Exoplanet Forum: Transit Chapter

A condensed version of the Transits Chapter
from the Exoplanet Forum Proceedings,
made available to the Decadal Survey,
Planetary Systems and Star Formation Panel

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1.0 Introduction. Transits provide enormous astrophysical leverage to reveal the physical nature of extrasolar planets. The transit itself, supplemented by high precision radial velocity observations, gives us the *mass* and *radius* of the planet. This in turn constrains the planet's bulk composition. Absorption of starlight passing through the planet's atmosphere during transit (Figure 8-1) tells us the composition and scale height of the exoplanet atmosphere (e.g., Charbonneau et al. 2002, Swain et al. 2008b). Modulation of the combined light of the system during secondary eclipse provides a direct detection of the planet's emergent spectrum (Figure 8-1, and Charbonneau et al. 2005, Deming et al. 2005, 2006, Grillmair et al. 2007, Richardson et al. 2007, Swain et al. 2008a). Since the planet's emergent radiation peaks in the infrared (IR) spectral region, secondary eclipse measurements are primarily focused on the IR.

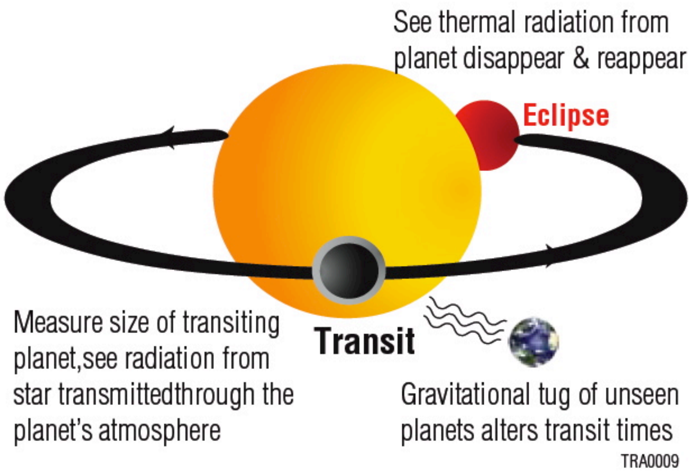

Figure 8-1. Transit geometry provides the astrophysical leverage that allows direct detection and in-depth characterization of close-in extrasolar planets.

Figure 8-2 shows one aspect of recent scientific results from transit measurements, namely the empirical mass-radius relation for exoplanets down to the size of Neptune (GJ 436b, Gillon et al. 2007, Deming et al. 2007). As noted on Figure 8-2, the nature and origin of giant planets with radii too large for their mass is currently a major open question in exoplanetary science.

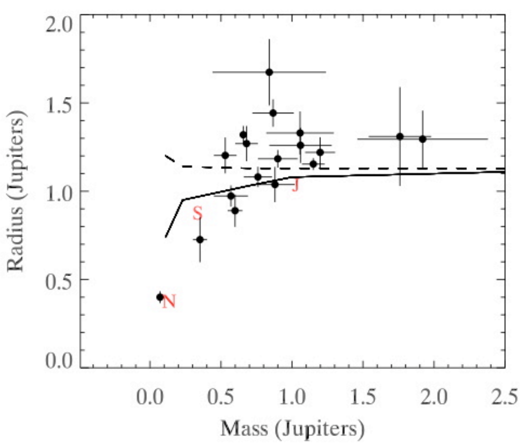

Figure 8-2. Mass-radius relation for transiting exoplanets to date. The solid and dashed lines are theoretical relations from Bodenheimer et al. (2003), for planets with (solid line), and without (dashed line) a heavy element core. Note that several giant planets have radii that exceed even the coreless models by substantially more than the observational errors.

