



Beyond Equilibrium Temperature: How the Atmosphere/Interior Connection Affects the Onset of Methane, Ammonia, and Clouds in Warm Transiting Giant Planets

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Abstract

The atmospheric pressure–temperature profiles for transiting giant planets cross a range of chemical transitions. Here we show that the particular shapes of these irradiated profiles for warm giant planets below ~ 1300 K lead to striking differences in the behavior of nonequilibrium chemistry compared to brown dwarfs of similar temperatures. Our particular focus is H_2O , CO , CH_4 , CO_2 , and NH_3 in Jupiter- and Neptune-class planets. We show that the cooling history of a planet, which depends most significantly on planetary mass and age, can have a dominant effect on abundances in the visible atmosphere, often swamping trends one might expect based on T_{eq} alone. The onset of detectable CH_4 in spectra can be delayed to lower T_{eq} for some planets compared to equilibrium, or pushed to higher T_{eq} . The detectability of NH_3 is typically enhanced compared to equilibrium expectations, which is opposite to the brown dwarf case. We find that both CH_4 and NH_3 can become detectable at around the same T_{eq} (at T_{eq} values that vary with mass and metallicity), whereas these “onset” temperatures are widely spaced for brown dwarfs. We suggest observational strategies to search for atmospheric trends and stress that nonequilibrium chemistry and clouds can serve as probes of atmospheric physics. As examples of atmospheric complexity, we assess three Neptune-class planets, GJ 436b, GJ 3470b, and WASP-107, all around $T_{\text{eq}} = 700$ K. Tidal heating due to eccentricity damping in all three planets heats the deep atmosphere by thousands of degrees and may explain the absence of CH_4 in these cool atmospheres. Atmospheric abundances must be interpreted in the context of physical characteristics of the planet.

Unified Astronomy Thesaurus concepts: [Exoplanet atmospheres \(487\)](#)

1. Introduction

1.1. Atmospheric Characterization

Even 25 yr after the discovery of gas giant exoplanets (Mayor & Queloz 1995), we are still in our infancy in characterizing the atmospheres of these worlds. Over the past two decades, astronomers have made fantastic strides to obtain spectra of exoplanets, but we still have much to do. In the realm of transiting planets, observers have often been hindered by instruments aboard space- and ground-based telescopes that were never designed for precision time series spectrophotometry. Even as dozens of planets have been seen in transmission spectroscopy (e.g., Sing et al. 2016) and occultation spectroscopy or photometry (e.g., Kreidberg et al. 2014; Garhart et al. 2020), our ability to understand the physics and chemistry of hydrogen-dominated atmospheres has been limited, principally by low signal-to-noise ratio observations and limited wavelength coverage. On the side of the directly imaged planets, telescopes like Keck, the Very Large Telescope, and Gemini have allowed more robust atmospheric spectroscopy, but with a sample size that is so far limited in number (e.g., Konopacky et al. 2013; Macintosh et al. 2015; Gravity Collaboration et al. 2019).

It is with brown dwarfs, now numbering over 1000, with temperatures down to 250 K (Luhman 2014; Skemer et al. 2016), where robust atmospheric characterization has taken place over the past 25 yr. The major transitions in atmospheric

chemistry and cloud opacity have now been unveiled (Burrows et al. 2001; Kirkpatrick 2005; Helling & Casewell 2014; Marley & Robinson 2015), although major open questions still exist on the role of clouds in shaping the spectra across a range of T_{eff} and surface gravity. However, it should be clear that relying solely on the classic “stellar” fundamental quantities of T_{eff} , $\log g$, and metallicity has already shown its faults for these objects. For instance, time variability can reach tens of percent, and effects due to rotation rate (Artigau 2018) and viewing angle have now been seen as important to take into account for atmospheric characterization (Vos et al. 2017).

To understand the atmospheres of giant planets, we will certainly need a *larger* sample size than the brown dwarfs, for a similar level of understanding, as planets have many additional complicating factors (Marley et al. 2007). For instance, substantial recent work has gone into assessing the Spitzer IRAC 3.6/4.5 colors of cooler transiting planets, in order to better assess atmospheric metallicity and the role of CH_4 and CO absorption (Kammer et al. 2015; Triaud et al. 2015; Wallack et al. 2019; Dransfield & Triaud 2020). The wide diversity of colors at a given T_{eq} , much wider than is seen in brown dwarfs at a given T_{eff} (Beatty et al. 2014; Dransfield & Triaud 2020), has been interpreted as needing a large dispersion in atmospheric metallicity and potentially C/O ratio.

