From Interacting Binaries to Exoplanets: Essential Modeling Tools
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Towards a Theory for the Atmospheres, Structure, and Evolution of Giant Exoplanets

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Abstract. In this short review, I summarize some of the salient features of the emerging theory of exoplanets in general, and of giant exoplanets in particular. A focus is on the characterization of transiting planets at primary and secondary eclipse, but various other related topics are covered, if only briefly. A theme that clearly emerges is that a vibrant new science of comparative exoplanetology is being born.

Keywords. planets and satellites: general; (stars:) planetary systems; stars: low-mass, brown dwarfs; stars: atmospheres

1. Introduction

It can be said, without fear of hyperbole, that we are living in the heroic age of exoplanetary studies. Since the discovery of 51 Peg b by Mayor & Queloz (1995), astronomers have discovered more than 1500 planets beyond the solar system. The majority of the latter are gas giants discovered from the ground and with the *Kepler* (Borucki *et al.* 2010) and CoRoT (Baglin *et al.* 2006) space telescopes, but more than a hundred "Neptunes" are now known, and many so-called "super-Earths" have been detected. In the next few years, we are likely to determine the statistics of the orbits, radii, and masses of exoplanets, constraining not only their origins and dynamics, but their atmospheres. In the process, we will determine, if only as a byproduct, the galactic context of our own planetary cohort.

Importantly, more than 120 transiting planets have been discovered from the ground and most of these are close enough to be followed-up to obtain radial-velocity masses. Excitingly, many of these can be studied photometrically and spectroscopically at secondary and primary eclipse to derive temperatures and compositions, both from the ground and using *Spitzer* and HST/NICMOS space assets. What is more, the phase orbital light curves of some of the closest giant exoplanets have now been measured at various wavelengths. Collectively, with such data we are learning a great deal about the structures, chemistry, and atmospheres of exogiants. Indeed, the pace with which this field is moving is outstripping all predictions.

This extraordinary pace is such that theory and theoretical studies will have a full smorgasbord of issues, problems, and puzzles to address for the foreseeable future. Moreover, new theory will be crucial to interpret the flood of incoming data. Clearly, summarizing this effort would be a daunting task. Rather, for this short review, I cherry-pick from some of my own efforts at interpretation and understanding to communicate just a fraction of the findings and thoughts that have emerged in the last few years in response to the need to explain these new objects. The reader can be assured that there is much more.

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2. The Radii of Brown Dwarfs and Giant Exoplanets

Observers have used theoretical evolutionary models of brown dwarfs for many years to determine the physical properties, in particular the effective temperatures, surface gravities, masses, ages, and compositions, of the objects they find and study. Theory is the essential tool with which to convert data into meaning (Burrows *et al.* 2001). One of the best techniques to constrain physical theory is with eclipsing/transiting systems (Johnson *et al.* 2011; Bouchy *et al.* 2011; Deleuil *et al.* 2008) in the brown dwarf realm, rare as they are, since in this way radii can be determined and compared with published models. However, model radii depend upon more than the equation of state (EOS) (Saumon, Chabrier, & Van Horn 1995). In fact, a brown dwarf radius at a given age and mass is a function of atmospheric metallicity, bulk helium fraction, and the cloud models employed by the theorist. The latter is the most problematic aspect of brown dwarf theory, for though silicate and iron clouds can dominate the atmospheres of L dwarfs, the specific particle size and spatial distributions and particle optical properties are barely understood (Helling *et al.* 2001). Given this, there is a range of radii expected for brown dwarfs of a given age and mass, and this ambiguity had not been properly appreciated.

Recently, however, Burrows, Heng, & Nampaisarn (2011) have found that the spread in radius at a given mass and age can be as large as ∼10% to ∼25%, with higher-metallicity, higher-cloud-thickness atmospheres resulting quite naturally in larger radii. For each 0.1 dex increase in [Fe/H], radii increase by ∼1% to ∼2.5%, depending upon age and mass. They also find that, while for smaller masses and older ages brown dwarf radii decrease with increasing helium fraction (Y) (as expected), for more massive brown dwarfs and a wide range of ages they increase with helium fraction. The increase in radius in going from $Y = 0.25$ to $Y = 0.28$ can be as large as ∼0.025 R_J (∼2.5%). Furthermore, they find that for very-low-mass (VLM) stars, an increase in atmospheric metallicity from 0.0 to 0.5 dex increases radii by ∼4%, and from -0.5 to 0.5 dex by ∼10%. They suggest that opacity due to higher metallicity might naturally account for the apparent radius anomalies in some eclipsing VLM systems. Ten to twenty-five percent variations in radius exceed errors stemming from uncertainties in the equation of state alone. This serves to emphasize that transit and eclipse measurements of brown dwarf radii recently published using *Kepler* and CoRoT constrain numerous effects collectively, importantly including the atmosphere and condensate cloud models, and not just the equation of state. At all times, one is testing a multi-parameter theory, and not a universal radius−mass relation.