The different geometries of transit and secondary eclipse allow localization of atmospheric knowledge: transit spectroscopy probes the atmospheric interface between the day and night hemispheres of a tidally-locked planet (Swain et al. 2008b), whereas secondary eclipse measurements probe the emergent spectrum of the dayside. Moreover, measurements of transiting systems have been extended well beyond the times of transit and eclipse, to include observations in the combined light of star and planet at a large range of orbital phases. In instances where the planet's rotation is tidally locked to its orbit, these measurements can be inverted to yield the distribution of emergent intensity versus longitude on the planet (Knutson et al. 2007). The observational techniques used for transiting systems can also be extended to non-transiting systems, so it is valuable to consider a generalization of the transit technique, namely exoplanet characterization in combined light. Without a transit, the planet radius cannot be measured directly, and that is a significant limitation. Nevertheless, much can be learned, for example from observing fluctuations in IR intensity that are phased to the planet's known radial velocity orbit (e.g., Harrington et al. 2006).

Table 8-1. Science enabled by transits.

Orbital Phase	***Science Enabled***
Transit (primary eclipse)	Radius measurement Mass measurements (when combined with radial velocity) Bulk composition inferred from mass & radius Atmospheric absorption spectroscopy Detection of unseen planets via timing variations Measurement of the relative inclination of stellar spin angular momentum versus planetary orbital angular momentum, via the Rossiter-McLaughlin effect
Secondary eclipse	Measurement of the emergent spectrum of the planet Measurement of orbit eccentricity (or limits thereon) Ultra-high spatial resolution, mapping the disk of the planet (in longitude, expected to be achieved by JWST)
Other orbit phases	Longitudinal temperature maps and inferences concerning zonal winds Spectroscopy of the planet at all longitudinal aspects (in principle, but not yet achieved)

1.1.1 Science Enabled by Transits

The science enabled by transit measurements can be concisely summarized in Table 8-1. The quantity of results obtained by the transit technique is large, and growing rapidly. **Virtually everything we know about the physical nature of exoplanets has come from a combination of radial velocity and transit measurements.**

1.1.2 Measurement Requirements

The principal requirement of transit measurements is high photometric and spectrophotometric precision, on relatively bright stars. This need for precision derives from the fact that transit measurements are made in the combined light of the star plus planet. Hence the planet signal is greatly diluted by the stellar photons, and the measurement precision must be as high as possible. Moreover, the time scale of the photometric noise is crucial. Since transits are typically a few

hours in duration, the precision of individual measurements should improve as the inverse square-root of the measurement time, for times exceeding several hours. Since a photometric baseline is required before and after transit, a reasonable time scale for the required stability is ~ 20 hours. Since both visible and IR measurements are important for transits (Figure 8-1), the instrumentation should be designed to reach the fundamental limits determined by the stellar photon noise (primarily important in the visible) and the background noise caused by the thermal emission of the instrument, telescope, and zodiacal dust (primarily important in the IR).
For more extended ("around-the-orbit") science, the phenomena being measured have time scales of several days, so ~ 20 day stability is needed.

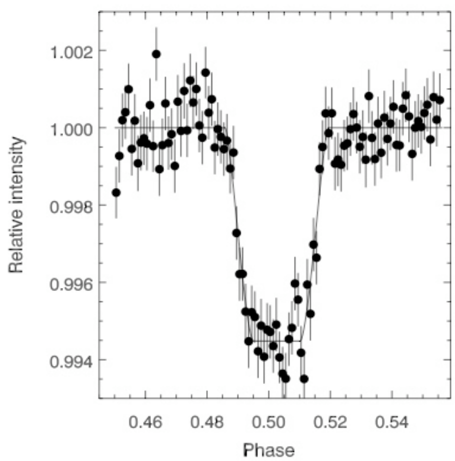

Figure 8-3. Example of a Spitzer exoplanet detection, the secondary eclipse of HD 189733b (Deming et al. 2006). By detecting the eclipse Spitzer is able to make a direct measurement of the IR flux from the planet.

Ground-based photometry has made great strides, and is achieving sub-milli-magnitude precision in favorable cases (Johnson et al. 2009). However, for most exoplanet characterization science, space-borne observations will be necessary. The best location for a space-borne transit mission is heliocentric orbit, or placement at a Lagrangian point. Although significant transit science can be done from near-Earth orbit, those orbits have two principal limitations: 1) long uninterrupted observing times, such as are needed for exoplanet around-the-orbit observations, are generally not possible from a near-Earth location, and 2) proximity to the Earth results in time-variable scattered light and thermal radiation that can interfere with achieving the necessary precision.

