THEORETICAL TRANSIT SPECTRA FOR GJ 1214b AND OTHER “SUPER-EARTHS”

ALEX R. HOWE AND ADAM S. BURROWS

Department of Astrophysical Sciences, Peyton Hall, Princeton University, Princeton, NJ 08544, USA; arhowe@astro.princeton.edu, burrows@astro.princeton.edu

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ABSTRACT

We present new calculations of transit spectra of super-Earths that allow for atmospheres with arbitrary proportions of common molecular species and haze. We test this method with generic spectra, reproducing the expected systematics and absorption features, then apply it to the nearby super-Earth GJ 1214b, which has produced conflicting observational data, leaving the questions of a hydrogen-rich versus hydrogen-poor atmosphere and the water content of the atmosphere ambiguous. We present representative transit spectra for a range of classes of atmosphere models for GJ 1214b. Our analysis supports a hydrogen-rich atmosphere with a cloud or haze layer, although a hydrogen-poor model with \( \lesssim 10\% \) water is not ruled out. Several classes of models are ruled out, however, including hydrogen-rich atmospheres with no haze, hydrogen-rich atmospheres with a haze of \( \sim 0.01 \mu m \) tholin particles, and hydrogen-poor atmospheres with major sources of absorption other than water. We propose an observational test to distinguish hydrogen-rich from hydrogen-poor atmospheres. Finally, we provide a library of theoretical transit spectra for super-Earths with a broad range of parameters to facilitate future comparison with anticipated data.

Key words: methods: data analysis—planets and satellites: atmospheres—planets and satellites: composition—techniques: spectroscopic

Online-only material: color figures

1. INTRODUCTION

Ground- and space-based transit surveys are discovering a growing number of exoplanets in the super-Earth range, defined alternately as between 1 and 10 Earth masses or between 1 and 2 Earth radii. The largest such survey, being conducted by the Kepler spacecraft, has already announced hundreds of super-Earth candidates (Kepler objects of interest) and one confirmed super-Earth in the “habitable zone” (Borucki et al. 2011), although only a few of these candidates have been confirmed. Nevertheless, these surveys have yielded several exoplanets for which it is possible to begin characterizing their atmospheres via transit spectroscopy. This has been attempted by several groups for GJ 1214b (Bean et al. 2011; Berta et al. 2011b; Croll et al. 2011; Crossfield et al. 2011; Desert et al. 2011; De Mooij et al. 2011), an estimated 6.55 Earth-mass (\( M_\oplus \)) planet orbiting an M-dwarf star with an equilibrium temperature near 500 K (Charbonneau et al. 2009), with conflicting results. In particular, measured transit depths in the K and Ks bands are in direct conflict, and proposed atmospheric models have been unable to fit observations in other bands simultaneously.

GJ 1214’s faintness \( (m_V = 14.67) \) makes it a challenge for spectroscopic observations. However, the recent possible discovery of a very similar planet orbiting HD 97658 \( (m_V = 7.8) \) and the discovery of transits of 55 Cnc e around a naked-eye star (Winn et al. 2011) hold promise for improved spectroscopic characterizations in the near future. These stars bring their own challenges of smaller transit depths and fewer nearby comparisons stars, but efforts are nonetheless underway to characterize them.

While transit and radial velocity observations can together constrain a planet’s mass and radius (and thus its density), this leaves significant degeneracies in its bulk composition. Planets with similar masses and radii can take on different compositions, ranging from a mini-Neptune with a thick H/He layer to a true super-Earth composed mostly of silicates with a high-molecular-weight atmosphere to a “water world” whose bulk composition and atmosphere both have high water content (Valencia et al. 2007; Fortney et al. 2007; Seager et al. 2007; Sotin et al. 2007; Rogers & Seager 2010). To further confuse matters, recent observations suggest that some giant exoplanets may have significantly higher C/O ratios than their parent stars, opening up the additional possibility of carbon-rich compositions (Madhusudhan et al. 2010).

GJ 1214b faces the additional complication that while its measured mass and density suggest a hydrogen-dominated atmosphere, the measured radius of the parent star, GJ 1214, is significantly larger than predicted by stellar models (Charbonneau et al. 2009). If the star is 15% smaller than was measured, as these stellar models predict, GJ 1214b would be correspondingly smaller and denser (given the same transit depth), and a hydrogen-rich atmosphere would not be indicated. This uncertainty means that we cannot definitively distinguish between a hydrogen-rich and a hydrogen-poor atmosphere without spectroscopic data (Miller-Ricci & Fortney 2010; Carter et al. 2010).

Spectroscopic observations of both secondary eclipses (“emission”) and transits (“transmission”) of exoplanets have proven successful in characterizing the atmospheres of gas giants, e.g. (Burrows & Orton 2011; Charbonneau et al. 2002; Deming et al. 2005; Knutson et al. 2008; Swain et al. 2008), and observations to characterize super-Earths continue. Transit spectra are particularly useful for measuring compositions. While secondary eclipses can be used to measure temperatures and compositions, the transit spectrum is most directly sensitive to the column depth at the limb of individual molecular and atomic species and is only weakly dependent on temperature (for a given scale height). In this paper, we present calculations of transit spectra for GJ 1214b for a variety of atmospheres in order to improve the current fits to the data. We also present models for HD 97658b and provide a library of models for future exploration of transit spectra of super-Earths.
Transit spectroscopy measures the apparent size of a planet in various wavelengths, which depends on the averaged properties of the planet’s atmosphere. Because exoplanets cannot be resolved by current telescope technology, this transit spectrum is a measure of the total amount of starlight blocked in transit at each wavelength. Ignoring the effects of limb darkening, this includes a fixed component due to the solid disk of the planet, plus a wavelength-dependent component absorbed or scattered by the atmosphere. Within the atmosphere, different altitudes will contribute different amounts to this component because of the variations with pressure. However, molecular absorption features should still emerge from these spectra in a predictable way, enabling abundance characterization of planetary atmospheres based on transit observations. Conversely, the absence of these features in the observed spectrum might be indicative not only of their absence, but of a cloud or haze layer, as is inferred in the atmosphere of HD 189733b (Pont et al. 2008), but one should keep an open mind that a small scale height that reduces the cross section of the atmosphere could also cause this effect. The molecular features can be characterized by the relative increase in transit depth when compared with the continuum (or with a local minimum in transit depth if the continuum is obscured), a contrast that we hereafter refer to as the “amplitude” of the spectral features.

