THEATMOSPHERIC CIRCULATION OF THE SUPER EARTH GJ 1214b: DEPENDENCE ON COMPOSITION AND METALLICITY

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ABSTRACT

We present three-dimensional atmospheric circulation models of GJ 1214b, a 2.7 Earth-radius, 6.5 Earth-mass super Earth detected by the MEarth survey. Here we explore the planet’s circulation as a function of atmospheric metallicity and atmospheric composition, modeling atmospheres with a low mean molecular weight (MMW; i.e., H2-dominated) and a high MMW (i.e., water- and CO2-dominated). We find that atmospheres with a low MMW have strong day–night temperature variations at pressures above the infrared photosphere that lead to equatorial superrotation. For these atmospheres, the enhancement of atmospheric opacities with increasing metallicity lead to shallower atmospheric heating, larger day–night temperature variations, and hence stronger superrotation. In comparison, atmospheres with a high MMW have larger day–night and equator-to-pole temperature variations than low MMW atmospheres, but differences in opacity structure and energy budget lead to differences in jet structure. The circulation of a water-dominated atmosphere is dominated by equatorial superrotation, while the circulation of a CO2-dominated atmosphere is instead dominated by high-latitude jets. By comparing emergent flux spectra and light curves for 50× solar and water-dominated compositions, we show that observations in emission can break the degeneracy in determining the atmospheric composition of GJ 1214b. The variation in opacity with wavelength for the water-dominated atmosphere leads to large phase variations within water bands and small phase variations outside of water bands. The 50× solar atmosphere, however, yields small variations within water bands and large phase variations at other characteristic wavelengths. These observations would be much less sensitive to clouds, condensates, and hazes than transit observations.

Key words: atmospheric effects – methods: numerical – planets and satellites: atmospheres – planets and satellites: composition – planets and satellites: individual (GJ 1214b)

Online-only material: color figures

1. INTRODUCTION

As the number of extrasolar planets detected by various ground- and space-based surveys grows, so do the number of so-called “super Earths,” exoplanets with masses of 1–10 Earth masses. Many of these super Earths transit their host stars along our line of sight, which allows us to directly observe their atmospheres by using the same techniques that are used for observing hot Jupiters (e.g., Redfield et al. 2008). Such a case is true for GJ 1214b, a 2.7 Earth-radius, 6.5 Earth-mass super Earth detected by the MEarth survey (Charbonneau et al. 2009). Because GJ 1214A is an M-type star only 13 pc away, the system has proven to be a favorable target for follow-up observations (e.g., Bean et al. 2010, 2011; Berta et al. 2012; Croll et al. 2011; Crossfield et al. 2011; Narita et al. 2012; de Mooij et al. 2012; Fraine et al. 2013; Teske et al. 2013; Colón & Gaidos 2013; Wilson et al. 2014; Kreidberg et al. 2014).

Charbonneau et al. (2009) concluded that the measured mass and radius of GJ 1214b is most consistent with an interior that is water-dominated, with a hydrogen–helium envelope that is 0.05% the mass of the planet. Rogers & Seager (2010) modeled the planet’s interior structure and concluded that if water were present in the planet’s atmosphere, it would be a supercritical fluid. Hence, GJ 1214b should not have a solid surface. Nettelmann et al. (2011) also modeled the interior of GJ 1214b assuming a two-layer (homogeneous envelope overlying a rock core) structure and found their results favor a composition similar to that of Charbonneau et al. (2009). Valencia et al. (2013) used an internal structure and evolution model (H/H2 or H2O envelope overlying an Earth-like nucleus) to test a range of possible compositions, finding that only a small amount of H/He is needed to explain the planet’s mass and radius.

In anticipation of follow-up observations of GJ 1214b, Miller-Ricci & Fortney (2010) modeled transmission and emission spectra for a range of atmospheric compositions, from hydrogen-dominated (i.e., those with a low mean molecular weight, MMW, atmosphere) to CO2- and H2O-dominated (i.e., those with a high MMW). They found that if the planet’s atmosphere was H2/He-dominated, the primary transit depth would show larger variations with wavelength than if the planet had an H2O- or CO2-dominated atmosphere; this is because of the larger atmospheric scale height for an H2-dominated atmosphere in comparison with a high MMW atmosphere. This would lead to enhanced spectral features that should be detectable by current ground- and space-based instrumentation.