This lesson is all the more important when studying transiting giant exoplanets. Though much lower in mass than the average brown dwarfs, they have similar radii. However, the differences are revealing. A close-in transiting exoplanet is irradiated by its primary and this radically changes its atmosphere on both its day and night sides. The profiles on these atmospheres match onto their convective cores and it is the loss of energy and the concomitant decrease in core entropy that determines a gas giant's radius. For each irradiated giant planet, one must perform custom models that take into account stellar irradiation, planet mass, system age, and, if possible, bulk and atmospheric composition. The latter is by and large unknown, and the stellar age and metallicity are not reliably obtained for the vast majority of stars. In addition, proximity to its primary and even slight orbital eccentricity can lead to tidal heating of unknown magnitude and convection and rotation can generate magnetic fields of significance that could play a role in day/night heat redistribution and in both core and atmospheric heating. Finally, giant planets can have central cores of denser material (ice and rock) of unknown mass, as well as envelopes enriched in heavy elements.

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The result is an imperfect theory with which to interpret planet transit data. Nevertheless, there are two trends that bear mentioning. The first is that when one generates the requisite custom models for a large number of irradiated, transiting planets and introduces a dense core to improve the fits, a trend with stellar metallicity emerges. For no giant planet orbiting a lower-metallicity star do Burrows *et al.* (2007a) or Guillot *et al.* (2006) infer a large inner core. Conversely, for no giant planet orbiting the highest-metallicity stars do these authors infer a small inner core. Intriguingly, the core masses Burrows *et al.* (2007a) find for exogiants transiting near-solar metallicity stars are close to those estimated for Jupiter and Saturn. The upshot is that a roughly montonically-increasing relationship between stellar metallicity and estimated core mass emerges from the study of transiting giant planets collectively. Note that stellar metallicity was not used in the planet modeling. Hence, these twin correlations may speak to the mechanism of giant planet formation and are in keeping with the core-accretion model of their origin.

The second trend is the more well-known. There are a number of close-in transiting giants with radii that are too large to be explained by the default theory. Examples are WASP-12b ($\sim$1.736 R_J), TreS-4 ($\sim$1.706 R_J), WASP-19b ($\sim$1.991 R_J), and HAT-P-32b ($\sim$2.037 R_J). While measurement errors are certainly possible, anomalously large radii seem indicated in an interesting subset of transiting giant exoplanets. Culprits could be core or deep-atmosphere heating (tidal or magnetic), extreme age errors (a much younger planet is bigger), large planet atmospheric opacities (similar to the effect for the brown dwarfs alluded to earlier), or, again, radius measurement errors. Whatever the reason, resolving this apparent anomaly is one of the most important goals of those studying the newly-discovered close-in giant planets.

3. On Using Deuterium Burning to Distinguish Giant Exoplanets from Brown Dwarfs

Gas giant planets and brown dwarfs share many characteristics. They both have molecular atmospheres, whose mass is dominated by hydrogen and helium. Their atmospheric opacities are dominated by a small set of compounds, notably water, methane, carbon monoxide, and often various cloud species. The most important constituents of their cores are hydrogen and helium and their EOS is in a realm in which Coulomb and degeneracy effects compete. The upshot is that, over two orders of magnitude in mass from $\sim$0.3 to $\sim$100 M_J, the cold radius of such objects differs by no more than $\sim$30-40% from 1 R_J.

