Planetary Systems in the Universe - Observation, Formation and Evolution
Proceedings IAU Symposium No. 202, ©*2004 IAU*
Alan Penny, Pawel Artymowicz, Anne-Marie Lagrange, & Sara Russell, eds.

Extrasolar Planet Transit Observations—Findings and Prospects

Timothy M. Brown

High Altitude Observatory/National Center for Atmospheric Research, 3450 Mitchell Lane, Boulder, CO 80303, USA

Abstract. We now know of one extrasolar planet, HD 209458 b, that is seen to transit the disk of its parent star, and we may expect many others to be discovered in due course. These transiting planets will be important to our understanding of planets in general because they allow many kinds of measurements of the physical properties of the planet – measurements that are not possible for less fortuitous orbital alignments. These include, among others, estimates of the density, temperature, and composition of the planetary atmosphere. Moreover, transits provide a means of detecting planets that cannot yet be seen by other methods. In this paper I describe the progress that has been made so far in making some of these measurements, and the prospects for the future

1. Introduction

In 1999, the first extrasolar planet to transit the disk of its parent star was discovered (Charbonneau et al. 2000, Henry et al. 2000). This is the first of what will prove to be an important subset of extrasolar planets. Just as eclipsing binary stars play an important role in our understanding of stellar physics, transiting planets will be important for our understanding of planets, and for similar reasons—transits allow measurements of the planets' physical properties that cannot be obtained under other circumstances. Microlensing observations may reveal the presence of a planet, and radial velocity measurements may tell you its distance from its star and something of its mass, but if you want to know its size, or composition, or surface temperature, then you had better hope that its orbit is oriented so that transits occur; if not, you are out of luck.

The first round of transit observations of HD 209458 b showed that the planet blocks roughly 1.7% of the star's light at the center of the transit (see Figure 1). By simple geometrical arguments, this implies that the planetary radius is roughly 0.13 times that of the star, or approximately 1.3 R_{Jup}. Since $m \sin i$ is known to be 0.69 M_{Jup} from radial velocity measurements (Mazeh et al. 2000, Henry et al. 2000), and since the existence of transits imply that $\sin i$ is very nearly unity, one may immediately estimate the planet's mean density to be roughly 0.3 g/cm^3. This value is small enough that the planet must be gaseous (composed almost entirely of H and He). Indeed, one may be able to say more: an isolated planet would lose energy by radiation and would shrink to less than 1.3 R_{Jup} within a few million years of its formation (Burrows et al. 2000). Subsequent irradiation of an already-cool planet would expand only the outer layers, leading to a planet smaller than what is observed. Thus, the

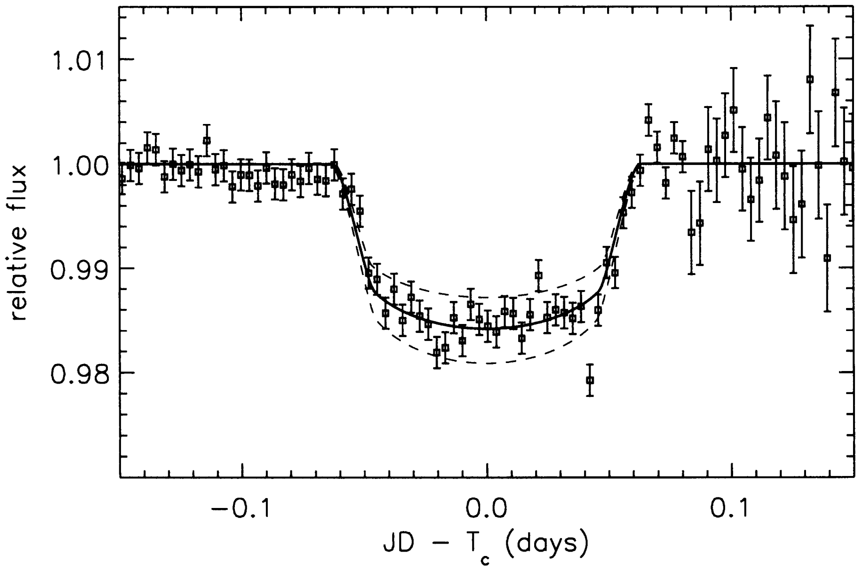

Figure 1. Time series of the relative intensity of HD 209458 during the transit of its planet, from Charbonneau et al. (2000). The plotted data are a superposition of observations from transits on 9 and 16 Sep 2000, rebinned to 5 minute resolution. The errors grow rapidly after the transit because of increasing airmass as the star set.

large radius of HD 209458 b suggests that the planet arrived at its present 0.04-AU distance from its star within a relatively short time of its formation. The simple measurement of the planet's approximate radius therefore tells us not only something about its bulk composition, but also about its history.