Transit spectroscopic observations by most groups, however, favor a flat transmission spectrum, consistent with a high MMW (e.g., water) atmosphere or an atmosphere with high-altitude clouds or hazes (e.g., Bean et al. 2010, 2011; Berta et al. 2012; Narita et al. 2012; de Mooij et al. 2012; Fraine et al. 2013). Still, observations by other groups favor a low MMW atmosphere (Croll et al. 2011), particularly if methane is depleted (Crossfield et al. 2011). Photochemical modeling by Miller-Ricci Kempton et al. (2012) also supports a methane depletion,
consistent with methane photolysis, but note that this process is not efficient at the pressure levels probed by transmission spectroscopy.

The composition will affect not only the atmospheric opacities (hence absorption of starlight and emission of infrared radiation) but also the atmospheric scale height, dry adiabatic lapse rate, and hence the dynamical stability and circulation of the atmosphere. The circulation will determine the location of hot and cold regions in the atmosphere, which, in turn, shapes light curve and spectral behavior at photospheric levels. In light of these considerations, we model the atmospheric circulation of GJ 1214b, testing a multitude of atmospheric compositions. The circulation of GJ 1214b has been explored by other groups (Menou 2012; Zalucha et al. 2012). However, our circulation model incorporates the most rigorous radiative transfer scheme used to model the atmosphere thus far (see below). In Section 2, we describe our general circulation model (GCM), the Substellar and Planetary Atmospheric Radiation and Circulation (SPARC)/MITgcm, and describe our model integrations. In Section 3, we present results from our model integrations and identify general trends in circulation and temperature structure with metallicity and composition. In Section 4, we generate emergent flux spectra and light curves in anticipation of future instrumentation on board the James Webb Space Telescope (JWST), Thirty Meter Telescope (TMT), and other ground- and space-based facilities.

2. MODEL

2.1. The SPARC/MITgcm

We model the atmospheric circulation of GJ 1214b by using the SPARC model (Showman et al. 2009), which couples the MITgcm, a GCM maintained at the Massachusetts Institute of Technology (Adcroft et al. 2004), with a two-stream implementation of the multi-stream, non-gray radiative transfer scheme developed by Marley & McKay (1999). To emphasize its heritage, we refer to this model as the SPARC/MITgcm. The MITgcm solves the primitive equations, a simplification of the Navier–Stokes equations assuming local hydrostatic balance, which is valid in stably stratified atmospheres with horizontal length scales greatly exceeding vertical length scales. The primitive equations are solved on a cubed sphere grid, allowing for longer stepping and better accuracy near the poles in comparison with a latitude–longitude grid. The radiative transfer code solves for the upward and downward fluxes through a given vertical column of atmosphere in the GCM, which determines the heating rate used to update the temperature and winds. For each chosen atmospheric composition (see below), we divide the opacities into 11 frequency bins using the correlated-k method (Goody et al. 1989; for more details on the SPARC/MITgcm, including recent updates to the model, see Showman et al. 2009 and Kataria et al. 2013). Each model integration has a horizontal resolution of C32 (~64 × 128 in latitude and longitude) and 40 or 76 pressure levels. The pressure levels extend from a mean pressure of 200 bars at the top to 0.2 mbar at the top, evenly spaced in log pressure. The top level extends from a pressure of 0.2 mbar to zero.

The SPARC/MITgcm has been successfully adapted to investigate a variety of aspects of the atmospheric dynamics of hot Jupiters and hot Neptunes (Showman et al. 2009, 2013; Lewis et al. 2010; Parmentier et al. 2013; Kataria et al. 2013). While the MITgcm is classically an Earth GCM, this is the first time the SPARC/MITgcm in its entirety has been used to model the circulation of a super Earth. However, given the likelihood that GJ 1214b does not have a solid surface on the basis of its mass, radius, and temperature, we can use the SPARC/MITgcm with few adjustments. Utilizing the SPARC/MITgcm for rocky, terrestrial exoplanets will be a task for future studies.

