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WASP-32b: A Transiting Hot Jupiter Planet Orbiting a Lithium-Poor, Solar-Type Star

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ABSTRACT. We report the discovery of a transiting planet orbiting the star TYC 2-1155-1. The star, WASP-32, is a moderately bright ($V = 11.3$) solar-type star ($T_{\rm eff} = 6100 \pm 100$ K, [Fe/H] $= -0.13 \pm 0.10$). The light curve of the star obtained with the WASP-South and WASP-North instruments shows periodic transitlike features with a depth of about 1% and a duration of 0.10 day every 2.72 days. The presence of a transitlike feature in the light curve is confirmed using z-band photometry obtained with Faulkes Telescope North. High-resolution spectroscopy obtained with the Coralie spectrograph confirms the presence of a planetary mass companion. From a combined analysis of the spectroscopic and photometric data, assuming that the star is a typical main-sequence star, we estimate that the planet has a mass $M_{\rm p}$ of $3.60 \pm 0.07\ M_{\rm Jup}$ and a radius $R_{\rm p} = 1.19 \pm 0.06\ R_{\rm Jup}$. WASP-32 is one of a small group of hot Jupiters with masses greater than $3\ M_{\rm Jup}$. We find that some stars with hot Jupiter companions and with masses $M_\star \approx 1.2\ M_\odot$, including WASP-32, are depleted in lithium and that the majority of these stars have lithium abundances similar to field stars.

1. INTRODUCTION

The Wide Angle Search for Planets (WASP) project (Pollacco et al. 2006) is currently one of the most successful wide-area surveys designed to find exoplanets transiting relatively bright stars. Other successful surveys include Hungarian-made Automated Telescope Network (HATnet; Bakos et al. 2004), XO (McCullough et al. 2005), and Trans-Atlantic Exoplanet Survey (TrES; O'Donovan et al. 2006). The Kepler satellite is now also starting to find many transiting exoplanets (Borucki et al. 2010). There is continued interest in finding transiting exoplanets, because they can be accurately characterized and studied in some detail; e.g., the mass and radius of the planet can be accurately measured. This gives us the opportunity to explore the relationships between the density of the planet and other properties of the planetary system: e.g., the semimajor axis, the composition and spectral type of the star, etc. Given the wide variety of transiting planets being discovered and the large number of parameters that characterize them, statistical studies will require a large sample of systems to identify and quantify the relationships between these parameters. These relationships can be used to test models of the formation, structure, and evolution of short-period exoplanets. Here, we report the discovery of a hot Jupiter companion to the star WASP-32 and show that this star is lithium-poor, compared with other stars of similar mass.

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2. OBSERVATIONS

The two WASP instruments each consist of an array of eight cameras with Canon 200 mm f/1.8 lenses and 2048× 2048 e2v CCD detectors providing images with a field of view of $7.8° \times 7.8°$ at an image scale of $13.7''$ pixel^{-1} (Pollacco et al. 2006; Wilson et al. 2008). The star TYC 2-1155-1 (=1 SWASP J001550.81 + 011201.5) was observed 5906 times in one camera of the WASP-South instrument in Sutherland, South Africa, during the interval from 2008 June 30 to 2008 November 17. Our transit detection algorithm (Collier Cameron et al. 2007) identified a periodic feature with a depth of approximately 0.01 magnitudes recurring with a 2.72 day period in these data. The width and depth of the transit are consistent with the hypothesis that it is due to a planet with a radius of approximately $1\ R_{\rm Jup}$ orbiting a solar-type star. The proper motion and catalog photometry available for TYC 2-1155-1 suggest that it is a mid-F-type main-sequence star. We therefore added this star to our program of follow-up observations for candidate planet-host stars.

A further 4156 observations of TYC 2-1155-1 were secured with WASP-South in the interval from 2009 June 28 to 2009 November 18. TYC 2-1155-1 was also observed by the WASP-North instrument 2687 times during the interval from 2008 August 4 to 2008 November 30 and 4308 times during the interval from 2009 August 5 to 2009 October 20. All these data are shown as a function of phase in Figure 1. All photometric data presented are this article are available from the NStED (NASA/IPAC/NExScI Star and Exoplanet Database).[9]

We obtained 15 radial velocity measurements of WASP-32 during the interval from 2009 September 1 to 2009 December 22 with the Coralie spectrograph on the Euler 1.2 m telescope located at La Silla, Chile (Table 1). The amplitude of the radial velocity variation with the same period as the transit light curve (Fig. 2) and the lack of any correlation between this variation and the bisector span establish the presence of a planetary mass companion to this star (Queloz et al. 2001).

