SF2A 2012
S. Boissier, P. de Laverny, N. Nardetto, R. Samadi, D. Valls-Gabaud and H. Wozniak (eds)

INTERFEROMETRIC DETERMINATION OF EXOPLANET HOST STARS' FUNDAMENTAL PARAMETERS: θ CYGNI, 14 ANDROMEDAE, υ ANDROMEDAE AND 42 DRACONIS.

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Abstract. We have performed observations of three exoplanet host stars using the VEGA interferometer, located on the CHARA array (Mount Wilson, CA): 14 And, υ And and 42 Dra. The data collected allow to estimate accurate fundamental parameters and exoplanets masses, which bring new reference values. Contrary to them, the fourth star we observed, θ Cygni, shows unexplained variabilities when we apply a model of limb-darkened diameter. This star is already suspected to have a quasi-periodic radial velocity of ~ 150 days, detected by SOPHIE/ELODIE on the OHP, that no known stellar variations mode can explain. Kepler observations also revealed solar-like oscillations, and γ Dor pulsations have also been suspected for this star. We propose a binary model that could explain these variabilities. The best solution decreases the $\chi^2_{reduced}$ for half of VEGA data and corresponds to a companion with 15% of flux, and a distance to the primary star ρ included between 17.6 and 26.9 mas. For the CHARA/CLASSIC data, the best solution gives a flux ratio of $\sim 7\%$ and a ρ of ~ 25 mas that decreases the $\chi^2_{reduced}$ by a factor 2.

Keywords: Stars: fundamental parameters, Technique: high angular resolution, Instrumentation: interferometry

1 Introduction

Since the discovery of the first exoplanet (Mayor & Queloz 1995), many methods have been used to detect exoplanets host stars. The most successful one is the radial velocity (RV) method. Up to now, it has allowed to discover 535 planets. The transiting method povides the flux received from the star and the different in flux caused by the planet transiting in front of it, and allows to measure exoplanets's diameter. To enable a precise measure of exoplanets' radius and minimum masses, one can couple RV measurements with interferometric ones. Indeed, high angular resolution facilities, like the spectro-interferometer VEGA on CHARA (Mourard et al. 2009), allows to reach the first zero of visibility, and thus to access a precise measurement of the limb-darkened diameter (LDD). Diameters calculated in this way have an accuracy of more than 2%, and the exoplanets' minimum masses derived have an accuracy up to 7.6%. Waiting for Gaia first results - accurate distances of stars - one of the most important parameter still missing to study the atmospheres and structure of stars is their physical radius. By extension, the study of perturbating elements on the surface of stars, like spots or transiting exoplanets, can be improved with the arrival of this new parameter. We have performed observations of three exoplanets host stars, 14 And, υ And and 42 Dra, that host between one and four exoplanets. We have measured their LDD, calculated their radius and their exoplanets minimum masses from these measurements. They are presented in Section 3. The case of θ Cygni is different. Suspected to behave in a different way, we have performed observations of this star for two years. The squared visibilities we obtained from VEGA show discrepancies, that none of our models can fit. The RV of this star shows a quasi-period of ~ 150 days that cannot be explained neither, but brings the hypothesis of eitheir a complex planetary system orbiting around it or a hidden companion. This discussion is reported in Section 4, and detailed explanations are given in Ligi et al. (2012).

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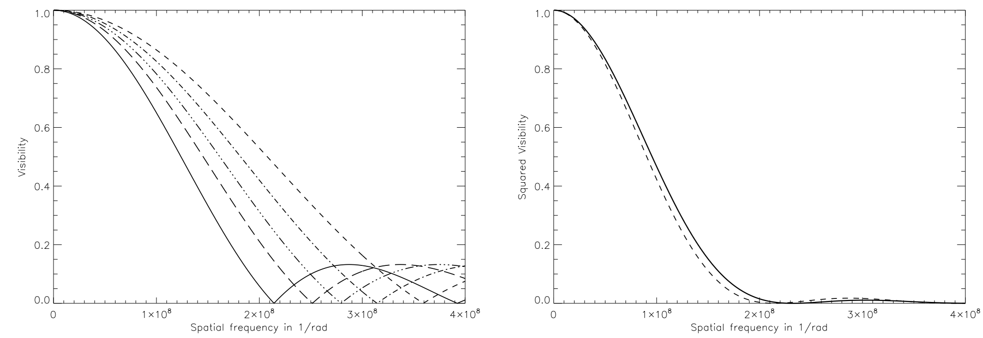

Fig. 1. Left: Theoretical visibilities for a VEGA-like instrument and different uniform disk diameters: 0.6 (solid line), 0.7, 0.8, 0.9 and 1.0 mas (long dashed line). **Right:** Squared visibility obtained for a UD diameter (solid line) and a LD diameter (dashed line). We can see the difference between both curves around the first zero of squared visibility.

