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HD 209458 and the Power of the Dark Side

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Abstract. The rich wealth of observational data, and matching theoretical investigations, of the transiting planet of HD 209458 stands in sharp contrast to systems for which only the radial velocity orbit is known. In this paper, I summarize the current status of these observations, and motivate a variety of projects that should be accessible with existing instruments. I describe observational estimates of the planetary radius, and discuss the relevant sources of uncertainty. I compare these estimates to those based on theoretical structural models. This discussion motivates the observational pursuit of three quantities that could be derived from measurements of the secondary eclipse: These are the albedo, the temperature, and the orbital eccentricity. I review the recent detection of the sodium D lines in the planetary atmosphere, and discuss ongoing work to search for molecular features in the near infrared. I also outline the use of the Rossiter effect to study the alignment of the orbit with the stellar equatorial plane, and transit timing to search for additional objects in the system.

1. Introduction

We are fortunate to know of a transiting extrasolar planet of a nearby, relatively bright star. Although the method of photometric transits as a detection technique is still very much under development, its application to study the planet of HD 209458 has proved immensely successful: HD 209458 b is the only extrasolar planet for which reliable estimates of the radius and mass are available. The calculated density proves that the planet is indeed a gas giant, with a composition primarily of hydrogen and helium. In the 2.5 years since its discovery, numerous observers have seized upon the opportunities afforded by an extrasolar planet that periodically transits its parent star. My goal in this contribution is both to detail the current state-of-the-art in such observations, and outline a series of projects that, with care, should be accessible to current instruments. This discussion serves to motivate wide-field surveys for bright transiting extrasolar planet systems (see Borucki et al. 2001, Brown & Charbonneau 2000, and numerous contributions in this volume). It is only for such objects that some of the projects below will be permitted in the near future.

2. The Planetary Radius

2.1. Observational Estimates

Numerous groups (Charbonneau et al. 2000; Deeg, Garrido, & Claret 2001; Henry et al. 2000; Jha et al. 2000) have presented photometric observations of the transit with a typical precision of 2 mmag and a sampling rate of roughly 10 minutes. At this level of measurement, attempts to estimate the planetary radius R_p are frustrated by a significant degeneracy: Picturing the transit as two quantities (a depth and a duration), then it is possible to fit the data with a family of models, where an increase in R_p is matched by a similar increase in the stellar radius R_* (thus preserving the transit depth), and a decrease in the orbital inclination i (thus preserving the time to transit the chord across the star). As a result, these groups used initial constraints on R_* and the stellar mass M_*, based on stellar model fits to the observed temperature, brightness, Hipparcos parallax, and metallicity (Jha et al. 2000; Mazeh et al. 2000). The typical uncertainties in R_* were $\sim$10%, which transfered directly to the uncertainty in R_p. As a result, there persisted a significant uncertainty in R_p, which was due to limitations in our stellar evolutionary models, and specifically our ability to constrain R_*.

More recently, Brown et al. (2001) observed 4 transits with the STIS spectrograph aboard *HST*, achieving a photometric precision of 0.1 mmag and a cadence of 80 s. These data broke the degeneracy described above, since the small changes in the slope of ingress and egress as a function of i and R_* could now be distinguished. They derived estimates of $R_p = 1.35 \pm 0.06\, R_{\rm Jup}$ and $R_* = 1.15 \pm 0.05\, R_{\odot}$. They still needed to assume a value for M_* (but not R_*). The degeneracy in the estimate of R_p resulting from the uncertainty in the mass is given by

$$\frac{\Delta R_p}{R_p} \simeq 0.3\, \frac{\Delta M_*}{M_*}. \tag{1}$$

This relation results from the fact that, for model fits to an observed transit curve, $R_p \propto R_* \simeq v_{orb}\, \Theta_{\rm I}$, where v_{orb} is the planetary orbital velocity and $\Theta_{\rm I}$ is the transit duration. The quantity $\Theta_{\rm I}$ is observed (and thus fixed), and $v_{orb} \propto M_*^{1/3}$. Equation (1) results in the limit of small $\Delta M_*/M_*$.

Cody & Sasselov (2002) have undertaken a detailed study of stellar evolutionary models of HD 209458 and the resulting uncertainties in R_p. In particular, they point out that the mass-radius relation at constant luminosity yields the dependence

$$\frac{\Delta R_p}{R_p} \simeq -\, \frac{\Delta M_*}{M_*}, \tag{2}$$

which is nearly orthogonal to that resulting from light-curve fitting (equation 1). They recommend explicitly assuming the relationship between R_* and M_* resulting from model fitting, rather than independently considering each with uncorrelated uncertainties. The result should be to reduce the net effective uncertainty in the estimate of R_p.

