

Hubble's view of transiting planets

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The *Hubble Space Telescope* is uniquely able to study planets that are observed to transit their parent stars. The extremely stable platform afforded by an orbiting spacecraft, free from the contaminating effects of the Earth's atmosphere, enables *HST* to conduct ultra-high precision photometry and spectroscopy of known transiting extrasolar planet systems. Among *HST*'s list of successful observations of the first such system, HD 209458, are (1) the first detection of the atmosphere of an extrasolar planet, (2) the determination that gas is escaping from the planet, and (3) a search for Earth-sized satellites and circumplanetary rings. Numerous wide-field, ground-based transit surveys are poised to uncover a gaggle of new worlds for which *HST* may undertake similar studies, such as the newly-discovered planet TrES-1. With regard to the future of *Hubble*, it must be noted that it is the only observatory in existence capable of confirming transits of Earth-like planets that may be detected by NASA's *Kepler* mission. *Kepler* could reveal Earth-like transits by the year 2010, but without a servicing mission it is very unlikely that *HST* would still be in operation.

1. Introduction

When both the photometric transits and the radial velocity variations due to an extrasolar planet are observed, we are granted access to key quantities of the object that Doppler monitoring alone cannot provide. In particular, precise measurements of the planetary mass and radius allow us to calculate the average density and infer a composition. Such estimates enable a meaningful evaluation of structural models of these objects, including whether or not they possess a core of rocky material. These inferences, in turn, enable direct tests of competing scenarios of planet formation and evolution. Moreover, the transiting configuration permits numerous interesting follow-up studies, such as searches for planetary satellites and circumplanetary rings and studies of the planetary atmosphere.

In this review, I discuss the status of work in the field with a focus on the key contributions, both past and near-future, enabled by the *Hubble Space Telescope*. I begin by reviewing the properties of the transiting planets discovered to date, as well as the numerous ground-based efforts to detect more of these objects. I then consider the various follow-up studies of these gas-giant planets that are enabled by *HST*, as well as *HST*'s potentially unique role in following-up Earth-sized objects detected by NASA's *Kepler* mission. I finish by discussing two *HST*-based searches for transiting gas-giant planets. Throughout this contribution, I restrict my attention to studies of *transiting* planets; for an introduction to the broader range of *HST*-based studies of extrasolar planets, see Charbonneau (2004).

2. The current sample of transiting planets

At the time of writing, there are six extrasolar planets known to transit the disks of their parent stars: HD 209458b (Charbonneau et al. 2000, Henry et al. 2000) was initially identified through Doppler monitoring, TrES-1 (Alonso et al. 2004) was discovered by the small-aperture, wide-field Trans-Atlantic Exoplanet Survey (TrES) network, and the four others were found by Doppler follow-up of a list of more than 100 candidates identified by the OGLE team (Udalski 2002a, 2002b, 2002c, 2003): OGLE-TR-56b (Konacki et al.

2003), OGLE-TR-111b (Pont et al. 2004), OGLE-TR-113b (Bouchy et al. 2004; Konacki et al. 2004), and OGLE-TR-132b (Bouchy et al. 2004).

As a result of the recent flurry of discoveries, we can construct a mass-radius plot for transiting extrasolar planets, shown in Figure 1. From this plot, it is clear that all but one of the planets have radii that are consistent with a value that is only modestly inflated (typically <15%) over the Jupiter radius. This is in keeping with the predictions of models which include the effects of stellar insolation (Guillot et al. 1996; Burrows et al. 2000; Baraffe et al. 2003; Bodenheimer et al. 2003; Chabrier et al. 2004). There is a growing consensus among theorists that the large radius of HD 209458b, $1.35 \pm 0.06 R_{\text{Jup}}$, cannot be explained by stellar insolation effects alone, and indeed Figure 1 points to its anomalous nature. Guillot & Showman (2002) and Showman & Guillot (2002) considered a model in which a modest fraction of the incident stellar radiation is converted into mechanical energy (winds), which could fill the energy decrement and hence explain the large radius. It is not clear, however, why this mechanism would not work as efficiently for the other objects. An alternative hypothesis is that the orbital eccentricity of HD 209458b is continually pumped by the presence of a more distant and, as of yet, undetected planet; the damping of the eccentricity in turn provides the energy source needed to explain the large radius (Bodenheimer et al. 2003). Fortunately, it should be possible to test this model observationally, initially through the offset in the timing of the secondary eclipse (indicating a non-zero orbital eccentricity; Charbonneau 2003b), and subsequently through the detection of the second planet via precise radial velocity measurements. Solving the mystery of HD 209458b will be an engaging challenge with a resolution likely in the next couple years.