Planets present additional complicating physics, such as heating from above, across a range of incident stellar spectral

types (Mollière et al. 2015), in addition to a range of UV fluxes. The planets will have diverse day–night contrasts and circulation regimes, likely with a very wide range of atmospheric metallicities (Fortney et al. 2013; Kreidberg et al. 2014) and nonsolar abundance ratios (Öberg et al. 2011; Madhusudhan et al. 2014; Espinoza et al. 2017). The cooling of the interiors of giant planets—even the cooler giant planets not affected by the hot Jupiter radius anomaly—is also still not fully understood (e.g., Vazan et al. 2015; Berardo & Cumming 2017).

Key science goals of the James Webb Space Telescope (JWST) and ARIEL are to obtain spectra of a wide range of planetary atmospheres (Beichman et al. 2014; Greene et al. 2016; Tinetti et al. 2018). In the realm of transiting giant planets, which have predominantly accreted their atmospheres from the protostellar nebula, one aspect of this science will be characterizing planets over a wide range of temperatures, to sample a wide range of transitions in atmospheric chemistry and cloud formation. A significant amount of previous theoretical and modeling work has gone into trying to predict and understand trends in the atmospheres of these planets, going back to important early works such as Marley et al. (1999) and Sudarsky et al. (2000), supplemented by later works like Fortney et al. (2008), Madhusudhan et al. (2011b), and Mollière et al. (2015). Most of these papers have pointed to planetary equilibrium temperature, T_{eq} , as the dominant physical parameter that determines atmospheric physics and chemistry, somewhat akin to T_{eff} in stars. While there are good reasons to think that this is indeed true, there are equally good reasons to think that T_{eq} is only a starting point and that other physical parameters can have a crucial effect on determining the atmospheric spectra that we will see.

Of course, T_{eq} is only part of the energy budget, and it is well understood that $T_{\text{eff}}^4 = T_{\text{eq}}^4 + T_{\text{int}}^4$, with T_{int} parameterizing the intrinsic flux from the planetary interior, and T_{eq} from thermal balance with the parent star. In Jupiter, for instance, T_{eq} and T_{int} are similar, with neither dominating the energy budget (Pearl & Conrath 1991; Li et al. 2018). Recently, Thorngren et al. (2019, 2020) pointed out that the radii of “hot” and “warm” Jupiter population can be used to assess the intrinsic flux coming from planetary interiors. Often Jupiter-like values of T_{int} (100 K) had been chosen for convenience, but the inflated radius of a typical hot Jupiter goes hand in hand with a hotter interior and much higher T_{int} values (assuming convective interiors).

This work gives us the ability to better assess the depth of the radiative–convective boundary (RCB) in these strongly irradiated planets. A key finding of Thorngren et al. (2019) was that the T_{int} values are typically larger (sometimes much larger) than previous expectations, which moves the RCB to lower pressures. A higher T_{int} can remove or weaken cold traps in these atmospheres, which can alter atmospheric abundances and the depth at which clouds form. Much additional work needs to be considered for these hot planets, perhaps much of it in the 3D context, given the large day–night temperature contrasts (Parmentier & Crossfield 2018).

The role of the current paper is to serve as a complement of sorts, and extension to, the work of Thorngren et al. (2019), but mostly for cooler planets. For planets below $T_{\text{eq}} \sim 1000$ K, a wide range of chemical and cloud transitions should occur (Marley et al. 1999; Sudarsky et al. 2000; Morley et al. 2012). What is not as appreciated, however, is that temperatures in the

deeper atmosphere, which are typically not visible, can play as large a role, or even a larger role, in determining atmospheric abundances as the visible atmosphere, which is dominated by absorbed starlight.

The temperatures of the deep atmosphere, while typically not measurable, can be constrained in a variety of ways. Observationally, flux from the deep interior can potentially be seen at wavelengths where the opacity is low (“windows”). This has been constrained for GJ 436b emission photometry (Morley et al. 2017a) and could potentially be done for a small number of other planets (Fortney et al. 2017). Another is cold-trapping gases into condensates via crossing a condensation curve in the deep atmosphere (Burrows et al. 2007; Fortney et al. 2008; Beatty et al. 2019; Sing et al. 2019; Thorngren et al. 2019).

As was done in Thorngren et al. (2019), the planetary radius can be used as a constraint, with assumptions about interior energy transport. Planetary thermal evolution/contraction models aim to understand the cooling of the planetary interior with time (e.g., Fortney et al. 2007; Baraffe et al. 2008). Furthermore, there are planets for which thermal evolution models can be made more uncertain—those that are undergoing tidal eccentricity damping. If this energy is dissipated in the planet’s interior, the temperature of the deep atmosphere can be significantly enhanced compared to simple predictions. Lastly, one can assess the role of disequilibrium chemistry tracers. Recently, Miles et al. (2020) have used observations of disequilibrium CO in cold brown dwarfs to understand atmospheric dynamics and temperature structures. They constrain the rate of atmospheric vertical mixing as a function of T_{eff} , providing strong evidence for a detached radiative zone, below the visible atmospheres, long predicted in these atmospheres (Marley et al. 1996; Burrows et al. 1997). It is these disequilibrium tracers that we turn to next, in more detail.