We obtained further photometry of TYC 2-1155-1 and other nearby stars on 2009 December 7 using the fs03 spectral camera on the Las Cumbres Observatory Global Telescope network's 2.0 m Faulkes Telescope North (FTN) at Haleakala, Maui, in order to better define the depth and width of the transit signal. The spectral camera used a 4096×4096 pixel Fairchild CCD with 15 μm pixels that were binned 2×2, giving an image scale of $0.303''$ pixel^{-1} and a field of view of $10' \times 10'$. We used a Panoramic Survey Telescope and Rapid Response System (Pan-STARRS) z filter to obtain 187 images covering one egress of the transit. These images were preprocessed using the WASP Pipeline (Pollacco et al. 2006) using a combined bias and flat frame, and the DAOPHOT photometry package (Stetson 1987) was used within the IRAF[10] environment to perform object detection and aperture photometry with an aperture size of 9 binned pixels in radius. Differential magnitudes were derived by combining the flux of 11 stable comparison stars that were within the instrumental field of view. The resulting light curve is shown in Figure 3. The coverage of the out-of-transit phases is quite limited, but the data are sufficient to confirm that transitlike features seen in the WASP data are due to the star TYC 2-1155-1 and to provide precise measurements of the depth of the transit and the duration of egress.

3. WASP-32 STELLAR PARAMETERS

The 15 individual Coralie spectra of WASP-32 were co-added to produce a single spectrum with an approximate signal-to-noise ratio of around 80:1. The standard pipeline reduction products were used in the analysis.

The analysis was performed using the methods given in Gillon et al. (2009b). The H_α line was used to determine the effective temperature ($T_{\rm eff}$), while the Na I D and Mg I b lines were used as surface gravity ($\log g$) diagnostics. The elemental abundances were determined from equivalent width measurements of several clean and unblended lines. Atomic line data were mainly taken from the Kurucz and Bell (1995) compilation, but with updated van der Waals broadening coefficients for lines in Barklem et al. (2000) and $\log gf$ values from Gonzalez and Laws (2000), Gonzalez et al. (2001), or Santos et al. (2004). Individual lines abundances were determined from the measured equivalent widths. The mean values relative to solar are given in Table 2.

A value for microturbulence (ξ_t) was determined from the Fe I lines using Magain's (1984) method. The quoted error

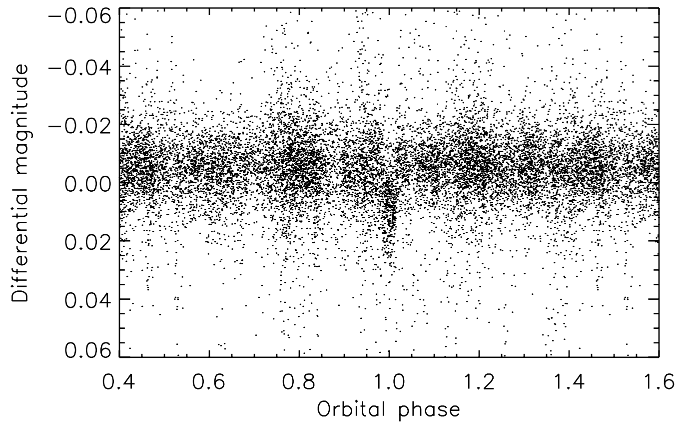

FIG. 1.—WASP photometry of WASP-32 folded on the orbital period $P = 2.71866$ days.

TABLE 1
RADIAL VELOCITY MEASUREMENTS OF STAR WASP-32

BJD −2,450,000	Radial velocity (km s^{-1})	$\sigma_{\rm RV}$ (km s^{-1})	Bisector span[a] (km s^{-1})
5075.8412	17.883	0.019	0.008
5117.6744	18.922	0.123	0.088
5125.6262	18.674	0.018	0.041
5126.6901	18.147	0.015	−0.027
5127.6192	17.980	0.014	0.009
5127.7019	18.003	0.016	0.018
5128.6424	18.761	0.015	0.024
5128.6669	18.739	0.018	0.090
5129.5810	17.976	0.016	0.003
5129.6984	17.866	0.016	−0.022
5179.5626	18.271	0.014	0.015
5180.5828	18.641	0.012	0.052
5181.5665	17.805	0.013	0.060
5185.5560	18.739	0.015	0.055
5188.5509	18.773	0.019	0.063

[a] Standard error of the bisector span measurements is $2\sigma_{\rm RV}$.