HD 209458b and TrES-1 are very similar in mass and equilibrium temperature, yet have dramatically different radii. As a result, we must abandon the simple expectation that the radius of an extrasolar gas-giant planet will be determined solely by its mass and degree of stellar insolation. Rather, we now know that the radii can be altered dramatically by additional processes. Identifying these mechanisms and understanding their implications for the structure of these planets will be a rewarding task for the near future.

As discussed in Section 4, only relatively nearby systems will be bright enough for the majority of follow-up observations with *HST* that have been completed for HD 209458b. Indeed, of the six known systems, only HD 209458b and TrES-1 satisfy the brightness criterion. Since we would like to increase the number of similarly accessible planets, I consider next the current ground-based surveys for these objects.

3. Ground-based surveys for new targets

Of the roughly 20 ground-based transit surveys (Horne 2003; Charbonneau 2003a)† that are either in operation or planned for the near future, only those that survey bright ($V < 13$) stars will find planets that may be pursued with the *HST*-based techniques described in the following section. Among these surveys are SuperWASP (Street et al. 2003), PASS (Deeg et al. 2004), HATnet (Bakos et al. 2004), Vulcan (Borucki et al. 2001), KELT (Pepper et al. 2003), and TrES (e.g., Alonso et al. 2004). All of these surveys use fast optics (typically consisting of a commercially available camera lens) and a correspondingly coarse pixel scale (typically 10–20 arcsec/pixel) to monitor thousands (and sometimes tens of thousands) of field stars. The dominant challenge facing such searches is no longer that of obtaining the requisite photometric precision (better than 1%) and

