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The properties of super-Earth atmospheres

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Abstract. Extrasolar super-Earths likely have a far greater diversity in their atmospheric properties than giant planets. Super-Earths (planets with masses between 1 and 10 $M_\oplus$) lie in an intermediate mass regime between gas/ice giants like Neptune and rocky terrestrial planets like Earth and Venus. While some super-Earths (especially the more massive ones) may retain large amounts of hydrogen either from accretion processes or subsequent surface outgassing, other super-Earths should have atmospheres composed of predominantly heavier molecules, similar to the atmospheres of the rocky planets and moons of our Solar System. Others still may be entirely stripped of their atmospheres and remain as bare rocky cores. Of the two currently known transiting super-Earths one (GJ 1214b) likely falls into the former category with a thick atmosphere, while the other (CoRoT-7b) falls into the latter category with a very thin or nonexistent atmosphere. I review some of the theoretical work on super-Earth atmospheres, and I present methods for determining the bulk composition of a super-Earth atmosphere.

Keywords. planetary systems

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1. Introduction

Super-Earths with masses between 1 and 10 $M_\oplus$ represent a fundamentally new class of planets that do not exist in our solar system. These planets lie in the intermediate mass range between the terrestrial planets of our solar system and the gas/ice giant Neptune. A natural question that arises is ‘What defines the dividing line between small gas/ice giants (“mini-Neptunes”) and scaled-up rock-dominated terrestrial planets?’ The division between these two classes of planets may depend on varied parameters such as the history of formation for a particular planet, its mass, and properties of its host star. While terrestrial planets in our solar system have not retained molecular hydrogen in their atmospheres over their lifetimes, super-Earths are predicted to have higher surface gravities, and some of these planets could likely retain massive hydrogen atmospheres.

Recent discoveries of transiting super-Earths give the first constraints on the bulk composition of these planets. However, significant degeneracies exist in the theoretical mass-radius relationship predicted for super-Earths, given that these planets can be composed of a combination of iron, rock, ices, and atmospheric gasses (e.g. Fortney *et al.* 2007). Follow-up observations will therefore be necessary to further constrain the composition of super-Earth planets.

Two transiting super-Earths are currently known. The first, CoRoT-7b (Léger *et al.* 2009) is highly irradiated, and its measured density is consistent with a planet that possesses no significant atmosphere. If the planet does have an atmosphere, it is most likely experiencing atmospheric blow-off and would need to be constantly replenished by surface outgassing (Valencia *et al.* 2010). The second transiting super-Earth, GJ 1214b, (Charbonneau *et al.* 2009) has a low observed density, and fits to the observed mass and radius of this planet imply that it must have a massive atmosphere. Two distinct classes of planets have been proposed that both fit the observed density of GJ 1214b. One is

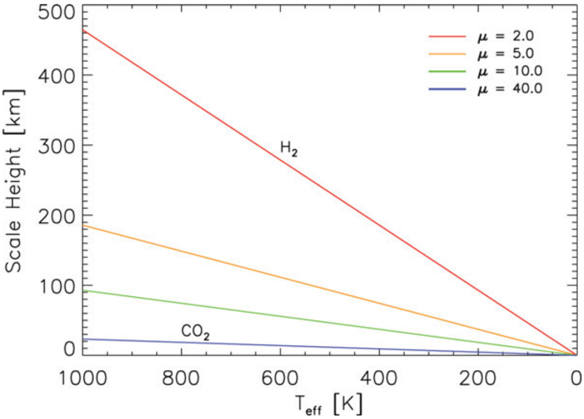

Figure 1. Atmospheric scale height for GJ 1214b as a function of effective temperature for atmospheric compositions ranging from pure hydrogen ($\mu = 2$) to mostly CO_2 ($\mu = 40$). The transmission signature of an exoplanet scales directly proportionally with scale height.

a mostly rock planet with a hydrogen atmosphere that comprises ~1% of the planet's overall mass ("mini-Neptune"). The other possibility is that the planet is composed mostly of water with a small rocky core and a thick water vapor atmosphere ("water-world") (Nettelmann *et al.* 2011; Rogers & Seager 2010).

A key difference between the two classes of planets for GJ 1214b is that they are predicted to posses very different atmospheres that should in turn produce fundamentally different atmospheric signatures. While the mini-Neptune scenario implies an atmosphere composed of mostly hydrogen (and possibly helium) with trace amounts of water, methane, or ammonia, the water-world scenario produces an atmosphere almost entirely composed of water steam. The distinctly different compositions of these two classes of atmospheres will produce spectral features in emission or transmission that are indicative of their overall makeup. Furthermore, the two classes of atmospheres also have atmospheric scale heights that differ from each other by up to an order of magnitude. The equation for scale height is given by:

$$H = \frac{kT}{\mu g} \tag{1.1}$$

where k is Boltzmann's constant, T is the atmospheric temperature, and g is the surface gravity. The mean molecular weight μ is only 2 times that if the hydrogen atom for a hydrogen dominated atmosphere but increases by a factor of 9 if the atmosphere is composed primarily of water vapor (see Fig. 1).

