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WASP-8b, a retrograde transiting planet in a multiple system⋆

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ABSTRACT

We report the discovery of *WASP-8b*, a transiting planet of 2.25 ± 0.08 M_{Jup} on an eccentric 8.15-day orbit, strongly inclined and moving in a retrograde direction to the rotation of its late-G host star. Evidence is found that the star is in a multiple stellar system with two other companions. The dynamical complexity of the system indicates possible secular interactions like the Kozai mechanism and is suggestive of a formation scenario alternative to the "classical" disc-migration theory for this system.

Key words. stars: planetary systems – stars: individual: *WASP-8*– Planet-star interactions – technique: photometry– technique: spectroscopy– technique: radial velocities

1. Introduction

Transiting planets provide a wealth of information on the structure and formation of planets. The measurement of planet radius combined with its mass revealed a surprising diversity of mean densities and in particular "inflated" hot Jupiters. Spectroscopic measurement of the Rossiter-McLaughlin effect on the radial velocity during transits indicates that some of these planets may not be aligned with the rotation axes of their stars (see references in Winn (2010)). The diversity of observed spin-orbit misalignments is somewhat similar to that seen earlier in the orbital and mass distribution of the first series of planets detected by radial velocity surveys (see refs in Udry & Santos (2007)). The burst of recent detections of transiting planets is the outcome of successful ground-based wide transit searches surveys among which WASP (Pollacco et al. 2006) stands as being the most prolific.

These recent discoveries have stimulated theoretical studies on alternative formation scenarios to the sole migration theory (Wu & Murray 2003; Lin et al. 1996). These alternative theories address the discoveries of eccentric hot Jupiters on orbits not aligned with the rotation equator of their star (Wu & Murray 2003; Fabrycky & Winn 2009; Nagasawa et al. 2008; Barker & Ogilvie 2009).

2. Observations

2.1. The WASP-8 multiple stellar system

The star *WASP-8* (TYC2 7522-505-1) at α(2000): 23h 59m 36.07s, δ(2000): $-35°$ 1' 52.9", was observed in 2006 and 2007 by the WASP-south telescope (Pollacco et al. 2006). It is a V = 9.79 magnitude star with a Tycho (B−V) color of 0.73 suggesting a G8 spectral type. With the Infrared Flux Method (IRFM) (Blackwell & Shallis 1977), using GALEX, TYCHO-2, USNO-B1.0 R-magnitude and 2MASS broad-band photometry, a T_{eff} of 5610 ±140 K was estimated. The IRFM yields a distance of 87±7 pc.

WASP-8 is identified in the CCDM catalogue (CCDM 23596-3502) as the A component of a multiple stellar system of three stars. The B component is a 15th magnitude red star, 4 arcsec south of A and the third component C is a 10th magnitude star (HIP 118299, HD224664) 142 arcsec north of A. The radial velocity of HD224664 is 4.7 km s^{-1} and stable over two years (Mayor priv com.) but different from the WASP-8 value of -1.5 km s^{-1}. The proper motion of both components is different as well. It is therefore unlikely that C and A are physically associated and belong to the same stellar system.

We measured the photometry and position of *WASP-8* and its nearby star (B component) with the Euler CCD Camera of the 1.2m Euler swiss telescope at La Silla (see Fig. 1). We obtained, by comparing with nearby stars, a magnitude difference Δm_V = 4.7, Δm_I = 3.5, a separation of 4.83 ± 0.01" and PA = 170.7 ± 0.1°. Assuming that *WASP-8* and its B component are part of a multiple system, the color indices would match an M star. A similar photometric analysis of the individual 2MASS archive images indicates Δm_J = 2.7, Δm_H = 2.2 and Δm_K = 2.1 suggesting as well an M star. The value mentioned in the Washington Visual Double Star Catalog measured 70 years ago indicates 4.0" and PA=170°(Mason et al. 2001). This suggests little, if any, relative motion of the two stars over the 70-year time span between theses observations. When compared with the proper motion in right ascension of *WASP-8*, about 100 mas/yr (Zacharias et al. 2004), this indicate a common proper

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⋆ Based on observations made with HARPS spectrograph on the 3.6-m ESO telescope and the EULER Swiss telescope at La Silla Observatory, Chile