† <http://star-www.st-and.ac.uk/~kdh1/transits/table.html>

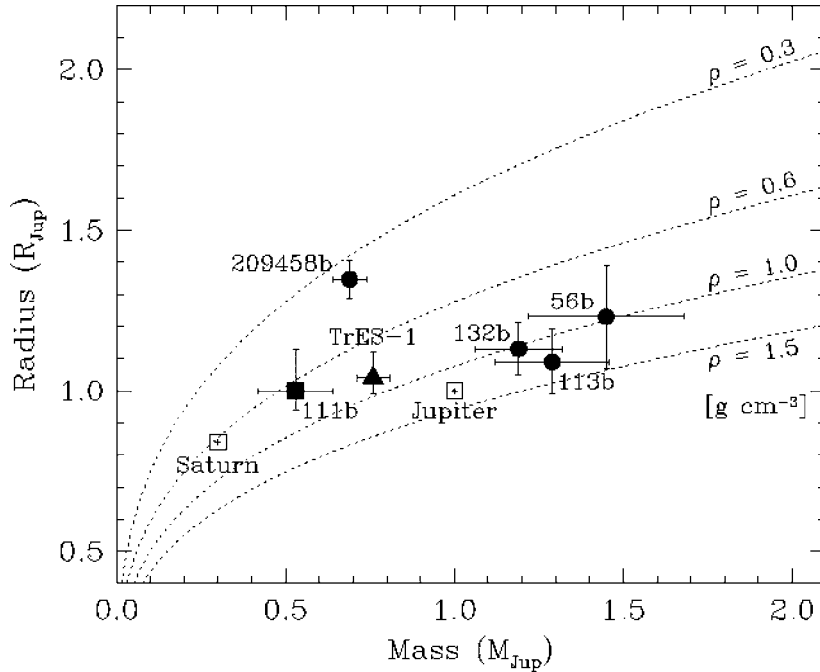


FIGURE 1. Radius versus mass for all known transiting planets. The values and uncertainties are taken from Brown et al. (2001) for HD 209458b, Sozzetti et al. (2004) for TrES-1, Torres et al. (2004a) for OGLE-TR-56b, Pont et al. (2004) for OGLE-TR-111b, Bouchy et al. (2004) for OGLE-TR-113b, and Moutou et al. (2004) for OGLE-TR-132b. Lines of constant density are also indicated. Reprinted with permission from Sozzetti et al. (2004).

sufficient phase coverage (typically 300 hours) on a sufficient number of stars (>5000), but rather that of identifying the astrophysical false positives (Latham 2003; Charbonneau et al. 2004b; Mandushev et al. 2004; Torres et al. 2004b), which are predicted to occur with a frequency of roughly 10 times that of true planetary systems (Brown 2003). These impostors each consist of a stellar system containing an eclipsing binary that precisely mimics the single-band light curve of a gas-giant planet transiting a Sun-like star. Fortunately, the stars surveyed by these projects are bright, which has several ramifications. First, the targets typically have well-determined 2MASS[‡] colors and USNO-B proper motions (Monet et al. 2003)[¶], so that the likelihood that a given target is a nearby late-type dwarf can be readily evaluated. Second, the stars are easily accessible to spectrographs mounted on modest-aperture telescopes, where observing time is often easily available: Initial spectroscopic monitoring with a lower Doppler precision ($\sim 1 \text{ km s}^{-1}$; Latham 2003) is one effective way to reject the majority of such contaminants before gathering precise ($\sim 10 \text{ m s}^{-1}$) radial velocity observations at much larger observatories where observing time is often heavily over-subscribed.

3.1. The TrES Network

The Trans-Atlantic Exoplanet Survey (TrES) consists of three telescopes: Sleuth[†] (Charbonneau 2003a; O'Donovan et al. 2004), STARE[‡] (Brown & Charbonneau 2000), and

[‡] <http://www.ipac.caltech.edu/2mass/releases/allsky/>

[¶] <http://www.nofs.navy.mil/projects/pmm/catalogs.html>

[†] <http://astro.caltech.edu/~ftod/tres/sleuth.html>

[‡] <http://www.hao.ucar.edu/public/research/stare/stare.html>

PSST (Dunham et al. 2004). Each instrument was developed independently, but with the intent that with their very similar capabilities, all three could monitor the same field of view. The Sleuth telescope consists of an $f/2.8$ commercial camera lens with an aperture of 10 cm. It images a $5.7^\circ \times 5.7^\circ$ patch of sky onto a $2\text{ k} \times 2\text{ k}$ thinned CCD, with a resulting pixel scale of 9.9 arcsec. Sleuth gathers data in the SDSS r filter (the other systems use Bessell R), but has a filter wheel with additional filters so that accurate colors of each target may be obtained. The system is located in an automated clamshell enclosure at Palomar Observatory, and each night's observing sequence is handled in a completely automated fashion by a local workstation running Linux. Due to its automated operation, Sleuth achieves a very high efficiency, gathering data on nearly every night weather permits. Calibration images are also obtained nightly. Each morning the entire sequence of images is compressed and transferred to the analysis workstation at Caltech. The other systems in the TrES network operate in a roughly similar fashion.

Over the past year, we have switched our analysis pipeline from one based on weighted-aperture photometry (i.e., Brown & Charbonneau 2000) to that of image subtraction (i.e., Allard 2000). This change has resulted in much better performance and produces time series with an rms very near the theoretical expectation. As a result, we have significantly increased the number of stars that we survey with the requisite photometric precision to roughly 10,000–15,000 per field (near the galactic plane).

