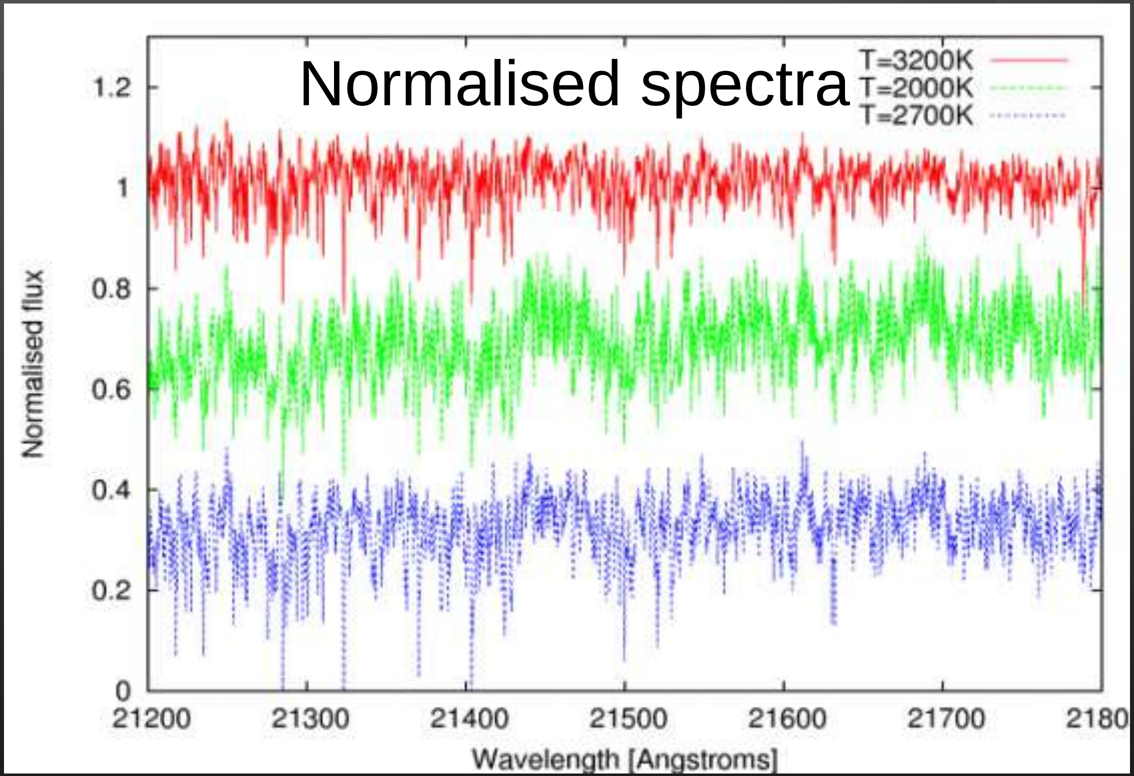
- Lower mass limit for companion: m_2 = 0.062 $M_{\odot}$
- Upper mass limit based on estimated flux limit of Reid & Mahoney observations gives m_2 = 0.095 $M_{\odot}$ (flux ratio of 4:1)
- 72% chance that i > 50º and m_2 < 0.08 $M_{\odot}$

RHy 403: Simulation

- Take spectra for worst case scenario
  – i.e. Maximum contrast for i = 90º

$m_1 = 0.15\ M_{\odot}$, $T_1 = 3200$ K $m_2 = 0.062\ M_{\odot}$, T2 = 2100 K

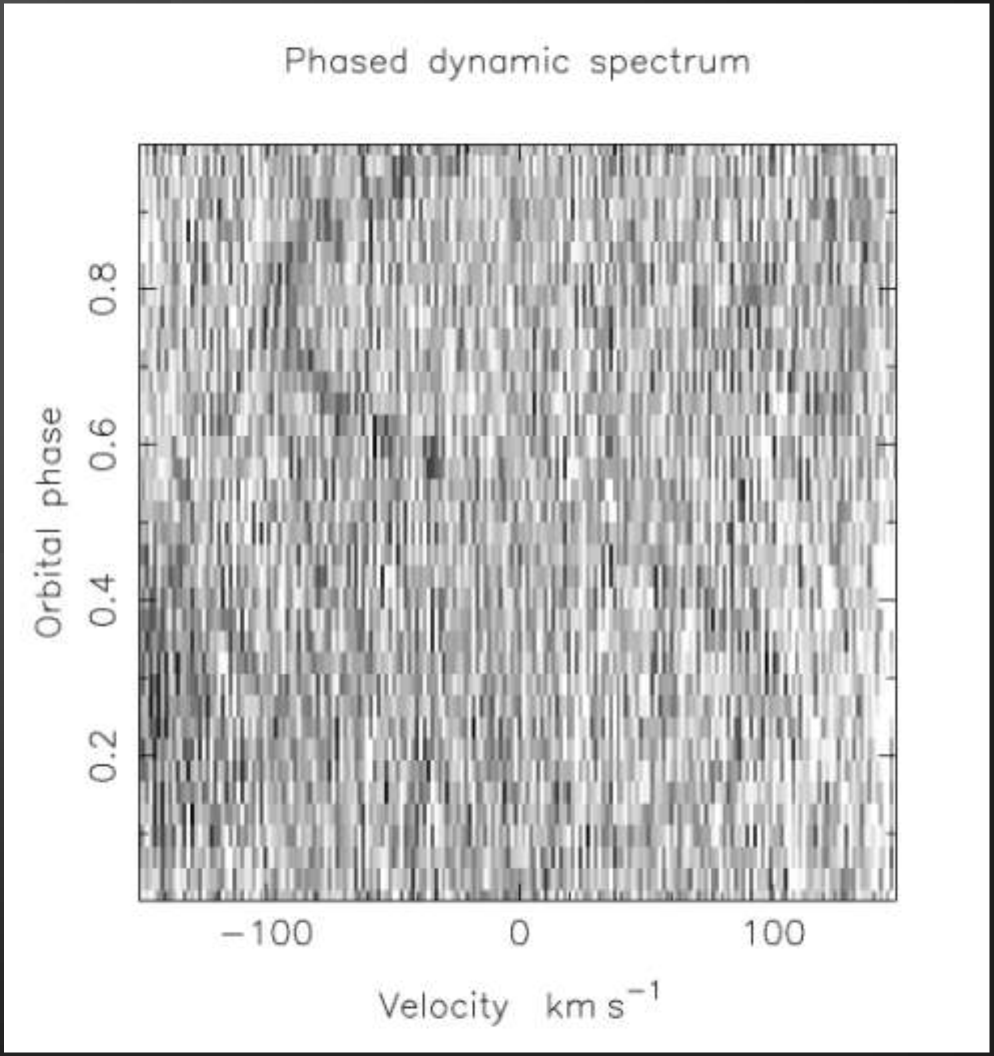
- CRIRES K band simulation at R ~ 40,000



