The Astrophysical Journal, 656:552–559, 2007 February 10

HAT-P-1b: A LARGE-RADIUS, LOW-DENSITY EXOPLANET TRANSITING ONE MEMBER OF A STELLAR BINARY[1,2]

G. Á. Bakos,[3,4] R. W. Noyes,[3] G. Kovács,[5] D. W. Latham,[3] D. D. Sasselov,[3] G. Torres,[3] D. A. Fischer,[6] R. P. Stefanik,[3] B. Sato,[7] J. A. Johnson,[8] A. Pál,[9,3] G. W. Marcy,[8] R. P. Butler,[10] G. A. Esquerdo,[3] K. Z. Stanek,[11] J. Lázár,[12] I. Papp,[12] P. Sári,[12] and B. Sipőcz[9,3]
Received 2006 August 12; accepted 2006 September 21

ABSTRACT

Using small automated telescopes in Arizona and Hawaii, the HATNet project has detected an object transiting one member of the double star system ADS 16402. This system is a pair of G0 main-sequence stars with age about 3 Gyr at a distance of ~139 pc and projected separation of ~1550 AU. The transit signal has a period of 4.46529 days and depth of 0.015 mag. From follow-up photometry and spectroscopy, we find that the object is a "hot Jupiter" planet with mass about $0.53 M_J$ and radius $\sim 1.36 R_J$ traveling in an orbit with semimajor axis 0.055 AU and inclination about 85.9°, thus transiting the star at impact parameter 0.74 of the stellar radius. Based on a data set spanning 3 yr, ephemerides for the transit center are $T_C = 2453984.397 + N_{tr} \times 4.46529$. The planet, designated HAT-P-1b, appears to be at least as large in radius, and smaller in mean density, than any previously known planet.

Subject headings: binaries: general — planetary systems — stars: individual (ADS 16402AB)

Online material: color figure

1. INTRODUCTION AND SUMMARY

The 10 currently known transiting extrasolar planets occupy a special place among the nearly 200 known exoplanets because their photometric transits yield unambiguous information on their masses and radii. Five of these transiting planets were found through spectroscopic and photometric follow-up of candidates discovered by the OGLE project (these are OGLE-TR-10b, OGLE-TR-56b, OGLE-TR-111b, OGLE-TR-113b, and OGLE-TR-132b; Udalski et al. 2002a, 2002b, 2002c, 2003, 2004, respectively). For references to the follow-up confirmation papers for these objects, see the Extrasolar Planets Encyclopedia.[13] The parent stars of these planets are all rather faint, making effective follow-up somewhat difficult. The other five[14] transiting exoplanets orbit nearby, bright stars: HD 209458b (Charbonneau et al. 2000; Henry et al. 2000), TrES-1 (Alonso et al. 2004), HD 149026b (Sato et al. 2005), HD 189733b (Bouchy et al. 2005), and XO-1b (McCullough et al. 2006). These planets are of special interest, as accurate parameter determination as well as other types of follow-up are possible. For this reason, a number of wide-field surveys using small telescopes are underway (see, e.g., Charbonneau et al. 2006a). Indeed, two of the five known transiting planets around nearby stars, TrES-1 and XO-1b, were detected by such surveys. (The other three were first detected by radial velocity measurements).

The HATNet project,[15] initiated in 2003 by G. Á. B, is also a wide-field survey that aims for the discovery of transiting planets around bright stars. It currently comprises six small wide-field automated telescopes, each of which monitors $8^\circ \times 8^\circ$ of sky, typically containing 5000 stars bright enough to permit detection of planetary transits through the typically 1% photometric dips they induce on their parent stars. The instruments are spread in a two-station, longitude-distributed network, with four telescopes at the F. L. Whipple Observatory (FLWO) in Arizona and two telescopes at the Submillimeter Array (SMA) in Hawaii. Technical aspects of HATNet will be described in a forthcoming paper, but for instrumentation, observations, and data flow, see Bakos et al. (2002, 2004). Here we report on the first detection by HATNet of a transiting extrasolar planet. This planet, which we hereafter label HAT-P-1b, orbits a tenth-magnitude star, and thus is well suited for follow-up with large ground-based and space telescopes.

The existence of HAT-P-1b was first inferred from a 0.6% (6 mmag) deep transit-like dip seen in the *I*-band light curve of the stellar system ADS 16402 (Aitken Double Star Catalogue; Aitken & Doolittle 1932), obtained by the combination of the HAT-5 instrument at FLWO and HAT-8 at the SMA. The members of this binary stellar system are a pair of nearly identical G0 V stars, ADS 16402A ($I \approx 9$) and ADS 16402B ($I \approx 9.6$), separated by 11.2″. The system appears as a single, elongated source in the HAT images because this separation is less than the 14″ pixel^{-1} image resolution. Initial follow-up spectroscopy at the FLWO 1.5 m telescope showed the absence of radial velocity variations of either star at a level of 1 km s^{-1} or larger, demonstrating that the source of the photometric dips could

[1] Based in part on data collected at the Subaru Telescope, which is operated by the National Astronomical Observatory of Japan.

[2] Based in part on observations obtained at the W. M. Keck Observatory, which is operated by the University of California and the California Institute of Technology. Keck time has been granted by NASA.

[3] Harvard-Smithsonian Center for Astrophysics (CfA), Cambridge, MA; gbakos@cfa.harvard.edu.

[4] Hubble Fellow.

[5] Konkoly Observatory, Budapest, Hungary.

[6] Department of Physics and Astronomy, San Francisco State University, San Francisco, CA; fischer@stars.sfsu.edu.

[7] Okayama Astrophysical Observatory, National Astronomical Observatory, Kamogata, Asakuchi, Okayama, Japan.

[8] Department of Astronomy, University of California, Berkeley, CA.

[9] Department of Astronomy, Eötvös Loránd University, Budapest, Hungary.

[10] Department of Terrestrial Magnetism, Carnegie Institute of Washington, DC.

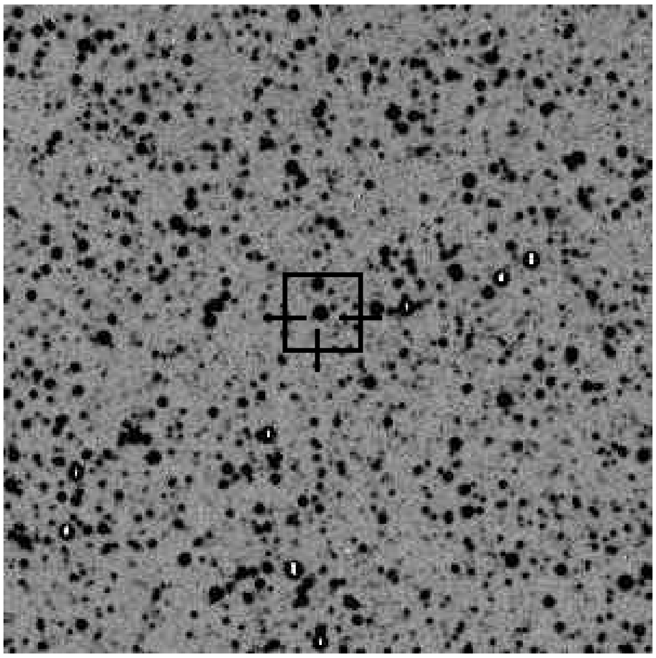
[11] Department of Astronomy, The Ohio State University, Columbus, OH.