In order to handle the large number of astrophysical false positives identified by the TrES survey, we have recently assembled a new telescope named Sherlock (Charbonneau et al. 2004b; Kotredes et al. 2004) that will be dedicated to such follow-up work. Sherlock is located in the same enclosure as Sleuth at Palomar Observatory. It is based on a commercially available $f/6.3$ Schmidt-Cassegrain telescope with an aperture of 25 cm. It images a $0.5^\circ \times 0.5^\circ$ field-of-view onto a $1\text{ k} \times 1\text{ k}$ thinned CCD, and is equipped with a filter wheel housing a selection of relatively narrow-band interference filters. Each night, we identify any active candidates that are predicted to present eclipses, and perform high-cadence multi-color photometry of the highest-priority target. Sherlock is able to distinguish several forms of false positives for two reasons: First, the increased angular resolution (1.7 arcsec/pixel) compared to the TrES instruments (10 arcsec/pixel) resolves most stellar blends that occur due to projection along the line-of-sight; in such a scenario, the light curve of the isolated source as seen by Sherlock typically presents a significantly deeper eclipse, which is no longer consistent with a transiting planet. Second, stellar blends (physically associated or not) in which the blending and occulted stars are of significantly different temperature will present eclipse depths that vary in color in excess of the small effects due to limb-darkening. The follow-up photometry provided by Sherlock is complementary to spectroscopic work similarly aimed at identifying the impostors (i.e., Latham 2003). Notably, we plan to operate Sherlock in a fully-automated manner, and the small amount of labor, compared to the spectroscopic follow-up, makes this method an appealing one by which to reject the bulk of such astrophysical false positives.

3.2. The New World of TrES-1

Alonso et al. (2004) present the detection of the planet TrES-1, a transiting hot Jupiter with an orbital period of 3.03 days. This work, combined with a detailed analysis of the stellar spectrum by Sozzetti et al. (2004), permits a precise estimation of the planetary mass $M_p = 0.76 \pm 0.05 M_{\text{Jup}}$ and radius $R_p = 1.04^{+0.08}_{-0.05} R_{\text{Jup}}$. As noted above, the $3\text{-}\sigma$ discrepancy between the value of the radius of TrES-1 and that of HD 209458b, $R_p = 1.35 \pm 0.06 R_{\text{Jup}}$, despite the similarity in mass and degree of stellar insolation, is an interesting puzzle with several possible resolutions. As discussed in the following section, *HST* may play a central role in identifying the correct answer.

It is critical to note that TrES-1 is only the second transiting planet for which the bulk of *HST*-based studies (described in the next section) may be pursued; planets identified by the OGLE survey orbit stars that are simply too faint. In the following section, we review these *HST*-based investigations.

4. *HST* studies of transiting extrasolar gas giants

Nearly the entirety of *HST*-based studies of transiting exoplanets to date has focused on HD 209458 (one exception is the ACS-HRC campaign to observe two transits of OGLE-TR-56)†. I summarize these efforts below; for a more detailed description, see Charbonneau (2003b; 2004).

4.1. Improved estimates of planetary parameters

Ground-based efforts to obtain precise time series photometry of HD 209458 are limited to a precision of ~ 2 mmag and a cadence of ~ 10 minutes (Charbonneau et al. 2000; Henry et al. 2000; Jha et al. 2000; Deeg, Garrido, & Claret 2001). With data of this quality, estimations of the planetary radius (and other parameters) are confounded by a significant degeneracy between the planetary and stellar radii and the orbital inclination. In short, by increasing the planetary and stellar radii in tandem to preserve their ratio, the same transit depth can be produced, and reducing the orbital inclination preserves the chord length across the star to match the observed transit duration. Since independent estimates of the stellar radius from stellar models (e.g., Cody & Sasselov 2002) were typically limited to a precision of $\sim 10\%$, estimates of the planetary radius retained this significant uncertainty.