[9] See http://nsted.ipac.caltech.edu/.

[10] IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy (AURA) under cooperative agreement with the National Science Foundation.

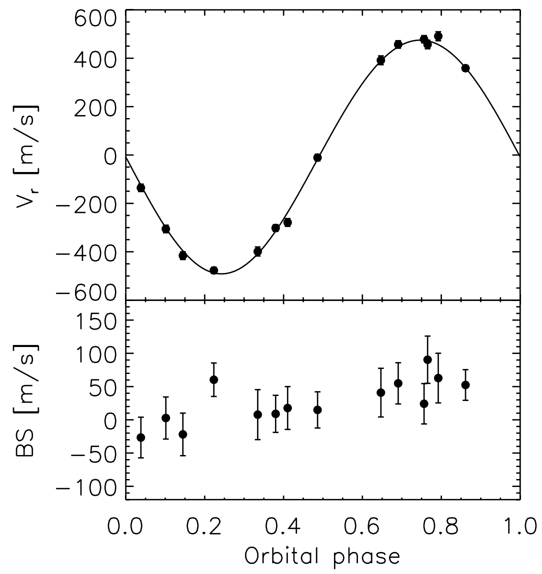

FIG. 2.—Radial velocity and bisector span measurements for WASP-32. *Upper panel*: Radial velocity data (points with error bars) with our model for the spectroscopic orbit (*solid line*). *Lower panel*: Bisector span measurements. (One point with large error bars is not shown here.)

estimates include those given by the uncertainties in $T_{\rm eff}$, log g, and ξ_t, as well as the scatter due to measurement and atomic data uncertainties.

The projected stellar rotation velocity ($v \sin i$) was determined by fitting the profiles of several unblended Fe I lines. A value for macroturbulence ($v_{\rm mac}$) of 4.7 ± 0.3 km s^{-1} was assumed, based on the tabulation by Gray (2008), and an instrumental FWHM of 0.11 ± 0.01 Å, determined from the telluric lines around 6300 Å. A best-fitting value of $v \sin i = 4.8 \pm 0.8$ km s^{-1} was obtained.

3.1. Planetary Parameters

The Coralie radial velocity measurements were combined with the WASP-South, WASP-North, and FTN z-band photometry in a simultaneous Markov-chain Monte Carlo (MCMC)

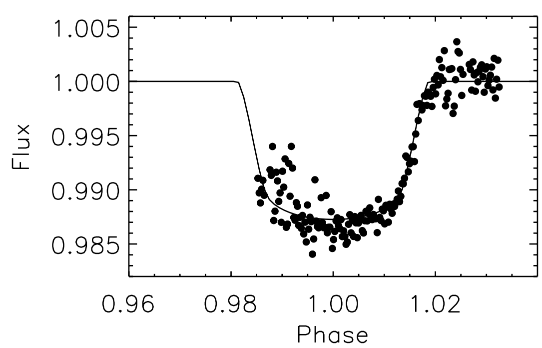

FIG. 3.—FTN z-band photometry of the transit of WASP-32 (*points*) together with a model light curve for our best-fitting model parameters (*solid line*).

TABLE 2
STELLAR PARAMETERS OF WASP-32 FROM SPECTROSCOPIC ANALYSIS

Parameter	Value
$T_{\rm eff}$ (K)	6100 ± 100
log g	4.4 ± 0.2
ξ_t (km s^{-1})	1.2 ± 01
$v \sin i$ (km s^{-1})	4.8 ± 0.8
[Fe/H]	-0.13 ± 0.10
[Si/H]	-0.06 ± 0.10
[Ca/H]	-0.02 ± 0.12
[Ti/H]	-0.07 ± 0.10
[Cr/H]	-0.10 ± 0.09
[Ni/H]	-0.16 ± 0.08
log A(Li)	1.58 ± 0.11