1.2. “Hidden” Atmospheric Chemistry

Due to nonequilibrium chemistry via vertical mixing, deep atmosphere temperatures can matter as much as temperatures in the visible atmosphere in determining observable abundances. This well-understood process affects abundances when the mixing timescale for a parcel of gas, t_{mix} , is shorter than the chemical conversion timescale, t_{chem} , for a given chemical reaction. Well-studied reactions are CO to CH₄ and N₂ to NH₃. These timescales can be so long that the gas in the visible atmosphere (at, say, 1 mbar) will be representative of pressure–temperature (P – T) conditions at ~ 1 –1000 bars, as we will readily show. The effects of nonequilibrium chemistry on the atmospheric abundances and resulting spectra in giant planet (both solar system and extrasolar) and brown dwarf atmospheres have previously been extensively studied (Fegley & Lodders 1996; Saumon et al. 2003, 2006; Visscher et al. 2010; Madhusudhan et al. 2011b; Moses et al. 2011; Visscher & Moses 2011; Venot et al. 2012; Moses et al. 2013; Miguel & Kaltenecker 2014; Zahnle & Marley 2014; Macdonald & Madhusudhan 2017; Molaverdikhani et al. 2019, 2020; Miles et al. 2020; Venot et al. 2020), and here we will not break new ground on the chemistry. Rather, following the carbon and nitrogen chemistry work of Zahnle & Marley (2014), we will point out several novel complexities that arise when applying nonequilibrium chemistry to the quite inhomogeneous exoplanet population. Given the very large uncertainties in vertical mixing speeds, in particular for these irradiated atmospheres that are mostly radiative rather than convective (where mixing-

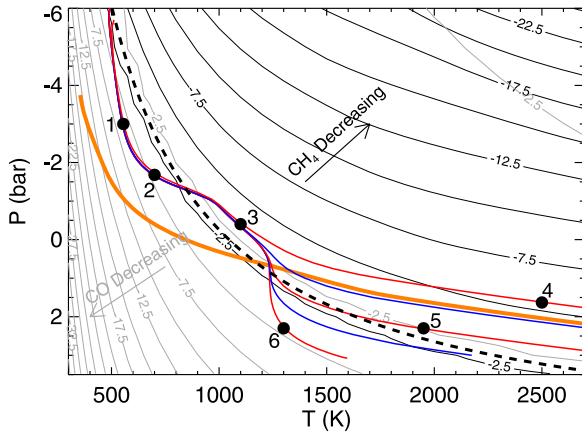


Figure 1. Model P - T profiles for a $10\times$ solar atmosphere at 0.15 au from the Sun. The five profiles all have $T_{\text{eq}} = 710$ K and show (alternating red and blue) five values of T_{int} , at 60, 100, 200, 300, and 400 K, and a Jupiter-like gravity of 25 m s^{-2} . Also shown by the thick orange curve is the T_{eff} of a 1000 K brown dwarf with a gravity of 1000 m s^{-2} . Equal-abundance contours for CH_4 are shown in dark gray and show the log (base-10) of volume mixing ratios of CH_4 that fall off by many orders of magnitude toward the upper right. Correspondingly, light-gray contours show the same for CO, toward the lower left, where CH_4 is the dominant absorber. CO and CH_4 have an equal abundance at the thick dashed black curve. These mixing ratio contours assume equilibrium chemistry. The numbered black filled circles are called out specifically in the text.

length theory could plausibly be used), in addition to uncertainties in thermal evolution models, as well as the currently unknown atmospheric metal enrichments, we will show that a very wide range of behavior should be expected. For instance, one should not expect a single transition temperature in T_{eq} from CO-dominated to CH_4 -dominated atmospheres, an area of active study already with Hubble and Spitzer (Stevenson et al. 2010; Morley et al. 2017a; Kreidberg et al. 2018; Benneke et al. 2019).