2 Basics of interferometry

Interferometry is a high angular resolution technique allowing to study the spatial brightness distribution of celestial objects through measuring their spatial frequencies. By measuring the fringe contrast, also called visibility, one is able to determine the size of stars, thanks to the van Cittert-Zernike theorem (Born et al. 1980). The simplest representation of a star is a uniform disk (UD) of angular diameter θ_{UD}. The corresponding visibility function is given by

$$V^2 = \left| \frac{2J_1(x)}{x} \right|^2, \tag{2.1}$$

where $J_1(x)$ is the first-order Bessel function and $x = \pi B \theta_{UD} \lambda^{-1}$. B represents the length of the projected baseline, λ the wavelength of the observation. In Figure 1 (left), we see that the zero of visibility is reached at different spatial frequencies according to the star's diameter. However, stars are not uniformly bright: a better representation of the surface brightness is the LD disk. The main differences between the two profiles arise close to the zero of visibility and in the second lobe, as shown in Figure 1 (right). Thus, the higher the spatial frequency, the smaller structures at the stellar surface we can see. The LDD is conventionally described by the function $I_\lambda[\mu]$, where μ is the cosine between the normal to the surface at that point and the line of sight from the star to the observer and u_λ the limb darkening coefficient (Hanbury Brown et al. 1974):

$$I_\lambda[\mu] = I_\lambda[1][1 - u_\lambda(1-\mu)]. \tag{2.2}$$

A good approximation of the θ_{LD} is given by (Hanbury Brown et al. 1974)

$$\theta_{LD}[\lambda] = \theta_{UD}[\lambda] \times \left[\frac{1 - u_\lambda/3}{1 - 7u_\lambda/15} \right]^{1/2} . \tag{2.3}$$

The Claret & Bloemen (2011) coefficients are listed in tables and depend on the effective temperature and the stellar surface gravity.

3 Observations of three exoplanets host stars and results

3.1 Observations with VEGA/CHARA

The CHARA array hosts six one-meter telescopes arranged in a Y shape that are oriented to the east (E1 and E2), south (S1 and S2) and west (W1 and W2). The baselines range between 34 and 331 m and permit a wide range of orientations. VEGA is a spectro-interferometer working in the visible wavelengths at different spectral resolutions: 6000 and 30000. Thus, it permits the recombination of two, three or four telescopes, and a maximum angular resolution of $\simeq$ 0.3 mas. We performed the stars observations in the 3T configuration, from October to November 2011. These observations provided measurements close to the zero or up to the second lobe of squared visibility. Then, we used empirical laws to determine the stars' fundamental parameters. First, we used the Equation 3.1 to calculate the radius:

$$R \pm \delta R(R_\odot) = \frac{\theta_{LD} \pm \delta\theta_{LD}}{9.305 \times (\pi \pm \delta\pi)}. \tag{3.1}$$

Then, to estimate the mass, we used the modulus of the gravitational acceleration $||\vec{g}|| = GM/R^2$, where G is the gravitational constant. The error of the mass estimate is dominated by the uncertainty in parallax. Finally, the black body law $L = 4\pi R^2 \sigma T_{\rm eff}^4$ gives the effective temperature $T_{\rm eff}$ and the mass function combined to Kepler's third law gives the exoplanets masses:

$$M_{pl}\sin(i) = \frac{M_*^{2/3} P^{1/3} K (1-e^2)^{1/2}}{(2\pi G)^{1/3}}, \tag{3.2}$$

where K is the velocity semi-amplitude and e the planet eccentricity.