TABLE 3
SYSTEM PARAMETERS FOR WASP-32

Parameter (unit)	Value	Note
P (days)	2.718659 ± 0.000008	Orbital period
T_c (HJD)	$2{,}455{,}151.0546 \pm 0.0005$	Time of midtransit
T_{14} (days)	0.101 ± 0.002	Transit duration
T_{12} (days)	0.0161 ± 0.0015	Ingress duration
$\Delta F = R_{\rm P}^2/R_*^2$	0.0124 ± 0.0004	...
$b = a\cos(i)/R*$	0.64 ± 0.04	...
i (°)	85.3 ± 0.5	Orbital inclination
K_1 (m s^{-1})	487 ± 5	Semi-amplitude of spectroscopic orbit
γ (m s^{-1})	$18{,}281 \pm 1$	Radial velocity of barycenter
$e\cos\omega$	-0.015 ± 0.006	...
$e\sin\omega$	0.007 ± 0.011	...
e	0.018 ± 0.0065	Orbital eccentricity
ω	130 ± 30	Longitude of periastron
M_* ($M_\odot$)	1.10 ± 0.03	Stellar mass
R_* ($R_\odot$)	1.11 ± 0.05	Stellar radius
log g_* (cgs)	4.39 ± 0.03	Logarithmic stellar surface gravity
ρ_* ($\rho_\odot$)	0.80 ± 0.10	Mean stellar density
$M_{\rm P}$ ($M_{\rm Jup}$)	3.60 ± 0.07	Planetary mass
$R_{\rm P}$ ($R_{\rm Jup}$)	1.18 ± 0.07	Planetary radius
log $g_{\rm P}$ (cgs)	3.77 ± 0.04	Logarithmic planetary surface gravity
$\rho_{\rm P}$ ($\rho_{\rm J}$)	2.2 ± 0.4	Mean planetary density
a (AU)	0.0394 ± 0.0003	Semimajor axis of the orbit
$T_{\rm P}$[a] (K)	1560 ± 50	Planetary equilibrium temperature

NOTE.—An assumed main-sequence mass-radius relation is imposed as an additional constraint in this solution, so the mass and radius of the star are not independent parameters—see Collier Cameron et al. (2007) for details.

[a] The planet equilibrium temperature, $T_{\rm P}$, is calculated assuming a value for the Bond albedo $A = 0$.

analysis to find the parameters of the WASP-32 system. The shape of the transit is not well defined by the available photometry, so we have imposed an assumed main-sequence mass-radius relation as an additional constraint in our analysis of the data. The stellar mass is determined from the parameters $T_{\rm eff}$, $\log g$, and [Fe/H] using the procedure described by Enoch et al. (2010). The code uses $T_{\rm eff}$ and [Fe/H] as MCMC jump variables, constrained by Bayesian priors based on the spectroscopically determined values given in Table 2. The parameters derived from our MCMC analysis are listed in Table 3.

Note that in contrast to previous analyses of this type, we now use the parameters $\sqrt{e}\cos\omega$ and $\sqrt{e}\sin\omega$ in the MCMC analysis. This removes a bias in the analysis toward larger values of e; i.e., using $e\cos\omega$ and $e\sin\omega$ effectively imposes a prior probability distribution for $e \propto e^2$, whereas using $\sqrt{e}$ cos ω and $\sqrt{e}\sin\omega$ is equivalent to a uniform prior for e. Nevertheless, the MCMC solution suggests a marginal detection of a nonzero orbital eccentricity (2.8σ). This result can be confirmed by measuring the phase of the secondary eclipse, which is expected to be displaced from phase 0.5 by 40 minutes, given our best estimate of $e\cos\omega$.

The χ^2 value of the fit to our 15 radial velocity measurements is $\chi^2_{\rm rv} = 16.7$. There are six free parameters; P and T_0 are determined almost entirely by the light curves, K and γ are determined entirely by the radial velocity data, but e and ω are constrained by both data sets. The number of degrees of freedom is $N_{\rm df} \approx 15 - 3 = 12$. We did not consider it necessary to increase the standard errors of the radial velocity data to account for external noise due to stellar activity (jitter), since $\chi^2_{\rm rv} \approx N_{\rm df}$.