If the atmosphere is non-isothermal or not vertically mixed, this further complicates the results. Also, the limb of the planet as seen in transit represents the terminator, where there is likely to be circulation and a change in temperature and composition. Indeed, the physics at the terminator is more complicated than any model to date. However, one-dimensional theoretical spectra are not strongly dependent on these factors and provide valuable zeroth-order approximations to estimate atmospheric compositions (Miller-Ricci et al. 2009). In our models, hydrogen-rich atmospheres are taken to be in chemical equilibrium, while hydrogen-poor atmospheres are taken to be vertically mixed.

The physical parameters of an exoplanet should have predictable effects on its transit spectrum. These mainly act through the scale height of the atmosphere, which is given by

\[ H = \frac{kT}{\mu g}, \]

(1)

where \( k \) is Boltzmann’s constant, \( T \) is the atmospheric temperature, \( \mu \) is the mean molecular weight, and \( g \) is the surface gravity. If the atmosphere is approximately isothermal, \( T \) is the “equilibrium temperature.”

The amount of starlight absorbed in transit is proportional to the depth of the atmosphere and, thus, to its scale height. This should be visible in the transit spectra as proportional changes in the amplitudes of the spectral features and the slope of the Rayleigh continuum. Therefore, these amplitudes should be directly proportional to the temperature of the atmosphere and inversely proportional to its mean molecular weight. To first order, the amplitudes of spectral features should also be inversely proportional to surface gravity, but this relation is not exact since gravity changes slightly with altitude. In very thick atmospheres, the lower gravity at high altitudes should make the scale height larger, resulting in an even larger atmosphere and larger amplitudes than a simple estimate might suggest.

The remaining parameters that affect the transit spectrum are related to the composition structure of the atmosphere. In particular, for a hydrogen-rich atmosphere, metallicity is important. While for a hydrogen-rich atmosphere metallicity does not have a strong effect on mean molecular weight, the relatively large absorption opacities of metal compounds compared with molecular hydrogen mean that significantly larger-amplitude spectral features will be found at larger metallicities than at smaller ones. The addition of clouds or haze should have the opposite effect. The wavelength dependence of extinction opacity for haze is usually smaller than for molecular species, so the corresponding spectral features should be weaker. In the simplest case of a uniformly opaque cloud layer, suggested by Croll et al. (2011) and Bean et al. (2011) for GJ 1214b, only molecular absorption above the cloud tops contributes to the variation in the spectrum, and the molecular features are suppressed. All of these relations are seen in our calculated spectra.

We present new calculations of theoretical transit spectra of extrasolar super-Earths, including Mie scattering and a range of molecular compositions. Modeling of transit spectroscopy has been established for super-Earths previously, for example, in Miller-Ricci & Fortney (2010), and it has been used to try to characterize the atmosphere of GJ 1214b. However, we present a number of new results and models including spectra for sub-solar metallicities, enhanced C-to-O ratios, and explicit calculations for a range of haze models. We also outline a library of models for super-Earths with different parameters.

We present our methodology in Section 2. We present general conclusions and demonstrations of the systematics described above in Section 3. We apply our method to GJ 1214b in Section 4 in an attempt to produce a better fit to observations than current models. We then present some general conclusions in Section 5.

2. METHODOLOGY

For each atmosphere model, we produce a theoretical spectrum by computing the transit depth at 2500 frequency points between 0.3 and 10 \( \mu \)m. At each frequency point, we numerically integrate the optical depth along the line of sight of each impact parameter, then integrate the effective area over all impact parameters. For transiting planets, we use the initial observed transit depth as a fiducial value for the radius and then normalize the spectrum by computing the average transit depth over the observational bandpass, equating this to the observed depth. Without independent knowledge of the radius of the solid surface, a procedure like this is necessary for all models and modelers.

We use an isothermal temperature–pressure (\( T-P \)) profile at the equilibrium temperature. However, we set \( T = 470 \) K for GJ 1214b based on the work of Miller-Ricci & Fortney (2010), who find with more ambitious calculations that this is approximately correct over the pressure range probed by transit spectroscopy, although their approach does not fully capture the conditions at the terminator and should not be considered more reliable than any other model. Additionally, transit spectra have been shown not to be strongly dependent on the exact \( T-P \) profile used (Miller-Ricci et al. 2009). We do account for the variation of gravity with altitude when computing the pressure profile, although this effect is only a few percent in transit depth, depending on the scale height of the atmosphere. We implement haze using the Mie approximation for a monodispersed, constant abundance haze between upper and lower pressure levels. We also include the option of completely opaque cloud decks by cutting off transmission at all frequencies at pressures greater than a specified level (Crossfield et al. 2011).

Our chemical equilibrium abundances for molecular species were taken from Burrows & Sharp (1999) and molecular line
and collisional opacities were taken from Sharp & Burrows (2007). We compute Rayleigh cross sections on a per-molecule basis, based on each species electric polarizability and assumed to represent wavelengths at which the species in question is assumed to have zero absorption opacity. Scattering opacity is not included. (A color version of this figure is available in the online journal.)

Figure 1. Absorptive opacities of the pure molecular species H2O, CO2, H2, CH4, NH3, and CO in cm² g⁻¹ plotted against wavelength in microns at a temperature of 500 K and a total atmospheric density of 10⁻⁴ g cm⁻³, corresponding to a pressure of 1 mbar, which is the approximate pressure probed by transit spectroscopy. Vertical discontinuities extending far past the bottom of the plot represent wavelengths at which the species in question is assumed to have zero absorption opacity. Scattering opacity is not included. (A color version of this figure is available in the online journal.)

The appearance of GJ 1214b’s spectrum (Miller-Ricci & Fortney 2010; Bean et al. 2011; Désert et al. 2011). We consider an elevated C/O ratio because such a possibility has been advanced for giant planets, including those with a low C/O ratio in the host star (Madhusudhan et al. 2010) and for terrestrial planets (Kuchner & Seager 2005). The C/O ratio is especially important because it strongly affects the abundances of common molecular species such as H2O, CO, CO2, and CH4.