3.2 14 *Andromedae*

14 And (HD221345, HIP116076, HR8930) hosts one exoplanet of minimum mass $M_2 \sin i = 4.8 M_{\rm J}$ discovered in 2008. It has been shown that this star does not exhibit measurable chromospheric activity (Sato et al. 2008). This star is well-fitted by a LD diameter model that provides a $\chi^2_{\rm reduced}$ of 2.8 (see Figure 2). It is obtained with the Claret coefficient $u_\lambda = 0.700$, defined by the effective temperature and the $\log(g)$ given by Sato et al. (2008). It follows a LDD of 1.51 ± 0.02 mas. The radius, $T_{\rm eff}$ and mass found with VEGA are given in Table 1. Baines et al. (2009) found a LDD of 1.34 ± 0.01 mas for 14 And, which is smaller by $\sim 10\%$ than the one we found with VEGA. But we recorded the data in the V band, whereas their values were recorded in the K band. Sato et al. (2008) found that 14 And's exoplanet minimum mass is $M_{\rm pl}\sin(i) = 4.8 M_{\rm Jup}$, which is close to our result (see Table 2), but was derived from radial velocity data, which induces a different bias.

3.3 υ *Andromedae*

υ And (HD9826, HIP7513, HR458) is a bright F star that has undergone numerous spectroscopic investigations (Fuhrmann et al. 1998, and references therein). Four exoplanets are known to orbit around it: they were discovered between 1996 and 2010 (Schneider et al. 2011; Butler et al. 1999; Lowrance et al. 2002; Curiel et al. 2011). The data points obtained at low spatial frequency are slightly lower than the LDD model. This explains the higher $\chi^2_{\rm reduced}$ than for the other stars, which equals 6.9 (Figure 2). Then, we obtained $\theta_{\rm LD} = 1.18 \pm 0.01$ mas using $u_\lambda = 0.534$. υ And was observed by van Belle & von Braun (2009) with the Palomar Testbed Interferometer (PTI), who estimated its LDD to be 1.02 ± 0.06 mas. Baines et al. (2008) found a higher diameter with CHARA/CLASSIC (McAlister et al. 2005): 1.11 ± 0.01 mas. However, it appears that, due to the dispersion in their measurements, the value of their error bars could be underestimated. In our case, the formal uncertainty is also very small but the high value of the $\chi^2_{\rm reduced}$ indicates a poor adjustment by this simple model. No value is consistent with the respective other, ours being separated from McAlister et al. (2005)'s by more than 5σ. More observations are definitively necessary to improve the accuracy and reliability of these measurements. However, the minimum masses of υ And's exoplanets are consistent with those calculated by Curiel et al. (2011) and Wright et al. (2009), but remain lower by $\simeq 10\%$ on average, when we use the orbital periods, semi-amplitudes, and eccentricities they both give (Table 2).

3.4 42 *Draconis*

42 Dra (HD170693, HIP90344, HR6945) is an intermediate-mass giant star around which a $3.88 \pm 0.85 M_{\rm J}$ exoplanet has recently been discovered (Döllinger et al. 2009). The $\chi^2_{\rm reduced}$ obtained for 42 Dra is the lowest one: 0.2. The LDD model perfectly fits the data points. This leads to a $\theta_{\rm LD}$ of 2.12 ± 0.02 mas with a Claret coefficient of $u_\lambda = 0.725$. Baines et al. (2010) found a similar LDD to ours for 42 Dra: 2.04 ± 0.04 mas. Given the few studies of this star, this additional measurement brings a new accurate confirmation of the diameter. Concerning the planet's fundamental parameter, we found a similar $M_{\rm pl}\sin(i)$ to that calculated by Döllinger et al. (2009) (Table 2).

Table 1. Summary of the fundamental parameters of 14 And, υ And, 42 Dra and θ Cyg calculated using VEGA interferometric data. $\theta_{\rm LD}$ is the limb-darkened diameter in mas. The radius and mass are given in solar units and $T_{\rm eff}$ is given in K.

Star	Radius	Mass	$T_{\rm eff}$
14 And	12.82±0.32	2.60±0.42	4450±78
υ And	1.70±0.02	1.12±0.25	5819±78
42 Dra	22.04±0.48	0.92±0.11	4301±71
θ Cyg	1.503±0.007	1.32±0.14	6767±87

Table 2. Calculated exoplanets masses of 14 And, υ And and 42 Dra from interferometric data and comparison with previous work ([a]Sato et al. 2008 ; [b]Curiel et al. 2011 ; [c]Döllinger et al. 2009).