1.1.3 Previous and Planned Transit Missions

Major advances in our knowledge of the physical nature of exoplanets have come from the Great Observatories, principally Hubble and Spitzer, and recent examples are shown in Figures 8-3 and 8-4. HST observations yielded the first detection on an exoplanet atmosphere (Charbonneau et al. 2002), and Spitzer observations gave us "first light" for exoplanet emission (Charbonneau et al. 2005, Deming et al. 2005). Many follow-up results are summarized below in the description of a new combined light mission, and in reviews by Charbonneau et al. (2007), and Deming (2008). Although the Great Observatories were not specifically designed for exoplanet observations, their general capabilities are sufficient to deeply exploit the transit geometry, and produce abundant cutting edge science.

1.2 Observatory Concepts

Transit missions fall into two general categories: search and characterization. Here we describe an all-sky transit search mission, and two examples of transit characterization. In the case of the characterization missions, we first describe a combined-light mission that is quite general, and that can make inferences about the emergent spectra of close-in exoplanets in combined light, even for systems that do not transit. We also describe a characterization mission that extends transit spectroscopy into the ultraviolet spectral region, where the transit absorption signatures can be quite large.

An All-sky Transit Survey: The purpose of a mission like Kepler is to identify exoplanets as small as Earth in size, both in order to find individual planets and to get statistical data on the population and distribution of such planets. Kepler observes stars typically of magnitudes 10 to 14 in a field just over 100 square degrees in size (about 1/400 of the sky). We are also interested in finding planets relatively nearby to our solar system, because the greater observed brightness of nearby stars and planets permit more detailed characterization to be achieved. So an all-sky survey, albeit less deep than Kepler, is needed. An all-sky survey merely out to magnitude 12 should find at least eight times as many planets as Kepler does, and the ones found would, on average, be four times closer than the Kepler planets. The recent inference that Super Earths are common around solar-type and lower main sequence stars (Mayor et al. 2008) adds greatly to the motivation for an all-sky survey. An all-sky survey would find the closest transiting Super Earth or transiting Earth analog. The Mayor et al. (2008) results imply that there will be a large number of transiting Super Earths orbiting nearby solar-type stars, and the closest example is likely to be the planet that can be characterized to the highest signal-to-noise ratio.

A Combined-Light Characterization Mission (CLM): Dramatic measurements made with the Spitzer and Hubble space telescopes have redefined the field of exoplanet characterization (e.g., Barman 2007, Beaulieu et al. 2008, Charbonneau et al. 2002, 2005, Deming et al. 2005, 2006, 2007, Demory et al. 2007, Gillon et al. 2007, Grillmair et al. 2007, Harrington et al. 2006, 2007, Knutson et al. 2007, 2008, Richardson et al. 2007, Swain et al. 2008a,b); collectively, this work has decisively established that detailed characterization of exoplanet atmospheres is feasible. Today, due to the extraordinary and unforeseen success of the Spitzer and Hubble space telescopes, we can discuss the observational signatures of exoplanet atmospheres including weather, vertical and longitudinal temperature profiles, molecular abundances (including prebiotic molecules), dayside to night side atmospheric chemistry changes, and the role of photochemistry. Of equal significance to this scientific advance is the method by which the breakthroughs were made wherein the *combined light* star-planet system is measured. Spitzer and Hubble space telescope measurements do not spatially resolve the exoplanets; rather, information about the exoplanet is extracted from precise measurements in the "light curve" or changes in the spectrophotometric intensity arising from the planet during its orbit. Further, observations of different portions of the light curve have demonstrated the ability to **localize molecular abundances** to specific regions of the exoplanet atmosphere and explore, for example, the differences between dayside and nightside atmospheric chemistry.