For hydrogen-poor models, we use vertically mixed atmospheres that can include H2, CO2, H2O, CH4, NH3, CO, and N2 in arbitrary proportions by volume. We assume nitrogen to have Rayleigh scattering opacity only.

To test the code, we compute transit spectra for atmospheres with pure molecular compositions and for solar metallicities over a range of metallicities, temperatures, and opaque clouds placed at varying altitudes. These calculations successfully reproduce the relations predicted by systematics, and they are discussed in detail in Section 3. The spectra for pure molecular atmospheres succeed in reproducing the molecular opacity features of each species (compare Figures 1 and 3). Smooth regions in the spectra represent the Rayleigh continuum (or, if the continuum is sufficiently transparent, the cloud tops or the planet’s solid surface) at wavelengths where absorption is negligible.

We also compute spectra for GJ 1214b with compositions similar to those used in Miller-Ricci & Fortney (2010) with a “surface pressure” of 1 bar. At this pressure level, the atmosphere becomes opaque at all wavelengths in most models, so a
deeper atmosphere will not affect the spectrum. Our spectra successfully reproduce the molecular features of the Miller-Ricci & Fortney (2010) computations. They have systematically larger transit depths than Miller-Ricci & Fortney (2010) in the molecular features by 10%–20%, and they agree to better than 10% with the slope of the Rayleigh continuum. The systematic offsets are most likely due to the use of different opacity tables.

3. GENERIC MODEL RESULTS

For convenience, all generic spectra are computed using the physical parameters of GJ 1214b as given in Tables 1 and 2, except as specified. They are also normalized to the initial measurement of GJ 1214b: 1.35% (13500 ppm) in the MEarth band of 0.7–1.0 μm (Charbonneau et al. 2009).

Generic spectra computed for hydrogen-rich atmospheres for which abundances are a fraction or multiple of solar are shown in Figure 4. These spectra show transit depths increasing with metallicity. This is expected since metals are the main source of extinction in a haze-free atmosphere. However, for this normalization, the transit depth of the Rayleigh scattering tail decreases with increasing metallicity. This is because of the normalization to the MEarth band, in which absorption dominates. The spectral features in that band increase in amplitude with increasing metallicity relative to the Rayleigh continuum, so the continuum has a smaller relative transit depth at large metallicities.

Two other hydrogen-rich atmosphere models are shown in Figure 5. Swapping the abundances of carbon and oxygen for those of methane. Some of these features overlap and, thus, those wavelengths are not strongly affected. The greater extinction

Figure 3. Transit depth in percent vs. wavelength in microns for generic transit spectra for hypothetical exoplanets with pure molecular atmospheres. The scale heights of the atmospheres are inversely proportional to their molecular weights. This proportionately affects the magnitudes of the spectral features, along with the slope of the Rayleigh continuum. Smooth regions of the spectra represent the absorption features shown in Figure 1. Each spectrum was computed using the physical parameters and normalization for GJ 1214b.

(A color version of this figure is available in the online journal.)

Table 1

| Name             | Radius ($R_\oplus$) | Mass ($M_\oplus$) | $a$ (AU) | Period (days) | $i$ (deg) | $e$         |
|------------------|---------------------|-------------------|---------|---------------|----------|-------------|
| GJ 1214b         | 2.678 ± 0.13        | 6.55 ± 0.98       | 0.0143  | 1.5803925     | 88.62±0.36 | <0.27       |
| 55 Cancri e     | 2.00 ± 0.14         | 8.63 ± 0.35       | 0.01560 | 0.736537      | 83.4     | 0.17 ± 0.04 |
| HD 97658b        | 2.93 ± 0.28         | 6.4 ± 0.7         | 9.4957  | <89.0         | 0.13±0.06 |
| COROT-7b         | 1.58 ± 0.1          | <21.7             | 0.0172  | 0.85358       | 80.1 ± 0.3 | 0           |
| Kepler-10b       | 1.416±0.033         | 4.56±0.17         | 0.01684 | 0.837495      | 84.4     | 0           |
| Kepler-22b       | 2.38 ± 0.13         | <82               | 0.849   | 289.8623      | 89.76±0.025 | 0.042   |
| Venus f          | 0.950               | 0.815             | 0.728   | 224.7         | 86.61    | 0.0068      |

Notes.  
1. From Demory et al. (2011).  
2. From Léger et al. (2009).  
3. 2σ limit.  
4. From Batalha et al. (2011).  
5. From Borucki et al. (2011).  
6. From Basilevsky & Head (2003).

Table 2

| Name             | $m_V$ | Radius ($R_\odot$) | Mass ($M_\odot$) | $T_{\text{eff}}$ (K) | Luminosity ($L_\odot$) | [Fe/H] | log(g) (cm s$^{-2}$) |
|------------------|-------|-------------------|------------------|----------------------|------------------------|--------|---------------------|
| GJ 1214          | 14.67 | 0.2110            | 0.157            | 3026                 | 0.00328                | +0.39  | 4.991               |
| 55 Cancri e      | 5.95  | 0.943             | 0.963            | 5234                 | 0.582d                 | +0.31  | 4.45                |
| HD 97658         | 7.8   | 0.70              | 0.75             | 5119                 | 0.30                   | −0.30  | 4.52                |
| COROT-7b         | 11.668| 0.87              | 0.93             | 5275                 | 0.49f                  | +0.038 | 4.50                |
| Kepler-10b       | −11   | 1.051             | 0.895            | 5627                 | 1.004                  | −0.15  | 4.35                |
| Kepler-22b       | 11.664| 0.979             | 0.970            | 5518                 | 0.79                   | −0.29  | 4.44                |

Notes.  
1. Uncertainties have been omitted for compactness.  
2. From Berta et al. (2011a).  
3. From Demory et al. (2011).  
4. From von Braun et al. (2011).  
5. From Léger et al. (2009).  
6. From Guenther et al. (2010).  
7. From Borucki et al. (2011).  
8. [M/H].  
9. From Batalha et al. (2011).  
10. From Burckei et al. (2011).
opacity of methane at near-infrared wavelengths causes the Rayleigh continuum to be normalized to a lower transit depth. For the model with no methane, the spectrum is more strongly dominated by water features, and the normalization is not strongly affected.

The effects of temperature on the generic transit spectra are shown in Figure 6. A higher temperature results in a larger scale height, and, as expected, a larger continuum slope at short wavelengths. As the temperature increases, two major chemical changes are evident as well—the suppression of methane and the appearance of strong alkali metal lines.