2.2. Theoretical Understanding

The inflated size of R_p relative to our own Jupiter was predicted by Guillot et al. (1996) prior to the discovery of transits in the HD 209458 system. Burrows et al. (2000) point out that the large radius results from the inability of the planet to cool in the hot environment resulting from the intense stellar insolation: The stellar flux incident upon HD 209458 b is roughly 20,000 times that received at Jupiter. They find that the planet must have migrated inwards to its current location in less than $\sim$10 Myr after its formation. Guillot & Showman (2002) re-examine the sources of opacity in the planetary atmosphere, and find that the models of Burrows et al. (2000) may have deposited the stellar radiation too deep in the atmosphere. They calculate cooler model atmospheres, and predict a value for R_p significantly below the observed value. The inclusion of a core of high-density material (Bodenheimer, Lin, & Mardling 2001) increases the disparity.

The realization that the observed R_p may be significantly larger than that predicted from theoretical calculations has lead several groups to consider additional sources of energy in the bulk of the planet. Bodenheimer et al. (2001) show that tidal dissipation of orbital eccentricity could provide the required input. However, the orbit would be circularized on a time scale of $\sim 10^8$ yr, and thus a mechanism to excite the orbital eccentricity would also be required. Showman & Guillot (2002) show that terrific winds may be expected on HD 209458 b, and describe a model that allows for a downward transport of kinetic energy of $\sim$1% of the incident stellar flux, sufficient to maintain the observed R_p.

The contribution of observers in this debate is to better quantify the relevant observables. Three quantities of interest are (1) the actual temperature of the planet, (2) the fraction of stellar flux absorbed by the planet, and (3) additional sources of energy (in the bulk of the planet) beyond the effect of insolation. In the next section, I describe how observations of the secondary eclipse (the passage of the planet behind the star) will allow estimates of these quantities, should the requisite precision be achieved.

3. Pursuing the Secondary Eclipse

3.1. Reflected Light

Planets shine in reflected light with a flux (relative to their stars) of

$$\left(\frac{f_p}{f_*}\right)_\lambda (\alpha) = \left(\frac{R_p}{a}\right)^2 p_\lambda \, \Phi_\lambda(\alpha), \tag{3}$$

where a is the semi-major axis, p_λ is the geometric albedo, and $\Phi_\lambda(\alpha)$ is the phase function (the flux from the planet when viewed at a phase angle α relative to the flux received when the planet is at opposition). Charbonneau et al. (1999) and Collier Cameron et al. (2001) have presented upper limits on p_λ for the hot Jupiter orbiting τ Boo, and Collier Cameron et al. (2002) have presented a similar study of the innermost planet of Ups And. Since these planets do not transit, the authors assumed values for the R_p, α (a function of i), and $\Phi_\lambda(\alpha)$, which complicated the interpretation of their results.

The situation is greatly simplified in the case of HD 209458, since R_p and i are known with high accuracy (Charbonneau & Noyes 2000). Furthermore, near the time of secondary eclipse, the planet seen just before ingress or just after egress is only $\sim 6°$ from opposition. Under the approximation $\Phi(6°) \simeq \Phi(0°) \equiv 1$, equation (3) yields the prediction for the depth of secondary eclipse,

$$\left(\frac{\Delta f}{f}\right)_\lambda \simeq 2.0 \times 10^{-4}\, p_\lambda. \tag{4}$$

Thus p_λ can be measured directly. Brown et al. (2001) demonstrated that STIS should be able to achieve the required precision.

The quantity p_λ is one element in an estimate of the total energy deposited into the planetary atmosphere. This is expressed as $1 - A$, where A is the Bond albedo. Converting from p_λ to A requires both p_λ over the wavelength range where the star outputs most of its energy, and an estimate of $\Phi_\lambda(\alpha)$. A theoretical investigation by Seager, Whitney, & Sasselov (2000) shows that a wide variety of phase functions are possible. The Canadian MOST satellite (Matthews et al. 2000) will attempt to measure the phase variability of several hot Jupiters. In addition to providing the last step in an estimate of A, the measurement of $\Phi_\lambda(\alpha)$ is highly diagnostic of sources of scattering in the atmosphere.