2.2. Model Integrations

We model six atmospheric compositions for GJ 1214b, adapted from Miller-Ricci & Fortney (2010). First, we model H2-dominated (i.e., low MMW) compositions at 1×, 30×, and 50× solar, which have MMWs of 2.228, 2.936, and 3.424 g mol−1, respectively. These models assume molecular species are in chemical equilibrium abundances at the local temperature and pressure, accounting for rainout of species that have condensed. For the high metallicity cases, all species except for H2/He are enhanced by their respective factors. Second, we model an H2O-dominated atmospheric composition, which is composed of 99% H2O and 1% CO2. Third, we model a CO2-dominated atmospheric composition (99% CO2, 1% H2O). Lastly, we model an intermediate high MMW case, with a composition of 50% CO2 and 50% H2O.

For each model integration, we assume the winds to be initially zero and assign each vertical atmospheric column the global mean, radiative equilibrium temperature–pressure profile calculated using a one-dimensional (1D) radiative transfer code. Liu & Showman (2013) have shown that hot, synchronously rotating exoplanets exhibit circulation patterns that are insensitive to initial conditions. Figure 1 shows the pressure–temperature (P–T) profiles used in these initial conditions. We calculated the hydrogen-dominated, 1D P–T profiles by using the radiative transfer code of Fortney et al. (2005, 2006, 2008), adapted from Marley & McKay (1999). We generated the H2O- and CO2-dominated 1D profiles by using the code of Miller-Ricci et al. (2009). Both codes calculate the temperature structure self-consistently assuming radiative equilibrium. The SPARC/MITgcm self-consistently solves for the flow as dynamics and heating evolve.

In changing the atmospheric composition, we are also changing the MMW, the specific heat, and the scale height. We
calculate the specific heat by using the method described in Cooper & Showman (2006). This is given on a per mass basis as

\[ c_p = c_p1 \cdot X_1 + c_p2 \cdot X_2 + \cdots + c_{pn} \cdot X_n, \]  

where \( c_{pn} \) and \( X_n \) are the specific heat and mixing ratio of the \( n \)th atmospheric constituent, respectively.

The scale height, \( H \), is given by \( H = R \ell / g \), where \( R \ell \) is the specific gas constant, \( T \) is the effective temperature, and \( g \) is the planetary gravity. The values of molecular mass, \( c_p \), and \( H \) for each composition are listed in Table 1 and vary over an order of magnitude.

For each simulation, we use a dynamical timestep of 25 or 10 s with a radiative timestep of 500 or 200 s. The simulations were each run for approximately 5000 Earth days, with outputs every 100 days.

3. RESULTS

3.1. Hydrogen-dominated Atmospheric Composition

For all three \( \text{H}_2/\text{He} \)-dominated models, the atmospheres possess an equatorial superrotating jet, with speeds exceeding 1 km s\(^{-1}\). Each model also exhibits a pair of jets in the high latitudes. This is seen in Figure 2, which plots the zonal-mean zonal wind\(^5\) averaged over a planetary orbit for the \( 1 \times \), \( 30 \times \), and \( 50 \times \) solar composition. Overplotted in red are zonal-mean isentropes, contours of constant potential temperature. For the \( 1 \times \) solar case, the high-latitude jets are centered at roughly 60\(^\circ\), with peak speeds comparable to those at the equator. For the high metallicity cases, the high-latitude jets are centered at \( \sim 70\(^\circ\) \), with speeds of 700 m s\(^{-1}\).

Two trends in circulation are seen as the metallicity is increased. First, the peak speeds of the jet increase; equatorial jet speeds range from \( \sim 1.1 \) km s\(^{-1}\) in the \( 1 \times \) solar case to greater than 1.7 km s\(^{-1}\) in the \( 50 \times \) solar case. Second, the depth of the high-latitude jets decrease with increasing metallicity; jets in the solar case extend to pressures of approximately 1 bar, while the jets in higher metallicity cases extend to only \( \sim 300 \) mbar.

Similar trends are seen in circulation models of hot Neptune GJ 436b (Lewis et al. 2010). The trends in circulation are a result of enhanced opacity associated with higher metallicities, which leads to shallower heating in the atmosphere (Fortney et al. 2008; Dobbs-Dixon & Lin 2008; Showman et al. 2009; Lewis et al. 2010).