An opaque cloud layer can suppress the molecular spectral features if it lies at high enough altitudes. If light is not sufficiently blocked as it grazes the cloud tops, the observed radius should be very near the cloud tops in that wavelength. This effect is demonstrated in Figure 7, which includes spectra with cloud layers at different pressure levels. Flat, horizontal sections of the spectra represent wavelengths at which the atmosphere is transparent down to the cloud tops. If the clouds are deeper than the 1 bar level, they are usually obscured at all wavelengths, so higher pressures have no effect on the spectrum. However, for some atmospheres composed of pure molecular species, such as carbon dioxide, light can penetrate deeper at some infrared wavelengths, where both absorption and scattering are negligible, so these flat regions due to clouds can persist to very high pressures in such an atmosphere.

Models for pure atmospheric compositions are shown in Figure 3, to be compared with Figure 1, which depicts the absorption opacities for the same species at a fixed temperature and density. Nitrogen is assumed to have Rayleigh scattering opacity only, as are the other species at wavelengths outside their respective absorption bands. All of these results are consistent with the expected dependencies on physical and atmospheric parameters and, thus, provide a further validation of our methodology.

We add haze to the atmosphere using the Mie approximation for spherical particles. We find that dense hazes \((n \gtrsim 10^5 \text{ cm}^{-3})\) for most typical sizes) are essentially opaque in the wavelength range we study and result in flat regions in the spectrum. However, very thin hazes \((n \lesssim 10^2 \text{ cm}^{-3})\) for typical particle sizes) become transparent at some wavelengths. In general, these thin hazes tend to produce sloped regions of the spectrum.
Howe & Burrows

Figure 4. Transit depth in percent vs. wavelength in microns for generic transit spectra computed for exoplanets with hydrogen-rich atmospheres of varying metallicities. For convenience, all of the generic spectra are computed using the physical parameters \( R = 2.678 \, R_\oplus, M = 6.55 \, M_\oplus, T = 470 \, K \) of GJ 1214b, except as specified, and they are normalized to the initial measurement of GJ 1214b. This normalization is 1.35% (13500 ppm) absorption averaged over the MEarth band of 0.7–1.0 \( \mu \)m (Charbonneau et al. 2009). Smooth sections of the graph represent the Rayleigh continuum. The continuum falls with increasing metallicity because the normalization occurs in a band where scattering dominates at low metallicities, but absorption dominates at high metallicities, with very large absorption features forcing the continuum down. The atmosphere is taken to be deep enough that the surface is obscured in transit at all wavelengths, and solar relative abundances and equilibrium chemistry are assumed. Water and methane features are prominent. Transit depth remains elevated between 2 and 3 \( \mu \)m because of a broad collision-induced absorption feature in hydrogen.

(A color version of this figure is available in the online journal.)

Figure 5. Transit depth in percent vs. wavelength in microns for generic transit spectra computed for exoplanets with hydrogen-rich atmospheres with non-solar relative abundances. Blue: solar abundances with the abundance of methane set to zero. The resulting spectrum is strongly water dominated. Red: solar abundances with carbon and oxygen abundances exchanged, resulting in a C/O ratio of \( \sim 2 \). This causes water features to be muted and methane features to be enhanced. The persistence of a large transit depth coinciding with the “water feature” at 2.7 \( \mu \)m is caused by a broad collision-induced absorption H\(_2\) feature. The spectra are computed using the physical parameters and normalization for GJ 1214b.

(A color version of this figure is available in the online journal.)

Figure 6. Transit depth in percent vs. wavelength in microns for generic transit spectra computed for exoplanets with solar-abundance atmospheres at various equilibrium temperatures. Higher temperatures result in larger scale heights and larger transit depths. The slope of the Rayleigh continuum also increases with temperature due to this effect. At and above 700 K, the methane abundance drops, resulting in weaker overlapping methane and water features (seen blueward of 1.7 \( \mu \)m) and much weaker isolated methane features (seen redward of 1.7 \( \mu \)m), leaving a more water-dominated spectrum. The 4.7 \( \mu \)m CO line and narrow alkali metal lines begin to appear at 700 K and become very prominent by 1000 K. The spectra are computed using the physical parameters and normalization for GJ 1214b.

(A color version of this figure is available in the online journal.)

Figure 7. Transit depth in percent vs. wavelength in microns for generic transit spectra computed for exoplanets with solar-abundance atmospheres with achromatically opaque cloud decks at various pressure levels. The 1 bar level represents a cloudless atmosphere, that is, any clouds are deep enough that they are obscured by molecular absorption and scattering. Horizontal smooth regions indicate wavelengths where the atmosphere is transparent down to the cloud deck, so that the planet presents a fixed radius in transit with respect to wavelength. With very high cloud decks, many features are smoothed out, and those that remain are much weaker. If the clouds are above the 10 mbar level, they also obscure the Rayleigh continuum, leaving it horizontal. The slope of the Rayleigh continuum decreases gradually before this point, since the clouds partially and achromatically obscure it. The spectra are computed using the physical parameters and normalization for GJ 1214b.

(A color version of this figure is available in the online journal.)

4. GJ 1214b

4.1. Prior Observations

The photometric and spectroscopic data for GJ 1214b available at this writing are shown in Figure 9. Désert et al. (2011), working in the Warm Spitzer 3.6 and 4.5 \( \mu \)m bands, observed a flat transit spectrum of GJ 1214b and concluded that its atmosphere must have a small scale height and, thus, a high molecular
weight, probably with a large proportion of water. Bean et al. (2010), working in the $I$ band, came to the same conclusion, although they also suggested that the planet could have a layer of clouds or hazes above the 300 mbar level.

This picture changed when Croll et al. (2011) observed a deep $K_s$-band transit, but shallow $J$ and $CH_2On$ (1.69 $\mu$m) band transits, suggesting a hydrogen-rich, low-molecular-weight atmosphere, observable in the $K$ band, that included a haze layer to mute features at other wavelengths. The anomalous $K_s$-band feature was attributed to either water or methane.