Building on the extraordinary successes of Spitzer and Hubble, we advocate that NASA consider a combined-light exoplanet characterization mission. This mission would focus on the detection of molecules in exoplanet atmospheres. By detecting and determining the abundances of molecules, the principal goal of a combined-light mission would **determine the conditions, composition, and chemistry** of exoplanet atmospheres. A high priority for the combined-light mission is observing habitable zone planets for (1) the detection of prebiotic molecules and (2) characterization of the nature of photochemical and thermochemical contributions to atmospheric carbon chemistry. Given an appropriate target, such as an exoplanet in a 15 to 25 day orbit around a nearby M star, a combined-light mission could determine a detailed picture of the atmospheric chemistry of a planet where life could exist. A combined-light mission could also characterize the solid surfaces of rocky planets.

Determining the conditions, composition, and chemistry of exoplanet atmospheres would be accomplished by interpreting the observed spectra using retrieval methods (Tinetti et al. 2007) to extract molecular abundances and the pressure-temperature profiles; this knowledge would be localized by repeating the retrieval for different portions of the planet's orbit. Examples of important target molecules are H_2O, CH_4, CO, CO_2, and NH_3; all these species have strong absorption bands in the 2–5-µm wavelength range. Each of these molecules probes the atmospheres in different ways. CO and CH_4 are primary reservoirs of carbon; the CO/CH_4 ratio is sensitive to temperature. CO_2 probes the vertical temperature profile and the vertical mixing ratio (potentially a diagnostic of photochemistry) using the v=13–15 bands. CO_2 also serves as a proxy for CO, while CO and CH_4 abundances differing from thermochemical equilibrium might indicate photochemistry. For tidally locked, hot-Jovian planets, the chemistry of the atmosphere is expected to change, particularly the [CO]/[CH_4] ratio, as a function of orbital phase and, in some cases, a dayside hot stratosphere might form (Burrows et al. 2007, Fortney et al. 2008, Knutson et al. 2007); the [CO]/[CH_4] ratio at the terminator is also a potential diagnostic of variability, possibly associated with large scale eddies generated by zonal winds. Although atmospheric heating will be characterized by Spitzer photometry, spectroscopy is required to probe how the atmosphere chemistry changes from the dayside to the night side. The targets accessible to a combined-light mission cover a range of exoplanet sizes, temperatures, and stellar spectral types and will reveal the influences of the stellar primary on the exoplanet atmosphere. Thus, a combined-light mission would enable us to understand the effect of radiation forcing from the stellar primary on photochemistry and stratosphere formation.

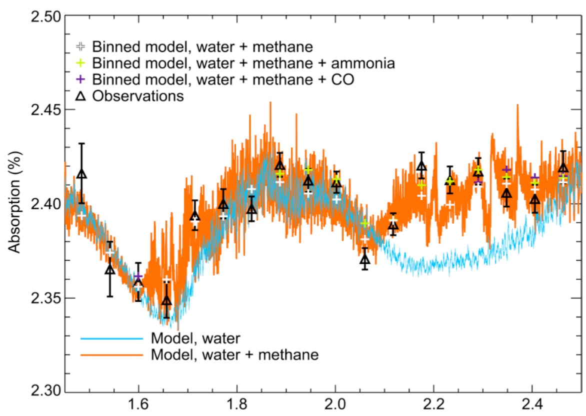

Figure 8-4. A comparison of observations (black triangles) with a model of water (blue) and water + methane in an absorption spectrum of the planet HD 189733b (Swain et al. 2008b). These data are the first detection of an organic molecule in an exoplanet atmosphere and were obtained with HST/NICMOS. A combined-light exoplanet characterization mission could deliver data of similar quality for many exoplanets and would extend the spectral coverage into the thermal infrared.

An Ultraviolet Transit Mission: Transiting exoplanets have all been discovered at optical wavelengths and the majority of characterization studies have been performed at optical and infrared wavelengths. Optical and infrared wavelengths yield information about the atmospheric albedo (e.g., Rowe et al. 2006), atomic abundances (e.g., Redfield et al. 2008), molecular abundances (e.g., Tinetti et al. 2008) and thermal radiation of the planet (e.g., Knutson et al. 2007), and shorter wavelengths can yield information about haze, atomic species, and condensed particles in the atmosphere and the interaction of the planet with the stars.