We can first look at an illustrative example of why vertical mixing from different atmospheric depths can strongly affect observed abundances and spectra, by exploring the behavior of CO, CH_4 , and H_2O . Figure 1 shows the atmospheric P - T profile for a planet at 0.15 au from the Sun, with $T_{\text{eq}} = 710$ K. Five models are shown, with decreasing T_{int} , leading to cooler interior adiabats. Underplotted in light gray are curves of constant volume mixing ratio (mole fraction) for CO, to the lower left, following the chemical equilibrium calculations of Visscher et al. (2010) and Visscher (2012). Underplotted in dark gray is the same for CH_4 , to the upper right. The thick dashed black curve shows the equal-abundance boundary, where the mixing ratio of $\text{CO} = \text{CH}_4$:

$$\log_{10} P \approx 5.05 - 5807.5/T + 0.5[\text{Fe}/\text{H}], \quad (1)$$

for P in bars, T in K, and $[\text{Fe}/\text{H}]$ as the metallicity (Visscher 2012). When we turn to nitrogen chemistry in Section 4.2, we will use the analogous $\text{N}_2 = \text{NH}_3$ equal-abundance curve:

$$\log_{10} P \approx 3.97 - 2721.2/T + 0.5[\text{Fe}/\text{H}]. \quad (2)$$

Numbered black filled circles in Figure 1 have been placed along the profiles. Point 1 is at 1 mbar, a pressure that would be readily probed in transmission spectroscopy. Point 2 is at 700 K, where the local temperature is equal to T_{eff} , a good representation of the mean thermal photosphere in emission. Points 1 and 2 are in the CH_4 -dominated region, with point 2 having $\sim 10\times$ more CO. Moving down to point 3, all profiles are now in the CO-dominated regime, where the CH_4 abundance falls off

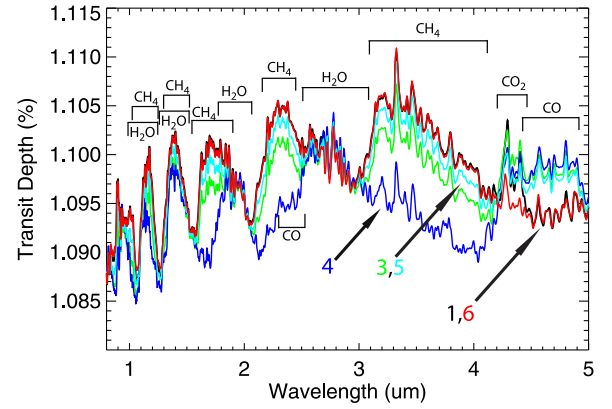


Figure 2. Corresponding transmission spectra for the P - T profiles and chemical abundance points from Figure 1. The main absorption features of H_2O , CO, CH_4 , and CO_2 are labeled. Transmission spectra that use the “quenched” chemical abundances from points 1, 3, 4, 5, and 6 are labeled with arrows. Spectra are normalized to wavelengths where H_2O is the main absorber, to show the relative roles of CO and CH_4 in shaping spectra. The transit models assume $1 R_J$ at a pressure of 1 kbar, a gravity of 25 m s^{-2} , and stellar radius of the Sun.

dramatically with temperature. Point 4 is deeper in the atmosphere along the hottest adiabat, in the CO-rich region, with a decrease in CH_4 compared to point 3. Points 5 and 6 are along cooler adiabats, with point 5 having abundances quite similar to point 3. Point 6 is quite interesting, in that, while it is in the deep part of the atmosphere, it is clearly within the CH_4 -dominant region and has the same CH_4 and CO abundances as point 2. This complexity should be contrasted with the profile of a $T_{\text{eff}} = 1000$ K, $\log g = 5$ brown dwarf, plotted by the thick orange curve. For the brown dwarf, as a parcel of gas moves along from high pressure to low, there is a monotonic increase in CH_4 and decrease in CO.

As one would expect, the spectra that use the quenched abundances, brought up to the visible atmosphere from the black points of Figure 1, vary considerably as the abundances of CO and CH_4 vary by orders of magnitude. In addition, the abundance of H_2O changes depending on whether CO is present as well. We demonstrate this for five different models shown in Figure 2. For points to the “right” of the CO/ CH_4 equal-abundance curve, like points 3, 5, and especially 4, the CO band is much stronger and CH_4 is weaker. The spectra from points 1 and 6 are substantially similar, given their relative positions in CO/ CH_4 phase space. The lack of monotonic behavior in the mixing ratio (and observability) of CH_4 as a function of the quench pressure was also pointed out by Molaverdikhani et al. (2019, see their Figure 2), although they did not explore variations in the lower boundary condition, which is our focus here.