- Shift primary and secondary spectra onto binary orbit and attenuate secondary spectrum with contrast ratio 10:1 **S/N = 35**
- For Hyades age system, expect contrast ratio 18:1

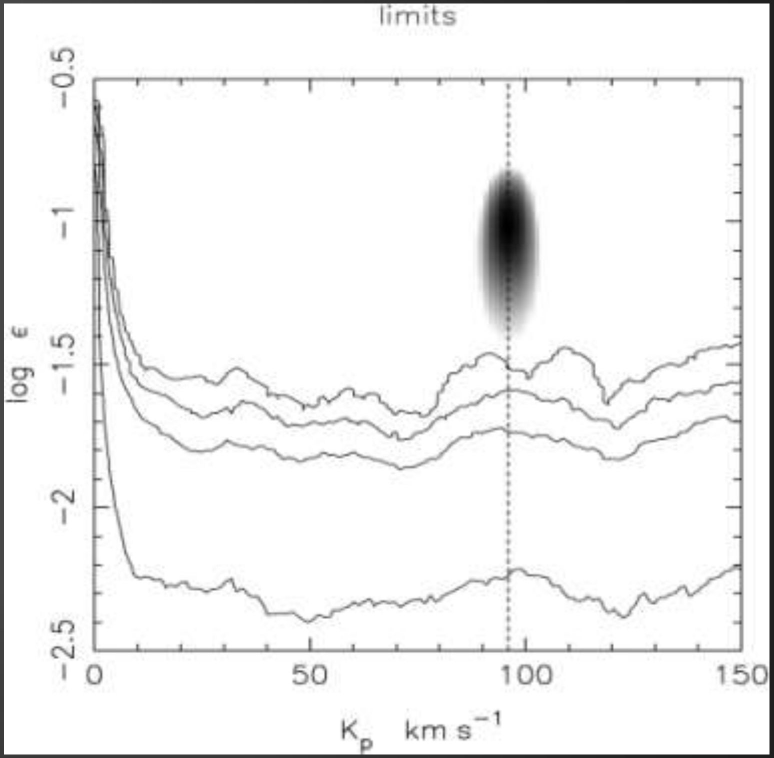
RHy 403: Simulation/Recovery

- Spectral timeseries of ***18 spectra***
- Apply deconvolution using secondary spectrum
- Remove orbital signature of primary
- Secondary RV signature is just visible in timeseries



RHy 403: Recovery

- χ^2 landscape plot of contrast ratio (log ε) vs K_p
- Secondary signature is calibrated and recovered with contrast ratio log ε = -1 (10:1)
- 99.9% confidence contrast ratio 28:1
- 99% confidence ratio 38:1



- If non-eclipsing, spectral typing can give estimate of primary mass and therefore inclination
- For a tidally locked system such as RHy 403, with sufficient resolution, profile widths are set by sytsem geometry and enable estimate of radii

Summary

- Determination of spectroscopic parameters such as mass/mass ratio for high contrast binaries looks promising
- Good for assessing and tuning the technique as applied to high contrast planetary systems
- Current technology (CRIRES) can push to K = 12 with same confidence limits and two nights of observation
- Cross-dispersed R~50,000 will enable K ~ 13-14 for a RHy 403-like system
- For systems with contrast ratio which is too high for conventional cross-correlation technique but lower than simulated, could probe to K ~ 15

UPF Update

- UKIRT Planet Finder – cross-dispersed near-infrared high resolution spectrograph
- PPAN considered the statement of interest for UPF in early March (PI Hugh Jones)
- Recommended submission of a major project proposal to the STFC