[12] Hungarian Astronomical Association, Budapest, Hungary.

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

[14] Discovery of TrES-2 (O'Donovan et al. 2006) was announced during the refereeing of this paper.

[15] See http://www.hatnet.hu.



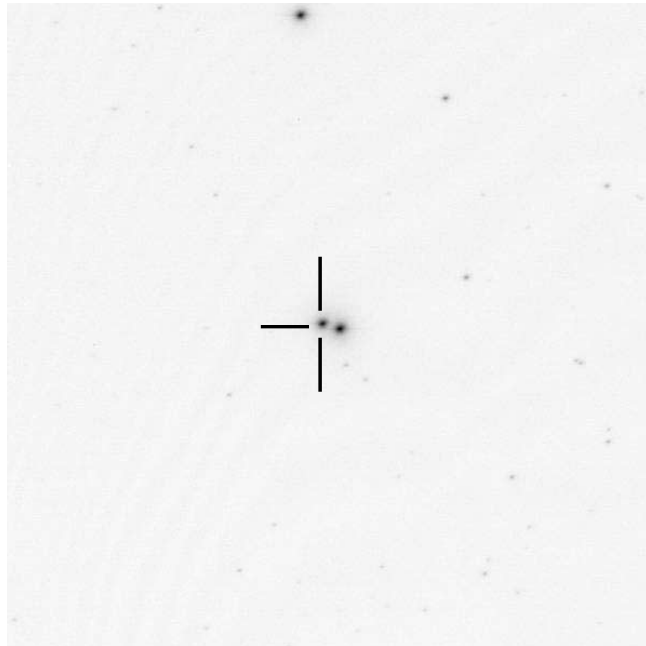


FIG. 1.—*Left*: 70′ × 70′ (300 pixels wide) stamp of a typical image taken by HAT-5. The stamp width is about 1/7 of the original frame. ADS 16402 is in the middle (the two components are merged into a bright star). Peaks of saturated stars are masked and shown in white. *Right*: Stamp from an image taken with the FLWO 1.2 m telescope. It is 6.8′ × 6.8′ (600 pixels wide) and corresponds to the small box on the left panel. ADS 16402B (marked with the cross) is well separated from ADS 16402A. [*See the electronic edition of the Journal for a color version of this figure.*]

not be due to a common false positive, namely an M dwarf star transiting in front of one of the stars. Subsequent spectroscopy at the Subaru telescope, using N2K project observing time (Fischer et al. 2005; Sato et al. 2005), and later at the W. M. Keck telescope revealed sinusoidal velocity variations of ADS 16402B with an amplitude of 60 m s^{-1}, thus suggesting the existence of a $0.5M_J$ planet transiting that star. After excluding blend scenarios, the combination of the photometric and spectroscopic data leads to the conclusion that this object, HAT-P-1b, is indeed a planet and has a radius comparable to that of HD 209458b and a somewhat lower mean density. In the remainder of this paper we discuss all of the above points in more detail.

2. OBSERVATIONS

2.1. *HATNet Discovery Photometry*

ADS 16402 (also BD +37 4734, $\alpha = 22^h57^m46.8^s$, $\delta = +38^\circ40'28''$, J2000.0) is a visual double star system that also bears the name HJ1832, as it was discovered by John Herschel (Herschel 1831). The system lies in HATNet survey field G205 (centered at $\alpha = 22^h55^m$, $\delta = +37^\circ30'$). Between 2003 October 13 and 2004 January 30, 2059 observations were made of this field by the HAT-5 telescope and 901 by HAT-8 . A small stamp taken from a typical HATNet image is shown on the left panel of Figure 1. Exposure times were 5 minutes at a cadence of 5.5 minutes. Light curves were derived by aperture photometry for the 6400 stars in G205 bright enough to yield photometric precision of better than 2% (reaching 0.3% in some cases). In deriving the light curves, we made use of the Trend Filtering Algorithm (TFA; Kovács et al. 2005) to correct for spurious trends in the data. This was particularly important for the light curve for ADS 16402, for which variable blending distorts the combined shape of the two close-lying unresolved components; indeed, the shallow transit signal in the combined light of the two stars is only barely visible in the raw light curve, while it is readily seen after application of TFA.

We then searched all the light curves for characteristic transit signals using the box-fitting least-squares (BLS; Kovács et al. 2002) algorithm, which seeks for box-shaped dips in the parameter space of frequency, transit duration, and phase of ingress. Candidate transit signals with the highest detection significance were then examined individually to isolate those with the best combination of stellar type (preferably main-sequence stars of spectral type mid-F or later), depth, shape, and duration of transit. One of these was ADS 16402, for which we identified a prominent boxcar-like periodicity with period 4.4656 days and transit depth in the combined light of the two stars of 6 mmag. Portions of five transits were observed during the observing interval. The upper panel of Figure 2 shows the combined data for these five transits, with different symbols for observations from HAT-5 (Arizona) and HAT-8 (Hawaii).

2.2. *Rejection-mode Spectroscopic Observations*

Initial follow-up observations were made with the CfA Digital Speedometer (DS; Latham 1992) in order to characterize the two individual stars comprising ADS 16402, as well as to search for evidence that the transit signal could be due to the transit of a late M dwarf in front of either of the stars, as has been found for many otherwise plausible planet transit candidates in the HATNet database. These observations indicated that both sources indeed have values of $T_{\rm eff}$ and $\log g$ consistent with main-sequence late F or early G dwarfs. The DS data revealed no sign of radial velocity variation in either of the two components, with upper limit of detection about 1.7 km s^{-1}. For a period of ~4.5 days this limit corresponds to a secondary mass of $15M_J$, thus ruling out the possibility that the transit signal is due to a low-mass stellar companion transiting one of the two stars.

