A spectral differential characterization of low-mass companions

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Different techniques to characterize low-mass companion to late type stars

- Radial Velocity Method but it gives only the minimum mass
- RV combined with
  - transits
  - astrometry
  - polarimetry
- Direct imaging (Chauvin et al., 2008)
- NIR spectroscopy (Rodler et al., 2012; Brogi et al., 2012) ‘demonstrated that atmospheric charaterization is possible for non-transiting planet‘(Ignas Snellen’s talk today before lunch)

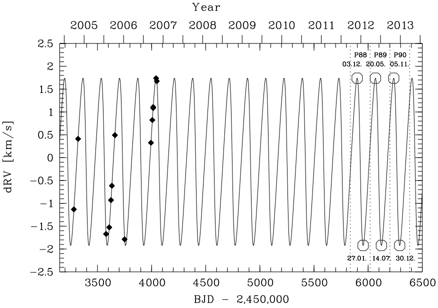
GJ1046b

GJ1046b is a companion to the inactive M2.5V star GJ1046 ($M = 0.398\ M_{Sun}$) that was found by Kürster et al. (2008).
GJ1046 was observed with the VLT-UT2+UVES as one of the target for RV survey of M dwarf in search for exoplanets (Kürster et al., 2003, 2006).

- Mass range : $[27\mathrm{M_{Jup}} : 112\mathrm{M_{Jup}}]$ (David Pinfield's talk yesterday)
- Semi-major axis $= 0.42$ AU $\Longrightarrow$ located in the "brown dwarf desert" (Dimitris Stamatellos's talk yesterday's evening)
- Orbital period $= 168.8$ days
- RV semi-amplitude $= 1.83\ \mathrm{kms}^{-1}$
- Eccentricity $= 0.28$

Main idea:

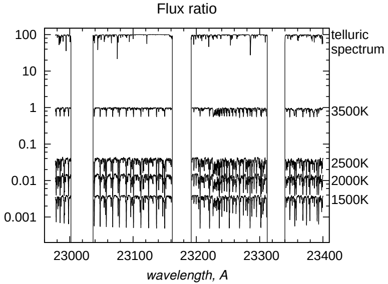
- Take one spectrum each near the maximum and the minimum of the RV curve of the star
- Shift them in wavelength in such a way that the stellar lines co-align
- Subtraction of the spectra taken at the two orbital phases ⇒ removing the stellar spectrum
- The companion lines will appear twice (positive and negative signal)



  - The difference between these two signals gives the star-to-companion mass ratio
  - The stellar mass is known ⇒ COMPANION MASS

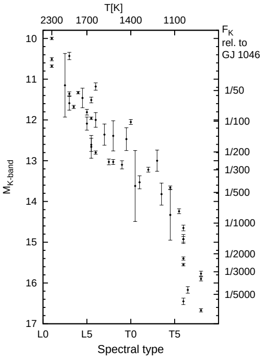
Spectral region

Star-to-companion brightness ratio should be sufficiently small.



For the chosen spectra of effective temperatures 2500K, 2000K and 1500K the absolute flux ratio in K band are 1/20, 1/60, 1/250, respectively
The telluric spectrum was taken from CRIRES exposure time calculator.

Testi 2009



Knapp et al. 2004

The most suitable instrument is Cryogenic High-Resolution Infrared Spectrograph (CRIRES)($R = 50.000$, $S/N = 500$) mounted at the ESO VLT.

Synthetic spectra

- Synthetic spectra for M dwarf and brown dwarf were computed using the WITA612 programme (Pavlenko, 2000)

- Assumptions:
  - local thermodynamic equilibrium
  - absence of sources and sinks of energy
  - solar abundances (Anders & Greverse 1989)

- Model structures of AMES-Cond and AMES-dusty (Allard et al. 2001) for the following range of parameters:
  - temperatures: 1500K, 2000K, 2500K and 3500K
  - $\log g = 5.0$
  - microturbulent velocity $= 2\ \mathrm{kms}^{-1}$
  - solar metallicity

Synthetic spectra

- The atomic line lists:
  - Vienna Atomic Line Database (VALD) (Kupka et al. 1999)
  - BT2 line list for H_2O (Barber et al. 2006)
  - CO line list (Goorvitch 1994)
- Wavelength step = 0.01Å
- Convolved with a Gaussian profile to match the spectral resolution of CRIRES of 50,000.
- Convolved with a rotational broadening profile (Gray 1976) with $v\sin i = 5\ \mathrm{kms}^{-1}$, $10\ \mathrm{kms}^{-1}$, $15\ \mathrm{kms}^{-1}$, $20\ \mathrm{kms}^{-1}$