This enhanced opacity with higher metallicity leads to differences in the planet’s horizontal and vertical temperature structure. In our models, the temperature difference from dayside to nightside varies with height throughout observable regions of the atmosphere for all three metallicities. However, at a given pressure, this day–night temperature difference is greater for higher metallicities. We compare the temperature variations as a function of pressure in Figures 3 and 4, Figure 3 plots the wind and temperature profiles for each atmospheric metallicity at three pressure levels: 1 mbar, 30 mbar, and 1 bar, which approximately bracket the range of pressures over which infrared (IR) photons escape to space (Figure 3). Indeed, at the shallowest pressure, 1 mbar, the \( 50 \times \) solar model exhibits the highest day–night temperature variations. At 30 mbar, day–night temperature differences are small, but the \( 50 \times \) solar case nevertheless exhibits the largest temperature variation from equator to pole. At 1 bar, only the \( 1 \times \) solar case exhibits significant temperature variation, as stellar energy is deposited deeper at low metallicity. These trends are illustrated further in Figure 4, which plots the maximum dayside–nightside temperature difference at each pressure level for each atmospheric composition. This is calculated at each pressure level by first latitudinally weighting the temperature at each longitudinal slice. We then determine whether each slice is on the dayside or nightside, then subtract the minimum (weighted) temperature on the nightside from the maximum (weighted) temperature on the dayside to determine the maximum dayside–nightside temperature difference. As shown in Figure 4, above photospheric pressures (less than \( \sim 10 \) mbar), the day–night temperature variation at each pressure increases with increasing metallicity. Given the expectation that the day–night heating drives the equatorial superrotation (Showman & Polvani 2011; Kataria et al. 2013), this would imply stronger superrotation with increasing metallicity, qualitatively explaining the trend seen in Figure 2. At pressures greater than 10 mbar, where radiative time constants are longer, the temperature varies in longitude by less than \( \sim 25 \) K. These trends in temperature and wind structure will affect resultant synthetic light curves and spectra (see Section 5).

3.2. Water and Carbon Dioxide Atmospheric Compositions

A comparison of high MMW atmospheric compositions yield major differences in the dynamical and temperature regimes of GJ 1214b. If the atmosphere is \( \text{H}_2\text{O} \)-dominated (Figure 5, top row), the atmosphere still possesses an equatorial superrotating jet, with peak speeds of \( \sim 900 \) m s\(^{-1}\), and high-latitude jets with speeds exceeding 500 m s\(^{-1}\). For a \( \text{CO}_2 \)-dominated atmosphere, however, equatorial superrotation is much weaker; instead, the dynamics are dominated by high-latitude jets, with peak speeds exceeding 500 m s\(^{-1}\) (Figure 5, bottom row). The 50% \( \text{CO}_2 \), 50% \( \text{H}_2\text{O} \) case, as expected, exhibits an intermediate behavior, whereby the atmosphere is dominated by broad, high-latitude jets and moderate equatorial superrotation (Figure 5, middle row). However, all three cases have higher equator-to-pole and day–night temperature variations at photospheric pressures.

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\(^5\) The zonal wind is defined as the east–west wind, where positive (negative) values denote an eastward (westward) wind; a zonal mean denotes an average in longitude. All zonal means are averaged in longitude along surfaces of constant pressure.
Figure 2. Zonal-mean zonal wind for H$_2$-dominated compositions of GJ 1214b. The plots correspond to atmospheric compositions of 1×, 30×, and 50× solar. Zonal-mean isentropes (potential temperature contours) are overplotted in red in intervals of 500 K. Note the winds are plotted on the same colorscale. (A color version of this figure is available in the online journal.)

(~10 mbar) than the low MMW models. These >100 K variations extend as deep as 100 mbar, an order of magnitude greater than the low MMW cases (Figure 4).

The changes in dynamical and temperature regimes between low and high MMW atmospheres and between water- and CO$_2$-dominated atmospheres can be attributed to differences in the vertical opacity structure and hence heating budget. For a CO$_2$-dominated atmosphere, the atmosphere is more transparent to visible radiation. Hence, the stellar energy is deposited deeper in the atmosphere as compared with hydrogen- and water-dominated atmospheres. The qualitative picture can be further confirmed by plotting the heating and cooling rates and visible and IR fluxes on the dayside and nightside (Figure 6). The top left panel shows the dayside net visible flux, which has a net downward direction. The water case absorbs the incoming stellar energy much higher in the atmosphere than the solar and CO$_2$ cases, which corresponds to a much larger specific heating rate at the top of the atmosphere where the atmospheric mass is much less (top right panel). Note also that the heating and cooling rates are smallest for the CO$_2$-dominated case, helping to explain the weak superrotation. The large variation in visible flux with height for the water-dominated case leads to a large specific heating rate at low pressures, where the atmospheric mass is less. The bottom two panels plot the net IR flux at the substellar and antistellar points, respectively. They show that the water-dominated case also emits flux at lower pressures compared to the other two compositions. Overall, the plots show that the CO$_2$-dominated case absorbs energy the deepest and the water-dominated case the highest.