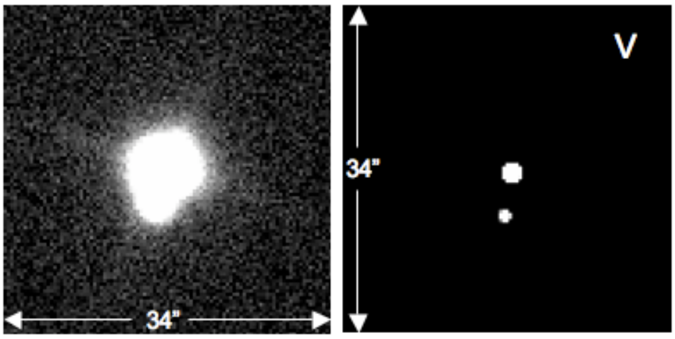

Fig. 1. Original (left) and deconvolved (right) V-band image from the Euler telesclope of the A and B component of *WASP-8*.

motion pair. Given that the distance of *WASP-8* is around 87 pc, the separation of the pair would be about 440AU. Using available differential photometry, we estimate the temperature of the B component at about Teff≈ 3700 K

2.2. Photometric and radial-velocity observations

WASP-8 was recorded simultaneously by two cameras of the WASP-South telescope during two seasons (2006 and 2007). Altogether 11224 independent photometric points have been recorded with a typical sampling of 8 minutes. Transit events were detected in data from the first observation season. This triggered radial velocity follow-up observations of *WASP-8* in November 2007 with the *Coralie* spectrograph installed on the Swiss Euler telescope (Baranne et al. 1996; Queloz et al. 2000; Pepe et al. 2002). After a few measurements we surprisingly found variations in the radial velocity with a period 3 times longer the one selected by the WASP transit-detection algorithm. From a full re-analysis of the photometry including new WASP data from the 2007 season, a revised transit period of 8.15 days was determined and found to be in full agreement with the radial-velocity measurements. No changes in the spectroscopic profile were detected, ruling out a blended eclipsing binary or starspots as the cause of the radial-velocity variation (Queloz et al. 2001) (see bottom diagram on Fig 2). In the next season (2008-2009), observations with *CORALIE* were continued, revealing of an additional drift in the γ velocity of the system (Fig. 3). Altogether 48 radial velocities with typical precision of 4 m s^{-1} were measured with *CORALIE* over a period of 573 nights.

One year later, on 25th August 2008, following up on the confirmation of the planet, a complete and densely sampled transit event was recorded in R band with the Euler 1.2m telescope to better characterize the transit parameters (Fig. 4). Additionally, to look for the Rossiter effect, on October 4th 2008, a spectroscopic transit was measured with the *HARPS* spectrograph installed on the 3.6m telescope at La Silla. During the sequence 75 spectra (44 in the transit) were measured with an exposure time of 300 s, corresponding to a typical signal to noise per pixel of 50. The radial velocity measurement from these spectra shows an obvious Rossiter-McLaughlin effect with a shape suggesting a non-coplanar orbit (Fig. 4). Additionally, four spectra were measured on the same night before and after the transit to get the rate of change of the radial velocity surrounding the Rossiter-McLaughlin effect. Three measurements were obtained later at other phases of the system to improve the matching and zero point correction between *CORALIE* and *HARPS* data. During the measurement of the transit sequence, a significant change in

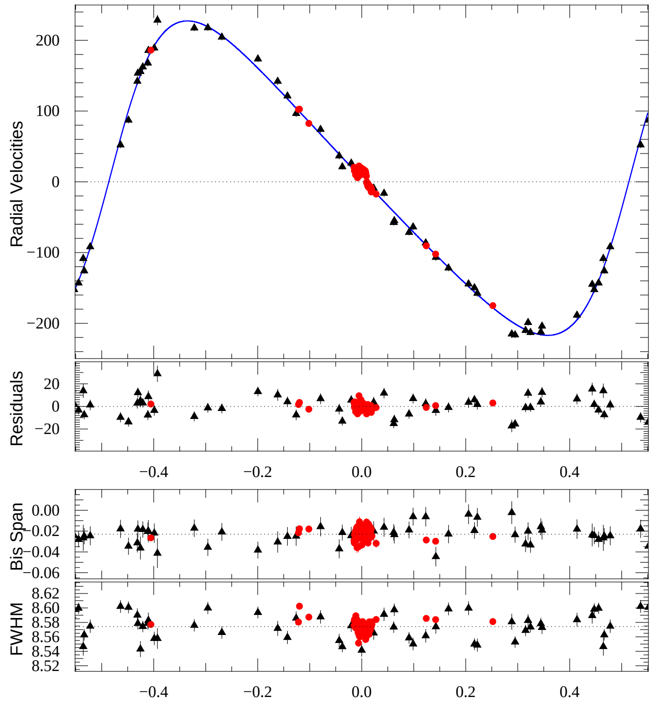

Fig. 2. Top: Overall Keplerian fit of the RV data for Wasp-8b. Black triangles indicates *Coralie* data and red dots the *Harps* data. The long term drift was removed from the velocity to plot the figure in phase. Phase 0 is set at the time of the transit and not according to the usual radial velocity definition. **Bottom**: Bissector Span and FWHM (in km s^{-1}unit) plotted with the phase of the orbit. The *HARPS* radial velocity data were shifted to correct from the γ velocity difference with *CORALIE* .