Transmission spectroscopy provides a strong constraint on atmospheric scale height by probing spectral features that arise from absorption of stellar light through the limb of the planet during transit. These spectral features tend to sample layers ranging over several scale heights in the planet's atmosphere, so planets with larger scale heights will produce correspondingly larger spectral features in transmission. For this reason transmission spectroscopy is a promising way to determine the bulk composition of an exoplanet atmosphere and should be useful for breaking the degeneracy between the two classes of planets proposed for GJ 1214b. In what follows we present models of GJ 1214b's atmosphere for a range of possible atmospheres of this planet.

2. Results for GJ 1214b

(See Miller-Ricci & Fortney (2010) for more details.)

For GJ 1214b we investigate six different atmosphere scenarios ranging from hydrogen-rich to hydrogen-poor. The cases are outlined as follows:

(*a*) *Solar composition atmosphere* – Hydrogen, helium, and metals appear in solar abundance ratios (Asplund *et al.* 2005). For this case and the two that follow, the abundances of the molecular species that make up the atmosphere are computed in chemical equilibrium (see Miller-Ricci & Fortney 2010).

(*b*) *30 × Enhanced metallicity atmosphere* – Here we use the base composition of atmosphere (a), but in this case the abundances of all species except for H and He are enhanced by a factor of 30.

(*c*) *50 × Enhanced metallicity atmosphere* – Here the metallicity is enhanced to 50 times relative to solar.

(*d*) *100% water (steam) atmosphere*

(*e*) *50% water, 50% CO_2 atmosphere*

(*f*) *CO_2 atmosphere plus trace gasses* – This model atmosphere is composed of 96.5% CO_2 with other trace gasses appearing in Venusian abundances, notably 3.5% N_2 and 20 ppm H_2O.

For each scenario we produce transmission and secondary eclipse spectra using a 1-D radiative transfer code (see Miller-Ricci *et al.* (2009) and Fortney *et al.* (2008)) to determine the observable signature of GJ 1214b's atmosphere.

Transmission Spectra: The approximate size of spectral features in transmission (relative to the stellar background) is given by

$$\Delta D \approx \frac{20 H R_{pl}}{R_*^2} \tag{2.1}$$

where H is the atmospheric scale height, and we have assumed that spectral features can probe regions of the planet's atmosphere ranging in depth by up to 10 scale heights. For GJ 1214b, if the planet possesses a hydrogen-dominated atmosphere, this corresponds to a value for ΔD of up to 0.3% relative to its M-dwarf host star.

In Fig. 2 we show the results from our spectral modeling of GJ 1214b. Transmission spectra for the three hydrogen-rich atmospheres are dominated by absorption features due to water and methane. These atmospheres have low mean molecular weight and correspondingly large atmospheric scale heights, resulting in transmission features that appear on the level of 0.1-0.3% relative to the host star, which agrees with our back-of-the-envelope calculation above. For the high mean molecular weight atmospheres (cases (d), (e), and (f)) the scale height is an order of magnitude or more smaller, and transmission features are only present at $\sim 0.01\%$ relative to the stellar light. For these atmospheres spectral features of water and/or CO_2 are present but would be exceedingly difficult to observe with current instrumentation.

Emission Spectra: Secondary eclipse spectra for GJ 1214b are shown in Fig. 3. We predict secondary eclipse depths of up to 0.3% if redistribution of heat to the night side of the planet is inefficient, and 0.2% if heat circulation is efficient. Unfortunately, shortward of 5 μm at wavelengths that can be probed by the Warm Spitzer mission the secondary eclipse depths are predicted to be quite small – generally less than a few hundred parts per million. This level of precision is unlikely to be attainable with Warm Spitzer and we therefore await mid-infrared instrumentation such as MIRI aboard JWST to measure secondary eclipse spectra for GJ 1214b.