On the basis of the results presented in Showman & Polvani (2011), one would expect that the 1× solar case, which has the strongest superrotation, should absorb visible flux at lower pressures than the other two compositions, where day–night temperature variations and forcing are largest. However, as described above, the water-dominated case has the shallowest flux deposition. This suggests that the differences in specific heat (and therefore scale height) might also play a role in the differences in energy budget and dynamical regimes. To test this hypothesis, we ran two models: the first with 1× solar atmospheric opacities but a specific heat, MMW, and scale
height set to the CO$_2$-dominated value, and a second model that has the reverse (CO$_2$-dominated atmospheric opacities, 1× solar specific heat, MMW, and scale height). The 1× solar opacity case does show flow features similar to that of the CO$_2$-dominated case in Figure 5, with high-latitude jets and weak superrotation at the equator. A detailed analysis of these differences, specifically for the CO$_2$-dominated case, will be a task for future studies.

4. COMPARISON TO OTHER CIRCULATION MODELS OF GJ 1214b

We can compare our results with the other circulation models of GJ 1214b, particularly Menou (2012), which models three of the atmospheric compositions included in this paper (water-dominated, 1× and 30× solar), though with a different circulation model (the Intermediate General Circulation Model; Hoskins & Simmons 1975), radiative transfer scheme (double-gray), and model setup. In comparing the hydrogen-dominated models (see Figure 2 in Menou 2012), one can see broad agreement, with equatorial superrotation in the 1–2 km s$^{-1}$ range and high-latitude eastward winds. However, the jet structure is different—the equatorial jets in Menou (2012) extend to deeper pressures than our models. These differences could stem from differences in the radiative transfer scheme but also from

Figure 3. Wind and temperature at approximately 1 mbar (top row), 30 mbar (middle row), and 1 bar (bottom row) for H$_2$-dominated compositions of GJ 1214b. Each column corresponds to atmospheric compositions of (from left to right) 1×, 30×, and 50× solar. The black line denotes the substellar longitude. Each row is plotted on the same colorscale.

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

Figure 4. Maximum day–night temperature difference as a function of pressure for the 50× solar case (blue) and the water-dominated case (red). This was calculated by first computing a weighted-average of temperature as a function of longitude, then differencing the maximum and minimum temperatures on the dayside and nightside, respectively.

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

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Figure 5. Zonal-mean zonal wind (left column) and wind and temperature at 30 mbar (right column) for high MMW atmospheric compositions of GJ 1214b. Each pair of plots correspond to atmospheric compositions of (from top to bottom) 99% H₂O, 1% CO₂; 50% H₂O, 50% CO₂; and 99% CO₂, 1% H₂O. Zonal-mean isentropes are overplotted in red in intervals of 250 K. The panels in each column are shown with the same colorscale.

(A color version of this figure is available in the online journal.)
differences in the bottom boundary (10 bars versus 100 bars in our model).

In comparing water-dominated circulation models of GJ 1214b, we can also include results from Zalucha et al. (2013), who use a different setup of the MITgcm coupled to a Newtonian relaxation scheme, including a surface at varying pressures. In all three models, there is again broad agreement, with an eastward equatorial jet with a width of approximately 50–60 degrees. However, the models again differ in jet speeds and structure. Equatorial wind speeds are greatest in Menou (2012), and Zalucha et al. (2013) model the weakest. Furthermore, both Menou (2012) and our results include eastward winds at high latitudes, while Zalucha et al. has westward winds at the same latitudes. These differences are most likely due to differences in the bottom boundary and radiative heating schemes.