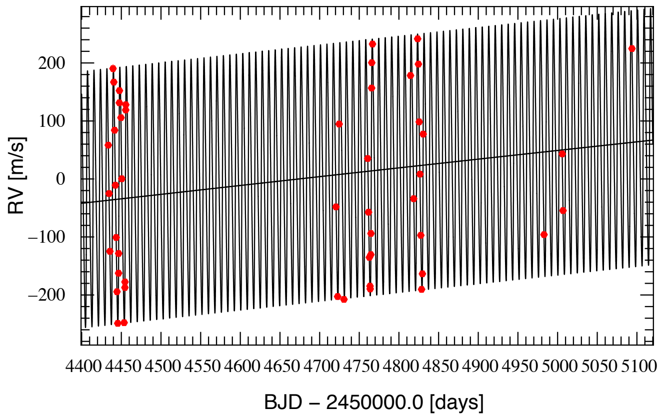

Fig. 3. *CORALIE* radial velocity measurements (red dots) of *WASP-8* superimposed to the best fit solution (solid line).

telescope focus happened at JD 54744.592, improving the flux entering the fiber by a factor 2.

3. Determination of system parameters

3.1. Spectral Analysis

The individual *HARPS* spectra were co-added and used for a detailed spectroscopic analysis of WASP-8. The results are displayed in Table 1. As in previous WASP-papers (Cameron et al. 2007) the analysis was performed using the UCLSYN spectral

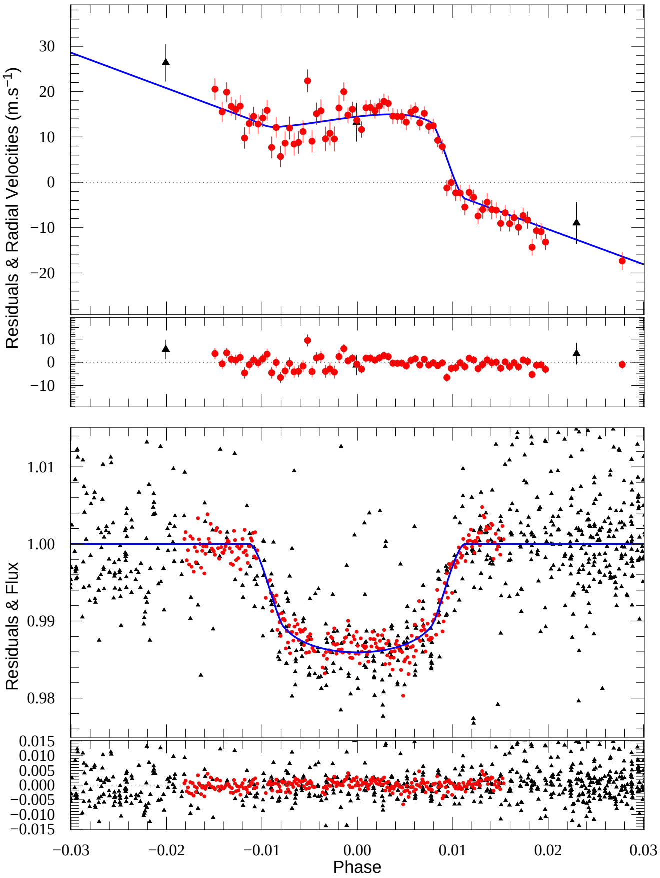

Fig. 4. Top: Radial velocity measurement phased with the transit (mid-transit is at 0). Black triangles are *CORALIE* data and red dots *HARPS* data. **Bottom**: Normalized transit photometry measurement of *WASP-8*. Black triangles indicates SuperWASP data and red dots the R-band Euler photometry data. The best fit model is superimposed in blue.