Planet	$P_{\rm orb}[days]$	K $[m.s^{-1}]$	e	$M_{\rm pl}\sin(i)[M_{\rm Jup}]$	
				This work	Previous work
14 And b	185.84±0.23	100.0±1.3	0	5.33±0.57	4.8[a]
υ And b	4.62±0.23	70.51±0.45	0.022±0.007	0.62±0.09	0.69±0.04[b]
υ And c	241.26±0.64	56.26±0.52	0.260±0.079	1.80±0.26	1.98±0.19[b]
υ And d	1276.46±0.57	68.14±0.45	0.299±0.072	3.75±0.54	4.13±0.29[b]
υ And e	3848.86±0.74	11.54±0.31	0.0055±0.0004	0.96±0.14	1.06±0.28[b]
42 Dra b	479.1±6.2	112.5	0	3.79±0.29	3.88±0.85[c]

4 The case of θ Cygni

4.1 *Interferometric observations*

θ Cyg (HD185395, $d = 18.33 \pm 0.05$ pc) is an F4V star with an M-dwarf companion of 0.35 $M_\odot$ orbiting at a projected separation of 2″ ($\simeq$ 46 AU) and with a differential magnitude of 4.6 mag in the H band, which translates into 7.9 mag in the V band (Desort et al. 2009) using Delfosse et al. (2000) data. More recently, Roberts (2011) published adaptative optics (AO) data obtained with the AEOS telescopes in 2002, and reported a differential magnitude in the Bessel I-band of 5.89±0.089 and a separation of 2.54″, compatible with a contrast of $\simeq 7$ at the V band. A quasi-periodical RV variation with a period of approximately 150 days was detected thanks to ELODIE and SOPHIE at the Observatoire de Haute-Provence (OHP), that no known stellar variation modes can explain.

We performed nine observations of θ Cyg with VEGA/CHARA (Mourard et al. 2009) from June 2010 to October 2011. We used the three-telescope capabilities of the instrument. This allowed to reach the second lobe of visibility and to possibly identify stellar pulsations. Added to that, interferometric observations in the visible wavelengths permit to probe the same domain as the spectroscopic results.

In a first analysis, we have considered all data points. We used the LitPro software[i] (Tallon-Bosc et al. 2008) and obtained a mean UD equivalent diameter of 0.726 ± 0.003 mas. This implies a $\chi^2_{\rm reduced}$ of 8.4, which clearly indicates dispersion in the measurements or possible variations of the diameter from night to night. We also tested a linear LDD model with a coefficient $u_\lambda = 0.5$ taken from Claret & Bloemen (2011) with $T_{\rm eff} = 6745$ K and $\log(g) = 4.2$. The adjustment of the whole data set (see Figure 2) gives the value $\theta_{\rm LD} = 0.760 \pm 0.003$ mas, with a reduced $\chi^2_{\rm reduced}$ equal to 8.5.

Our final value is consistent with the diameter estimated by van Belle et al. (2008) ($\theta_{\rm LD} = 0.760 \pm 0.021$ mas) with spectral energy distribution but smaller than Boyajian et al. (2012)'s diameter obtained with CLASSIC beam combiner ($\theta_{\rm LD} = 0.845 \pm 0.015$ mas and $\theta_{\rm LD} = 0.861 \pm 0.015$ mas in 2007 and 2008 respectively). θ Cyg's fundamental parameters were estimated in the same way as for the host stars. We took $\pi = 54.54 \pm 0.15$ mas according to van Leeuwen (2007). θ Cyg 's radius is then $R = 1.503 \pm 0.007 R_\odot$. The final uncertainty is equally due to errors in the parallax and the angular diameter. This results in a mass of $1.32 \pm 0.14 M_\odot$. Finally, the $T_{\rm eff}$ was calculated using the black body law, resulting in $T_{\rm eff} = 6767 \pm 87$ K, which is also consistent with the value given by Desort et al. (2009). Boyajian et al. (2012) found a lower $T_{\rm eff}$ of 6381 ± 65 K mostly due to a