2.3. *Follow-up Photometry Observations*

After identification of the ADS 16402 system as a candidate for harboring a transiting extrasolar planet, we used the TopHAT

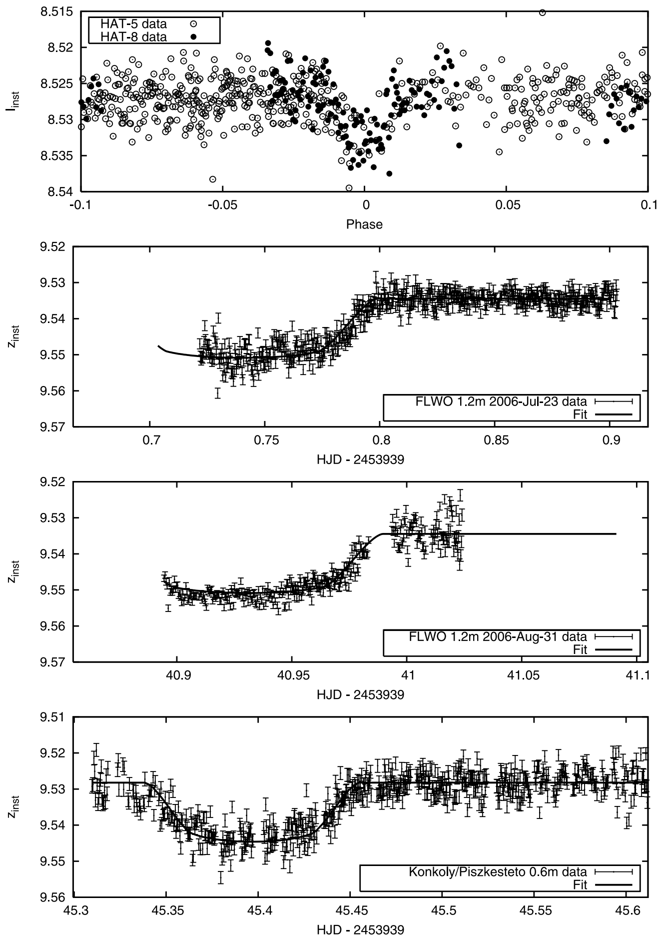


Fig. 2.—*Top*: HAT-5 (*open circles*) and HAT-8 (*filled circles*) TFA-corrected light curve from FLWO (Arizona) and SMA (Hawaii), respectively. Altogether, five transit events were observed successfully between the two sites. The data are phased at period $P = 4.46529$ days. Zero phase corresponds to the time of midtransit using the ephemeris discussed in the text. *Second and third panels*: Follow-up observations taken with KeplerCam on the FLWO 1.2 m telescope in *z* band on 2006 July 23 and 2006 August 31, respectively. Unfortunately, only the central and egress portions of the transit were observable. *Bottom*: The *I*-band data of a full transit taken by the Konkoly Observatory 0.6 m Schmidt telescope on 2006 September 5. Superimposed on the lower three panels are our best fits (§ 6) to the transit light curve.

telescope to search for evidence of a transit. TopHAT is a 0.26 m aperture automated telescope at FLWO, part of the HATNet, designed for follow-up of transit candidates (Bakos et al. 2006). With its pixel scale of 2.2″ pixel^{-1} it is able to resolve the two stars in the system. However, data were taken during the commissioning phase of TopHAT, when it had strongly variable focus, and, furthermore, conditions were nonphotometric. Nevertheless, we identified in the data a transit ingress event associated only with the star ADS 16402B.

Recent much higher quality observations using KeplerCam on the FLWO 1.2 m telescope have confirmed this, revealing the egress from the transit on 2006 July 23, and later on 2006 August 31. A small stamp from an FLWO 1.2 m image that clearly shows the two components of ADS 16402AB is exhibited in the right panel of Figure 1. The FLWO 1.2 m data were reduced using our own aperture photometry software (FIHAT/`fiphot`; A. Pál et al. 2007, in preparation). The photometry on individual frames was then transformed to a selected reference frame using some 100 stars as comparison in the $23' \times 23'$ field provided by KeplerCam (we refer to this step as smooth magnitude transformation). The resulting light curve for ADS 16402B already showed a smooth transit curve with a very high signal-to-noise ratio (S/N), but low-amplitude systematic variations were present. As a final correction, we exploited the fact that ADS 16402B has an ideal comparison star, namely ADS 16402A, with almost identical brightness, spectral type, and spatial position. The data shown in the second and third panels of Figure 2 thus correspond to the differential magnitude of ADS 16402B to ADS 16402A after the smooth magnitude transformation procedure (shifted back to an arbitrary $z \approx 9.53$ out-of-transit level).

Unfortunately, both FLWO 1.2 m transit events were partial; thus, we sought further opportunities to observe a full transit. Such an event was observed recently in the *I* band on 2006 September 5 using the 60/90/180 cm Schmidt telescope at the Piszkéstető mountain station of the Konkoly Observatory. Data are shown on the bottom panel of Figure 2 and were reduced in a manner similar to the FLWO 1.2 m data.

The HATNet, TopHAT, FLWO 1.2 m, and Konkoly Schmidt data together span 1058 days, or 237 periods. Combining all the transit timings in these data, we find improved ephemerides, $T_C(\mathrm{HJD}) = E_0 + N_{\mathrm{tr}} P$, where $E_0 = 2453984.397 \pm 0.009$, $P = 4.46529 \pm 0.00009$ days, and N_{tr} refers to the number of transits since the recent Konkoly Schmidt observation, which is a full transit observation and hence has the best timing measurement.

2.4. *High-Precision Spectroscopic Observations*

In addition to obtaining photometry follow-up data with the FLWO 1.2 m telescope, we obtained precise Doppler measurements of both ADS 16402A and ADS 16402B with the High Dispersion Spectrograph (HDS) on the 8.2 m Subaru telescope (Noguchi 2002) to confirm the planetary nature of the HATNet photometric signal.

The HDS spectral format spans 3500–6100 Å over a mosaic of two CCDs, and the 0.8″ slit yielded a resolution ($\lambda/\Delta\lambda$) of 55000. With only four observations we determined that the brighter component, ADS 16402A, had low rms velocity scatter, while component ADS 16402B exhibited velocity variations that were well represented by a sine curve with an amplitude of about 60 m s^{-1}, a period equal to the photometric period, and a time of conjunction consistent with that predicted from the transit ephemeris. To improve phase coverage, nine observations of ADS 16402B were subsequently obtained at W. M. Keck telescope over eight nights in 2006 July using HIRES (Vogt et al. 1994). The spectrometer slit at Keck is 0.86″, yielding a similar spectral resolution of about 55000 with a spectral format from ~3200–8800 Å. The Subaru and Keck data were used to more fully characterize the stellar properties of the system (§ 3), as well as to obtain a definitive radial velocity orbit (§ 4).

3. STELLAR PROPERTIES OF THE ADS 16402 SYSTEM

3.1. *SME Analysis of the Individual Stars*

We have carried out spectral synthesis modeling of the iodine-free Keck template spectra for both ADS 16402A and ADS 16402B using the SME software (Valenti & Piskunov 1996), plus the wavelength ranges and atomic line data described by Valenti & Fischer (2005). Results for T_{eff}, log *g*, *v* sin *i*, and [Fe/H] for both stars are shown in the first four lines of Table 1. Given the derived values of T_{eff}, the stars appear to fit the MK classification of G0, rather than the F8 classification reported in the literature.

