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Mass Determination of Sub-stellar Companions Around Young Stars - The Example of HR 7329

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Abstract. Lowrance *et al.* (2000) found a faint companion candidate about 4 arcsec south of the young A0-type star HR 7329. Its spectral type of M7-8 is consistent with a young brown dwarf companion. Here we report spectroscopic J band observations using the integral field spectrograph SINFONI at VLT, enabling a new estimation of effective temperature, extinction and surface gravity of the object and hence its mass. Although the data were reduced carefully, the presence of a spike within the point spread function of the object in each spectral image hampered the precise estimation of the properties of HR 7329. Nevertheless, we will show with the example of this sub-stellar companion how mass estimates independent of evolutionary models of directly imaged sub-stellar companions can be obtained, after removing most of the strong influence of the spike in the present data, and present a new mass estimation of HR 7329 B/b based on the values gained.

Keywords. stars: low-mass, brown dwarfs, imaging, atmospheres, techniques: spectroscopic

1. Introduction

The A0-type star HR 7329 [also called η Tel at a distance of 47.7 ± 1.5 pc (Perryman *et al.* 1997), V = 5.0 mag according to SIMBAD] is a member of the β Pic moving group (Zuckerman *et al.* 2001). It has an age of 12 Myr (Zuckerman *et al.* 2001); see Torres *et al.* (2008) for a review about this association.

Lowrance *et al.* (2000) discovered a 6 mag fainter companion candidate ~ 4 arcsec south of HR 7329 with coronagraphic images using NICMOS at the Hubble Space Telescope (HST) and also obtained a spectral type of M7-8. Guenther *et al.* (2001) confirmed the spectral type with an infrared (IR) H band spectrum obtained with the Infrared Spectrograph and Array Camera (ISAAC) at the European Southern Observatory (ESO) 8.2-m Very Large Telescope (VLT) Antu (Unit Telescope 1, UT 1), in April 2000.

Further information on the primary HR 7329 and its sub-stellar companion can be found in Neuhäuser *et al.* 2011 and references therein. While the significance for common proper motion did not exceed $\sim 1\sigma$ in Guenther *et al.* (2001), using an acquisition image and measuring the separation and position angle (PA) between HR 7329 A and B, Neuhäuser *et al.* 2011 presented 10 new astrometric imaging observations, which allowed us to confirm the common proper motion by more than 21σ (see Neuhäuser *et al.* 2011 for additional information on possibly detected orbital motion and further information on e.g. eccentricity or periastron distance from a possible interaction with the debris disc of HR 7329).

2. Observations

We used the adaptive-optics integral-field spectrograph SINFONI, mounted at UT 4 of the ESO VLT, to obtain spectra that do not suffer from wavelength-dependent slit losses that occur on normal spectrographs with narrow entrance slits in combination with AO.

The observations of the HR 7329 companion were carried out in H+K (resolution 1500) and J (resolution 2000) band in the night of 18 May 2009. Two nodding cycles with an integration time of 300s per frame were obtained each. We chose the maximum possible pixel scale (50 x 100 mas) of the instrument leaving HR 7329 A as the AO guide star outside of the FoV (3 arcsec $\times$ 3 arcsec). All observations were done at good airmass ($\sim$1.2) and good seeing conditions of $\sim$0.6 arcsec (optical DIMM seeing).

HIP 94378, a B5 V star, was used as the telluric standard for the J band. In order to correct for the features of this standard star, the Pa-β absorption at $\sim$1.282 μm of HIP 94378 was fitted by a Lorentzian profile and removed by division.

3. Data reduction

We used the SINFONI data reduction pipeline version 2.0.5 offered by ESO (Jung *et al.* 2006) with reduction routines developed by the SINFONI consortium (Abuter *et al.* 2006). After standard reduction, all nodding cycles were combined to a final data cube. We used the *Starfinder* package of IDL (Diolaiti *et al.* 2000) and an iterative algorithm to remove the halo of HR 7329 A, both described in detail in Seifahrt *et al.* (2007). See Fig. 1 for an image of this algorithm, including the removal of most of the strong influence of a spike of the primary star, superimposed onto the point spread fuction of the companion and having to much influence in H+K for its usage here.

4. Results

We have used the combination of the non-equilibrium, stationary cloud model DRIFT (Helling *et al.* 2008) with the general-purpose model atmosphere code PHOENIX

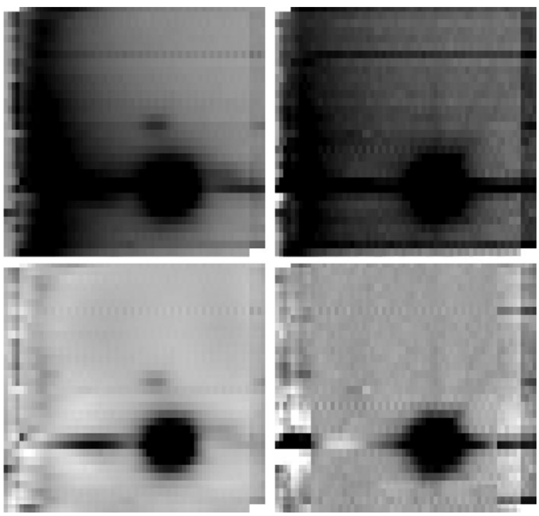

Figure 1. Cleaning of the J band (left) and H+K band (right) cubes. Always shown are the median along the wavelength of the cubes with and without cleaning at the same cut levels from top to bottom, respectively. See text for more information.