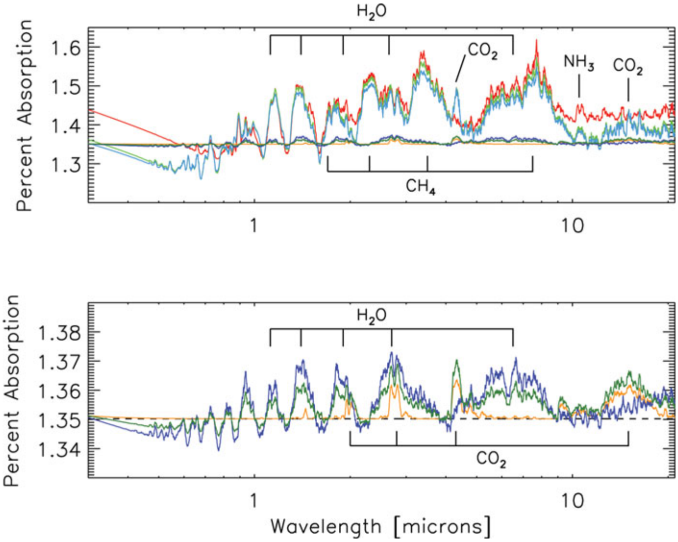

Figure 2. Top: Transmission spectra for atmospheres with differing composition – solar composition (red), 30 × solar metalicity (blue), 50 × solar metalicity (light green), water steam (purple), 50% water - 50% CO_2 (dark green), CO_2 with trace quantities of water (orange). All spectra are for models with efficient day-night circulation and have been normalized to the planet's observed radius of 2.678 $R_\oplus$ in the MEarth bandpass covering 650 - 1050 microns. Bottom: Same as above but zoomed in to show the spectra for the three atmospheres composed of heavier molecules. The dashed black line indicates the radius of a planet with no atmosphere. (From Miller-Ricci & Fortney 2010.)

Longward of 5 *mu*m a whole host of water, methane, CO_2, and ammonia features are present, which will be useful diagnostics of atmospheric chemistry. We note that the spectra for the three hydrogen-dominated atmosphere scenarios ((a), (b), and (c)), all strongly resemble the secondary eclipse spectrum of a "water world" (scenario (d)) despite the very different atmospheric and bulk composition between these two classes of planets. This results from the fact that water is the main source of opacity in each of these atmospheres. For this reason, secondary eclipse spectroscopy may not be useful in breaking the degeneracy between a "water world" and "mini-Neptune" composition of GJ 1214b, and transmission spectroscopy with its strong dependence on scale height is the more decisive method for differentiating between these two classes of models.

Clouds: The presence of clouds can additionally complicate the interpretation of transmission spectra. Clouds impede the transmission of stellar light through a planetary atmosphere below the height where the cloud optical depth equals unity. The overall effect is to flatten out the observed transmission spectrum, since deeper levels in the planet's atmosphere are no longer probed by the incoming stellar light.

We use a toy model to test the effect of clouds at various heights on the transmission spectrum of GJ 1214b. Specifically, we model the cloud deck by cutting off all transmission of stellar light below the height of the cloud deck. We examine clouds ranging in height (in terms of pressure) from 300 mbar to 1 mbar for a solar composition atmosphere (shown in Fig. 4). We note that high clouds in the planet's atmosphere can considerably alter the appearance of the transmission spectrum, and a solar composition atmosphere with very high clouds may be indistinguishable from a high mean molecular weight water (steam) atmosphere over large wavelength ranges.