The ultra-precise light curve by Brown et al. (2001) was produced by using STIS to disperse the large number of photons over as many pixels as possible (to retain a high observing efficiency and mitigate flat-fielding effects), and subsequently summing the recorded counts to produce a photometric index with a typical precision of 1.1×10^{-4} and a cadence of 80 s. The quality of these data breaks the former degeneracy (principally as a result of the precise measurement of the slope and duration of ingress and egress). As a result, the authors derived a precise estimate of the planetary radius, $R_p = 1.35 \pm 0.06 R_{\text{Jup}}$, as well as that of the star, $R_s = 1.15 \pm 0.05 R_{\text{Sun}}$ (consistent with, but more precise than the *Hipparcos* value). This estimate is still subject to the uncertainty in the independent estimate of the stellar mass, M_s , but the effect is small since the uncertainty in the radius is only weakly dependent upon that of the mass, i.e., $\Delta R_p/R_p \simeq 0.3 \Delta M_s/M_s$.

More recently, Charbonneau et al. (2004a) gathered new STIS data at lower resolution, but spanning a large wavelength range, 290–1080 nm. The data can be subdivided into various effective bandpasses prior to forming the photometric time series, and the resulting light curves clearly show the predicted color-dependence due to limb-darkening. As a result, it should be possible to assume limb-darkening coefficients based on a stellar model, and derive a very precise estimate of the planetary radius.

4.2. Searches for planetary satellites, circumplanetary rings, and reflected light

Brown et al. (2001) also noted that the STIS data described above was sufficiently precise that terrestrial-sized objects present in the HD 209458 system could be revealed. This sensitivity was unprecedented: although ground-based searches for Earth-sized objects are possible for small stars such as the M-dwarf binary CM Dra (e.g., Doyle et al. 2000;

† <http://www.stsci.edu/cgi-bin/get-proposal-info?9805>

Deeg et al. 2000), no instrument had previously demonstrated the ability to see such small objects in transit across a star the size of the Sun. Brown et al. (2001) concluded that they could exclude the presence of a planetary satellite with radius larger than $1.2 R_{\text{Earth}}$ (although not for all possible values of the putative satellite's orbital period and phase). Similarly, they excluded the presence of opaque circumplanetary rings with a radius greater than $1.8 R_p$, since such a ring system would have resulted in large deviations during ingress and egress, which were not seen.

Brown et al. (2001) also examined their data for offsets in the times of the center of the planetary eclipses; such offsets would result from a massive planetary satellite. Since the centroid of each eclipse could be measured with a precision of 6 s, they were able to exclude satellites more massive than $3 M_{\text{Earth}}$. More recently, Schultz et al. (2003) used *HST*'s Fine Guidance Sensors (FGS) to obtain photometry with an exceptional cadence of 0.025 s and a SNR of 80. By targeting times of ingress and egress, they will place stringent constraints on any timing variations in this system.

Exquisite photometry of a hot-Jupiter system might also enable the detection of the light reflected from the planet. This effect has been sought using a spectroscopic technique from the ground for several hot-Jupiter systems (Charbonneau et al. 1999; Collier Cameron et al. 2002; Leigh et al. 2003), but as of yet, only upper limits have been obtained. The eclipsing geometry of the HD 209458 system presents an attractive opportunity; precise photometry during times of secondary eclipse could detect the decrement in light as the planet passes behind the star. Not only would such data enable an evaluation of the wavelength-dependent albedo, but these data would also constrain the orbital eccentricity through the timing of the secondary eclipse (Charbonneau 2003b). This project is also being pursued by the *MOST* satellite (Walker et al. 2003; Matthews et al. 2004)†, which has achieved unprecedented precision despite its small aperture. However, *HST* retains the spectroscopic information (either through STIS, or grism modes of ACS), whereas *MOST* has a single fixed bandpass.