(Hauschildt & Baron 1999), see e.g. Witte *et al.* (2011) and references therein for additional information. We used an almost complete grid of DRIFT-PHOENIX models in the range of $T_{eff} = 1000 \ldots 3000$ K, $\log g = 3.0 \ldots 5.5$, and [M/H]=-0.6 ... 0.3 in steps of 100 K, 0.5, and 0.3, respectively. Moreover, we still need to account for reddening of our spectra, see Schmidt *et al.* (2008) for more details on the method.

We find a best fit for the companion candidate of HR 7329 at $T_{eff} = 2800 \pm 400$ K, a visual extinction $A_V = 2.75\,^{+7.25}_{-2.75}$ mag, $\log g = 4.25 \pm 0.25$, and [Me/H]=-0.3, shown in Figs. 2 & 3. All values are derived from our χ^2 minimization analysis. Unfortunately not all of the influence of the superimposed spike could be removed, hence not allowing for a more precise determination of the properties of the companion given above.

5. Implications

Using the newly derived value of extincition we can correct the luminosity of the companion of $\log(L_{bol}/L_\odot) = -2.627 \pm 0.087$ (Neuhäuser *et al.* 2011) to $\log(L_{bol}/L_\odot) = -2.504^{+0.220}_{-0.151}$, giving $R = 0.238^{+0.104}_{-0.077}\,R_\odot$ or $R = 2.33^{+1.015}_{-0.748}\,R_{Jup}$ using the derived temperature value, and finally, using the derived surface gravity, we find a mass of HR 7329 B/b of $M = 38.6^{+45.1}_{-30.0}\,M_{Jup}$, very well consistent with the value of $20 - 50\ M_{Jup}$ derived from evolutionary models (Neuhäuser *et al.* 2011). A more precise mass estimate could be

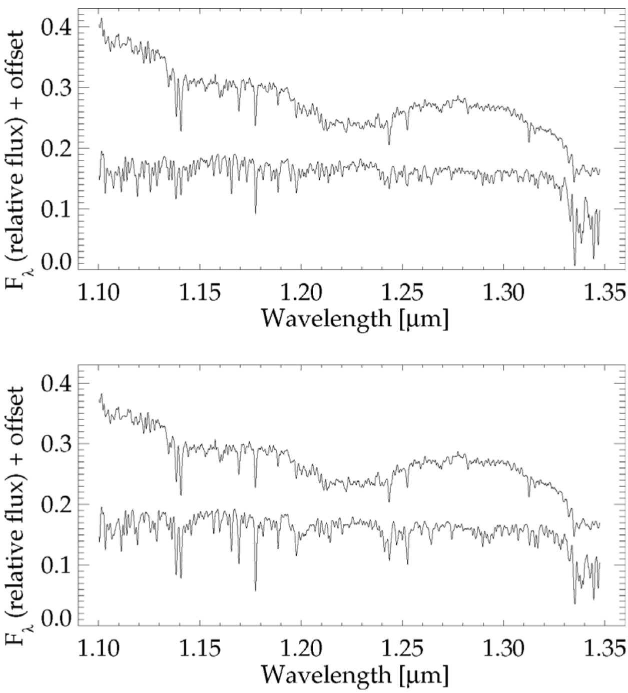

Figure 2. J band spectra. *From top to bottom in each panel:* Our SINFONI spectrum of the HR 7329 companion in spectral resolution 1500 in comparison to the best-fitting Drift-Phoenix synthetic spectra (same spectral resolution) of $T_{eff} = 2800$ K, $\log g = 4.0$, [Me/H]= 0.0 and a visual extinction of $A_V = 3.35$ mag (*top panel*) and of $T_{eff} = 2800$ K, $\log g = 4.5$, [Me/H]=-0.6 and a visual extinction of $A_V = 2.14$ mag (*bottom panel*). Note that the surface gravity sensitive features, as e.g. the equivalent width of the alkali lines of K I at $\sim 1.25\ \mu$m, of the observed spectrum lie inbetween the surface gravity values of the two synthetic model spectra shown here, giving a surface gravity of $\log g = 4.25 \pm 0.25$.

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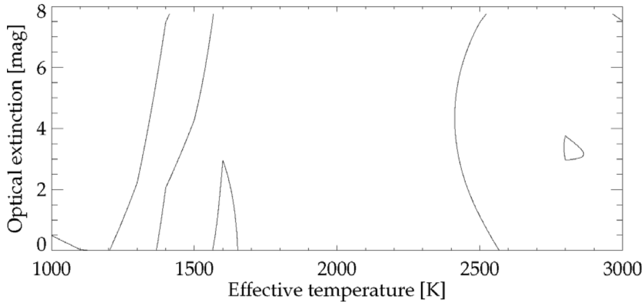

Figure 3. Result of the χ^2 minimization analysis for the HR 7329 companion. Plotted are the best value (*point like on the right hand side*) and the 1, 2, and 3 sigma error contours (*towards lower temperatures*) for effective temperature $T_{\rm eff}$ and optical extinction A_V, determined from comparison of our SINFONI J band spectrum and the Drift-Phoenix model grid, yielding a best fitting temperature of $T_{\rm eff} = 2800 \pm 400$ K and an extinction of $A_V = 2.75^{+7.25}_{-2.75}$ mag.

found if new spectra are observed without the influence of a spike, since the uncertainties of temperature and possibly surface gravity could be reduced.

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Discussion

K. Allers: I enjoyed your talk. The extinction values you find for 2M1207 A and b are very different. Is this expected or easily explained?

T. Schmidt: As suggested in Mohanty *et al.* (2007), 2M1207 b might have an edge-on disk, as also found for the primary 2M1207 A. This would also explain the underluminosity of the planetary mass companion candidate 2M1207 b in comparison to evolutionary model predictions for the effective temperature found from spectroscopy (Mohanty *et al.* 2007, Patience *et al.* 2010).