Such a wide range of internal adiabats, for a given upper atmosphere, is quite possible owing to the differences in cooling histories in giant planets. It is by now widely appreciated that giant planets cool over time, most dramatically at young ages, and that more massive planets take longer to cool (Marley et al. 1996; Burrows et al. 1997; Chabrier & Baraffe 2000). For reference, in Figure 3 we plot cooling tracks for planets from 10 to $0.1 M_J$ ($32 M_{\oplus}$) for ages from 10^7 to 10^{10} yr, using the models of Fortney et al. (2007) and Thorngren et al. (2016). At an age of 3 Gyr, for instance, T_{int} values of 50–350 K span the population. Such model planets would in reality all have different surface gravities, which would then yield different P - T profile shapes, even at the same orbital separation, as shown in Figure 4. This plot is for the expected

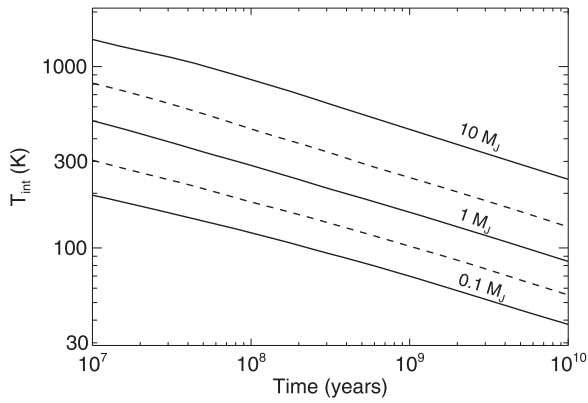


Figure 3. Thermal evolution of giant planets at 0.1 au from the Sun, after Fortney et al. (2007) and Thorngren et al. (2016). Plotted are the intrinsic effective temperature, T_{int} , for models at 10, 3, 1, 0.3, and 0.1 M_J ($32 M_{\oplus}$), from top to bottom. For reference, Jupiter today has $T_{\text{int}} = 99$ K. A wide range of T_{int} values are possible at old ages, given a range of planetary masses, and a wide range of T_{int} values are possible at a given mass, over time.

surface gravity for the five planet masses (at an age of 3 Gyr) shown in Figure 3.

Taken as a whole, these simple examples serve as motivation to explore a wider range of parameter space for H/He-dominated atmospheres. The aim then is to show that a range of factors other than equilibrium temperature can have significant impacts, even *dominant* impacts, on atmospheric abundances and spectra. We also explore how nonequilibrium chemistry can serve as a tracer for understanding the deep temperature structure for these atmospheres, at pressures far below where one can probe directly. After describing our methods in a bit more detail, we investigate these factors, first for well-known transiting Neptune-class planets GJ 436b, GJ 3470b, and WASP-107. After that, we will explore carbon chemistry more generally, followed by nitrogen chemistry more generally, before our discussion (with caveats) and conclusions.

2. Model Description

2.1. Atmospheric Structure and Spectra

The model atmosphere methods used here have previously been extensively described in the literature. We compute planet-wide average (“ 4π re-radiation of absorbed stellar flux”) 1D radiative–convective equilibrium models using the model atmosphere code described in the papers of Marley & McKay (1999), Marley et al. (1996), and Fortney et al. (2005, 2008) and the general review of Marley & Robinson (2015). The radiative transfer methods are described in McKay et al. (1989). The model uses 90 layers, typically evenly spaced in log pressure from 1 μ bar to 1300 bars. The equilibrium chemical abundances follow the work of Lodders & Fegley (2002), Visscher et al. (2006, 2010), and Visscher (2012). The opacity database is described in Lupu et al. (2014) and Freedman et al. (2014). Transmission spectra are calculated using the 1D code described in Morley et al. (2017b).

2.2. Interiors and Tidal Heating

As already mentioned, the giant planet thermal evolution models use the methods of Fortney et al. (2007) and Thorngren et al. (2016). These thermal evolution calculations use an extensive grid of 1D nongray solar-composition radiative–convective atmosphere

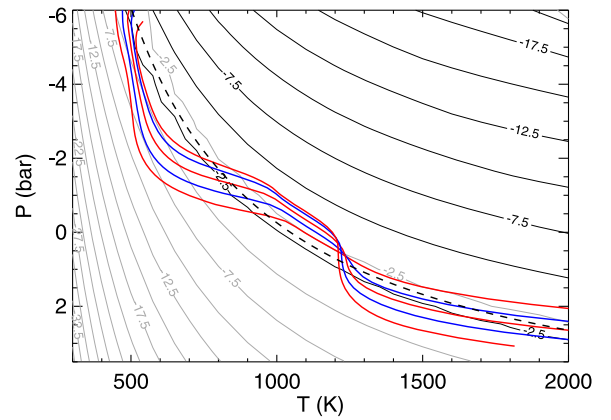


Figure 4. Model P – T profiles (with $T_{\text{eq}} = 710$ K) for a $10\times$ solar atmosphere at 0.15 au from the Sun, this time based on thermal evolution models. The five profiles (alternating red and blue) show five values of T_{int} , at 52, 77, 117, 182, and 333 K, and respective surface gravities $g = 5.8, 9.8, 24, 65$, and 225 m s^{-2} . Equal-abundance contours for CH_4 are shown in black, and light-gray contours show the same for CO . CO and CH_4 have an equal abundance at the thick dashed black curve. These mixing ratio contours assume equilibrium chemistry.

