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PRECISE RADIUS ESTIMATES FOR THE EXOPLANETS WASP-1b AND WASP-2b

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ABSTRACT

We present precise *z*-band photometric time series spanning times of transit of the two exoplanets recently discovered by the SuperWASP collaboration. We find planetary radii of 1.44 ± 0.08 and 1.04 ± 0.06 R_J for WASP-1b and WASP-2b, respectively. These error estimates include both random errors in the photometry and also the uncertainty in the stellar masses. Our results are 5 times more precise than the values derived from the discovery data alone. Our measurement of the radius of WASP-2b agrees with previously published models of hot Jupiters that include both a 20 $M_\oplus$ core of solid material and the effects of stellar insolation. In contrast, we find that the models cannot account for the large size of WASP-1b, even if the planet has no core. Thus, we add WASP-1b to the growing list of hot Jupiters that are larger than expected. This suggests that "inflated" hot Jupiters are more common than previously thought and that any purported explanations involving highly unusual circumstances are disfavored.

Subject headings: planetary systems — stars: individual (WASP-1, WASP-2) — techniques: photometric

Online material: machine-readable tables

1. INTRODUCTION

The wide-field surveys for transiting exoplanets have finally begun to strike gold. For nearly 10 years, numerous groups have attempted to use small-aperture lenses to identify transits of bright stars over large patches of the sky. This turned out to be much more difficult than initially expected, and the first success was achieved only 2 years ago (Alonso et al. 2004). Since then, progress has accelerated, and in the month of 2006 September alone, three different survey teams announced the discovery of four transiting exoplanets.

The Trans-Atlantic Exoplanet Survey (TrES) reported the discovery of their second planet, TrES-2 (O'Donovan et al. 2006), the first extrasolar planet detected in the field of view of the NASA *Kepler* mission (Borucki et al. 2003) and the most massive exoplanet known to transit a nearby bright star. The HATNet project announced the discovery of HAT-P-1b (Bakos et al. 2007), a hot Jupiter orbiting one star of a visual binary, and the lowest density hot Jupiter yet detected. Most recently, the SuperWASP team announced the discovery of two planets, WASP-1b and WASP-2b (Collier Cameron et al. 2007), that are the subject of this paper. Thus, including the discovery of a planet by the XO project earlier this year (McCullough et al. 2006), four independent teams have now demonstrated the capability of identifying transiting hot Jupiters using very modest (typically 10 cm) aperture automated observatories. Several more projects also seem poised for success (for a review of current and near-future transit-search projects, see Charbonneau et al. 2007).

The reason why transiting planets are so precious, and why the exoplanet community is ebullient over the progress in finding them, is that only for transiting planets can one measure both the mass and the radius. This in turn permits one to confront observations with theoretical models of planetary structure. For the moment, this confrontation is limited to the interesting case of the hot Jupiters, for the simple reason that close-in planets are much more likely to exhibit transits.

Prior to the detection of such objects in transiting configurations, our naive expectation was that hot Jupiters would be similar to Jupiter in structure, with a modest increase in radius due to the effects of stellar insolation (e.g., Guillot et al. 1996; Lin et al. 1996). However, among the 14 cases that have since been discovered, there is a large range in measured radii. At one extreme lies HD 149026b (Sato et al. 2005; Charbonneau et al. 2006), whose small radius bespeaks a central core of solid material that composes roughly 70% of the planet by mass. At the other extreme is HD 209458b (Knutson et al. 2007), whose radius significantly exceeds the predictions of insolated structural models (see, e.g., Baraffe et al. 2003 or Bodenheimer et al. 2003, and for a contrary view, Burrows et al. 2003 or Arras & Bildsten 2006). The recently discovered planet HAT-P-1b (Bakos et al. 2007) is also larger than theoretically expected. This suggests that in those two planets, at least, there is a source of internal heat that was overlooked by theoreticians. Fortney et al. (2006) have suggested that all hot Jupiters are subject to an additional energy source, but that the effect is masked for some of these planets by a large abundance of heavy elements.

Various mechanisms for producing this heat have been explored, although certainly not exhaustively. Bodenheimer et al. (2001, 2003) proposed that there is a third body in the system that excites the eccentricity of the hot Jupiter. Ongoing tidal dissipation would then provide the requisite energy, even if the mean eccentricity were as small as a few percent. However, subsequent observations have placed an upper bound on the current eccentricity below the value required (Deming et al. 2005; Laughlin et al. 2005a; Winn et al. 2005), and they have not revealed any third body. Showman & Guillot (2002) argued instead that the heat could be provided by the conversion of several percent of the incident stellar radiation into mechanical energy that is subsequently transported deep into the planetary interior. Alternatively, Winn & Holman (2005) invoked ongoing tidal dissipation due to a nonzero planetary obliquity. Ordinarily, the obliquity would be driven

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to very small values, but it is possible for hot Jupiters to exist in a stable Cassini state (a resonance between spin and orbital precession) with a significant obliquity.

Although measurements of either the winds or the spin states of hot Jupiters may not be forthcoming soon, a possible avenue for progress would be to examine the rate of occurrence of the anomalously large hot Jupiters relative to the hot Jupiter population as a whole (being mindful of the observational biases that favor the detection of large planets, as quantified by Gaudi 2005). In particular, the most puzzling aspect of the Showman & Guillot (2002) mechanism is why it should act on some but not all hot Jupiters. Conversely, the Cassini state described by Winn & Holman (2005) requires some fine-tuning, making it an unattractive explanation if "inflated" planets turn out to be relatively common.