3.2. *Simultaneous Evolutionary-Track Fitting*

The two stars are very likely to comprise a physical pair for the following reasons. First, they have common proper motion

TABLE 1

Summary of Stellar Parameters for ADS 16402AB

Parameter	ADS 16402A	ADS 16402B
From SME Analysis (§ 3.1)		
$T_{\rm eff}$ (K)	6047 ± 56	5975 ± 45
log g	4.13 ± 0.10	4.45 ± 0.06
$v \sin i$ (km s^{-1})	7.1 ± 0.3	2.2 ± 0.2
[Fe/H] (dex)	+0.12 ± 0.05	+0.13 ± 0.02
Simultaneous Evolutionary-Track Fitting (§ 3.2)		
Mass ($M_\odot$)	1.16 ± 0.11	1.12 ± 0.09
Radius ($R_\odot$)	$1.23^{+0.14}_{-.010}$	$1.15^{+0.10}_{-0.07}$
log L_* ($L_\odot$)	0.26 ± 0.15	$0.18^{+0.17}_{-0.14}$
M_I (mag)	3.4 ± 0.3	3.7 ± 0.3
Age (Gyr)	3.6	
Z	0.025	
Other Parameters		
I (mag)	9.035 ± 0.05	9.563 ± 0.05
ΔI (mag)	0.53 ± 0.03	
Mean Distance (pc)	139^{+22}_{-19}	
Projected Separation (AU)	1550^{+250}_{-210}	

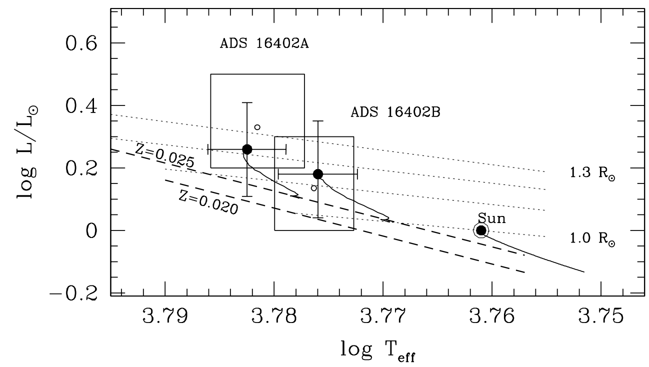


Fig. 3.—Stellar evolution tracks (*solid curved lines*) for ADS 16402A and B corresponding to the best mutual fit (*filled circles with error bars*). The two stars are physically bound, and they are assumed to be coeval and to have the same abundance, as determined by the SME analysis. Initial parameters from SME are shown with open circles with their respective (overlapping) error boxes. The two tracks stop at 3.6 Gyr, so that the line joining their endpoints defines the local isochrone. The straight dashed lines plot the ZAMS for metallicity $Z = 0.020$ and 0.025. For clarity, the ZAMS for $Z = 0.030$ is not shown in the figure; it is displaced by the same amount above the ZAMS for $Z = 0.025$ as the latter is above the ZAMS for $Z = 0.020$. Dotted lines illustrate lines of equal radius. The position of the Sun and its track to its current age are also shown.

(Halbwachs 1986). Second, their relative apparent magnitudes compared to the absolute magnitude expected for main-sequence stars with $T_{\rm eff}$ and log g given in Table 1 indicate that they are at a common distance. This also implies that their true tangential velocities are very similar and that their real separation is small (projected separation being ~1550 AU). Third, based on the six DS velocities for each star acquired over a time interval of 234 days, they have common radial velocity within the errors: $V_{\rm rad,A} = -3.43 \pm 0.32$(rms) $\pm$ 0.14(sys) km s^{-1} and $V_{\rm rad,B} = -2.94 \pm 0.56$(rms) $\pm$ 0.25(sys) km s^{-1}. Finally, they have identical metallicity within the uncertainties. The physical companionship implies that the two stars are coeval and provides the opportunity to perform simultaneous evolutionary-track fitting.

Furthermore, because of their common distance, the difference in their apparent magnitudes yields an accurate measurement of the ratio of their luminosities. The I magnitudes of ADS 16402A and ADS 16402B, respectively, are 9.03 and 9.56. These values were determined by cross-correlating the I magnitudes for the Landolt (1992) standard stars with the J, H, and K magnitudes of the 2MASS Point Source Catalogue (Skrutskie et al. 2006) and by deriving a weighted linear regression between J, H, K, and I. The linear relation based on ~400 stars is very well defined and has an rms of 0.06 mag. The I magnitude difference, $\Delta I = 0.53 \pm 0.03$, is more accurately determined than the individual magnitudes because the stars are nearly identical in spectral type and brightness, so that systematic errors are significantly canceled.

By exploiting the physical association of the two stars, their common abundances, age, and their known luminosity ratio, we carried out a simultaneous evolutionary-track fitting. This in turn leads to a much better determination of the parameters of ADS 16402B than would be the case if it were a single star.

Initial parameters (Fig. 3, *open circles*) and their error boxes (Fig. 3, *rectangles*) were based on the atmospheric parameters obtained with the SME analysis of the Subaru spectra. While the errors in $T_{\rm eff}$ are taken directly from Table 1, the absolute luminosities rely on the estimated gravity and iteration with the mass determination, and this procedure is imprecise. However, the ratio of the luminosities of the two stars is well constrained and is used in initializing the isochrone fitting to both stars.

The value of [Fe/H] found from spectral synthesis corresponds to the range of metal abundance by mass $Z = 0.020$–0.030. We have calculated stellar evolution tracks of ADS 16402A and ADS 16402B using Z in this range (Fig. 3). The straight line that would connect the centers of the two error boxes is steeper than the theoretical isochrones (the straight line that would connect the end tips of the two evolutionary tracks) for any Z in the range $Z = 0.020$–0.030. All possible solutions are some sort of compromise within the observational error boxes imposed by the requirement for equal age, with the obvious additional constraint that each track must begin on the zero-age main sequence (ZAMS) appropriate to the chosen value of Z. For different Z's, different mass ranges sweep the two error boxes, smaller ones for $Z = 0.020$ and progressively larger for higher Z. Their distribution is normal, i.e., symmetric. The observational error box of ADS 16402B, from the SME analysis (Fig. 3), overlaps with the ZAMS for any Z, and, naturally, the star cannot lie below the ZAMS for the accepted abundance, so this constrains the possible solution from the lower bounds of log g and log L. The distribution of possible stellar radii is asymmetric due to these constraints and this leads later to asymmetric error bars of the planetary radius.

Our best-fit theoretical isochrone is for $Z = 0.025$ and roughly bisects the line connecting the centers of the SME error boxes. This gives masses of 1.12 ± 0.09 $M_\odot$ and 1.16 ± 0.11 $M_\odot$ and radii of $1.15^{+0.10}_{-0.07}$ $R_\odot$ and $1.23^{+0.14}_{-0.10}$ $R_\odot$ for ADS 16402B and ADS 16402A, respectively, and an age of 3.6 Gyr for the system (see Table 1); we use these in the further analysis.