Table 1. Stellar parameters of *WASP-8* derived from spectroscopic analysis. The quoted error estimates include that given by the uncertainties in T_{eff}, log g and ξ_t, as well as the scatter due to measurement and atomic data uncertainties

T_{eff}	5600 ± 80 K	[Na/H]	+0.22 ± 0.07
log g	4.5 ± 0.1	[Mg/H]	+0.21 ± 0.04
ξ_t	1.1 ± 0.1 km s^{-1}	[Si/H]	+0.29 ± 0.09
$v \sin i$	2.0 ± 0.6 km s^{-1}	[Ca/H]	+0.24 ± 0.12
[Fe/H]	+0.17 ± 0.07	[Sc/H]	+0.23 ± 0.05
log A(Li/H)+12	1.5 ± 0.1	[Ti/H]	+0.24 ± 0.08
		[V/H]	+0.30 ± 0.08
dist	87±7 pc	[Cr/H]	+0.17 ± 0.09
age	3-5 Gyr	[Co/H]	+0.29 ± 0.07
		[Ni/H]	+0.23 ± 0.07

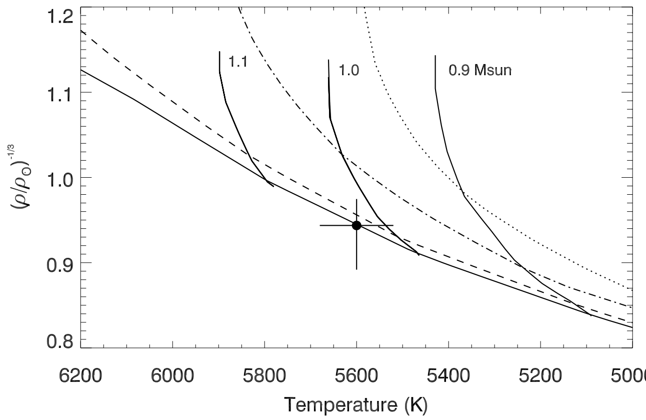

Fig. 5. Comparison of the best-fitting stellar parameters from the transit profile and spectroscopic analysis with evolutionary models interpolated at [Fe/H]=0.17. The isochrones are 100 Myr, 1 Gyr, 5 Gyr and 10 Gyr. The evolutionary tracks are indicated for 0.9, 1.0 and 1.1 Msun.

synthesis package and ATLAS9 models without convective overshooting with H_α and H_β Na I D and Mg I b lines as diagnostics for T_{eff} and (log g). The abundances and the microturbulence was determined similarly to the work done in Gillon et al. (2009) and used as an additional T_{eff} and log g diagnostics (Smalley 2005). However, Israelian et al. (2009) have noted that stars with planets have lower lithium abundances than normal solar-type stars, so the lithium abundance may not be a good age indicator for these stars.

The Li I 6708Å line is detected in the spectra indicating an abundance of log A(Li/H) + 12 = 1.5 ± 0.1, suggesting an age of 3-5Gyr according to Sestito & Randich (2005)

The rotational broadening $v \sin i$ was measured by fitting the observed HARPS profiles of several unblended Fe I lines. A typical value for macroturbulence v_{mac}= 2 km s^{-1} was adopted and an instrumental profile determined from telluric absorption lines around 6300Å. We find that the most likely value is $v \sin i$ = 2.0 ± 0.6 km s^{-1}, which is within the typical range for a G dwarf of intermediate age.

3.2. Analysis of the planetary system

This whole set of data demonstrates without doubt the presence of a giant planet transiting the star *WASP-8*. We analyzed together the photometric (WASP and Euler data) and the radial velocity data, including the spectroscopic transit sequence in this context. Our model is based on the transit modeling by Mandel & Agol (2002) and the radial velocity description by Giménez (2006). The best parameters and their error bars are computed through a MCMC convergence scheme solving all parameters together. For details about the code and the fitting technics see Triaud et al. (2009); Collier Cameron et al. (2007). To obtain a coherent solution we determine the mass of the star by comparing the spectroscopically-determined effective temperature and the stellar density outcome of the MCMC adjustment , with evolutionary tracks and isochrones of the observed metallicity from the stellar evolution model of Girardi et al. (2000). We converge iteratively on a stellar mass of 1.04(+0.02 -0.09) $M_\odot$ and an age less than 6 Gyr (see on Fig. 5).