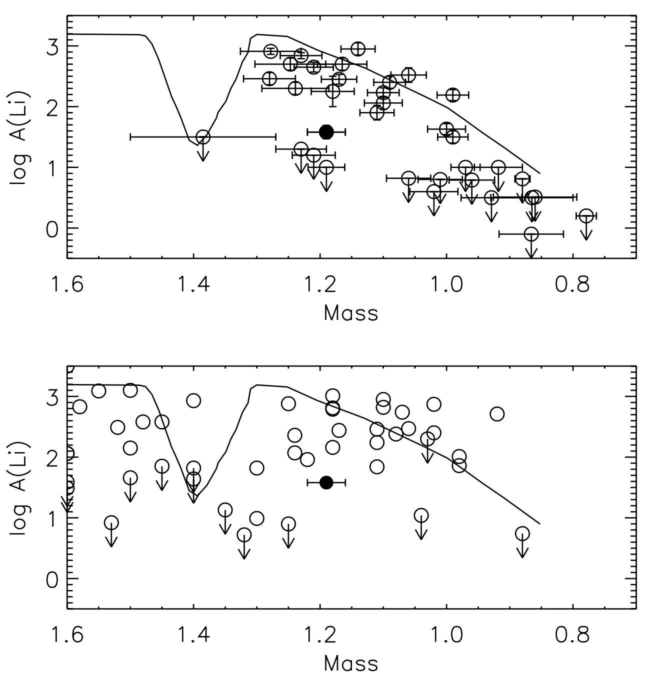

FIG. 4.—*Upper panel*: Lithium abundance as a function of stellar mass for transiting hot Jupiter planet-host stars. Upper limits are indicated with downward-pointing arrows. WASP-32 is plotted with a filled symbol. The solid line is the mean relation for the Hyades stars from Lambert and Reddy (2004). *Lower panel*: Lithium abundance for thin-disk stars with [Fe/H] > -0.2 from Lambert and Reddy.

TABLE 4
LITHIUM ABUNDANCES AND MASSES FOR PLANET-HOST STARS

Star	Mass ($M_\odot$)	log A (Li)	Reference
HD189733	0.87 ± 0.05	< -0.1	1,2
HD209458	1.17 ± 0.04	2.7 ± 0.1	1,2
OGLE-TR-10	1.24 ± 0.05	2.3 ± 0.1	1,2
OGLE-TR-56	1.25 ± 0.06	2.7 ± 0.1	1,2
OGLE-TR-111	0.86 ± 0.07	<0.51	1,2
OGLE-TR-113	0.78 ± 0.02	<0.2	3,2
TrES-1	0.93 ± 0.05	<0.5	1,2
WASP-1	1.28 ± 0.04	2.91 ± 0.05	1,4
WASP-2	0.88 ± 0.01	<0.81	1,5
WASP-3	1.22 ± 0.09	2.25 ± 0.25	6
WASP-4	0.96 ± 0.036	<0.79	7
WASP-5	1.02 ± 0.038	<0.6	7
WASP-6	0.87 ± 0.07	<0.5	8
WASP-7	1.19 ± 0.029	<1.0	9
WASP-8	0.99 ± 0.024	1.5 ± 0.1	10
WASP-12	1.28 ± 0.041	2.46 ± 0.1	11
WASP-13	1.10 ± 0.030	2.06 ± 0.1	12
WASP-14	1.23 ± 0.033	2.84 ± 0.05	13
WASP-15	1.21 ± 0.034	<1.2	14
WASP-16	1.01 ± 0.035	<0.8	15
WASP-17	1.23 ± 0.040	<1.3	16
WASP-18	1.21 ± 0.031	2.65 ± 0.08	17
WASP-19	0.97 ± 0.023	<1.0	18
WASP-20	1.09 ± 0.025	2.40 ± 0.10	19
WASP-21	0.99 ± 0.025	2.19 ± 0.09	20
WASP-22	1.10 ± 0.025	2.23 ± 0.08	21
WASP-24	1.17 ± 0.028	2.45 ± 0.08	22
WASP-25	1.00 ± 0.030	1.63 ± 0.09	23
WASP-26	1.11 ± 0.027	1.90 ± 0.12	24
WASP-28	1.06 ± 0.028	2.52 ± 0.12	25
WASP-30	1.14 ± 0.027	2.95 ± 0.10	26
WASP-32	1.19 ± 0.030	1.58 ± 0.11	
WASP-34	1.06 ± 0.035	<0.82	27
TrES-3	0.92 ± 0.04	<1.0	28
TrES-4	1.39 ± 0.10	<1.5	28