The absolute I magnitude of ADS 16402B is $M_I = 3.74 \pm 0.3$ mag (with bolometric correction of +0.55 mag). From its apparent I magnitude of 9.56 ± 0.06 mag (see above), and by neglecting reddening (being a nearby source at $b = 20°$), we derive a distance of 146^{+24}_{-21} pc. The same calculation for ADS 16402A yields 131^{+21}_{-17} pc. We estimate the distance of the ADS 16402AB system as the average of the two, 139 ± 20 pc. The 11.2″ separation of the two components then implies a projected separation of 1550 ± 250 AU. All derived stellar parameters, along with absolute and apparent I magnitudes, magnitude difference, mean

TABLE 2
RADIAL VELOCITIES FOR ADS 16402B

HJD−2453000 (days)	Radial Velocity ($m\ s^{-1}$)	Uncertainty ($m\ s^{-1}$)	Observatory
897.11285	−2.89	5.00	Subaru
899.12678	52.53	4.77	Subaru
900.12008	−34.51	4.65	Subaru
901.10260	−37.51	4.88	Subaru
927.06848	−37.76	3.84	Keck
927.96558	−28.27	3.90	Keck
931.03690	−12.10	3.83	Keck
931.94061	−46.59	3.92	Keck
932.03590	−42.95	3.83	Keck
932.99985	3.53	3.85	Keck
933.92455	66.16	4.04	Keck
934.90368	49.20	4.92	Keck
934.90692	49.21	4.00	Keck

distance, and projected separation of the stellar components of ADS 16402, are given in Table 1.

4. SPECTROSCOPIC ORBIT OF ADS 16402B

The Subaru HDS Doppler observations were obtained through an iodine absorption cell (in front of the spectrometer slit for this observing run) to provide a fiducial wavelength scale and to model the instrumental point spread function (Kambe et al. 2002). We measured the star's radial velocity from each high-resolution spectrum using a synthetic stellar template that was created by modifying a close-match spectrum from a library of high-resolution template spectra obtained at Keck (Johnson et al. 2006). Doppler velocities at Keck are also modeled from observations taken through an iodine cell; however, a standard template observation (obtained without the iodine cell) was used for the reference spectrum (Butler et al. 1996). Exposure times at both Subaru and Keck were typically 500 s, yielding an S/N of about 150.

Emission in the core of the Ca H and K lines was measured in each of the Keck spectra to assess the chromospheric activity of ADS 16402A and B. With five spectra for ADS 16402A, we measure an average value for $S_{\rm HK} = 0.16$, corresponding to $\log R'_{\rm HK} = -4.923$, for the A component, and an average value of nine spectra yields $S_{\rm HK} = 0.14$ and $\log R'_{\rm HK} = -5.03$ for the B component. These values indicate low chromospheric activity. Our estimate for intrinsic astrophysical velocity jitter is 3.7 $m\ s^{-1}$ for both stars (Wright 2005).

Radial velocity measurements from Subaru and Keck were used together to derive an orbital fit. The reference velocities were those from Keck, and an offset (Δ_v) between Subaru and Keck was also fitted for in the orbital solution. Velocity measurements are given in Table 2, along with observation times and errors. The velocity offset of $\Delta_v = 14.5\ m\ s^{-1}$ has been already applied to the Subaru data shown in the table, and the expected velocity jitter of 3.7 $m\ s^{-1}$ has already been added in quadrature to the uncertainties listed in the table. The photometric period of 4.46529 days and the midtransit time from the photometric ephemerides were fixed in this model. We also assumed zero eccentricity, based on the theoretical expectation of circular orbits for periods as short as this. In summary, the fitted parameters were the γ velocity of the Keck data points, the K semiamplitude, and the Δ_v velocity difference between Keck and Subaru. To determine the uncertainties, 100 Monte Carlo fitting trials were run. In each trial, the best-fit Keplerian model was subtracted from the velocities and the residuals were shuffled and added back with replacement to the theoretical velocities. From these trials, we

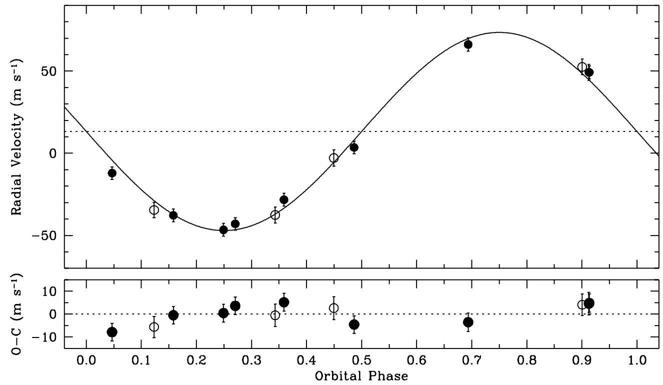


FIG. 4.—Radial velocities from Subaru and Keck, folded with the period of 4.46529 days. Phase 0 corresponds to the predicted time of midtransit from the orbital ephemeris given in text. Open circles represent Subaru data (after the 14.5 $m\ s^{-1}$ shift described in the text), and filled circles show Keck measurements.

find a velocity semiamplitude $K = 60.3 \pm 2.1\ m\ s^{-1}$, an rms of 5.11 $m\ s^{-1}$, and a reduced $\chi^2 = 1.54$. The final fit is overplotted on the radial velocity data in the upper panel of Figure 4. The lower panel shows the residuals.

Adopting a stellar mass of $1.12 \pm 0.09\ M_\odot$, we derive $a_{\rm rel} = 0.0551 \pm 0.0015$ AU and $m \sin i = 0.53 \pm 0.04 M_{\rm J}$. Using an inclination $i_P = 85.9° \pm 0.8°$ (§ 6 below), this yields a planetary mass $M_P = 0.53 \pm 0.04 M_{\rm J}$. The orbital elements and uncertainties are summarized in Table 3.

There is a small but nonnegligible systematic trend in the residuals of the orbital fit (lower panel of Fig. 4). We note that the fit is improved if the eccentricity and ω are allowed to float, and we get $e = 0.09 \pm 0.02$ and $\omega = 80.7° \pm 7.6°$ with rms of 3.2 $m\ s^{-1}$ and reduced $\chi^2 = 0.53$. The nonzero eccentricity is only suggestive, however, because of (1) the small number of data points, and (2) the unrealistically small reduced χ^2. Nevertheless, implications of this finding are potentially very important, and we elaborate further on them in the discussion (§ 7).