4.3. Atmospheric transmission spectroscopy

Based on theoretical predictions (Seager & Sasselov 2000; Brown 2001; Hubbard et al. 2001) that hot Jupiters such as HD 209458b should present strong alkali metal features in their transmission spectra, Charbonneau et al. (2002) pursued this effect with STIS. They detected an increase in the transit depth of $(2.32 \pm 0.57) \times 10^{-4}$ in a 1.2 nm bandpass centered on the Na D lines at 589.3 nm. After ruling out alternate explanations for this effect, they concluded that this decrement was indeed due to absorption from atomic sodium in the planetary atmosphere. Notably, the observed signal was only 1/3 that predicted from their fiducial model, a cloudless atmosphere with a solar abundance of sodium in atomic form. One explanation for this decrease may be the presence of clouds high in the atmosphere, effectively reducing the size of the atmosphere viewed in transmission. Such clouds would likely reduce other transmission spectral features in a similar fashion, and indeed recent ground-based work in the infrared seems to confirm this interpretation (Deming et al. 2004).

Using STIS in the UV, Vidal-Madjar et al. (2003) detected a 15% decrement in the flux at Ly α during times of eclipse, which they interpret as evidence for ongoing atmospheric escape of a significant quantity of hydrogen (Lecavelier des Etangs et al. 2004). In a more recent paper, Vidal-Madjar et al. (2004) also present evidence of a corresponding decrement in lines of carbon and oxygen, indicating their presence in the cloud of material surrounding the planet; however, the effect for these features is detected with significantly

† <http://www.astro.ubc.ca/MOST/>

less statistical significance than that of Ly α . The precise mechanism of escape, and the connection (if any) of this extended material to the inflated value of the radius remain open questions that demand further study.

5. Connection to the *Kepler* mission

The NASA *Kepler*[†] mission (Borucki et al. 2003a; 2003b) is scheduled for launch in 2007, and may make the first detection of an extrasolar Earth-like planet. Indeed, if most Sun-like stars have such planets, dozens should be detected. *Kepler* will therefore set the scale for future efforts to directly characterize such extrasolar Earths, since it will tell us how common these objects are, and, by inference, how far we might expect to look to locate the closest example.

As with the ground-based searches, *Kepler* will need robust techniques by which to discriminate true planetary transits from astrophysical false positives, notably stellar blends. It should be noted, therefore, that *HST/ACS* is likely the only instrument in existence that will be capable of confirming the photometric signals detected by the *Kepler* Mission. More importantly, *HST/ACS* would be able to provide photometry over several bandpasses that are distinct from the single, fixed bandpass used by *Kepler*. As discussed in Section 3, such photometry during times of eclipse can be used to search for a color-dependence to the transit depth, which would indicate that such a candidate is an impostor.

The following SNR calculation is adapted from one for upcoming DD observations of TrES-1 (T. M. Brown, R. L. Gilliland, et al., personal communication). Using ACS/HRC with the G800L grism to disperse the light from a $V = 12.0$ star over roughly 200 pixels allows collection of 5×10^7 e⁻ per exposure while staying 30% under saturation. Given the much higher efficiency of the G800L on ACS than the similar capabilities on STIS, and the significantly fainter typical magnitude for the *Kepler* candidate assumed here ($V = 12.0$) than HD 209458 ($V = 7.6$), it makes sense to use ACS (as opposed to STIS), regardless of STIS loss. Adopting an exposure time of 115 s, and using the 512 square subarray nearest the readout amp for HRC (which requires a readout overhead of 35 s), results in a net cadence of 150 s and an observing efficiency of 77%. The SNR per exposure will be 7150. Over the 13 hour duration of the eclipse (and accounting for the roughly 55 minute visibility per *HST*-orbit for the *Kepler* field-of-view), roughly 179 exposures could be obtained, for a photon-noise-limited precision of 1.05×10^{-5} . Since the determination of the eclipse depth is also affected by the precision of the out-of-eclipse data, this reduces to 1.48×10^{-5} (for a comparable duration out of eclipse). This represents a $5.7\text{-}\sigma$ detection of a Earth-sized object across a star with the solar radius. Of course, this calculation has not considered the effect of systematic errors, which may limit the precision to a level significantly worse than the theoretical photon-noise limit. Furthermore, *Kepler* candidates that are fainter than $V = 12.0$ would be detected with less confidence, unless the ratio of planet and stellar radii is increased.