Subtraction of spectra

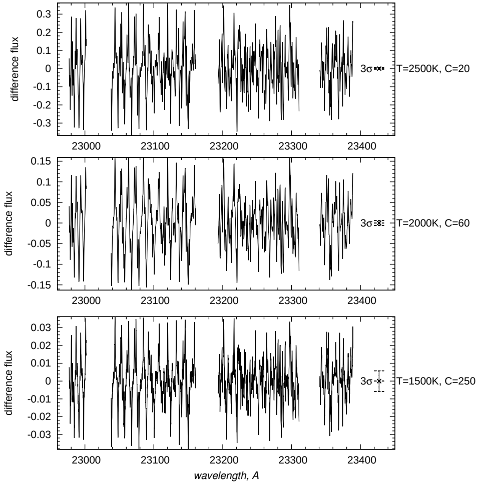
Assumption: Orbital solution for the primary is well-known from optical radial velocity data $\Rightarrow$ the stellar spectrum cancels.

$$df(\lambda_i) \;=\; f(\lambda_i) \;-\; f(\lambda_{i+\Delta\lambda}) \tag{1}$$

$$\Delta\lambda = \frac{\Delta RVM_1}{cM_2}\lambda \tag{2}$$

We generate Poisson distributed photon noise with $S/N \;=\; 500$ per spectral pixel for each of the spectra from different observational epochs.

Results from subtraction of spectra

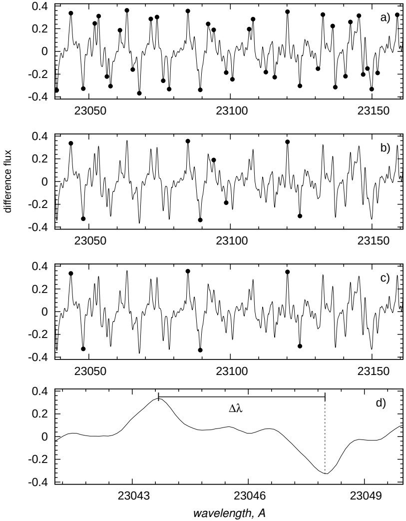


Minimum possible companion mass for GJ1046b $m_{2,min} = 26.85\ M_{Jup}$ that correspond to the largest possible wavelength shift

Companion difference flux with photon noise added.

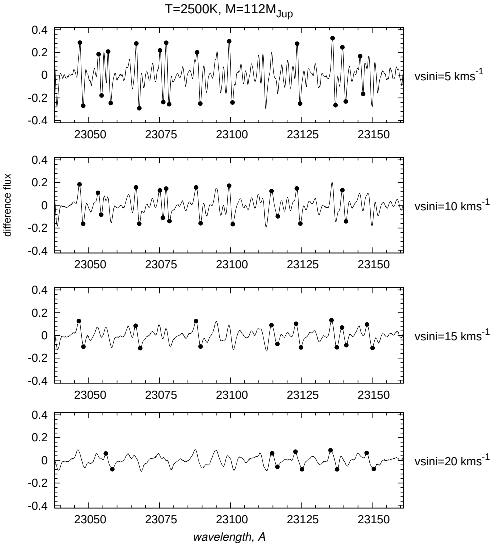
We can confirm that it is feasible to detect this difference companion spectrum in the planned observations with CRIRES.

Mass determination



- Initial guess shift
- Register all line peaks that exceed a selected threshold
- Filter out unsuitable peaks
- Visual inspection of blended profiles.
- Find average spectral shift and companion mass with errors via fitting of two gaussians

Rotational broadening



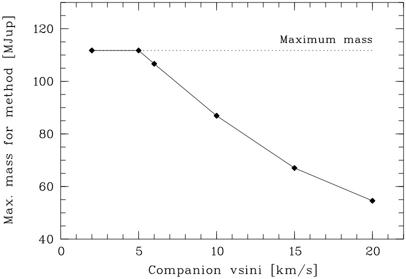
Companion parameters: $T = 2500K$, $M = 112M_{Jup}$ that correspond to minimum wavelength shift

Different companion rotational velocities: 5 kms^{-1}, 10 kms^{-1}, 15 kms^{-1}, 20 kms^{-1}

Rotational broadening of spectral lines leads to blending effect in the differential companion spectrum.