The free parameters of our model are: the depth of transit D, the width of transit W, the impact parameter b, the period P, the epoch of transit centre T_0, the RV semi-amplitude K, $e \cos \omega$ & $e \sin \omega$ (e being the eccentricity and ω the angle of the periastron), and $V \sin I \cos\beta$ & $V \sin I \sin\beta$, with $V \sin I$ being the projection of the stellar equatorial rotation, and β the projection of the angle between the stellar spin axis and the planetary orbit axis. Additionally, free normalization factors for each lightcurve (WASP and Euler) and each set of radial velocity (γ_H for *HARPS* and γ_C for *CORALIE*) allow for possible differences in instrumental zero points. From these parameters, *physical* parameters can be derived to characterise the planetary system. The best set of parameters that minimize the χ^2 (reduced χ^2 is 0.86 for our

Table 2. Fitted and physical parameters of the *WASP-8* planetary system. The error bars are calculated at 68 % of the statistical distributions.

Parameters (*units*)		
D	0.01278	(+0.00023 − 0.00042)
W (days)	0.1836	(+0.0022 − 0.0034)
b ($R_\star$)	0.609	(+0.029 − 0.070)
P (days)	8.158716	(+0.000018 − 0.000011)
T_0 (BJD-2450000)	4679.33434	(+0.00035 − 0.00058)
K ($\mathrm{m\,s^{-1}}$)	222.20	(+0.81 − 0.62)
$d\gamma/dt$ ($\mathrm{m\,s^{-1}\,yr^{-1}}$)	58.2	(+1.1 − 1.5)
$e\,cos\,\omega$	0.02291	(+0.0006 − 0.0014)
$e\,sin\,\omega$	−0.3072	(+0.0016 − 0.0028)
$V\,sin\,I\,cos\,\beta$	−0.649	(+0.046 − 0.099)
γC^a ($\mathrm{m\,s^{-1}}$)	−1565.72	(+0.12 − 0.24)
γH^a ($\mathrm{m\,s^{-1}}$)	−1550.86	(+0.74 − 0.28)
$V\,sin\,I\,sin\beta$	1.44	(+0.19 − 0.13)
$R_p/R_\star$	0.1130	(+0.0010 − 0.0019)
$R_\star/a$	0.0552	(+0.0018 − 0.0031)
$\rho_\star$ ($\rho_\odot$)	1.19	(+0.22 − 0.11)
$R_\star$ ($R_\odot$)	0.953	(+0.032 − 0.058)
$M_\star$ ($M_\odot$)	1.033	(+0.058 − 0.050)
$V\,sin\,I$ ($km.s^{-1}$)	1.58	(+0.16 − 0.09)
R_p/a	0.00625	(+0.00026 − 0.00045)
R_p (R_J)	1.048	(+0.042 − 0.079)
M_p (M_J)	2.247	(+0.083 − 0.074)
a (AU)	0.0802	(+0.0015 − 0.0013)
i (°)	88.52	(+0.25 − 0.12)
e	0.3082	(+0.0028 − 0.0017)
ω (°)	−85.68	(+0.14 − 0.27)
β (°)	114.2	(+4.6 − 3.9)

[(a)] computed at JDB=2454691.15781

best solution) are listed in Table 2 as well as their related computed physical parameters.

The fit indicates a giant planet with an eccentric ($e = 0.3$) 8.16-day orbit and an additional long term radial velocity drift of $58\,\mathrm{m\,s^{-1}\,yr^{-1}}$. The planet is dense with $2.25\,M_j$ and a radius of $1.05\,R_j$ in contrast with the majority of hot Jupiters that are "inflated". Surprisingly, the projected angle between the orbital and stellar spin axes is found to be $\beta = 114.4°^{+4.6}_{-3.9}$ suggesting a retrograde orbit. Notice that $V\,sin\,I = 1.58\,\mathrm{km\,s^{-1}}$ is in accordance with the line rotation broadening $v \sin i$ (in table 1) derived by the spectral analysis.

We checked for a possible impact on our result of the partial defocusing of HARPS during the transit spectroscopic sequence. We divided this series into two subsets and considered for each of them a independent offset (γ). We obtain a solution with a marginal improvement of the χ^2. By comparing the solution obtained from these two sets with the complete set, the angle β was changed by $1.5\,\sigma$. The defocusing problem that occurred during the spectroscopic transit does not affect the results of this paper.