models, which serve as the upper boundary condition. The interior H/He equation of state is that of Saumon et al. (1995). We make the standard, typical assumption of a fully convective H/He envelope, and these evolution models also have a $10 M_{\oplus}$ ice/rock core.

Tidal heating, to be investigated in a Section 3, uses the extensive tidal evolution equations derived in Leconte et al. (2010). We determine the tidal heating rate (in energy per second) with Equation (13) in this work. We will show that for some planets this tidal heating flux from the interior can be orders of magnitude higher than that calculated from normal secular cooling of the interior.

2.3. Nonequilibrium Chemistry

When treating nonequilibrium chemistry, an important topic in this paper, we make extensive use of the findings of Zahnle & Marley (2014). These authors provide quenching relations that are derived by fitting to the complete chemistry of a full ensemble of 1D kinetic chemistry models. We use the standard “quench pressure” formalism, where we assume chemical equilibrium where the chemical conversion time, t_{chem} , is shorter than the vertical mixing time, t_{mix} . The local values of t_{mix} along a P – T profile use the standard assumption that $t_{\text{mix}} = L^2/K_{zz}$, where L is the length scale of interest, here assumed to be the local pressure scale height, H , and K_{zz} is the vertical diffusion coefficient. Other, potentially smaller values of L could be used (Smith 1998; Visscher & Moses 2011); however, as we discuss below, uncertainties in K_{zz} dwarf any uncertainty in L , so, following Zahnle & Marley (2014), we make the simplest choice.

For these strongly irradiated planets, atmospheres can be radiative until depths of tens of bars, even beyond ~ 1 kbar, depending on the value of T_{int} . The lower the value of T_{int} , the deeper the radiative zone, as shown in Figure 1. While in convective zones mixing-length theory can be used as a guide to values of K_{zz} (Gierasch & Conrath 1985), in radiative regions no such readily usable theory exists, although it is generally expected that radiative regions will have orders of magnitude lower K_{zz} values.

Some 3D circulation model simulations of hot Jupiters have attempted to gauge reasonable K_{zz} values. Parmentier et al. (2013) suggested a fit to models of planet HD 209458b that yielded $K_{zz} = 5 \times 10^8 / \sqrt{P_{\text{bar}}} \text{ cm}^2 \text{ s}^{-1}$. They suggest that cooler planets, like the ones treated here, should have slower vertical wind speeds and smaller values of K_{zz} . More recent work has tried to estimate K_{zz} from first principles (Zhang & Showman 2018a, 2018b; Menou 2019).

The chemical kinetics literature for irradiated planets shows a range of K_{zz} choices. These include basing values tightly on 3D simulations but, more commonly, choosing a wide range of constant-with-altitude K_{zz} values, to bracket a reasonable parameter space. It is this bracketing choice that we make here, as we aim to make the point that nonequilibrium chemistry must be important for a wide range of objects. For calculations for particular planets of interest it may be worthwhile to generate K_{zz} predictions from GCM simulations. We return to this point in Section 5. Follow-up work that couples planetary temperature structures with detailed predictions of K_{zz} profiles (Zhang & Showman 2018a, 2018b; Menou 2019), to predict atmospheric abundances, would be important and fruitful work.

Before exploring a wide range of planets, we first investigate how our models can be used to understand the atmospheric abundances of three (relatively) well-studied Neptune-class transiting planets, which have been the targets of many observations with Spitzer and Hubble.

3. The Atmospheres of Three Neptune-class Planets: GJ 436b, GJ 3470b, WASP-107b

Our first foray into why T_{eq} is not enough will be for the Neptune-class exoplanets, GJ 436b, GJ 3470b, and WASP-107b. These three planets have been the targets of extensive observational campaigns, in particular for GJ 436b, as it was the first transiting Neptune-class planet found (Gillon et al. 2007). The work on emission and transmission observations and their interpretation for this planet is large and difficult to concisely summarize. A recent review can be found in Morley et al. (2017a). The most significant finding, going back to Stevenson et al. (2010), is the suggestion that the planet’s atmosphere is far out of chemical equilibrium, with little CH_4 absorption and a likely high abundance of CO and/or CO_2 . An upper limit on the CH_4 abundance is published in Moses et al. (2013).