Mass determination results

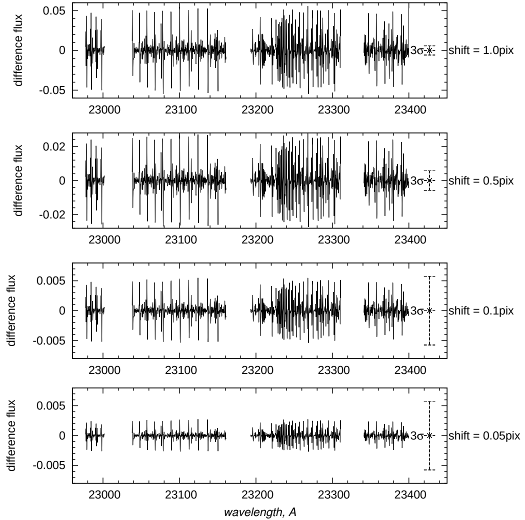
v sin$i$	M_{in} (M_{Jup})	M_{out}(M_{Jup})		
		2500K	2000K	1500K
5	26.85	26.11±0.22	26.93±0.32	27.08±0.14
10	26.85	27.00±0.28	26.60±0.49	26.65±0.27
15	26.85	26.80±0.35	26.45±0.58	26.85±0.41
20	26.85	26.91±0.58	26.67±0.47	26.76±0.24
5	111.74	107.7±1.3	107.0±4.0	110.0±1.9
10	86.91	85.7±1.8	83.9±1.3	88.0±2.5
15	67.04	64.49±0.89	65.98±0.60	71.3±1.9
20	54.57	54.5±1.4	56.2±2.4	56.1±1.1



Due to line blending the determination of masses is the regime between the two lines will yield values that are systematically too small.

If the system is synchronized then rotational velocity of the companion should be equal to 0.03 kms^{-1}

Host star M2.5V dwarf



Apart from the blending issue, we consider that the largest source of systematic errors in the wavelength calibration leading to imperfect alignment of the shifted stellar spectra before they get subtracted from each other.

We therefore simulated the residual host star spectral features that would arise from this mismatch.

Our simulations show that the host star spectrum cancels when the mismatch is equal to 0.05 pixels or less.

Companion spectrum reconstruction

We apply the method of singular value decomposition using the algorithm by Press et al. (1992) on difference spectrum.

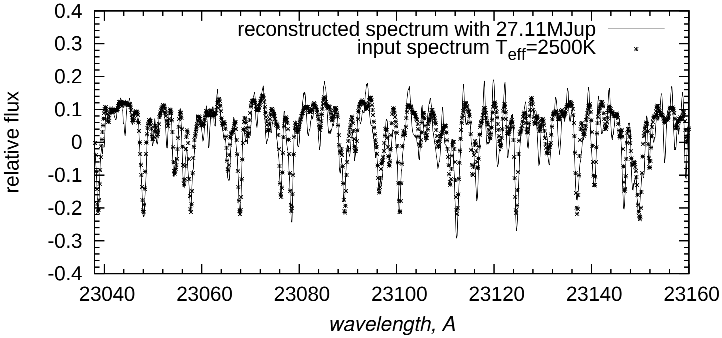
$$\begin{bmatrix} df_1 \\ df_2 \\ \vdots \\ df_N \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} & \cdots & A_{1M} \\ A_{21} & A_{22} & \cdots & A_{2M} \\ & \cdots & & \\ A_{N1} & A_{N2} & \cdots & A_{NM} \end{bmatrix} \times \begin{bmatrix} f_1 \\ f_2 \\ \vdots \\ f_N \end{bmatrix} \tag{3}$$

$M > N$ - the problem is ill-posed, i.e. underdetermined.

$A_{ij} = 1$ for $i = j$
$A_{ij} = -1$ for $i = j + \Delta i$
$A_{ij} = 0$ for all other cases.

Companion spectrum reconstruction result

We reconstructed this companion spectrum for the case of a companion mass of $27.11 M_{Jup}$, effective temperature of 2500 K, and rotational velocity of 5 $\mathrm{km s^{-1}}$.



Even with two spectra we still have quite good reconstruction of main features, but there are some discrepancies in the finer details.

Knowing the spectra of the companion several of its parameters can be obtained, such as spectral type of the companion, effective temperature and age.

Conclusions

- We have presented a spectral differential technique for the detection and characterization of an invisible close companion to late-type stars.
- We show that companion difference spectra with effective temperatures of 2500K, 2000K and 1500K would be possible to detect.
- One of the largest sources of systematic error comes from an imperfect wavelength calibration that leads to a mismatch of the shifted stellar spectra before they are subtracted from each other. Our simulations show that the host star spectrum cancels when the mismatch is equal to 0.05 pixels or less.
- We have demonstrated that the determination of the wavelength shift and therefore the companion mass can be made with very high accuracy for slowly rotating companions. Faster rotation of the companion complicates its mass determination, especially for high companion masses.
- Knowing the true wavelength shift value we have reconstructed of the spectrum using singular value decomposition. From the single (reconstructed) spectrum of the companion, additional parameters can be obtained that give us important information on the companion object.

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