5. EXCLUDING BLEND SCENARIOS

We have investigated the possibility that the measured radial velocity variations are due not to a planetary companion but rather to distortions of spectral line profiles arising from contamination of the spectrum by the presence of an unresolved binary companion to ADS 16402B, with an orbital period of ~4.4653 days and an amplitude of several tens of km s^{-1}. However, this would give rise to time-varying asymmetry in the spectral line bisectors (see, e.g., Santos et al. 2002; Torres et al. 2005). We have searched for such line bisector variations in our Subaru spectra and find no

TABLE 3
PARAMETERS OF THE HAT-P-1b PLANETARY SYSTEM

Parameter	Value
Period (days)	4.46529 ± 0.00009[a]
$T_{\rm mid}$ (HJD)	2453984.397 ± 0.009[a]
ω (deg)	0[a]
Eccentricity	0[a]
K_1 ($m\ s^{-1}$)	60.3 ± 2.1
$a_{\rm rel}$ (AU)	0.0551 ± 0.0015
$m \sin i$ ($M_{\rm J}$)	0.53 ± 0.04
i_P (deg)	85.9 ± 0.8
M_P ($M_{\rm J}$)	0.53 ± 0.04
R_P ($R_{\rm J}$)	$1.36^{+0.11}_{-0.09}$

[a] Fixed in the orbital fit.

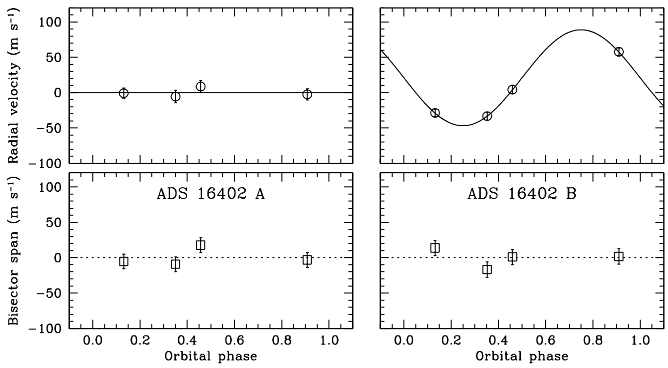


FIG. 5.—Comparison between the relative radial velocities and bisector spans of ADS 16402A (*left*) and ADS 16402B (*right*), based on the Subaru spectra. ADS 16402A shows no variation in either the velocity or the bisector spans (*left panels*), while ADS 16402B shows obvious velocity variations but does not show the variation in the bisector spans that would be expected if the velocity signal were the result of a blend with an eclipsing binary.

evidence for them. Comparison between the relative radial velocities and bisector spans of ADS 16402A and B is shown in Figure 5. The results are based on the Subaru spectra only because they were obtained on the same nights for both stars. Line bisectors for each spectrum were computed from the cross-correlation function averaged over all orders, which is representative of the average spectral line profile of the star. The cross-correlations were performed against a synthetic spectrum matching the properties of the stars. The bisector spans were then computed as the velocity difference between points chosen near the top and bottom of the bisectors (see Torres et al. 2005). ADS 16402A shows no variation in either the velocities or the bisectors spans. ADS 16402B, on the other hand, shows obvious velocity variations but does not show the concomitant change in the bisector spans that would be expected if it were the result of a blend with an eclipsing binary. If the light and velocity variations were the result of a blend with an eclipsing binary, the bisector spans would be expected to vary with a similar amplitude as the velocities (see, e.g., Queloz et al. 2001). That scenario is therefore ruled out by these observations.

We have also modeled the light curve as a blend, following Torres et al. (2004b), subject to all available observational constraints. Specifically, we calculated model light curves for a three-star system consisting of a slightly evolved early G star primary plus a later type secondary and a tertiary that together comprise an eclipsing binary, with the requirement that the brightness of the secondary be no more than ~10% that of the primary (to have escaped detection in the DS spectra) and that the light curve of the eclipsing binary, attenuated by the much brighter primary, should be indistinguishable from the observed light curve in the FLWO 1.2 m data. However, we have found it impossible to construct an acceptable light curve in this fashion.

Based on the above, we conclude that ADS 16402B is orbited by a transiting object that gives rise to the observed photometric and radial velocity variations. From the 60 m s^{-1} amplitude of the radial velocity orbit (§ 4), we conclude that the object must have mass about $0.53M_{\rm J}$ and hence must be an extrasolar planet.

6. THE TRANSITING PLANET HAT-P-1b AND ITS PROPERTIES

In order to determine more precisely the physical characteristics of HAT-P-1b and its orbital parameters, we have carried out model fitting of the different sets of photometric data shown in the four panels of Figure 2. A simple goodness of fit was determined against the predicted flux values evaluated with the algorithm of Mandel & Agol (2002). We used the values for the stellar radius and mass (and their uncertainties) determined above and coefficients for stellar limb darkening for the Sloan *z*-filter by Claret (2004). First we fitted the original discovery data from HATNet with the appropriate correction for the flux of the binary star (unresolved on the HATNet images); the $R_P = 1.42R_{\rm J}$ and $i_P = 85.4°$ have large uncertainties, as anticipated, and might be subject to large systematic errors. We then fitted to the recent Konkoly Schmidt observations of a complete HAT-P-1b transit in *I* band the values of $R_P = 1.31 \pm 0.07R_{\rm J}$ and $i_P = 86.0° \pm 1.0°$ and a precise estimate of transit duration of $d = 0.11671$ days and center of transit $T_c = 3984.3967$. The latter value allows us to estimate accurately the T_c of the transit we observed just an orbital period earlier (August 31) at FLWO, where the beginning of the ingress is missing (see Fig. 2, *third panel from the top*). Combining both *z*-band transit curves from FLWO with a known T_c allows an independent fit; we get $R_P = 1.36 \pm 0.05R_{\rm J}$ and $i_P = 85.9° \pm 0.8°$. The fit is better because the quality and amount of photometric data is higher, and the limb darkening in *z* band is less. The fits to all data sets give us the same planet parameters within the error; henceforth, we use our best fit with the FLWO *z*-band transits.

The result for the planetary radius is $R_P = 1.36^{+0.11}_{-0.09}R_{\rm J}$, where the above statistical errors from the fit and systematic errors from the uncertainties of the stellar radius and mass ($^{+0.09}_{-0.07}$), have been added in quadrature. Due to the asymmetric error bars on the stellar radius (see above) we have asymmetric error bars on R_P, too. The orbital inclination is $i_P = 85.9° \pm 0.8°$. The radius, orbital inclination, and derived mass of the planet are included in Table 3.

An even better light curve with, e.g., the *Hubble Space Telescope* and a more detailed analysis of the parameters of the stellar pair could reduce that error considerably. The results of this ongoing work will be reported in a forthcoming paper, as soon as the multiband observations enable us to refine the binary system parameters.