[i]Available at http://www.jmmc.fr/litpro

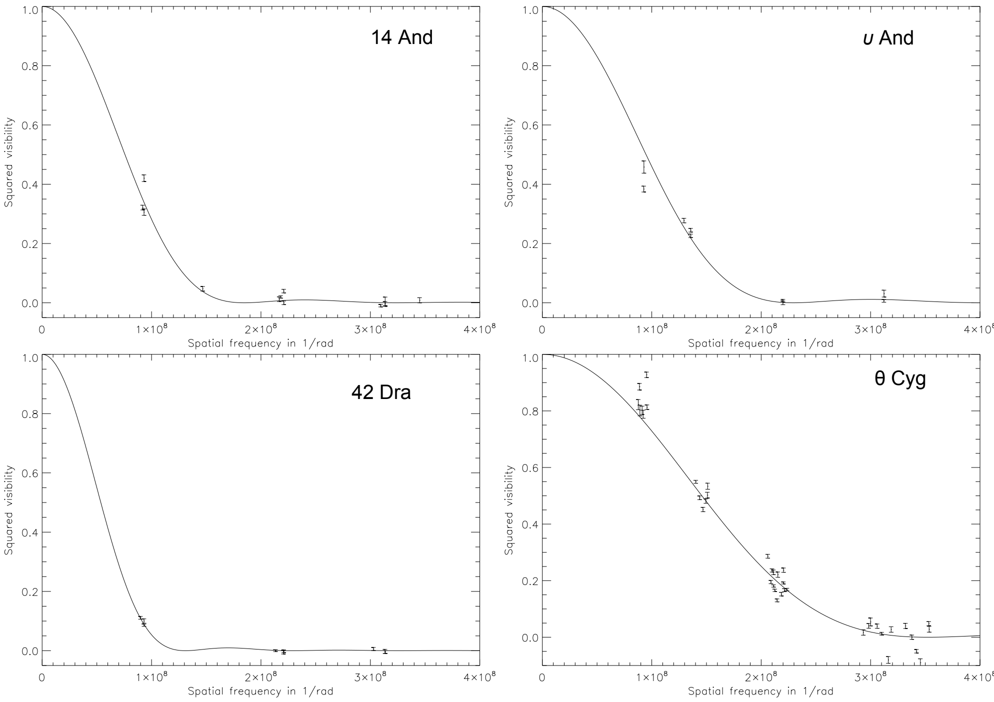

Fig. 2. Squared visibility of 14 And (top left), υ And (top right), 42 Dra (bottom left) and θ Cyg (bottom right) *versus* spatial frequency [1/rad] for VEGA data points. The solid line is the model of the limb-darkened angular diameter provided by the LITpro software.

larger LDD (see Table 1).

4.2 Discussion

As θ Cyg's visibility curve shows discrepancies, we suspect that it has unknown stellar variations or hides another companion.

Because θ Cyg's radial velocity is suspected to have a 150-day period (Desort et al. 2009), we studied a possible correlation between the variation of its diameter and the RV periodic behavior by looking its diameter night by night (see Ligi et al. 2012). It results in a variation with an amplitude of $\sim$ 13% in diameter peak to peak. Solar-like oscillations lead to lower variations in amplitude than that. Cepheid stars show similar-sized pulsations but are brighter, and their light curve presents much larger amplitude variations than θ Cyg's. Its luminosity and temperature would rather locate it near the instability branch of the HR diagram, identifying it as a δ Scuti or γ Dor star, which are also A- or F- type stars. This last possibility is also mentioned by Guzik et al. (2011), but the light curve they show does not reveal the typical γ Dor frequencies around 11 μHz, which are specific for these pulsations. Finally, we note that if the 150-day period RV variations were due to diameter variations, they would be unrealistically large, and very significant photometric variations should have been detected by Kepler. We therefore conclude that stellar variations do not explain the observed features in a satisfactory manner. We therefore consider the possibility of an unseen stellar companion for θ Cyg, and see how the present interferometric data can help to test such a scenario.

The known M-type companion to θ Cyg clearly does not affect our visibilities, because of the large separation in position (2 seconds of arc) and the large difference in magnitude (around 7). We therefore consider the presence of a second and much closer companion. Given our current accuracies in visibility measurements, this companion could be detected by interferometric instruments if its flux contribution is higher than 2%. Because θ Cyg is not classified as SB2, such a flux ratio would imply a pole-on bound system or a visual unbound binary. In this framework we performed several tests on our data set. Because the VEGA visibilities are, at first approximation, dominated by one main resolved source, that is the primary component, we adopted a diameter of the companion of 0.2 mas, corresponding to an unresolved source. The UD diameter of the primary was fixed to $\theta_{\rm UD} = 0.726$ mas, which is the diameter obtained when merging all nights. Then, by assuming

a companion's flux in the range 2% to 15%, we obtained the position angle (PA) and angular separation (ρ) corresponding to the minimum $\chi^2_{\mathrm{reduced}}$. We performed the same tests with Boyajian et al. (2012)'s CLASSIC data from 2007-2008. In half of the cases of the VEGA sets, we found a solution with a better $\chi^2_{\mathrm{reduced}}$ than with a UD model. Generally, the best solution corresponds to a companion with 15% of flux, and a ρ included between 17.6 and 26.9 mas. However, in the other VEGA cases, the data do fit the binary model and no better solution is found.
In the CLASSIC data, the $\chi^2_{\mathrm{reduced}}$ is reduced by a factor 2 when we include the binarity and the best solution gives a flux ratio of about 7% and a separation of about 25 mas.