Short-period Earth-sized planets may be detected by *Kepler* early in the mission, and *HST/ACS* may still be operational at this point. However, true Earth analogs will be identified only as early as 2010, since these present transits only once a year, and two such events are required for a period estimate (*Kepler* requires three events for a reliable detection). Without a servicing mission, it is very unlikely that *HST* would still be in operation at that time. Given that the search for Earth-like planets is so central to future

[†] <http://www.kepler.arc.nasa.gov/>

NASA plans, the impact of the loss of *HST* to these plans should be considered in close detail.

6. *Hubble* as a survey instrument

The discussion above has focused on the use of *HST* to conduct follow-up studies of transiting extrasolar planets identified by other telescopes. However, *HST* has also proven to be a powerful transit survey instrument in its own right. The small field-of-view precludes the simultaneous survey of a sufficiently large number of bright stars, as is done for many of the ground based surveys. However, for certain fields-of-view, *HST*'s sharp point-spread function enables precise photometry of thousands of stars for which ground-based work cannot proceed. To date, *HST* has surveyed two such fields for transiting planets: the globular cluster 47 Tuc, and the Galactic Bulge.

6.1. *A transit search in the globular cluster 47 Tuc*

The use of *HST* as a survey instrument for transiting planets was pioneered by Gilliland et al. (2000). In July 1999, they monitored 34,000 main-sequence stars in the globular cluster 47 Tuc for 8.3 days. Star clusters make attractive hunting grounds for transiting planets for several reasons. First, the uniformity of age and metallicity of the cluster members provides the ideal laboratory setting within which to study the dependence of the planet population on these quantities. Second, since the stellar radii may be inferred from measurements of the apparent brightness and an evolutionary models for the cluster, the radius of the transiting secondary can also be reliably inferred. A key element in the design of the Gilliland et al. (2000) experiment was that a large range of stellar radii could be monitored for transiting planets, since the poorer photometric precision obtained for much smaller (and less massive stars) was counterbalanced by a corresponding increase in the depth of the transit. In particular, the stars surveyed ranged in size from roughly $1.5 R_{\text{Sun}}$ (corresponding to slightly evolved stars with masses of $0.87 M_{\text{Sun}}$, at visual magnitudes of $V = 17.4$) to main-sequence stars with radii of $0.51 R_{\text{Sun}}$ (corresponding to masses of $0.55 M_{\text{Sun}}$ and a visual magnitudes of $V = 21.9$).

The survey found no stars presenting planetary transits, which was very much at odds with the findings of the Doppler surveys: in the local solar neighborhood, roughly 1% of Sun-like stars have hot Jupiters; folding in the recovery rates and efficiencies specific to the *HST* 47 Tuc survey, approximately 17 such objects would have been expected. The core result of the survey was thus that the population of hot Jupiters in 47 Tuc was at least an order of magnitude below that of the local solar neighborhood. This disparity may be due in part to the decreased metallicity of 47 Tuc ($[\text{Fe}/\text{H}] = -0.7$), as the lower-metallicity environment may impede planet formation and/or migration. A likely additional effect is that of crowding: at the typical location of the Gilliland et al. (2000) observations (one arcminute from the core), the stellar density is roughly $10^3 M_{\text{Sun}} \text{pc}^{-3}$; gas giant planets at several AU from the star could be disrupted in the typical planetary system if it suffers a close dynamical encounter prior to the inward migration of the planet (at which point it is sufficiently bound to withstand such disruption).