2. Improved Photometry with HST

One can improve on the results just described by obtaining multicolor photometry (Jha et al. 2000) or by greatly increasing the photometric precision of the measurements. The latter has been done using the STIS spectrograph on the Hubble Space Telescope (Charbonneau et al. (these proceedings), Brown et al. 2001); the absence of atmospheric absorption and scintillation, and the remarkable pointing accuracy of the HST, yield extraordinary photometric precision even though the STIS instrument was designed with other purposes in mind. The STIS is a useful instrument for precise photometry because, when used with its CCD detector, it can disperse the light from a star over several thousand pixels. This means that it can collect more than 10^8 photons in a single detector readout time without saturating any pixels, allowing photometry that is accurate at the level of 100 μmag or so with sampling times of about 1 minute.

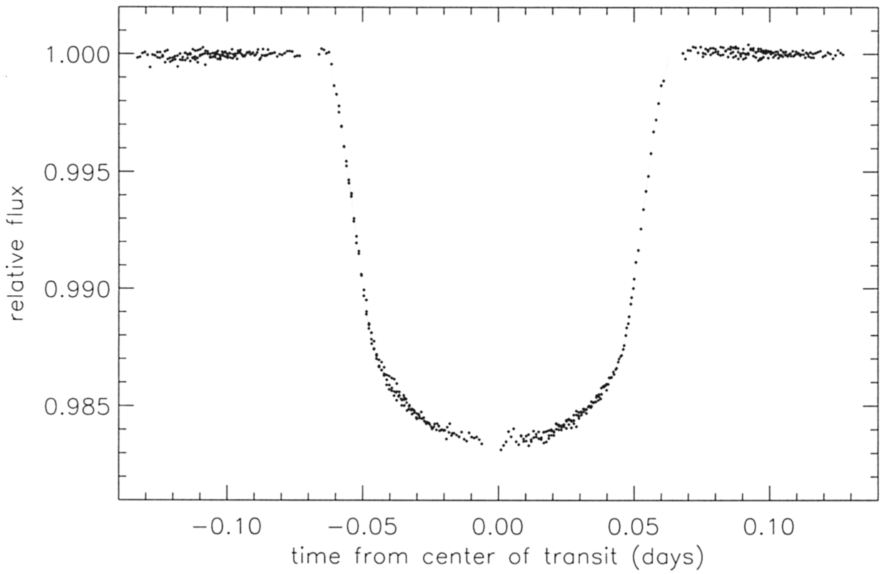

Figure 2. HST time series photometry of the transit of HD 209458 b. Shown is the superposition of partial transit light curves from 4 different transits. Because of the HST orbital orientation, the star was invisible for half of each 96-minute orbit. Thus, most time intervals in the Figure are covered by two sets of observations, but some intervals have only one, and a few have none. The solid line is the best-fit light curve for the model described in the text.

The HST observed HD 209458 during 4 transits spread over about one month during April and May 2000. Figure 2 shows a composite light curve derived from the combination of all of these transits. The observations are fit to within the estimated noise (about 120 μmag per sample, which is about 25% larger than the noise from photon statistics) by a model that invokes an opaque circular planetary disk passing in front of a limb-darkened star. Assuming the stellar mass to be $1.1 \pm 0.1\ M_{\odot}$, one may derive improved estimates for the planetary radius, the stellar radius, and the orbital inclination. These are $R_p = 1.347 \pm 0.060\ R_{Jup}$, $R_* = 1.146 \pm 0.050\ R_{\odot}$, and $i = 86.68° \pm 0.14°$. The bulk of the quoted errors result from the assumed uncertainty in the stellar mass, not from errors in the photometry.