Although the detection of the planets WASP-1b and WASP-2b (Collier Cameron et al. 2007) is an important opportunity to address these questions, the range of allowable planetary radii, $1.33 < R_p/R_J < 2.53$ for WASP-1b and $0.65 < R_p/R_J < 1.26$ for WASP-2b, is too broad to meaningfully constrain the models. In this paper, we present the analysis of newly acquired photometric time series that serve to reduce the uncertainties in the radii of both planets by a factor of 5. We then interpret the new radius estimates in the context of the known hot Jupiters and the published models of their physical structure. We end by noting particular opportunities for further follow-up presented by both planets.

2. OBSERVATIONS

We observed WASP-1 and WASP-2 on the nights of predicted transits, with the 1.2 m telescope of the Fred L. Whipple Observatory on Mount Hopkins, Arizona. The WASP-1 transit occurred on UT 2006 September 27, while the WASP-2 transit was on UT 2006 September 30. On each night, we used Keplercam to obtain a continuous sequence of 30 s integrations of the target and surrounding field stars. We employed the SDSS z filter, the reddest band available, to minimize the effects of differential extinction on the photometry and the effect of stellar limb darkening on the light curve. Keplercam employs a single 4096×4096 Fairchild 486 CCD; we used 2×2 binning. With a readout time of 9 s and total overhead of 12 s between exposures, the resulting cadence was 42 s. The field of view is $23' \times 23'$ with a $0.67''$ pixel^{-1} plate scale when binned. We used the offset guider to maintain the telescope pointing to within $5''$ throughout the night. On each night, we started observing well before the predicted time of ingress and ended well after egress.

For the WASP-1 event, we gathered 832 images over a time span of 9.7 hr, spanning an air mass range of 1.0–2.1 that reached its minimum value in the middle of the observing sequence. Light clouds were present during the first hour, and conditions were photometric afterward. Since the hour in which clouds were present occurred well before ingress, we decided to exclude those data in the analysis. The full width at half-maximum (FWHM) of the stellar images was typically $1.6''$, but occasionally degraded to $4''$. For the WASP-2 event, we gathered 426 images spanning a period of 4.9 hr under clear skies and spanning an air mass that began at 1.1 and increased to 2.1 over the observing sequence. The seeing was stable, varying only modestly between $1.5''$ and $1.9''$. For calibration purposes, we obtained dome flats and twilight sky flats on both nights along with a set of bias images.

3. DATA REDUCTION

To calibrate the images, we first subtracted an amplifier-dependent overscan bias level and then joined the images from each quadrant into a single frame. We filtered the bias images from each night of deviant pixels and averaged the cleaned biases to produce an average bias frame. We then used these average bias frames to subtract a residual spatially dependent bias pattern from the science images. We scaled our sky flat images to the same mean flux, and then averaged them (while filtering out deviant pixels) to produce nightly flat-field images, which we then used to flat-field each science image.

TABLE 1
PHOTOMETRY OF WASP-1

HJD	Relative flux	Uncertainty
2454005.64040	1.00235	0.00204
2454005.64088	0.99903	0.00202
2454005.64138	0.99851	0.00202

NOTES.—The time stamps represent the Heliocentric Julian Date at the time of midexposure. The data have been corrected for residual extinction effects, and the uncertainties have been rescaled as described in § 3. Table 1 is published in its entirety in the electronic edition of the *Astrophysical Journal*. A portion is shown here for guidance regarding its form and content. The data are also available from the authors on request.

We performed aperture photometry using the IRAF[6] PHOT task, which yielded estimates of the instrumental magnitudes and sky magnitudes for the target and comparison stars. We estimated the sky magnitudes from the median value in an annulus centered on the star after iteratively rejecting pixel values that deviated by more than 3 standard deviations from the mean. To obtain differential photometry of the target, we selected a group of field stars that were isolated and located on a portion of the detector that was cosmetically clean. We then calculated the statistically weighted mean magnitude of the comparison stars in each frame as follows: We estimated the photometric uncertainties based on the expectations of photon noise from both the star and underlying sky, as well as detector read noise and scintillation (as formulated by Gilliland et al. 1993). We then subtracted the mean magnitude of the comparison stars from those of all stars in our list, including the target star. We eliminated from the list any comparison star found to be variable or exhibiting a systematic trend in its brightness over time. We iteratively recalculated the differential correction in this manner, eliminating suspect comparison stars until we visually confirmed in plots of the light curves that all of the comparison stars did not vary outside of the expectations of the noise sources listed above. This procedure yielded nine comparison stars for the WASP-1 data and six comparison stars for the WASP-2 data. We selected the optimal photometric aperture (which depends primarily on the typical nightly seeing) and sky annulus to be the ones that minimized the rms deviation of the out-of-transit portions of the differential light curve of the target star. We selected photometric apertures with radii of $6.4''$ and $5.4''$ for the WASP-1 and WASP-2 data, respectively. For both nights, we selected an aperture for the sky annulus that spanned $8''$–$21''$.

Although the relative photometry removes the first-order effects of extinction, color-dependent effects are not removed. Stars of different colors are extinguished by different amounts through a given air mass. For this reason, we applied a residual extinction correction to the data. The correction function was determined as part of the model-fitting procedure that we describe in § 4.

The final photometry is given in Tables 1 and 2, and is plotted in Figure 1. The fluxes and their uncertainties reported in the tables have already been corrected for extinction. The reported uncertainties have been further rescaled such that $\chi^2/N_{\rm dof} = 1$ for the

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