Due to the uniformity of the stellar population and the data set, and the extensive set of detection tests performed, the Gilliland et al. (2000) result remains one of the few well-characterized (and hence astrophysically useful) null results for a survey of transiting extrasolar planets. Wide-field surveys such as TrES are of great interest because they may deliver bright, transiting planets for which the parameters can be accurately measured, and which are amenable to follow-up studies. However, these wide-field surveys are unlikely to yield meaningful constraints of the rate-of-occurrence of hot Jupiters as

a function of the properties and environment of the central star, due to the very diverse nature of the targets surveyed in their magnitude-limited field samples.

6.2. A transit search in a galactic bulge field

K. Sahu and collaborators (program GO-9750†) have recently undertaken an ambitious *HST*-based transit search that seeks to capitalize on the increased (relative to WFPC2) field-of-view and sensitivity allowed by ACS/WFC. In February 2004, they observed a field in the galactic bulge for seven days with ACS/WFC. In the 202×202 -arcsecond field-of-view, they expect to monitor roughly 167,000 F, G, and K dwarfs brighter than $V = 23$, for which they will obtain a photometric precision sufficient to detect the transit of a Jupiter-sized planet. If the rate of occurrence of hot Jupiters for these stars is the same as that in the solar neighborhood (roughly 1%), they may detect more than 100 such planets. The number of disk and bulge stars are approximately equal, and the membership of a given star to a population will be determined by proper motions from data obtained at a different epoch (these data are also in hand). Furthermore, the metallicity of stars in the field-of-view is expected to vary by more than 1.5 order of magnitude. As a result, this dataset might permit the detection of a sufficiently large and diverse group of hot Jupiters so that the dependence of rate-of-occurrence and planetary radius upon several properties of the primary (notably stellar type, disk vs. bulge membership, and metallicity) could be disentangled.

A note of caution must be sounded, however. As discussed earlier, the primary challenge facing transit surveys is no longer that of photometric precision and phase coverage, but rather that of rejecting the astrophysical false positives, whose photometric light curves precisely mimic that of a planetary transit (Charbonneau et al. 2004b; Latham 2003). For the brightest targets, VLT radial velocity monitoring may reveal the spectroscopic orbit. More importantly, a detailed spectroscopic analysis for blends of eclipsing binaries could be performed. However, even for the much brighter stars that have been surveyed for transits, it has proven extremely difficult to identify hierarchical triples, in which the light from a third, bright star dilutes the photometric and spectroscopic variability of the eclipsing binary. Two examples of the degree to which such systems may confound researchers are given by Torres et al. 2004b (for a system identified by the OGLE survey, Udalski et al. 2002a, 2002b, 2003) and Mandushev et al. 2004 (for a candidate found by the TrES network). For the bulk of candidates, however, no spectrograph in existence will be able to recover the Doppler orbit (for a detailed presentation of the signal-to-noise calculation, see Charbonneau 2003a). The investigators will then need to rely upon more indirect considerations (such as colors and proper motions) to argue in favor of a planetary interpretation. Whether this argument can be made convincingly for an object that displays a transit light curve but no measurable Doppler orbit remains to be seen. Moreover, since the planetary radius is approximately degenerate with mass across two orders of magnitude ($0.5\text{--}80 M_{\text{Jup}}$; Burrows et al. 2001), the value of each individual object will be diminished relative to those identified for brighter stars. These concerns aside, however, the prospect of perhaps doubling the number of known extrasolar planetary systems is a fascinating one indeed, and the results from this survey are eagerly awaited.

† <http://www.stsci.edu/cgi-bin/get-proposal-info?9750>

7. Final note regarding STIS

As I was finalizing this contribution, the STIS spectrograph went offline due to the failure of an internal 5V power supply[‡]. As described above, STIS was the most productive *HST* instrument with regards to follow-up studies of hot Jupiters. Fortunately, many investigations requiring high photometric and/or spectroscopic stability can be accomplished with ACS (using a grism element to handle to the high photon rates), as well as NICMOS and FGS. Notably, the typical brightness of the transiting hot Jupiters that will be identified over the next couple years by the numerous ongoing wide-field surveys is optimally suited for ACS rather than STIS, regardless of STIS loss.

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