REFERENCES.—(1) Southworth 2009; (2) Melo et al. 2006; (3) Torres et al. 2008; (4) Santos et al. 2006; (5) Smalley (private communication, 2010); (6) Pollacco et al. 2008; (7) Gillon et al. (2009b); (8) Gillon et al. 2009a; (9) Hellier et al. 2009b; (10) Queloz et al. 2010; (11) Smalley (private communication, 2010); (12) Skillen et al. 2009; (13) Joshi et al. 2009; (14) West et al. 2009; (15) Lister et al. 2009; (16) Anderson et al. 2010; (17) Hellier et al. 2009a; (18) Hebb et al. 2010; (19) Pollacco et al. 2010 (in preparation); (20) Bouchy et al. 2010; (21) Maxted et al. 2010; (22) Street et al. 2010; (23) Enoch et al. 2010 (in preparation); (24) Smalley et al. 2010; (25) West et al. 2010 (in preparation); (26) Anderson et al. 2010 (in preparation); (27) Smalley et al. 2010 (in preparation); (28) Sozzetti et al. 2009

The log g value derived from our MCMC solution is consistent with the log g value from the analysis of the spectrum, although this is a rather weak constraint, because the log g value from the analysis of the spectrum has a much larger uncertainty.

4. DISCUSSION AND CONCLUSIONS

Of the 69 transiting planets currently known with directly measured masses, only 11 (including WASP-32b) have masses greater than 3 M_{Jup}.[11] The discovery of WASP-32b will improve our understanding of how the properties of hot Jupiters vary with the planet's mass.

Israelian et al. (2009) claim that, on average, stars with planets have a lower lithium abundance than normal solar-type stars in the effective temperature range of 5600–5900 K. Sousa et al. (2010) claim that this result was not a consequence of the distribution of age or mass of the planet-host stars. Both of these claims have been disputed by Baumann et al. (2010), who find that the apparent connection between lithium abundance and the presence of an exoplanet in the sample of Israelian et al. (2009) can be explained by subtle biases in their sample. Israelian et al. did not identify any peculiarities in the pattern of lithium abundance for planet-host stars with $T_{\mathrm{eff}} \gtrsim 5850$ K. The trend of lithium abundance becomes more complex when these hotter, more massive, stars are considered. The relation between mass and T_{eff} also depends on the age and metallicity of the star, so the trend is only seen clearly if plotted as a function of mass, not T_{eff}.

For field stars with accurate parallaxes, T_{eff}, [Fe/H], and log g measurements, the mass of the star can be estimated by comparison with stellar models. Lambert and Reddy (2004) estimated the mass of 451 F-G stars using this method and compared their surface lithium abundance with similar stars in various open clusters. Their trend of lithium abundance versus mass for Hyades stars is shown in Figure 4, together with their results for F-G stars with $[\mathrm{Fe/H}] > -0.2$. The location of the prominent dip in the lithium abundance near masses of $1.4\ M_{\odot}$ moves to lower masses for stars with lower metallicities. The upper limit $T_{\mathrm{eff}} \approx 5850$ K used by Israelian et al. (2009) corresponds to a mass of approximately $1.1\ M_{\odot}$.

Also shown in Figure 4 are the measured lithium abundances for the transiting hot Jupiter systems listed in Table 4. Stellar masses for WASP planets in Table 4 have been recalculated using the method of Enoch et al. (2010) using the data specified in the reference provided, unless otherwise noted. The metallicities of these stars are similar to the field stars shown in this figure. The tendency suggested by Israelian et al. (2009) for planet-host stars with masses $\lesssim 1.1\ M_{\odot}$ to be lithium-poor is also seen to be present for transiting hot Jupiter planets. However, as Baumann et al. (2010) have shown, this tendency may be a consequence of the age and metallicity distribution of the samples and may be unconnected to the presence or absence of a planetary companion.

For more massive hot Jupiter systems there are a few hot Jupiter systems that are strongly lithium-depleted, but the majority of these more massive host stars have similar lithium abundances to field F-G stars. The position of WASP-32 in this diagram shows that there is a continuous range of lithium depletion for planet-host stars with masses of about $1.2\ M_{\odot}$. There is no obvious correlation between the properties of the stars or their planets and the degree of lithium depletion. A more detailed analysis of this issue would benefit from a homogeneous set of age and metallicity estimates for the host stars of hot Jupiter planets.

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[11] See http://exoplanet.eu.

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