Nevertheless, different origins and astronomical sociology seem to require that one be able to distinguish one family from another. I think it sensible to distinguish giant planets from brown dwarfs by their origins, but an origin is not an observable and we don't yet know how either class of objects forms, nor what their expected mass functions might be. The latter are likely to be different, but to overlap. In fact, despite the possibility that the mass functions of these families could overlap, what has emerged to distinguish one family from the other is a simple mass cut. Burrows *et al.* (1997) published evolutionary curves for H_2/He-rich objects with masses spanning a broad range from Saturn's to above 0.2 $M_\odot$. In their Figure 7, they (seemingly) arbitrarily distinguished "planets," and "brown dwarfs" by whether they burned deuterium. This border mass was near 13 M_J and, as a result, many began to use 13 M_J as the boundary between the giant planets and brown dwarfs. This was not the original intent of the authors, but it is a simple, one-dimensional condition that has stuck.

However, those who use such a simple criterion should be aware that this one number (13 M_J) ignores the fact that the burned fraction (e.g., whether 10%, 50%, or 90%), metallicity, and helium fraction all come into play when defining a deuterium-burning

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mass. Indeed, Spiegel, Burrows, & Milsom (2011) have shown that when these considerations are accounted for "the" deuterium-burning mass can vary from $\sim$12 M_J to $\sim$14 M_J. Hence, even this simple discriminant is not absolute. When one can at last separate these two families on the basis of origin via orbit, rotation, composition, presence or absence of a dense core, or whatever characteristics emerge in a statistical sense to distinguish them, a truly astronomically relevant naming convention will finally be available.

4. The Wavelength Dependence of the Transit Radii of Exoplanets

The transit method for exoplanet discovery and characterization hinges upon measurments of the periodic photometric variations in the stellar light caused by passage of the orbiting planet in front of the star. The magnitude of the fractional diminution in the stellar light is $(R_p/R_*)^2$, where R_p and R_* are the planet and star radius, respectively. Given R_*, R_p can be determined and, since the planet is in transit and the orbital inclination (i) is therefore measured, radial velocity measurements, which yield $m_p \sin(i)$, provide the planet's mass directly. With both mass and radius, one can do physics and constrain structural models.

However, the radius measured by this method is the "transit radius," which is the impact parameter from the planetary center of the stellar rays intercepted at the Earth that traverse a chord near the terminator for which the optical depth in the planet's atmosphere is of order unity. The optical depth in the radial direction, so important for planet "emission" spectra, is irrelevant here. Importantly, since giant planets have extended atmospheres and the opacities that go into determining the impact parameter are composition- and wavelength-dependent, the transit radius itself is a function of wavelength. The upshot is that the spectra of transit radii reflect atmospheric composition and scale heights and can be used, with profit, to identify atmospheric atoms and molecules. This is how Charbonneau *et al.* (2002) detected sodium in the atmosphere of HD 209458b, and how water, carbon monoxide, and, perhaps, carbon dioxide have been claimed in the atmospheres of other transiting planets. This technique is complementary to the traditional direct planetary spectral measurement technique for probing atmospheres and is more composition-dependent than the latter. Fortney *et al.* (2003) estimated that the potential radius variation in and out of water features in the near infrared could be as much as a few percent, a result echoed by Burrows *et al.* (2011b), who derived values near $\sim$5%. Hence, measurements of the spectral variation of transit radii provide direct and useful diagnostics of planet composition.

5. Interpretation of Planet Flux Measurements at Secondary Eclipse

Just before the secondary eclipse of a transiting planet by a star, astronomers can measure their summed light. During secondary eclipse, however, only the stellar light contributes to the signal. Therefore, the difference between these two measurements can yield the planet's flux. In the mid-infrared, this difference can be a few parts in 10^3 or 10^4 of the stellar flux and is measurable by *Spitzer*. Without needing to image separately planet from star, the planet's emissions can be obtained! True, this is a severely irradiated planet, and not one all-but-isolated from its parent star. Nevertheless, such data provide a wealth of information about the planet's atmosphere (its temperature, composition, and temperature profile), as well as its wind dynamics. Super-rotational flows and jet streams can advect heat deposited by the star downstream of the substellar point before it is re-radiated. The angular (and, hence, temporal) shift this causes with respect to the orbital ephemeris reflects, among other things, the wind speeds. Hence, measurement of secondary eclipse spectra and photometry has inaugurated the era of remote sensing

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and detailed characterization of exoplanets. The *Spitzer* space telescope has been the workhorse of these studies, and if JWST flies, it will provide an order of magnitude improvement over the still-precious *Spitzer* data.