Observations with this quality can be used to set interesting limits on the possible sizes of satellites or ring systems orbiting the planet (e.g., Sartoretti & Schneider 1999). From analysis of the light curve shapes, one may exclude the presence of satellites larger than about $1.2\ R_{\oplus}$, or opaque ring systems that extend further than $1.8\ R_p$ from the center of the planet. Measurements of the timing of the transits similarly exclude the presence of satellites with masses greater than about $3\ M_{\oplus}$. These limits could be substantially lowered if a dedicated spaceborne instrument were available to make repeated measurements.

3. Infrared Observations

In the thermal infrared ("thermal" in this context meaning wavelengths longer than the black-body emission peak for the planet, i.e., more than 3-5 μm), the brightness ratio between the star and the planet is much smaller than in visible light. In the long-wavelength limit, the ratio of stellar to planetary brightness would be the product of the ratio of the surface areas and the ratio of the temperatures, or roughly 300:1. It therefore makes sense to search for the secondary transit, when the planet goes behind the star, at these wavelengths (see Richardson et al., these proceedings). Since the ratio of surface areas is known, measurement of this number would yield a direct measurement of the effective temperature on the planet's day side; this in turn would constrain the Bond albedo and the rate of energy transport to the night side of the planet. No definitive observations of the secondary transit are yet available, but they are being pursued by several groups of observers, and are eagerly awaited.

4. Transit Spectroscopy

A more complex (but potentially more informative) process than those described so far involves observation of a spectral signature of the planetary atmosphere (Seager & Sasselov 2000, Brown 2001). This signature would be imprinted on the starlight passing through the outer parts of the planetary atmosphere. The principal effect at work is illustrated in cartoon form in Figure 3. The limb of the planet is defined as occurring at the radius at which the atmosphere becomes opaque to a tangential ray of light. But this radius depends upon wavelength. At wavelengths for which the atmosphere is relatively transparent, the limb radius is relatively small; at wavelengths where the atmosphere is relatively opaque, one must go higher (to lower densities) to reach a point where tangential rays are transmitted, and the limb radius is correspondingly larger. In simple cases, in which the absorbing species is uniformly distributed throughout the atmosphere, each factor of e increase in the opacity per gram implies an increase in the planetary radius by one scale height. In such cases, the apparent radius of the planet $R_P(\lambda)$ varies according to

$$R_P(\lambda) \;=\; R_0 \;+\; H \ln\left(\frac{\kappa(\lambda)}{\kappa_0}\right) \quad , \tag{1}$$

where H is the atmospheric density scale height, R_0 is the radius as seen at some fiducial wavelength, and κ_0 is the opacity per gram at the fiducial wavelength. At wavelengths where the opacity is high (because of molecular or other absorbing processes), the apparent radius of the planet is larger and more starlight is absorbed, resulting in a weak absorption line added to the stellar spectrum.

A useful measure of the transit-induced variation in the stellar spectrum is $\Re$, the ratio of the spectrum observed during transit to that observed before and after. I define also $\Re' = \Re - 1$, which is the fractional difference between the spectra taken in and out of transit. The strength of the absorption line signal in $\Re'$ is roughly the fraction of the area of the stellar disk blocked by an annulus whose radius is that of the planet and whose width is $H \ln(\kappa/\kappa_0)$. The opacity ratio between strong molecular lines and the nearby continuum may exceed 10^4,