3.2. Thermal Emission

Infrared photometry of the secondary eclipse offers the opportunity to estimate the planetary temperature. In the Rayleigh-Jeans limit, the depth of the secondary eclipse is given by the product of the observed depth of the primary eclipse (in the absence of limb-darkening) and the ratio of the object temperatures,

$$\frac{\Delta f}{f} \simeq \frac{T_p}{T_*}\left(\frac{R_p}{R_*}\right)^2 \simeq \frac{1500\,\mathrm{K}}{6000\,\mathrm{K}}\,0.0146 \simeq 4\,\mathrm{mmag}. \tag{5}$$

This signal is roughly 20 times that of equation (4). In practice, such observations are frustrated by bright thermal background levels: Infrared arrays tend to cover small areas of the sky (to avoid saturation from background thermal emission), which means that the bright calibration stars required for mmag-precision differential photometry are not available. The technique of slewing to nearby bright stars suffers from significant changes in extinction which occur even on short time scales at these long wavelengths.

An alternative approach is spectroscopy. Richardson et al. (2003) have analyzed VLT spectra with $R = 3300$ at 3.5–3.7 μm to search for the disappearance of planetary methane features at the time of secondary eclipse. They can reject a zero-albedo model at the 3σ level if they adopt $e = 0.01$ (best fit to the Doppler observations). However, their result is only 1σ below the model for $e = 0$.

3.3. Effects of Orbital Eccentricity

The current upper limit on the orbital eccentricity e from radial velocity measurements is consistent with zero ($e = 0.00967 \pm 0.014$; G. Marcy, personal communication). Theoretical considerations (Goldreich & Soter 1966) predict that the orbit should be circularized on a time scale of $\tau_e \simeq 3 \times 10^7\,(Q/10^5)$ yr (where Q is the tidal quality factor). Indeed, all known hot Jupiters with orbital periods P less than 5 days are observed to be circular.

A non-zero value of e could produce a measurable shift in the separation of the times of the center of primary ($t_{\rm I}$) and secondary ($t_{\rm II}$) eclipse away from a half-period. The approximate formula for the timing offset (see Kallrath & Milone 1998 and references therein) is:

$$\frac{\pi}{2\,P}\left(t_{\rm II} - t_{\rm I} - \frac{P}{2}\right) \simeq e\,\cos\omega \leq e, \tag{6}$$

where ω is the longitude of periastron. At the 2σ limit on the current uncertainty in e, the time of secondary eclipse could be offset by as much as 2.0 hrs, a shift that should be readily detectable if the precision to observe the secondary eclipse is obtained. In the case of a detection, equation (6) provides a lower limit on the true value of the eccentricity (and the radial velocity yields an upper limit on its value). Should no offset be seen, a significant upper limit would still be of interest, as it would rule out heating of the planet interior by tidal damping of the orbital eccentricity.

An eccentric orbit could also change the relative durations of the primary ($\Theta_{\rm I}$) and secondary ($\Theta_{\rm II}$) eclipses (again, see Kallrath & Milone 1998). The relevant formula is:

$$\frac{\Theta_{\rm I} - \Theta_{\rm II}}{\Theta_{\rm I} + \Theta_{\rm II}} \simeq e\,\sin\omega. \tag{7}$$

At the limit of the 2σ error bars on e, this yields a change of 14 minutes, a more ambitious measurement that the offset of equation (6). Nonetheless, equations (6) & (7) together allow for the direct evaluation of e and ω.

4. Atmospheric Transmission Spectroscopy

Shortly after the detection of the photometric transits of HD 209458 b, several groups (Seager & Sasselov 2000; Brown 2001; Hubbard et al. 2001) presented theoretical transmission spectra of the planetary atmosphere. The essential idea is that opacity sources in the atmosphere result in a wavelength dependence of the apparent radius as derived from transit observations. Thus, examining the ratio of stellar spectra taken in and out of transit may yield a probe of the dominant sources of opacity in the planetary atmosphere.

The large equilibrium temperature of the planet (~1500 K) implies a scale height of 550 km. Thus the atmosphere presents an annulus with a one-scale-height cross-sectional area (relative to the star) of $\Delta A/A = 2.6 \times 10^{-4}$. Some features may have effective depths of several scale heights, and thus signals as large as 1×10^{-3} could be produced.