5. INCLUDING EFFECTS DUE TO CO$_2$–CO$_2$ PIA

While we already include opacity effects due to pressure-induced absorption (PIA) from H$_2$–H$_2$ and H$_2$–He collisions (see Kataria et al. 2013), here we test the importance of including opacity effects due to PIA from CO$_2$–CO$_2$ collisions. Figure 7

\[ \text{Figure 6. Dayside net visible flux (top left), heating and cooling rates (top right), dayside net infrared flux (bottom left), and nightside net infrared flux (bottom right) as a function of pressure, for each major atmospheric composition: H-dominated (1 \times \text{solar composition, blue), H}_2\text{O-dominated (red), and CO}_2\text{-dominated (green). Fluxes are in units of W m}^{-2}, \text{while heating and cooling rates are in units of K s}^{-1}. (A color version of this figure is available in the online journal.)} \]

\[ \text{Figure 7. Optical depth as a function of wavelength for pure-water (blue), pure-CO}_2\text{(green), and pressure-induced absorption (PIA) due to CO}_2\text{–CO}_2\text{collisions (red). The dotted gray lines denote the boundaries of the 11 spectral bins used in the correlated-k calculation. Note that the CO}_2\text{–CO}_2\text{ PIA is only prominent in the longest wavelength (shortest wavenumber) bin. (A color version of this figure is available in the online journal.)} \]
compares the optical depth, $\tau$, of this opacity source with the optical depths for a pure water and pure CO$_2$ atmosphere. This optical depth is calculated as a product of the number of molecules per cm$^{-2}$, $N$, and the absorption coefficients, $\mathcal{K}$. The value of $N$ is defined as $nH$, where $n$ is the number density (in units of m$^{-3}$) and $H$ is the scale height. This can be further simplified by using the ideal gas law as $N = P/mg$. Here we calculate the optical depths for each composition in each wavelength interval at a temperature of 725 K and a pressure of 1 bar ($10^9$ egs).

As shown in Figure 7, the CO$_2$–CO$_2$ PIA is most important in the longest wavelength (shortest wavenumber) frequency bin (denoted by gray dotted lines). Only a small fraction of the planet’s flux is emitted in this wavelength range, and therefore we expect that the inclusion of CO$_2$–CO$_2$ PIA should not significantly affect the dynamical structure. Figure 8 compares the transient spin-up phase of two CO$_2$-dominated runs with (right column) and without (left column) the inclusion of CO$_2$–CO$_2$ PIA in zonal-mean zonal wind (top row) and wind and temperature profiles at 30 mbar (bottom row). There are minor differences between both cases; the westward flow at the top of the atmosphere extends to deeper pressures at the equator when PIA is included, and the PIA case exhibits a slightly different flow pattern at $\sim$30 mbar. However, the bulk features remain the same: the speeds and horizontal and vertical extent of the high-latitude jets and the temperature and shape of the hottest regions on the dayside do not differ significantly. Therefore, while it is important to include this opacity source, it does not dramatically change the dynamical and thermal structure of the atmosphere.

6. SIMULATED LIGHT CURVES AND SPECTRA

Using the outputs from our model integrations, we can generate light curves and spectra of GJ 1214b for each atmospheric composition. Most ground- and space-based observations of GJ 1214b have been obtained during transit, but their flat transmission spectra suggest the presence of clouds that prevent easy characterization of the atmosphere. Therefore, only dayside emergent flux spectra obtained at secondary eclipse and light curves will be able to constrain the planet’s atmospheric composition. Observations with the Spitzer Space Telescope were able to detect secondary eclipse (Fraine et al. 2013; Gillon et al. 2013), and future instrumentation on the JWST, Giant Magellan Telescope (GMT), and the TMT will improve on those observations. In anticipation of these and other future instruments, we generate theoretical spectra and light curves at wavelength
bands not specific to any particular instrument (see below). In this way observers may use these theoretical light curves and spectra to select the wavelengths that best suit their efforts.

We choose to focus on atmospheric compositions of $50\times$ solar and 99% H$_2$O/1% CO$_2$ (water-dominated), as these two models best illustrate the differences in emergent flux spectra and light curves that arise from differences in circulation and temperature structures. As discussed in Sections 3.1 and 3.2, at each pressure level the water-dominated case has a greater temperature difference from dayside to nightside than the $50\times$ solar case. Therefore, we expect the water-dominated case to exhibit larger flux variations with orbital phase than the $50\times$ solar case (Figure 4). However, this will vary widely as a function of wavelength, as the water spectrum is dominated by fundamental and combination vibrational bands in the near-IR and mid-IR. Within these water bands, the atmosphere is opaque, and hence observations at these wavelengths will probe lower pressures. Thus, according to Figure 4, we would expect greater day–night temperature variations and larger flux variation with orbital phase. At wavelengths outside of the water bands (i.e., in spectral windows), observations sense deeper, hotter regions of the atmosphere where day–night temperature variations are smaller; hence, there should be less flux variation with orbital phase.