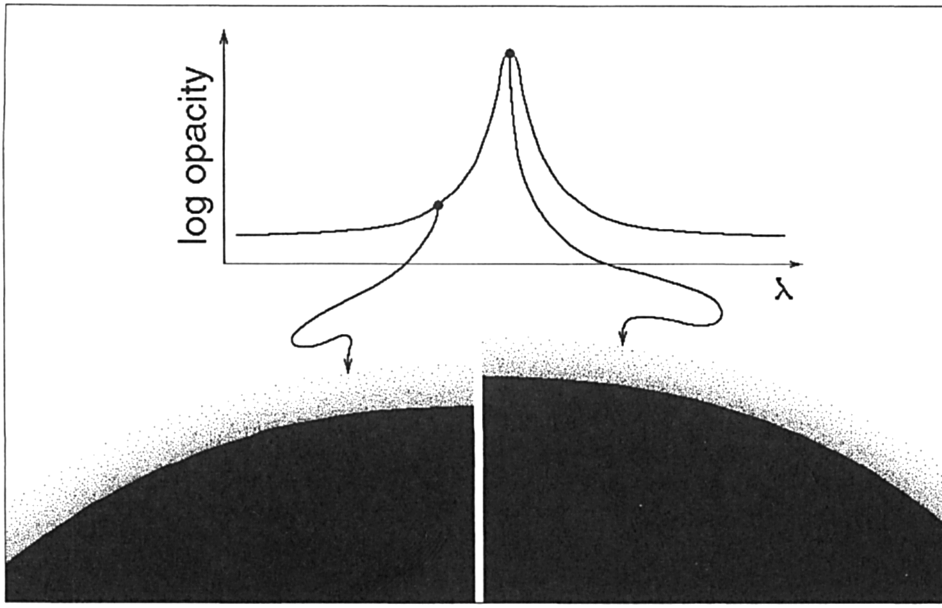

Figure 3. Cartoon illustrating how the apparent radius of a gaseous planet varies depending upon the opacity of its atmosphere. At wavelengths where the opacity is large, one must go to large radii before the density falls to a low enough value for tangential light rays to be transmitted.

so the width of the annulus may be as large as 10 scale heights. Moreover, the scale height in the atmosphere of a hot Jupiter may exceed 500 km, since the temperature is fairly high, while the surface gravity and mean molecular weight are low. As a result, the relative depths of absorption lines caused by the planet may be as much as a few times 10^{-3}. These are weak lines, to be sure, but since the stars that are to be observed are fairly bright, and since transits last for several hours, it is quite feasible to obtain spectra with the necessary precision.

The results of a moderately detailed model of HD 209458 b (albeit still with many limitations and assumptions) are shown in Figure 4 (Brown 2001). In this model, the principal sources of continuous opacity are Rayleigh scattering and the wings of lines of the alkali metals. The most important line sources are the alkali metals themselves, along with the abundant molecules H_2O, CO, and (to a lesser extent) CH_4. Notice that $\Re'$ is a negative number, typically -1.53%, corresponding to the total light blocked by the planet at the wavelengths where its atmosphere is the most transparent. The wavelength-dependent variations are as much as 0.2% in the cores of the strongest lines; this implies that the planet appears 1.06 times as large in the most opaque wavelengths as it does in the most transparent ones.

Modeled transit spectrum ratios $\Re'$ turn out to depend upon many details of the assumed planetary atmospheres. Thus, it is possible to use the observed spectra as diagnostics of conditions on the planet. Exploring the full extent of the possible measurements is beyond the scope of this paper, but diagnostics appear to exist (sometimes requiring extremely high spectral resolution or low

https://doi.org/10.1017/S0074180900217452 Published online by Cambridge University Press

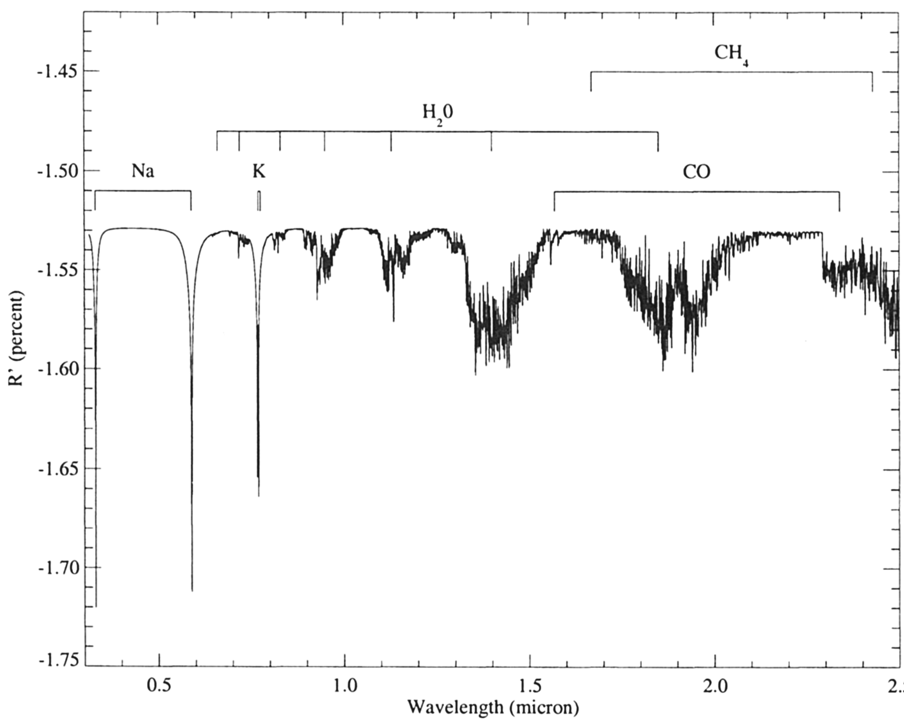

Figure 4. Model of the wavelength variation of $\Re'$ for a planet resembling HD 209458 b. Features caused by Na, K, H_2O, CO, and CH_4 are identified in the figure. This model assumes that the atmosphere contains an opaque cloud deck with the cloud tops lying at a pressure of 0.03 bar.