However, Crossfield et al. (2011), based on near-IR spectroscopy, argue that a hydrogen-rich atmosphere is not favored, and that if a large-scale-height atmosphere were present, it must be out of chemical equilibrium (e.g., depleted in methane) or muted by a haze or cloud layer. Bean et al. (2011) revised their earlier assessment with data in the $R$, $J$, $H$, and $K$ bands. These data support a high-molecular-weight atmosphere, particularly with shallow $K$-band transits. However, their reported results in the $R$ band show some evidence for a Rayleigh scattering tail at short wavelengths, with a slope consistent with a hydrogen-rich atmosphere.

The most recent observations continue to give conflicting results. De Mooij et al. (2011), taking measurements in a wide range of visible and infrared bands, obtained results that reinforce both the conclusion of both apparent Rayleigh scattering tail, but shallow $J$ and $CH_2On$ (1.69 $\mu$m) band transits, suggesting a hydrogen-rich, low-molecular-weight atmosphere, observable in the $K$ band, that included a haze layer to mute features at other wavelengths. The anomalous $K_s$-band feature was attributed to either water or methane.

To explain these conflicting results, one of the most widely postulated models is a hydrogen-rich atmosphere with a layer of clouds or haze near or above the 100 mbar pressure level (Croll et al. 2011; Bean et al. 2011), or above the 10 mbar level in Berta et al. (2011b). Haze has also been suggested to explain the weak alkali metal features in transits of the giant planet HD 189733b (Pont et al. 2008). The other alternative is a high-molecular-weight atmosphere with a high water content (Désert et al. 2011; Berta et al. 2011b).

### 4.2. Models without Haze

Assuming that GJ 1214b has a low albedo and its heat flow is distributed uniformly over its surface, its equilibrium temperature is ~555 K (Miller-Ricci & Fortney 2010). If we further assume that the characterization of a Rayleigh scattering tail is correct ($\alpha = 4$), then the complete data set suggests a mean molecular weight for GJ 1214b's atmosphere of around 2.7, based on the analytic model given in the Appendix. This mean molecular weight definitely represents a hydrogen-rich atmosphere, but it leaves the problem of the lack of expected spectral features unresolved.

Working from this initial prediction of a hydrogen-rich atmosphere, Figure 10 shows the spectrum of a solar-abundance atmosphere model for GJ 1214b compared with the observational data. It is normalized to the initial observation of GJ 1214b of a transit depth of 1.35% (13500 ppm) in the “MEarth” bandpass of 0.7–1.0 $\mu$m (Charbonneau et al. 2009). This model spectrum bears almost no resemblance to the data, since the features are far too large and of different relative proportions than the observed features. Water features are most prominent in the solar model spectrum, with one that coincides with the suspected 1.5 $\mu$m feature, except in magnitude. The Rayleigh continuum is visible as a smooth rise in transit depth blueward of 0.7 $\mu$m with a similar slope to the observed rise at short wavelengths, but a far lower transit depth. Also, absorption dominates over scattering well into the optical range, so that the Rayleigh tail is predicted primarily at wavelengths shorter than the observations. Methane features can also be identified, such as those at 2.2 and 3.3 $\mu$m,
although the prominent methane features at shorter wavelengths overlap with water features.

By ignoring one or more observed features at a time, the small amplitude of the remaining features can be explained by one or more of four possibilities: (1) the atmosphere contains low abundances of molecules with large opacities, (2) the atmosphere contains an opaque cloud layer that mutes the molecular absorption features, (3) the atmosphere contains a translucent haze layer that mutes the molecular absorption features, and (4) the atmosphere has a high molecular weight, which results in a smaller scale height, a shallower atmosphere, and, thus, a smaller variation in transit depth.

Figure 11 shows the spectrum of two low-metallicity hydrogen-rich models. Hydrogen has a relatively low absorption opacity compared with metal compounds, so reducing the metal abundance makes most of the features much smaller in amplitude. The model spectrum begins to conform with the data at metallicity of $[\text{Fe}/\text{H}] \lesssim -2$; the computed Rayleigh tail extends redward into the observed tail, and the spectrum is at least marginally consistent with most of the infrared observations, including the suggested 1.5 $\mu$m feature, the $K_s$ band, and the mid-infrared Spitzer bands. Furthermore, the computed Rayleigh tail extends redward into the observed tail and has a similar transit depth to observations, unlike in the solar-abundance model. This is a relatively good fit, but we do not support it because it conflicts with GJ 1214’s observed metallicity of $[\text{Fe}/\text{H}] = +0.39$ (Charbonneau et al. 2009), making the existence of an associated planet with such a low metallicity extremely unlikely. We therefore do not advance this solution.

Figure 12 portrays spectra of model atmospheres with solar abundances with the addition at an opaque cloud layer at various pressure levels. An opaque cloud layer near or above the 100 mbar level has been suggested in several other models for GJ 1214b (Croll et al. 2011; Bean et al. 2011), and above the 10 mbar level in Berta et al. (2011b). We find that the spectrum becomes flat enough to be consistent with observations only if the cloud layer cuts off near or above the 1 mbar level. In this case, only very large features remain visible in transit in the rarefied regions above the cloud layer. If the cloud tops are between 1 mbar and 0.1 mbar, the spectrum is consistent with most of the measured infrared features (the $K_s$ band being the primary exception) and would be a viable model if all of the high-amplitude features are rejected. Unfortunately, placing clouds at such a high altitude also suppresses the Rayleigh tail due to the molecular features, leaving the spectrum inconsistent with most of the measured infrared features, including the suggested 1.5 $\mu$m feature, the $K_s$ band, and the Spitzer bands.
with the observed short-wavelength rise. However, a translucent haze layer remains a viable alternative (see below).

Figure 13 provides spectra of model atmospheres with high molecular weights, consisting of various proportions of water, with the remainder nitrogen, which we take to have only Rayleigh scattering opacity. With a higher molecular weight, the scale height of the atmosphere is smaller, as are the amplitudes of the spectral features. Almost any proportion of water is consistent with most of the observed infrared features, again with the $K_s$ band being the primary exception. The best fit covers a broad range of abundances of $\lesssim10\%$ water, which reproduces the suspected $1.5\,\mu m$ feature in Berta et al. (2011b) and the $K$-band measurements of Bean et al. (2011). However, these models fail to produce the short-wavelength rise, and the lower abundances fail to produce the slight observed rise in the mid-infrared. The molecular weights of water and nitrogen result in a scale height so small that the slope of the Rayleigh tail is much less than that of the observed short-wavelength rise.