We see this behavior in theoretical emergent flux spectra for the water-dominated model (Figure 9, top panel). For both the water-dominated case and the $50\times$ solar case (bottom panel), the spectra are plotted at six orbital phases, from transit, where the nightside is visible (black spectra), to secondary eclipse (magenta spectra). The deep absorption features seen in the water-dominated case are fundamental vibrational bands of water vapor at 2.66, 2.73, and 6.27 $\mu$m, as well as combination bands at 1.13, 1.38, 1.88, and 2.68 $\mu$m. Inside the water bands where we are probing low pressure regions, the large day–night temperature variations lead to large flux variations with orbital phase. Outside of the bands (inside the spectral windows), we probe deeper pressures where there are small temperature differences and hence small phase variations.

Comparing the emergent flux spectra of the $50\times$ solar composition, we see the absorption features are not as deep and less dominated by water features. The difference between windows and non-windows is also less prominent. However, the $50\times$ solar case also exhibits variations in emergent flux with phase and wavelength, indicating that for both cases, different atmospheric pressure levels are probed at different wavelengths. This can be quantitatively shown by plotting the pressure probed in emergent flux, where the optical depth, $\tau$, is equal to one. We calculate the $\tau = 1$ level by first determining the brightness temperature, $T_{\text{bright}}$, as a function of wavelength and finding the pressure level at which the globally averaged temperature is equal to $T_{\text{bright}}$. The results are plotted in Figure 10 with a colorscale corresponding to the maximum temperature variation at each pressure level from Figure 4. For both atmospheric compositions, the wavelength regions with small (large) phase variations correspond to deeper (shallower) pressures, where day–night temperature variations are smaller (larger). Light curves of each composition further illustrate the differences between low and high MMW compositions. We plot the planet/star flux ratio as a function orbital phase for the water and $50\times$ solar compositions in Figure 11. In each case, an orbital phase of 0.0 corresponds to transit, while an orbital phase of 0.5 corresponds to secondary eclipse. Six light curves are plotted at the general wavelength bands $a$–$f$ listed in Table 2 and denoted in Figures 9 and 10. For the water-dominated case, flux variations are large in all but one band (band $a$, black line). At this band the $\tau = 1$ level corresponds to a pressure level of 0.1 bars, where day–night temperature variations are small. All other wavelength bands probe high in the atmosphere, where day–night temperature variations are large (Figure 10). For a $50\times$ solar composition, the flux variations are large for bands $a$, $b$, and $c$, which probe low-pressure regions where day–night

![Figure 9](image-url)

**Figure 9.** Emergent flux density (in units of erg s$^{-1}$ cm$^{-2}$ Hz$^{-1}$) for water-dominated (top panel) and $50\times$ solar (bottom panel) compositions at six orbital phases: transit, when the nightside is visible (black line); 60$^\circ$ after transit (red line); 120$^\circ$ after transit (green); secondary eclipse, when the dayside is visible (magenta). These phases are illustrated in the inset figure, shown in the bottom right of each panel. Black horizontal lines indicate the wavelength bands chosen for light curves plotted in Figure 11, from band $a$ to band $f$.

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

### Table 2

| Wavelength Band | Left Bound ($\mu$m) | Right Bound ($\mu$m) |
|-----------------|---------------------|----------------------|
| $a$             | 2.2                 | 2.45                 |
| $b$             | 2.5                 | 2.9                  |
| $c$             | 3.2                 | 3.5                  |
| $d$             | 4.25                | 4.4                  |
| $e$             | 5.5                 | 7.0                  |
| $f$             | 14.0                | 16.0                 |
Figure 10. $\tau = 1$ pressure level as a function of wavelength for the water-dominated (top) and 50× solar (bottom) cases. The colorscale corresponds to the maximum temperature variation from dayside to nightside, as plotted in Figure 4. Black horizontal lines indicate the wavelength bands chosen for light curves plotted in Figure 11, from band $a$ to band $f$. (A color version of this figure is available in the online journal.)