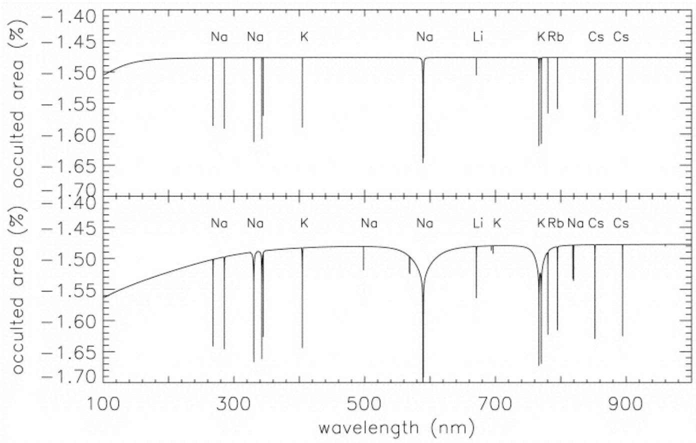

Figure 8-5. Model for the normalized in-transit minus out-of-transit spectra displaying some of the prominent atomic species in the UV and visible. Adopted from Seager & Sasselov (2000). The two panels show cases with different cloud-top heights.

High precision polarization studies can yield detailed information about the cloud particulate content, sizes, and cloud layer distributions (e.g., Seager, Whitney, & Sasselov 2000; Hough et al. 2006). For example, below 0.2 mm, Rayleigh scattering from H_2 is important. In general, photometric and polarization light curves are a function of the atmospheric opacity and the observational viewing angle and can, in principle, yield details about the day/night variations of the cloud layers and particulates (e.g., Seager, Whitney, & Sasselov 2000).

The first detection of an atomic species was made by observing the Na II doublet in absorption against the stellar host HD 209458 (Charbonneau et al. 2002). However, at ultraviolet wavelengths, absorption line studies of other species can provide information about the atomic and ionic species content of the planetary atmosphere. Various atomic species are visible in the stellar spectra including Na, K, and Li (Figure 8-5) and can probe different layers and physical conditions of the planetary atmosphere (Seager & Sasselov 2000).

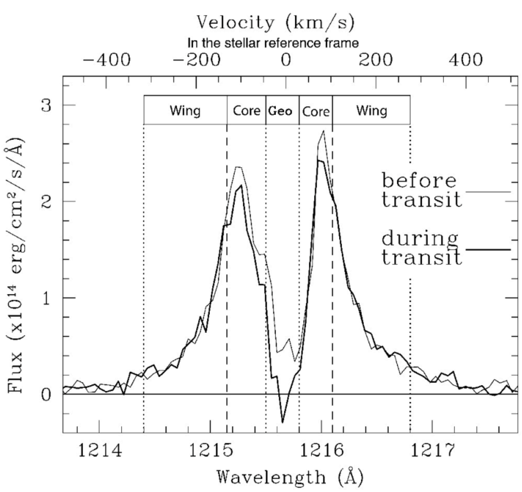

Figure 8-6. Observed HD 209458 Ly-α profiles in and out of transit, as observed by Vidal-Madjar et al. 2003 - suggesting that hydrogen is evaporating from the planetary atmosphere. Adopted from Vidal-Madjar et al. 2008.

For giant planets in short orbital periods (i.e., the hot Jupiters), the observed atmosphere transitions from being dominated by the planetary thermal emission to being dominated by reflected emission from the star. By studying the emission at shorter wavelengths, where reflectance dominates the exoplanet emission, studies of the planetary haze and cloud content can be performed. The scattering and polarization signatures become less diluted by thermal emission as the observation wavelengths grow shorter.

Absorption line studies of Lyman-α suggest that HD 209458b contains a large exo-sphere of hydrogen (Figure 8-6). Interpretations of this phenomenon include evaporation of the planetary atmosphere, where the particles are accelerated by radiation pressure (Vidal-Madjar et al. 2008). Other interpretations require an interaction with the stellar wind to achieve the observed velocities (Holmstrom et al. 2007). In either case, it seems clear that the planet and the star may be interacting, and UV spectroscopy has enabled the discovery (and a better understanding) of the process.

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