noise) for the atmosphere's composition, temperature, and vertical temperature gradient, the speed and possibly direction of its global wind fields, and the height and particle sizes in the uppermost cloud deck. For a discussion of these issues, see Brown (2001).

5. Transit Searches for Planets

The possibility of detecting extrasolar planets by searching for their photometric transits has been recognized for a long time (see, eg, the remarkably prescient discussion by Struve (1952)). Encouraged by the demonstrated presence of large planets in close orbits, several ground-based searches for transiting giant planets are now underway (eg. Borucki et al. 1999, Doyle et al. 2000). Also, as indicated by the HST observations described above, space-based photometry has the precision necessary to detect Earth-sized planets transiting Sun-sized stars. This should provide encouragement for dedicated space-borne searches for smaller extrasolar planets, as for example COROT (Michel et al. 2000), MONS (Kjeldsen, Bedding, & Christensen-Dalsgaard 2000), and the proposed Kepler mission (Koch et al. 1998). Finally, a recently-concluded HST search for hot Jupiters in the globular cluster 47 Tuc revealed no planetary transits at all among a search sample of 34000 Sun-like stars (Gilliland et al. 2000, Brown et al., these proceedings). In this large a sample, about 15 detections were expected. This implies that something about the cluster environment (including, perhaps, low initial metallicity) interferes with the formation, migration, or survival of giant planets.

Thus, searches for transiting planets may sometimes be informative even when they yield no detections. But in view of the great opportunities for in-depth study offered by planets with suitably-aligned orbits, it seems a safe prediction that the current transit search efforts will continue until they are successful, and that transits will become a regular tool of research on extrasolar planets.

References

Borucki, W.J., Caldwell, D.A., Koch, D.G., Webster, L.D., Jenkins, J.M., & Ninkov, Z. 1999, American Astronomical Society Meeting 195, 2401

Brown, T.M. 2001, ApJ, (submitted)

Brown, T.M., Charbonneau, D., Gilliland, R.L., Noyes, R.W., & Burrows, A. 2001, ApJ, (submitted)

Burrows, A., Guillot, T., Hubbard, W.B., Marley, M.S., Saumon, D., Lunine, J.I., & Sudarsky, D. 2000 ApJ, 534, L97

Charbonneau, D., Brown, T.M., Latham, D.W., & Mayor, M. 2000, ApJ, 529, L45

Doyle, L.R. et al. 2000, ApJ, 535, 338

Gilliland, R.L. et al. 2000, ApJ, (in press)

Henry, G.W., Marcy, G.W., Butler, R.P., & Vogt, S.S. 2000, ApJ, 529, L41

Jha, S., Charbonneau, D., Garnavich, P.M., Sullivan, D.J., Sullivan, T., Brown, T.M., & Tonry, J.L. 2000, ApJ, 540, L45

Kjeldsen, H., Bedding, T.R., & Christensen-Dalsgaard, J. 2000, in ASP Conf. Ser. 203, The Impact of Large-Scale Surveys on Pulsating Star Research, eds. L. Szabados & D. Kurtz (San Francisco: ASP), 73

Koch, D.G., Borucki, W., Webster, L., Dunham, E., Jenkins, J., Marriott, J., & Reitsema, H.J. 1998, Proc. SPIE, 3356, 599

Mazeh, T. et al. 2000, ApJ, 532, L55

Michel, E. et al. 2000, in ASP Conf. Ser. 203, The Impact of Large-Scale Surveys on Pulsating Star Research, eds. L. Szabados & D. Kurtz (San Francisco: ASP), 69

Sartoretti, P., & Schneider, J. 1999, A&AS, 134, 553

Seager, S., & Sasselov, D.D. 2000, ApJ, 537, 916

Struve, O. 1952, The Observatory, 72, 199