4.1. Detection of the Sodium D Lines

Using STIS, Charbonneau et al. (2002) have 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 sodium D lines (located at 589.3 nm) relative to the local continuum. They rule out alternate sources for this decrement (most notably stellar limb darkening), and consider implications for the planetary atmosphere. They find that the signal is roughly a factor of 3 smaller than their predictions for a cloudless model of the atmosphere with a solar abundance of sodium in atomic form. Although the interpretation of this result is far from unique, they quantify possible models to explain the observed signal: If the disparity between the signal and their fiducial model is due entirely to clouds, then a very high cloud deck (with cloud tops above 0.4 mbar) is required. Alternately, it may be that the atmosphere is depleted in atomic sodium: Models that leave less that 1% of a solar abundance of sodium in atomic form are capable of reproducing the results.

Since the detection, several groups have revisited models of the planetary atmosphere. Barman et al. (2002) consider non-LTE effects. Fortney et al. (2003) conduct a detailed examination of ionization and cloud formation, and are able to produce models that lie within the error bars of the detection.

4.2. Infrared Observations

Although sodium is spectroscopically very active, it is only a trace constituent of the planetary atmosphere. Molecules such as H_2O, CH_4, and CO are of much greater diagnostic potential. The molecule CO is of particular interest: The equilibrium temperature of HD 209458 b ($\sim$1500 K) happens to fall in the narrow regime where the dominant carbon bearing molecule switches from CO to CH_4, with CO preferred in the hotter state. A search for CO is aided by the lack of this feature in the telluric spectrum (unlike CH_4).

Brown, Libbrecht, & Charbonneau (2002) presented data from an exploratory night on HD 209458 with the NIRSPEC instrument on Keck II. The observing conditions were not ideal: They were required to use the adaptive optics system, the weather was poor, and the transit was not entirely visible from their longitude. All of these factors served to reduce the number of photons that they gathered. They presented an upper limit that was roughly a factor of 3 too great to test realistic models of the planetary atmosphere. Nonetheless, it is reasonable to suppose that great gains in the photon-noise limited signal-to-noise ratio (SNR) are possible by observing a couple transits centered near stellar meridian passage and under excellent weather conditions.

At high resolution, the orbital velocity of the planet must be taken into account. The planet's radial velocity shifts by roughly 30 km s^{-1} during the course of the transit. The detection of this change in the Doppler shift would provide convincing evidence that a candidate signal is planetary in origin.

5. Additional Effects During Transit

5.1. Rossiter Effect

Queloz et al. (2000) and Bundy & Marcy (2000) have presented radial velocities during transit. After subracting the known orbit, they find an initial redward, then blueward swing, caused by the planet's occultation of the approaching and receding limbs of the rotating star. This effect is called the Rossiter effect, after Rossiter (1924). These data confirm that the planet orbits in the same sense as the star rotates. Queloz et al. (2000) model their data in detail to show that the planetary orbit appears to be co-aligned with the apparent stellar equatorial plane. They calculate that the time scale for this alignment to result from the tidal influence of the planet upon the star is significantly longer than the age of the system. This indicates that the alignment is primordial, as would be expected for formation and migration of the planet in a protoplanetary disk. However, their uncertainties on the angle between the orbital plane and the stellar equatorial plane are very large: It would be of considerable interest to repeat their experiment and see if the relative alignment of the axes is less than several degrees (as is the case for the solar system). Furthermore, it should be possible to measure the actual distortion to the stellar line profiles (caused by the planetary occultation) in high-resolution, high-SNR spectra. Modeling these distortions should provide a radial velocity map of the star at the latitude of the transit. To date, only the net Doppler shift of the lines have been reported.

5.2. Transit Timing

Additional objects in the HD 209458 system may be revealed by variations in the observed times of center of transit (T_c) relative to the predictions of a simple orbital period. Brown et al. (2001) used STIS observations to rule out a planetary satellite with a mass in excess of 3 $M_{\oplus}$ (they also placed limits on the physical radius of a satellite). More recently, Schultz et al. (2003) have presented observations of 4 transits with the Fine Guidance Sensors (FGS) aboard *HST*. The FGS provided photometry with a SNR ratio of $\sim$80 and a very rapid sampling rate (0.025 s). Their observations targeted the times of ingress and egress. In addition to searching for planetary satellites or additional planets, these data can be combined with those of Brown et al. (2001) to derive an extremely precise estimate of the planetary orbital period. This period will be of great practical value since it will effectively remove timing uncertainties in planning and interpreting observations of future transits.

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