4. Discussion

The detection of a hot Jupiter on an eccentric orbit, misaligned with the stellar rotation axis and going retrograde raises many questions on the origins of this system. Although their solution lies beyond the scope of this paper, the visual faint companion and the drifting γ velocitiy of the system are key components of the puzzle. From the observed separation between the A and B component one can derive a most likely orbital semi-major axis ($a = 1.35\rho \approx 600$ AU) (Duquennoy & Mayor 1991) corresponding about to 10000 yr orbital period. Making the assumption that the eccentricity of that system is not extremely high, one would derive a typical yearly drift of γ of less than $1\,\mathrm{m\,s^{-1}\,yr^{-1}}$. The observed radial velocity drift is therefore unlikely related to the B component of the binary, suggesting an additional closer companion of both unknown mass and period. This intermediate body is likely to play a dynamical role, but its unknown mass and orbital period make it difficult to estimate this effect.

Aside from the complex dynamic situation of the whole system, the planet *WASP-8b* is a "standard" hot Jupiter. It orbits a metal-rich star matching the observed relationship between the rate of planet occurrence with the metallicity of the host star (Udry & Santos 2007). The period of *WASP-8b* is longer than the 3-4 days typical of most hot-Jupiter planets. The eccentricity of its orbit, however, gives it a periastron distance of 0.055 AU that is a more typical mean orbit distance for hot Jupiters.

The orbit misalignment of planet with the stellar rotation axis of *WASP-8* is measured through the β parameter. The true angle between the axes of the stellar and planetary orbits is usually called ψ and is statistically related to β through $\sin I$ (unknown) and the orbital inclination (i) (see Fabrycky & Winn (2009) for details). When β deviates significantly from zero this provides us with a lower limit for the ψ. When β is beyond 90° this means that the orbital spin is opposite to the stellar rotation providing that the orbit does not transit the star between its pole and its limb ($90° - i < I$). By combining $V\,sin\,I$, and the estimated age the star one can exclude a small I angle. Taken together with the large β value, we are led to the conclusion that a true retrograde orbit is the most likely scenario to consider for *WASP-8b*.

The origin of the unusual shape and the orientation of the orbit of *WASP-8b* is possibly related to the Kozai mechanism (Kozai 1962; Wu & Murray 2003) or the outcome of a violent dynamical interaction history. The evidence for two other bodies with a possible cascade of secular effects make the *WASP-8* system unique and interesting for further dynamical studies and a test case for formation scenarios for hot Jupiters alternative to the disc-migration mechanism (Lin et al. 1996).

References

Baranne, A., et al. 1996, A&AS, 119, 373
Barker, A. J., & Ogilvie, G. I. 2009, MNRAS, 395, 2268
Blackwell, D. E., & Shallis, M. J. 1977, MNRAS, 180, 177
Cameron, A. C., et al. 2007, MNRAS, 375, 951
Collier Cameron, A., et al. 2007, MNRAS, 380, 1230
Duquennoy, A., & Mayor, M. 1991, A&A, 248, 485
Fabrycky, D. C., & Winn, J. N. 2009, ApJ, 696, 1230
Gillon, M., et al. 2009, A&A, 496, 259
Giménez, A. 2006, ApJ, 650, 408
Girardi, L., Bressan, A., Bertelli, G., & Chiosi, C. 2000, A&AS, 141, 371
Israelian, G., et al. 2009, Nature, 462, 189
Kozai, Y. 1962, AJ, 67, 591
Lin, D. N. C., Bodenheimer, P., & Richardson, D. C. 1996, Nature, 380, 606
Mandel, K., & Agol, E. 2002, ApJ, 580, L171
Mason, B. D., Wycoff, G. L., Hartkopf, W. I., Douglass, G. G., & Worley, C. E. 2001, AJ, 122, 3466
Nagasawa, M., Ida, S., & Bessho, T. 2008, ApJ, 678, 498
Pepe, F., Mayor, M., Galland, F., Naef, D., Queloz, D., Santos, N. C., Udry, S., & Burnet, M. 2002, A&A, 388, 632
Pollacco, D. L., et al. 2006, PASP, 118, 1407
Queloz, D., et al. 2000, A&A, 354, 99
Queloz, D., et al. 2001, A&A, 379, 279
Smalley, B. 2005, Memorie della Societa Astronomica Italiana Supplement, 8, 130
Sestito, P., & Randich, S. 2005, A&A, 442, 615
Triaud, A. H. M. J., et al. 2009, A&A, 506, 377
Udry, S., & Santos, N. C. 2007, ARA&A, 45, 397
Winn, J. N. 2010, arXiv:1001.2010
Wu, Y., & Murray, N. 2003, ApJ, 589, 605
Zacharias, N., Monet, D. G., Levine, S. E., Urban, S. E., Gaume, R., & Wycoff, G. L. 2004, Bulletin of the American Astronomical Society, 36, 1418