7. DISCUSSION

Figure 6 shows the location of HAT-P-1b in a plot of planetary radius versus planetary mass for the now 11 known transiting

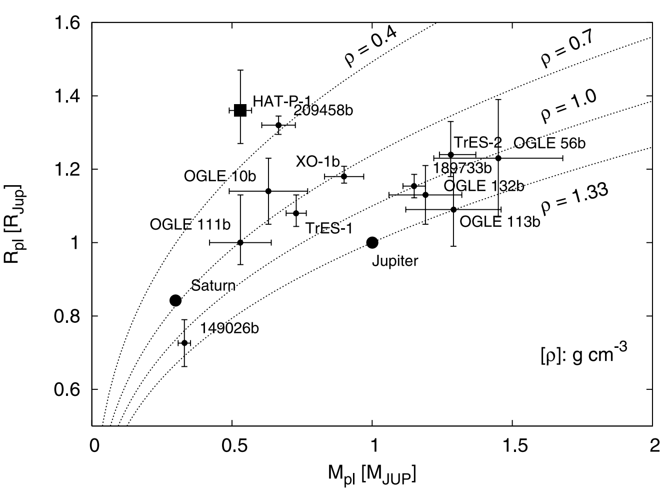


FIG. 6.—Mass-radius diagram depicting known transiting exoplanets plus Saturn and Jupiter (for comparison). Sources for the mass and radius values (in this order) are listed after the name of the planet: HAT-P-1b: this work; HD 209458b: Laughlin et al. (2005b), Knutson et al. (2007); HD 189733b: Bakos et al. (2006); OGLE-TR-111b: Pont et al. (2004); OGLE-TR-10b: Santos et al. (2006); OGLE-TR-132b: Moutou et al. (2004); OGLE-TR-56b: Torres et al. (2004a); OGLE-TR-113b: Bouchy et al. (2004), Konacki et al. (2004); TrES-1: Sozzetti et al. (2004); HD 149026: Sato et al. (2005), Charbonneau et al. (2006b); XO-1b: Holman et al. (2006); and TrES-2: O'Donovan et al. (2006).

exoplanets, plus Jupiter and Saturn. It is immediately apparent that HAT-P-1b is in an extreme position. It has a radius apparently as large as or larger than the largest known exoplanet, HD 209458b, and at the same time it has a mass that is significantly smaller. Thus, it has a lower mean density than any other known planet. Until now, HD 209458b was the only significantly anomalous transiting planet. Thus, Guillot (2005) noted that all of the transiting planets known at that time, with the exception of HD 209458b, fall within a mass-radius relation derived from modeling the interiors of strongly irradiated planets. All of the transiting planets detected subsequently, except HAT-P-1b, also fit the same relation. Among them, OGLE-TR-10b had been thought to be similarly anomalous (Konacki et al. 2005), but recent evidence (Holman et al. 2007; Santos et al. 2006; M. Holman 2006, private communication) points to a smaller planetary radius and normal density. Similarly, the XO-1b discovery paper (McCullough et al. 2006) derives a larger radius than the value later refined by Holman et al. (2006).

HD 209458b has a radius some 10%–20% larger than expected, given its age, mass, and expected temperature, including effects of irradiation. Possible solutions include (1) a fraction of a percent of the stellar flux irradiating HD 209458b could be transported to deep layers of order 100 bar and thereby keep the planet's radius puffed up (Showman & Guillot 2002), (2) there is a small eccentricity of its orbit forced by the presence of a so-far undetected planetary companion and leading to internal tidal heating (Bodenheimer et al. 2003), or (3) HD 209458b might be in a Cassini State, a dynamical state in which its rotation axis lies close to the plane of its orbit (Winn & Holman 2005), leading to large obliquity tides that cause heating at a significant depth, leading to the planet's large radius. A natural question about the first of these mechanisms is why all close-in hot Jupiters are not similarly bloated by that mechanism. A problem with the last two mechanisms is that both are ad hoc; they require unusual circumstances for which there is no independent evidence.

With the discovery of another planet, HAT-P-1b, which has a radius similar to and probably even larger than that of HD 209458b and an even smaller density, mechanisms requiring unusual circumstances seem less likely. Moreover, for HD 209458b, explanation 2 appears ruled out because Doppler data (Laughlin et al. 2005a; Winn et al. 2005) and transit timing variations data (Miller-Ricci et al. 2005) have excluded companion planets capable of enacting it.

In the case of HAT-P-1b, it remains possible that the system has a second planet capable of forcing its eccentricity and leading to internal tidal heating. Our current orbital solution (§ 4) suggests $e = 0.09 \pm 0.02$. If confirmed, such eccentricity would be a strong indication for the presence of a third body (second planet), because otherwise tidal dissipation would have circularized HAT-P-1b's orbit in $\sim 225(Q/10^6)$ Myr. The dissipation factor, Q, is poorly known for hot Jupiters, but is expected to lie between the values for Jupiter and solar-like stars (10^5–10^6). With forced orbital eccentricity $e = 0.09$, HAT-P-1b will be subject to internal tidal heating due to an energy dissipation rate

$$\frac{dE}{dt} = \frac{63}{4}\frac{e^2 n}{Q}\left(\frac{R_p}{a}\right)^5 \frac{GM_\star^2}{a},$$

where G is the gravitational constant, $M_\star$ is the mass of the star, a is the semimajor axis, n is the mean motion, and Q is the specific dissipation factor. With $e = 0.09$, the rate of energy dissipation in HAT-P-1b would be 3.0×10^{26} ergs s^{-1}, corresponding to energy dissipation per unit Jupiter mass of 5.7×10^{26} ergs s^{-1} M_J^{-1}. This rate is almost identical to the dissipation rate per unit Jupiter mass of 5.8×10^{26} ergs s^{-1} M_J^{-1} required to achieve a 20% increase in R_P for HD 209458b (no core model) and explain its anomalous low density (Bodenheimer et al. 2003). Therefore, we conclude that if the orbital eccentricity is confirmed, the anomalous R_P and low density of HAT-P-1b could be easily explained by tidal heating. The perturbing second planet would be detectable by both transit timing variations and Doppler velocities.

For now, however, all that can be said is that bloated planets are not that unusual, and, since a second perturbing planet is lacking in HD 209458b's case, perhaps some other explanation should be sought that can explain such planets more generally.