5 Conclusion and perspectives

We have performed VEGA/CHARA interferometric observations of four stars, three of them hosting exoplanets and the last one showing discrepancies in the squared visibility we obtained. After calculating the LDD of 14 And, υ And and 42 Dra with a minimum precision of $\sim 1,3\%$, we obtained accurate values of their exoplanets masses. However, θ Cyg diameter was not so easy to confirm. We studied its variation according to the observing night, and concluded that either unknown stellar variations or a hidden close companion could explain these variations. After modeling VEGA and CLASSIC data with a companion of diameter 0.2 mas, we concluded that a companion improve the interpretation of the CLASSIC data by a factor 2 when we consider a binary component, whereas it only improves half of the VEGA data. More observations with different CHARA beams combiners allowing a larger UV coverage and the measurement of closure phases would bring additional clues to understand this complex star.

The CHARA Array is operated with support from the National Science Foundation through grant AST-0908253, the W. M. Keck Foundation, the NASA Exoplanet Science Institute, and from Georgia State University. RL warmly thanks all the VEGA observers that permitted the acquisition of this set of data. RL also acknowledges the PhD financial support from the Observatoire de la Côte d'Azur and the PACA region. We acknowledge the use of the electronic database from CDS, Strasbourg and electronic bibliography maintained by the NASA/ADS system.

References

Baines, E. K., Döllinger, M. P., Cusano, F., et al. 2010, ApJ, 710, 1365

Baines, E. K., McAlister, H. A., ten Brummelaar, T. A., et al. 2009, ApJ, 701, 154

Baines, E. K., McAlister, H. A., ten Brummelaar, T. A., et al. 2008, ApJ, 680, 728

Born, M., Wolf, E., & Haubold, H. J. 1980, Astronomische Nachrichten, 301, 257

Boyajian, T. S., McAlister, H. A., van Belle, G., et al. 2012, ApJ, 746, 101

Butler, R. P., Marcy, G. W., Fischer, D. A., et al. 1999, ApJ, 526, 916

Claret, A. & Bloemen, S. 2011, A&A, 529, A75

Curiel, S., Cantó, J., Georgiev, L., Chávez, C. E., & Poveda, A. 2011, A&A, 525, A78

Delfosse, X., Forveille, T., Ségransan, D., et al. 2000, A&A, 364, 217

Desort, M., Lagrange, A.-M., Galland, F., et al. 2009, A&A, 506, 1469

Döllinger, M. P., Hatzes, A. P., Pasquini, L., et al. 2009, A&A, 499, 935

Fuhrmann, K., Pfeiffer, M. J., & Bernkopf, J. 1998, A&A, 336, 942

Guzik, J. A., Houdek, G., Chaplin, W. J., et al. 2011, ArXiv e-prints

Hanbury Brown, R., Davis, J., Lake, R. J. W., & Thompson, R. J. 1974, MNRAS, 167, 475

Ligi, R., Mourard, D., Lagrange, A. M., et al. 2012, A&A, 545, A5

Lowrance, P. J., Kirkpatrick, J. D., & Beichman, C. A. 2002, ApJ, 572, L79

Mayor, M. & Queloz, D. 1995, Nature, 378, 355

McAlister, H. A., ten Brummelaar, T. A., Gies, D. R., et al. 2005, ApJ, 628, 439

Mourard, D., Clausse, J. M., Marcotto, A., et al. 2009, A&A, 508, 1073

Roberts, Jr., L. C. 2011, MNRAS, 413, 1200

Sato, B., Toyota, E., Omiya, M., et al. 2008, PASJ, 60, 1317

Schneider, J., Dedieu, C., Le Sidaner, P., Savalle, R., & Zolotukhin, I. 2011, A&A, 532, A79

Tallon-Bosc, I., Tallon, M., Thiébaut, E., et al. 2008, in Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, Vol. 7013, 70131J

van Belle, G. T., van Belle, G., Creech-Eakman, M. J., et al. 2008, ApJS, 176, 276

van Belle, G. T. & von Braun, K. 2009, ApJ, 694, 1085
van Leeuwen, F. 2007, A&A, 474, 653
Wright, J. T., Upadhyay, S., Marcy, G. W., et al. 2009, ApJ, 693, 1084