(A color version of this figure is available in the online journal.)

As before, the addition of an opaque cloud layer only exacerbates the problem. This effect is illustrated in Figure 14, specifically, with a pure water atmosphere. As before, the addition of clouds improves the agreement with the observed molecular features, but obscures the Rayleigh tail, leaving it a flat continuum if the cloud tops are above 10 mbar.

Of the other molecules we consider, methane is the only one that might be consistent with the observations (Figure 15). A pure methane atmosphere fits the large transit depth observed in the $K_s$ band, but the overall fit is poor. A composition of $\lesssim10\%$ methane does better, fitting the mid-infrared data points and the $1.5\,\mu m$ feature well, but it predicts additional near-infrared features that are not observed, and it does not fit either of the conflicting $K$-band and $K_s$-band measurements. Alternatively, an abundance of $\lesssim10\%$ methane fits the suspected $1.5\,\mu m$ feature well, but predicts additional near-infrared features that are not observed. Thus, we do not advance methane as an alternative to water to explain the observed absorption features.

(A color version of this figure is available in the online journal.)

On the problem of the short-wavelength rise, the high-molecular-weight model could possibly be salvaged with the addition of a haze layer. Some possible haze components in this temperature range are polyacetylene, tholin, and sulfuric acid. Sulfuric acid is known to be in the atmosphere of Venus, but is considered less probable than carbon-based haze species, most notably due to the uncertainty of producing it in a water- or hydrogen-rich atmosphere. For this reason, and because...
its extinction opacity has a similar wavelength dependence to tholins at most wavelengths and particle sizes (see Figure 2), we do not consider it as a solution for GJ 1214b in this work. However, we do produce some general models including sulfuric acid haze in our online library. These similarities in behavior also mean that the haze composition is ambiguous without more data.

Figure 2 shows the extinction opacities of the all three of these haze components by particle size. At certain particle sizes, the opacities of these particles exhibit a slope significantly larger than that of the Rayleigh continuum, meaning that they could potentially be used to fit the observed rise, even in a hydrogen-poor atmosphere. Since we find that hydrogen-rich models also fail to recreate this rise without a haze layer, we reach the conclusion that if the short-wavelength rise is valid, then GJ 1214b possesses a haze layer, which necessarily mutates molecular absorption features, but produces a significant rise in transit depth at short wavelengths.

For a haze layer to recreate the observed rise in transit depth, it must be thick enough to avoid being nearly transparent at all wavelengths, which would produce a negligible effect on the spectrum. It must also be thin enough to avoid being nearly opaque at all wavelengths, since this would approach the limit of the opaque cloud layer, which also fails to agree with observations at short wavelengths. These limits vary with the particle density and the thickness of the haze layer.

For polyacetylene particles of any size, the wavelength dependence is weak at short wavelengths. A model representative of the effects of monodispersed polyacetylene haze in a hydrogen-poor atmosphere is shown in Figure 16. The pressure range of the haze layer is chosen to be 0.1–0.001 mbar to maximize the contribution above Rayleigh scattering to total extinction at large radii, which should increase the slope of the scattering tail. This haze model has a vertical optical depth of $\tau = 0.0034$ at 0.85 $\mu m$, the midpoint of the normalization band. The small slope of the opacity curve results in a similarly small slope of the scattering spectrum, only slightly larger than the pure Rayleigh tail without haze. There is very little effect on the rest of the spectrum. The resulting slope remains too low to account for the observed transit depth, so we do not support a polyacetylene haze in a high-molecular-weight atmosphere.

(A color version of this figure is available in the online journal.)
the large absorption features, especially the suggested 1.5 μm feature.

From Figure 2, the wavelength dependence of both haze species we consider is very similar at particle sizes of 1 μm and larger. Furthermore, the wavelength dependence is almost completely flat for 10 μm particles and is relatively flat with 1 μm particles, since the particles are similar in size or larger than the wavelengths of light of interest, so their effects are roughly proportional to their geometric cross sections. Figure 18 shows the effect of a solar-abundance atmosphere with various monodispersed tholin haze models with a particle size of 1 μm. At 0.85 μm, the vertical optical depths of the models are 0.20 for a particle density of 0.1 cm$^{-3}$ and 0.020 for a particle density of 0.01 cm$^{-3}$. Because of the flat wavelength dependence, especially in the visible, the resulting spectra are flattened uniformly to varying degrees, so that the short-wavelength rise is suppressed, and the model fails to achieve the goal of fitting the short-wavelength data. However, with a relatively large particle density of 0.1 cm$^{-3}$ and a high altitude of 0.1–0.001 mbar, the spectrum begins to conform with the near- and mid-infrared data. While it is easier to keep small particles aloft, we do not know the degree of turbulence in GJ 1214b’s atmosphere, so we do not make any judgment concerning the plausibility of these conditions. Further research is needed to investigate this issue.

Figure 19 shows a set of models with hydrogen-rich atmospheres with monodispersed tholin hazes with a particle size of 0.1 μm. At 0.85 μm, the vertical optical depths of the models are 0.82 for a particle density of 1000 cm$^{-3}$ and 0.082 for a particle density of 100 cm$^{-3}$. This figure demonstrates a problem that occurs in a large portion of the parameter space of hazes. While the haze dominates the atmospheric opacity at visible wavelengths, its opacity becomes too small at infrared wavelengths, resulting in infrared features that remain too large in amplitude to fit the data. This problem often persists even if the haze opacity saturates in the visible, and the layer becomes uniformly opaque at short wavelengths. Depending upon the choice of parameters, these models can be made to fit the short-wavelength rise in the data and could do so even if some of these data were refuted. However, in each case, the infrared features either are far too large to fit the data or are normalized to an incorrect transit depth.

Figure 20 provides models with hydrogen-rich atmospheres with monodispersed tholin hazes with a particle size of 0.01 μm. At 0.85 μm, the vertical optical depths of the models are 0.26 for a particle density of 10$^7$ cm$^{-3}$ and 0.026 for a particle density of 10$^6$ cm$^{-3}$. These spectra predict a short-wavelength rise that is steeper than in the observed data, such that the transit depth saturates near 0.5 μm. Any increase in particle density would increase the amount of saturation and result in a poorer fit to the data. Still, the lower opacity in the infrared results in infrared features that are too large in amplitude to fit the data. A decrease in haze altitude would also make the molecular features more prominent. Therefore, tholin particles in this size range in a hydrogen-rich atmosphere can be ruled out as an explanation of the spectrum of GJ 1214b.