More recently, Benneke et al. (2019) found that a joint retrieval of the emission and transmission data for GJ 3470b points to a somewhat similar conclusion, with a lack of CH_4 seen. And a transmission spectrum of WASP-107b by Kreidberg et al. (2018) finds no sign of CH_4 in the near-infrared. For both planets, these papers include CH_4 abundance upper limits.

While these three planets have masses and radii that differ by a factor of around 2, they share some interesting similarities. Perhaps most strikingly, they have T_{eq} values that are all within $\sim 100 \text{ K}$ of each other. This may suggest that the planets could have similar atmospheric properties. Another, perhaps surprising fact is that all three planets are on eccentric orbits. Here we assume $e = 0.16$ for GJ 436b, $e = 0.16$ for GJ 3470b, and $e = 0.11$ for WASP-107b. Most important to our current discussion is that we find that all three planets are currently undergoing significant eccentricity damping today.

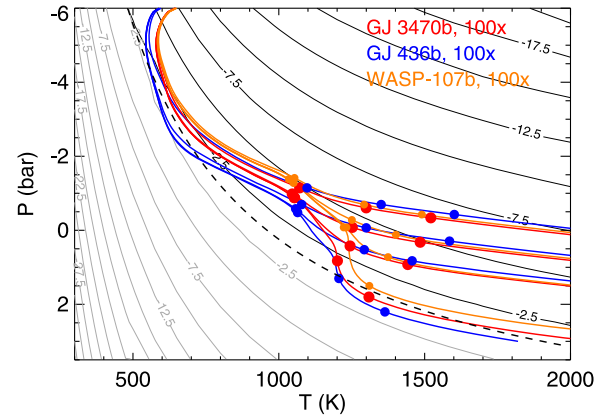


Figure 5. Atmospheric P - T profiles for planets GJ 436b, GJ 3470b, and WASP-107b, all at $100\times$ solar abundances. The light- and dark-gray equal-abundance curves are similar to those in Figure 1, although here we plot $100\times$ solar. For each planet, four interior adiabats are shown, for the case of no tidal heating (coolest), and $Q = 10^6, 10^5$, and 10^4 , from cooler to warmer. The sets of filled circles show the quench pressure for $\log K_{zz} = 4, 8$, and 12 , where larger K_{zz} values probe deeper.

Figure 5 shows model P - T profiles for all three planets, with GJ 436b in blue, GJ 3470b in red, and WASP-107b in orange. For simplicity, all are at $100\times$ solar, a value similar to the carbon abundance inferred for Uranus and Neptune. We note that retrieval work for GJ 436b (Morley et al. 2017a) suggests a metallicity higher than this value, retrievals for GJ 3470b suggest a metallicity lower than this (Benneke et al. 2019), and preliminary structure models (that did not take into account tidal heating) for WASP-107b also suggested a lower metallicity (Kreidberg et al. 2018). Our aim here is not to find best fits for the spectra of each planet but to suggest that tidal heating in the interior plays a large role in altering atmospheric abundances. We therefore feel that a simple, but plausible, metallicity can serve as an illustrative example.

A cursory glance shows that all three planets reside in a *remarkably similar* P - T space. For these planets four adiabats are shown. First, we will examine the coolest adiabats (lowest specific entropy), which are for models with no tidal heating ($T_{\text{int}} = 60 \text{ K}$), and then three warmer adiabats that assume $\log Q = 6, 5$, and 4 , from colder to hotter, as a lower Q means more tidal heating (Leconte et al. 2010). Tidal heating for these planets has a dramatic effect, warming the interior by hundreds to *thousands* of kelvin at a given pressure.

All three planets have three sets of filled circles on their profiles that show the quench pressure level for $\log K_{zz} = 4, 8$, and $12 \text{ cm}^2 \text{ s}^{-1}$.⁹ For the quench pressure for $\log K_{zz} = 4$, very sluggish mixing, tidal heating has a modest impact in shifting the expected chemical abundances to CO-richer and CH_4 -poorer territory, compared to, say, equilibrium chemistry at 1 mbar. However, for the depths probed at $\log K_{zz} = 8$ and 12 , the atmosphere models are significantly warmer and draw from a region of much higher CO and lower CH_4 if heating is present. We can explore and quantify this effect for a subset of models, which are shown in Figure 6, where each planet has its own panel. Abundances at 1 mbar are plotted for equilibrium chemistry and $\log K_{zz} = 4, 8$, and 12 . Thin lines are for no tidal heating, while thick lines include tidal heating, with $Q = 10^4$ —a reasonable

⁹ $\log K_{zz} \sim 10.5$ is the maximum allowed from mixing-length theory, for GJ 3470b and WASP-107b, for the hottest interior profiles shown, per Equation (4) from Zahnle & Marley (2014).