Our results demonstrate that one can break the degeneracy in determining the atmospheric composition of GJ 1214b by observing the planet in thermal emission. Large phase variations within water absorption bands and small variations in its spectral windows would indicate a water-dominated atmosphere. Other high MMW species that are highly absorbing, such as carbon dioxide, ammonia, or methane, might in principle exhibit their own characteristic pattern of light-curve amplitude with wavelength, depending on the wavelengths of their absorption bands and spectral windows. As shown in Figures 9 and 11, a hydrogen-dominated atmosphere should exhibit a pattern of light-curve amplitude with wavelength that differs significantly from that of a high MMW atmosphere such as one that is water-dominated.

While we present this method in a generalized sense, one should be able to utilize space-based instruments such as the Near-Infrared Spectrograph on board JWST or the Wide Field Camera 3 on the Hubble Space Telescope, although the latter has less spectral coverage and would require a multitude of orbits to achieve sufficient signal-to-noise. Instruments on the next generation of ground-based telescopes might also be able to utilize this technique, such as the near-IR spectrometer (GMTNIRS) on GMT or the Infrared Multi-object Spectrometer on TMT. However, full-phase light curves would be difficult to obtain from the ground in a single observation, and one would have to contend with the water vapor in Earth’s atmosphere. Therefore, reduction of ground-based observations would be much more difficult. In either case, in order to probe inside and outside water bands effectively as the method requires, spectral observations are necessary. Observations in photometric passbands (i.e., broadband observations like those on the Spitzer Space Telescope) might be able to apply this method but would smear out these spectral features.

These results are particularly favorable because they would generally be independent of the presence of clouds, minor equilibrium condensates, or photochemical haze. In transit, slant optical depths through the planet’s terminator can be
dozens of times larger than vertical optical depths (Fortney 2005), which can suppress absorption features (see Morley et al. 2013). In emission, however, paths are closer to vertical, suggesting that it is much easier for hazes to flatten the transmission spectrum than the emission spectrum. Still, if the clouds or hazes are sufficiently thick, they would absorb and scatter the emergent flux, which could in turn suppress emission features and flux phase variations. Given recent Kreidberg et al. (2014) results that GJ 1214b likely has clouds or hazes, future work will include exploring how clouds with varying compositions and particle sizes as well as photochemical hazes can affect the phase variations presented here.

7. CONCLUSIONS

We present three-dimensional atmospheric circulation models of the super Earth GJ 1214b, exploring changes in circulation as a function of metallicity and composition. For hydrogen-dominated atmospheres, atmospheric opacities are enhanced with increasing metallicity, leading to shallower atmospheric heating. This yields strong dayside–nightside heating and forcing that increases with metallicity, which in turn produces the highest day–night temperature variations and hence the strongest equatorial superrotation in the 50× solar model.

The water-dominated composition also exhibits superrotation at the equator and eastward jets at high latitudes, but the circulation of the CO2-dominated model is dominated mainly by high-latitude jets. All three high MMW models have higher horizontal temperature variations at a given (low) pressure than the low MMW models. These differences in temperature structure and circulation can be attributed to differences in opacity structure and scale height.

The theoretical dayside light curves and spectra presented here lead to a major prediction for how to break the current observational degeneracy in the composition of GJ 1214b’s atmosphere. In particular, the water bands dominate the spectra of the 99% H2O, 1% CO2 case. Within water absorption bands, large day–night temperature variations lead to large flux variations with phase. Outside of the water bands (within atmospheric windows), these phase variations are small. In comparison, a 50× solar atmosphere generally yields small phase variations at those wavelength bands and large phase variations at other characteristic bandpasses. Therefore, observing in emission would break the degeneracy to determining the atmospheric composition of GJ 1214b. One could potentially constrain the existence of water or other highly absorbing species by selecting wavelength bands inside and outside of their atmospheric windows and by comparing the extent of phase variations with that of a low MMW atmosphere. This diagnostic is much less sensitive than transit spectra to clouds, condensates, and hazes. However, sufficiently thick clouds and hazes would absorb and scatter emergent flux, thus diminishing emission features and flux variations with orbital phase.

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