(A color version of this figure is available in the online journal.)
the 0.1 μm models. The opacity saturates at short wavelengths, sometimes resulting in a flat spectrum in the visible, while lower infrared opacities result in near- and mid-infrared features that are too large to fit the data. In other cases, the opacity does not saturate at these wavelengths, but the slope of the predicted short-wavelength tail is much larger than is observed. Because of the difficulty of fitting the short-wavelength rise and the improbability of particles this small, we do not advance this model as an explanation for the observed features.

Polyacetylene has a spectral behavior similar to tholins at larger particle sizes (≥1 μm), and at smaller particle sizes (≤0.1 μm), it suffers from even lower infrared opacities than tholins, so the same problems persist that occur for tholins. A haze model that might successfully fit both the observed short-wavelength rise in the data and the low amplitudes of the infrared features is one for which the opacity follows a Rayleigh-like λ⁻⁴ behavior blueward of 1 μm and is roughly constant redward of 1 μm. None of the hazes we test fit this description.

4.4. Best-fit Models

Our best-fit models for GJ 1214b are given in Figure 21. We select five models by visual inspection. While this is not, in principle, the most accurate method, the systematic problems with the data set indicate that any quantitative assessment of the fits would not necessarily be any better. Moreover, many of our theoretical spectra are similar enough that a range of parameters of the haze layer (in some cases as large as a factor of two) would produce very similar fits. Thus, any quantitative fit would not produce a significant gain in precision over our “eyeball” technique.

Of our five selections, Model 1 is the only model we select that provides a good fit to the observed short-wavelength rise in transit depth. It utilizes a solar-abundance atmosphere with a tholin haze (although the choice of haze species is arbitrary) with a particle size of 0.1 μm, a particle density of 100 cm⁻³, and a pressure range of 10–0.1 mbar. This model has a vertical optical depth at 0.85 μm of τ = 0.082. It is consistent with many of the near- and mid-infrared data points, but the predicted spectral features have much larger amplitudes than are observed.

Models 2–4 are our best fits to the data points with low transit depths, with larger transit depths excluded. Model 2 does this with a solar-abundance atmosphere and a translucent tholin haze layer (the choice of haze species being arbitrary) with a particle size of 1 μm, a particle density of 0.1 cm⁻³, and residing in a pressure range from 10 to 0.1 mbar; it has a vertical optical depth at 0.85 μm of τ = 0.20. Model 3 instead uses solar abundances with a uniformly opaque cloud layer, with cloud tops at 0.3 mbar. This model provides a better fit in the near- and mid-infrared than the translucent haze.

Model 4 is our overall best fit using a high-molecular-weight atmosphere, specifically, 1% H₂O and 99% N₂ with no clouds or haze. However, this model is not very sensitive to the proportion of water (within an order of magnitude) or to the addition of any haze that does not significantly obscure the absorption features, or to the proportion of water (within an order of magnitude). Model 5 is our best fit to the short-wavelength rise with a high-molecular-weight atmosphere. It includes tholin haze with a particle size of 0.01 μm, a particle density of 10⁹ cm⁻³, and a pressure range of 0.1–0.001 mbar (vertical optical depth at 0.85 μm: 0.021). However, it is consistent with only the lower edge of the short-wavelength data distribution and is inconsistent with many of the data points in the distribution. Therefore, we conclude that if this rise is valid, GJ 1214b should have a hydrogen-rich atmosphere.

(A color version of this figure is available in the online journal.)
largest source of absorption is not water. We look forward to refining our model in light of additional data.

5. DISCUSSION AND CONCLUSIONS

We have developed a new capability to compute transit spectra of super-Earths that allows atmospheres with arbitrary proportions of common molecular species, along with hazes. Similar hazes have been used to characterize the atmospheres of giant planets, and they appear to be important in explaining the apparently conflicting observations of GJ 1214b. However, additional measurements are needed in a range of wavelengths to determine this object’s transit spectrum more precisely.

If the observed short-wavelength rise is valid, then GJ 1214b most likely possesses a hydrogen-rich atmosphere with a haze of small (∼0.1 μm) particles, although there is also the possibility of an atmosphere rich in nitrogen and water, with very small (∼0.01 μm), very high altitude (up to 0.001 mbar) tholin haze particles. The latter model is a poorer fit in the visible and is physically less probable, but it cannot be ruled out by the current data. However, the hydrogen-rich model provides a very poor fit redward of 1 μm.

Alternatively, the short-wavelength measurements may prove inaccurate, but the near-infrared measurements may be accurate, including the 1.5 μm suspected water feature and the low-amplitude K-band measurements. This is a particularly plausible scenario because of the greater stellar variability and lower luminosity for M-dwarfs in the optical. In this case, in order of goodness of fit, GJ 1214b likely possesses (1) an N2–H2O atmosphere, (2) a solar-abundance atmosphere, with thick, opaque clouds at or above the 1 mbar level, or (3) a solar-abundance atmosphere with a translucent haze with medium-to-large (≥1 μm) particles. For hydrogen-rich atmospheres, the models are not sensitive to the haze composition. High-molecular-weight models are not sensitive to the addition of hazes or clouds in general or to the abundance of water, within an order of magnitude. None of these models show a short-wavelength rise in transit depth or a Ks-band feature as deep as the one suggested by the data.

In both cases, our calculations rule out a hazeless (and cloudless) hydrogen-rich atmosphere, which predicts a transit depth in the optical that is much smaller than the data for any reasonable metallicity. We also rule out a hydrogen-rich atmosphere with tholin particles in the ∼0.01 μm range and a high-molecular-weight atmosphere with significant amounts of absorbing species other than water, such as NH3, CO, or CO2, which is inconsistent with the near-infrared data. Overall, the prospects for fitting the data appear better with a hydrogen-rich atmosphere, but we cannot rule out a hydrogen-poor composition.

Some of the data for GJ 1214b conflict, particularly those in the K band and Ks band. Even for the data that do not directly conflict, none of the models we test provide a good fit to all of the observed features simultaneously. However, we can rule out large classes of models that do not fit any of the observed features. In the case that all of the non-conflicting data are valid, we do not support any model without a haze layer.