Operation of the HATNet project is funded in part by NASA grant NNG04GN74G. Support for program number HST-HF-01170.01-A to G. Á. B. was provided by NASA through a Hubble Fellowship grant from the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Incorporated, under NASA contract NAS5-26555. G. K. wishes to thank support from Hungarian Scientific Research Foundation (OTKA) grant K-60750. We acknowledge partial support from the *Kepler* Mission under NASA Cooperative Agreement NCC2-1390 (D. W. L., Principal Invesigator). G. T. acknowledges partial support from NASA Origins grant NNG04LG89G. We thank Akito Tajitsu for his expertise and support of the Subaru HDS observations. We thank graduate students M. Ohmiya, S. Robinson, and K. Peek for help collecting data at Subaru and Keck. The Keck Observatory was made possible by the generous financial support of the W. M. Keck Foundation. D. A. F is a Cottrell Science Scholar of Research Corporation. We acknowledge support from NASA grant NNG05G164G to D. A. F. We would like to thank Carl Akerlof and the decommissioned ROTSE-I project for the generous loan of some of the lenses and CCDs that we use for operating HATNet. We owe special thanks to Emilio Falco, Dan Fabricant, James Moran, and Antony Schinckel for their help in establishing and operating the HATNet stations at FLWO and SMA. G. Á. B. wishes to thank the support given by telescope operators Mike Calkins and Perry Berlind in the operation of the FLWO HATNet station. We also thank Gergely Gálfi for useful discussions. This publication made use of the VizieR interactive catalog (Ochsenbein et al. 2000) at CDS, Strasbourg, and the 2MASS catalog.

REFERENCES

Aitken, R. G., & Doolittle, E. 1932, New General Catalogue of Double Stars within 120 Degrees of the North Pole (Washington: Carnegie Institution)
Alonso, R., et al. 2004, ApJ, 613, L153
Bakos, G., Noyes, R. W., Kovács, G., Stanek, K. Z., Sasselov, D. D., & Domsa, I. 2004, PASP, 116, 266
Bakos, G. Á., Lázár, J., Papp, I., Sári, P., & Green, E. M. 2002, PASP, 114, 974
Bakos, G. Á., Pál, A., Latham, D. W., Noyes, R. W., & Stefanik, R. P. 2006, ApJ, 641, L57
Bodenheimer, P., Laughlin, G., & Lin, D. N. C. 2003, ApJ, 592, 555
Bouchy, F., Pont, F., Santos, N. C., Melo, C., Mayor, M., Queloz, D., & Udry, S. 2004, A&A, 421, L13
Bouchy, F., et al. 2005, A&A, 444, L15
Butler, R. P., Marcy, G. W., Williams, E., McCarthy, C., Dosanjh, P., & Vogt, S. S. 1996, PASP, 108, 500
Charbonneau, D., Brown, T. M., Burrows, A., & Laughlin, G. 2006a, Protostars and Planets V, ed. B. Reipurth, D. Jewitt, & K. Keil (Tucson: Univ. Arizona Press), 701
Charbonneau, D., Brown, T. M., Latham, D. W., & Mayor, M. 2000, ApJ, 529, L45

Charbonneau, D., et al. 2006b, ApJ, 636, 445
Claret, A. 2004, A&A, 428, 1001
Fischer, D. A., et al. 2005, ApJ, 620, 481
Guillot, T. 2005, Annu. Rev. Earth and Planet. Sci., 33, 493
Halbwachs, J. L. 1986, A&AS, 66, 131
Henry, G. W., Marcy, G. W., Butler, R. P., & Vogt, S. S. 2000, ApJ, 529, L41
Herschel, J. F. W. 1831, MmRAS, 4, 331
Holman, M., et al. 2006, ApJ, 652, 1715
———. 2007, ApJ, 655, 1103
Johnson, J., et al. 2006, ApJ, 647, 600
Kambe, E., et al. 2002, PASJ, 54, 865
Knutson, H., et al. 2007, ApJ, 655, 564
Konacki, M., Torres, G., Sasselov, D. D., & Jha, S. 2005, ApJ, 624, 372
Konacki, M., et al. 2004, ApJ, 609, L37
Kovács, G., Bakos, G., & Noyes, R. W. 2005, MNRAS, 356, 557
Kovács, G., Zucker, S., & Mazeh, T. 2002, A&A, 391, 369
Landolt, A. U. 1992, AJ, 104, 340
Latham, D. W. 1992, in IAU Colloq. 135, Complementary Approaches to Double and Multiple Star Research, ed. H. A. McAlister & W. I. Hartkopf (ASP Conf. Ser. 32; Chelsea: ASP), 110
Laughlin, G., Marcy, G. W., Vogt, S. S., Fischer, D. A., & Butler, R. P. 2005a, ApJ, 629, L121
Laughlin, G., et al. 2005b, ApJ, 621, 1072
Mandel, K., & Agol, E. 2002, ApJ, 580, L171
McCullough, P. R., et al. 2006, ApJ, 648, 1228
Miller-Ricci, E., et al. 2005, BAAS, 207, 11008
Moutou, C., Pont, F., Bouchy, F., & Mayor, M. 2004, A&A, 424, L31
Noguchi, K., et al. 2002, PASJ, 54, 855
Ochsenbein, F., Bauer, P., & Marcout, J. 2000, A&AS, 143, 23
O'Donovan, F. T., et al. 2006, ApJ, 651, L61
Pont, F., Bouchy, F., Queloz, D., Santos, N. C., Melo, C., Mayor, M., & Udry, S. 2004, A&A, 426, L15
Queloz, D., et al. 2001, A&A, 379, 279
Santos, N. C., et al. 2002, A&A, 392, 215
———. 2006, A&A, 450, 825
Sato, B., et al. 2005, ApJ, 633, 465
Showman, A. P., & Guillot, T. 2002, A&A, 385, 166
Skrutskie, M. F., et al. 2006, AJ, 131, 1163
Sozzetti, A., et al. 2004, ApJ, 616, L167
Torres, G., Konacki, M., Sasselov, D. D., & Jha, S. 2004a, ApJ, 609, 1071
———. 2004b, ApJ, 614, 979
———. 2005, ApJ, 619, 558
Udalski, A., Pietrzynski, G., Szymanski, M., Kubiak, M., Zebrun, K., Soszynski, I., Szewczyk, O., & Wyrzykowski, L. 2003, Acta Astron., 53, 133
Udalski, A., Szewczyk, O., Zebrun, K., Pietrzynski, G., Szymanski, M., Kubiak, M., Soszynski, I., & Wyrzykowski, L. 2002a, Acta Astron., 52, 317
Udalski, A., Szymanski, M. K., Kubiak, M., Pietrzynski, G., Soszynski, I., Zebrun, K., Szewczyk, O., & Wyrzykowski, L. 2004, Acta Astron., 54, 313
Udalski, A., Zebrun, K., Szymanski, M., Kubiak, M., Soszynski, I., Szewczyk, O., Wyrzykowski, L., & Pietrzynski, G. 2002b, Acta Astron., 52, 115
Udalski, A., et al. 2002c, Acta Astron., 52, 1
Valenti, J. A., & Fischer, D. A. 2005, ApJS, 159, 141
Valenti, J. A., & Piskunov, N. 1996, A&AS, 118, 595
Vogt, S. S., et al. 1994, Proc. SPIE, 2198, 362
Winn, J. N., & Holman, M. J. 2005, ApJ, 628, L159
Winn, J. N., et al. 2005, ApJ, 631, 1215
Wright, J. T. 2005, PASP, 117, 657