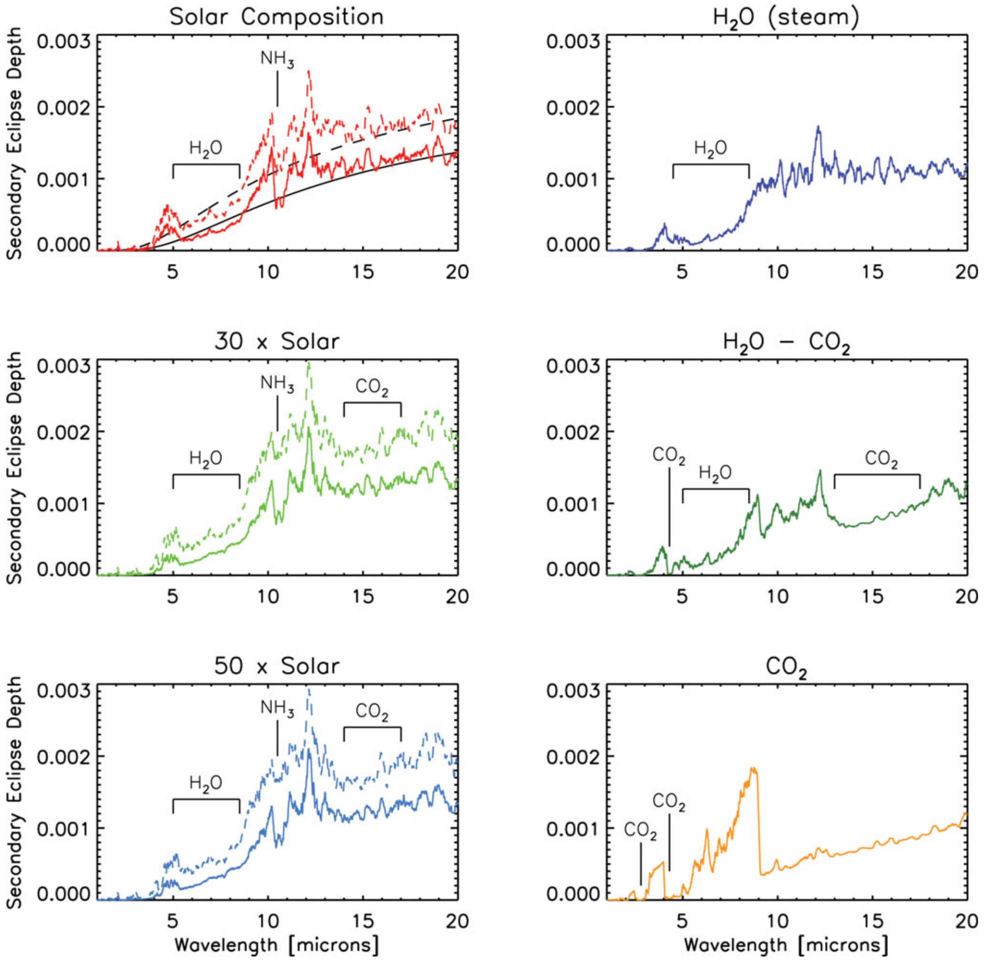

Figure 3. The contrast ratio between the day-side emission from GJ 1214b and the emitted light from its M-dwarf host star, plotted as a function of wavelength for 6 different possible atmospheric compositions. In the top left panel the black lines denote the contrast ratios that would be expected if the planet and star both emitted as blackbodies, with planetary T_{eff} of 555 K (solid) and 660 K (dashed). Dashed lines are spectra for models with inefficient day-night heat redistribution. Solid lines denote models with efficient heat circulation.(From Miller-Ricci & Fortney 2010.)

3. Conclusions

Of the two currently known super-Earths, GJ 1214b is far more likely to have a substantial permanent atmosphere. This planet is also conveniently suited to follow-up observations with current ground-based and spaced-based instrumentation. In transmission, GJ 1214b should vary in its observed transit depth by 0.1-0.3% as a function of wavelength *if the atmosphere is hydrogen-dominated*. If variations in the transit depth are observed to take place on this level, then GJ 1214b's atmosphere is unequivocally composed of predominantly hydrogen. If transit depth variations are not present, then interpretation is more complex, since the planet's atmosphere could be composed of higher mean molecular weight material like water vapor, but could also be hydrogen-rich but with high clouds or haze present.

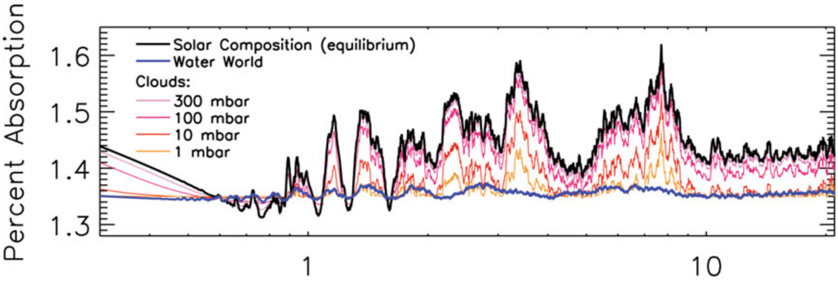

Figure 4. Toy model showing the approximate effect that clouds at differing heights would have on the transmission spectrum of GJ 1214b for solar composition. All transmission of stellar light is cut off at the height of the cloud deck in this simple model. Very high clouds considerably flatten out the transmission spectrum rendering a solar composition atmosphere virtually indistinguishable from a thick steam atmosphere at most wavelengths.

The planet GJ 1214b holds a special place in the family of super-Earths. Because this planet orbits a small M-dwarf and because the planet is low density and most likely possesses an atmosphere with a large scale height, GJ 1214b is uniquely suited to follow-up observations aimed at characterizing its atmosphere. In general, most super-Earths will not be nearly so easily followed up by characterization efforts. Most super-Earths will exhibit transmission and emission signatures at the level of only 1-100 parts-per-million relative to their host stars (see Miller-Ricci *et al.* 2009). This means that follow-up efforts will only be possible with next generation observing facilities like JWST (Deming *et al.* 2009) or any of the ground-based extremely large telescopes. Once these facilities come online, the effort can begin to study the overall diversity of super-Earth atmospheres. Models such as the ones presented here for GJ 1214b are instructive in illustrating the potential observable signatures of these different types of atmospheres.

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