We propose additional observational tests to distinguish hydrogen-rich from hydrogen-poor atmospheres. All of our hydrogen-rich models predict a strong water feature at 2.7 μm and a strong methane feature at 3.3 μm, both of which should be unambiguously larger in amplitude than the features predicted by any reasonable hydrogen-poor model. The hydrogen-rich models also predict a water feature at 1.9 μm that could give an unambiguous result depending on the actual atmospheric parameters. Therefore, data at these wavelengths would provide strong evidence to distinguish among these models.

Our models correctly reproduce the expected systematics of transit spectra of planets with varying metallicities, temperatures, and cloud layers. They also reproduce the expected features from molecular absorption. Nevertheless, our models use an isothermal T−P profile. While this is a good first-order approximation, a more accurate T−P profile is desired to produce a more accurate transit spectrum, along with an atmospheric circulation model of the behavior at the terminator, which will not be in thermal or chemical equilibrium. A photochemical model is also desired to determine the abundances of molecular species created or destroyed by photolysis.

No spectral observations of other super-Earths are available at the time of this writing, but we are able to make some projections about HD 97658b by assuming the same atmospheric properties as GJ 1214b, except for gravity and temperature. We have prepared an online library of theoretical transit spectra produced by our calculations, sampling the known and expected parameter space of super-Earths. This library includes models with equilibrium temperatures from 300 K to 1000 K and silicate-iron planets from 1 M⊕ to 10 M⊕. The library also includes models with atmospheric compositions of solar abundance, 0.3 × solar, 3 × solar, and pure H2O, CO2, and CO atmospheres, as well as a variety of haze models, including sulfuric acid hazes.

Very recently, we learned of the work of Murgas et al. (2012), who measured the transit depth of GJ 1214b at three additional wavelengths in the R band. For completeness, these data points are included in Figure 9. These points are consistent with the proposed rise in transit depth at short wavelengths; however, their uncertainties are too large to make any definite conclusions.

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APPENDIX

ANALYTIC MODEL

LeCavelier des Etangs et al. (2008) presented an analytic model of Rayleigh scattering in a planetary atmosphere as seen in transit. Here, we investigate the circumstances under which their model can also be applied to absorption. We find that the model accurately predicts the results of numerical calculations if the absorption opacity of the atmosphere is low, i.e., of the same order as the Rayleigh scattering opacity, but it significantly underpredicts the transit depth if the opacity is high. The fit is good enough at low opacities to justify this model as an estimator of the mean molecular weight of the atmosphere of GJ 1214b based on the slope of the short-wavelength rise in the data.

The analytic model begins with an approximation of the optical depth of transmission at an impact parameter z,

\[ \tau(\lambda, z) \approx \sigma(\lambda) n(z) \sqrt{2\pi R_p H}, \]  

(A1)
where \( R_p \) is the planetary radius, \( H \) is the scale height, and 
\[ n(z) = n_{0} \exp(-z/H) \]
is the particle density (\( n_0 \) being the density at the surface or reference altitude). Then, if \( R_{\text{obs}} \) is the observed radius of the planet at a particular wavelength, one can define \( \tau_{\text{eq}} \) by \( R_{\text{obs}} = R_p + z(\tau_{\text{eq}}) \). That is, \( \tau_{\text{eq}} \) is the optical depth at the impact parameter of the planet’s originally observed radius. Numerical calculations suggest that for a wide range of scale heights, \( \tau_{\text{eq}} \approx 0.56 \).

For a given wavelength of transmitted light, 
\[ 0.56 \approx \sigma(\lambda)n(z(\lambda))\sqrt{2\pi R_{\text{obs}}(\lambda)/H}, \]
or, solving for \( z \), the planet’s effective radius lies at an altitude of 
\[ z(\lambda) = H \ln\left( P_0\sigma_{\text{avg}}(\lambda)/0.56 \times \sqrt{2\pi R_{\text{obs}}(\lambda)/kT\mu g}\right), \]
where \( \sigma_{\text{avg}} \) is the average cross section per particle and \( P_0 \) is the base pressure.

The analytic model is valuable because it yields a single relation between the effective radius, temperature, and mean molecular weight of the atmosphere. If the wavelength dependence of the cross section is known, as it is for Rayleigh scattering, this formula allows a derivation of the temperature of the planet from its spectrum, since 
\[ d\ln \sigma/d\lambda \approx H d\ln \sigma/d\lambda. \]

If \( \sigma_{\text{tot}} = (\lambda/\lambda_0)^\alpha \), then 
\[ dR_{\text{obs}}/d\ln \lambda = dz/d\ln \lambda = \alpha H, \]
or, given \( H = kT/\mu g \), 
\[ \alpha T = \mu g dR_{\text{obs}}/k d\ln \lambda. \]

Alternatively, if the temperature is known, we can solve for the mean molecular weight:
\[ \mu = \frac{\alpha T k d\ln \lambda}{g dR_{\text{obs}}}. \]

Plugging in the parameters for GJ 1214b yields a mean molecular weight of about 2.7.

This model assumes that opacity is independent of temperature and pressure, which is nearly correct for Rayleigh scattering, but a poor approximation for molecular absorption. In the Rayleigh scattering regime, at short wavelengths where it dominates over absorption, we find that this model predicts the pressure at the effective radius within a few percent of numerical calculations. This corresponds to much less than one scale height, so the resultant transit depth is within a fraction of a percent of the numerical value. For absorption, the agreement is still within a factor of a few at most wavelengths, but the numerical calculations have a larger dispersion in effective radius. For wavelengths where the opacity is very high, this discrepancy can reach a factor of 100 in pressure, or about 5 scale heights.

The dispersion and the discrepancy at the highest opacities are likely due to the analytic model’s approximation that the opacity of the atmosphere at each wavelength is constant. Molecular absorption is often roughly constant over a wide pressure range, but it varies significantly at high pressures deep in the atmosphere and at the low pressures probed by very high opacities. Thus, the analytic model does a good job for Rayleigh scattering and when the total opacity is relatively low, probing higher pressures, but it becomes less accurate in cases where opacities are higher or are highly variable with temperature and pressure. However, it can be made accurate for particular pressure levels by a judicious choice of the “average” opacity.

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