5.1. *Inversions and Hot Upper Atmospheres*

In the course of such secondary eclipse studies, it was found that the spectra of some highly-irradiated giant planets show signs of superheated upper atmospheres and/or thermal inversions. The signature of the latter is the flipping from the classical absorption spectra of normal atmospheres into emission spectra − spectral troughs became peaks, and vice versa (Hubeny *et al.* 2003; Burrows *et al.* 2007b; Knutson *et al.* 2008). Inverted spectra (positive temperature gradients going outward) were indicated by the switch of the ratio of the IRAC1/IRAC2 flux ratio seen using *Spitzer* from greater than one (normal) to less than one (inverted). The upper atmosphere heating inferred could amount to an increase in atmospheric temperatures near the $\sim 10^{-2}$ bar pressure level of $\sim$1000-1500 K and an increase in the IRAC3 band flux of as much as a factor of three! The origin and cause of this inferred severe heating and anomalous thermal profile is unknown, but an as-yet-unidentified absorbing molecule is being sought. The effect is not small, for as much as tens of percent of the total intercepted stellar flux is implicated. This constitutes one of the great mysteries to emerge from the recent study of transiting exoplanets.

6. Albedos

A venerable tradition in Solar System science is the study of the reflected optical light from its cold planets, moons, and asteroids. When the optical and mid-infrared spectral "bumps" from such objects are well-separated and distinct, the interpretation of such bumps as optical "reflection" and "thermal emission" is well-justified. The darkness or lightness of such bodies in the optical, and the optical colors of their reflected light can indicate their compositions, and help determine their radii. The geometric albedo is a measure of the strength of this reflection, with high values below (but near) one indicating highly-reflective surfaces and low values below $\sim$5-10% indicating highly-absorbing surfaces. Cloudy atmospheres frequently have high albedos.

This tradition of reflection photometry and spectroscopy has been carried over into exoplanet research. However, the objects best measured in this manner, by *Kepler*, CoRoT, and MOST for instance, are the close-in, transiting, hot giants. Such objects can be self-luminous, and their optical reflection and thermal emission components can be quite close and overlap. Under these circumstances, the concept of a reflection albedo is ambiguous. Nevertheless, at times one can infer optical albedos and compare with theory. When such comparisons are performed, we find that the albedos of giant transiting exoplanets are quite low, below $\sim$10%, and likely often below $\sim$5%. Such low albedos were predicted (Sudarky, Burrows, & Pinto 2000; Burrows, Ibgui, & Hubeny 2008, and references therein) and are likely due to the presence and dominance in the optical of the broad sodium doublet. The same sodium feature is seen to dominate in the optical spectra of T dwarf brown dwarfs; another physical and chemical correspondence between brown dwarfs and hot giant planets.

7. Light Curves as a Function of Wavelength

Before the recent explosion in exoplanet research, the method most discussed with which to discover planets was by high-contrast imaging. The planet would be separated spatially on a plate or CCD from its bright parent star and probed individually. This

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classic approach, requiring high-contrast capabilities better than $\sim 10^{-4}$ to $\sim 10^{-6}$ for giant planets and $\sim 10^{-9}$ to $\sim 10^{-10}$ for exoEarths, is very technologically challenging, but there has been some recent success with the discovery of HR 8799bcd (Marois *et al.* 2008) and e, Fomalhaut b (Kalas *et al.* 2008), and βPic b. Specifically, the HR 8799 planets have contrast ratios of $\sim 10^{-4}$ and are at wide separations (far beyond a Jupiter orbit) from their parent, an A star. These discoveries are exciting and promise much more in the future to complement what is being learned from the plethora of transiting planets now known.

8. Conclusions

The pace of exoplanet research is truly astonishing and shows no signs of abating soon. This data-rich subject is creating a generation of theorists poised to challenge past orthodoxies and write new textbooks. Though interpretations of the extant data may be fraught with ambiguity, and many mistakes have no doubt been made in characterizing exoplanetary atmospheres and structure, the current efforts might be considered a training exercise with which a new generation of theorists is cutting its teeth, in preparation for an astonishing future.

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Discussion

S. Hinkley: Are the lack of points at low metallicity and high core mass another slam dunk for core accretion?

A. Burrows: Rather, I would say that this correlation is "quite suggestive" of the core-accretion scenario. It is still possible that heavy elements in the envelope of the planet, and not the core, can explain the correlation (though this too could be a signature of core accretion) and there are those who claim that the direct instability model can account for such envelope enrichment. Personally, I think those claims are a bit contrived, but one can't yet be definitive on this point.

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