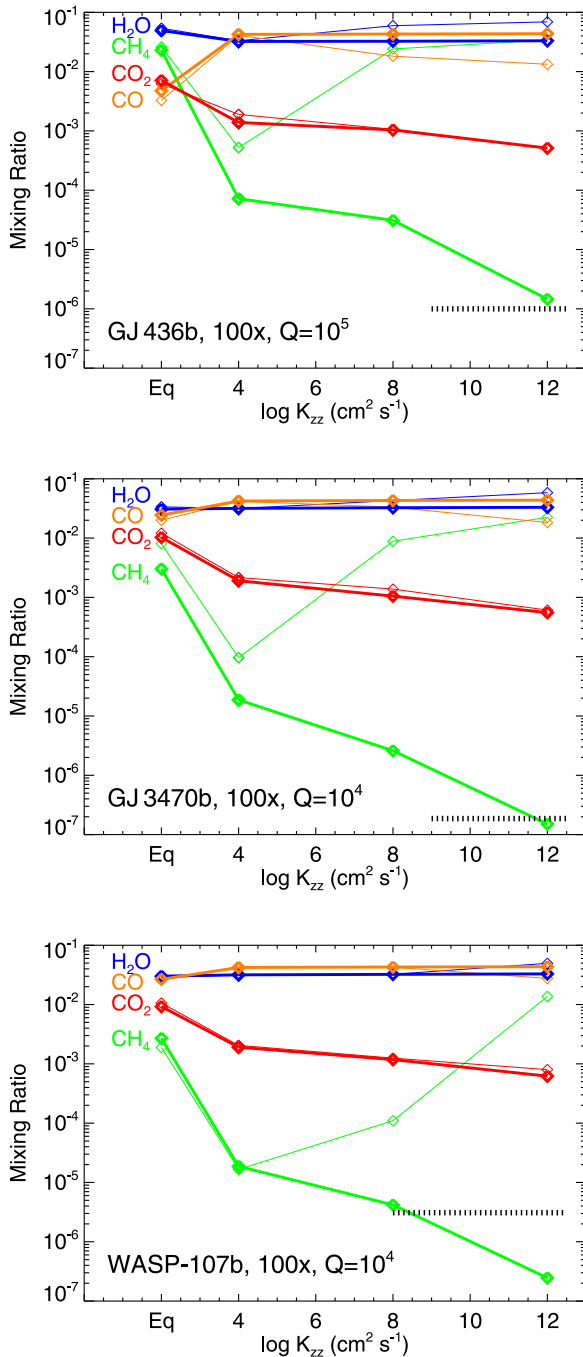


Figure 6. Top: chemical abundances at 1 mbar for three models of GJ 436b. H₂O is blue, CO is orange, CO₂ is red, and CH₄ is green. Plotted are abundances for equilibrium chemistry, and $\log K_{zz} = 4, 8$, and 12. Thin lines show no tidal heating, while thick lines use $Q = 10^5$. With tidal heating, the higher the K_{zz} , the higher the CO/CH₄ ratio. The dashed black line shows the CH₄ mixing ratio upper limit. Middle: similar to the top panel, but for GJ 3470b, again showing how nonequilibrium chemistry and tidal heating enhance the CO/CH₄ ratio, but with $Q = 10^4$. Bottom: similar to the top panel, but for WASP-107b, with $Q = 10^4$. Tidal heating and high K_{zz} can plausibly explain all observations.

estimate for Neptune (Zhang & Hamilton 2008)—for GJ 3470b and WASP-107b, and $Q = 10^5$ for GJ 436b, based on a fit to the planet’s thermal emission spectrum (Morley et al. 2017a). At our assumed 100× abundances with equilibrium chemistry, for all three planets CH₄ would be expected to be abundant, and even the dominant carbon carrier in GJ 436b and WASP-107b. The

retrieved 1 σ CH₄ upper limits, from free retrievals from all three atmospheres (Moses et al. 2013; Kreidberg et al. 2018; Benneke et al. 2019), are shown as dashed black lines.

There are two main effects to be seen in Figure 6. The first is in the large change in abundances for CH₄ (falling off dramatically) and CO (increasing), but more modestly, just in going from equilibrium chemistry to $\log K_{zz} = 4$. Another striking effect is the divergence in the behavior of the CH₄ abundance at $\log K_{zz} = 8$ and 12, between the no-tidal-heating model (thin lines) and the model with tidal heating. Based on the P – T profiles in Figure 5, we can see that no-heating models bring up CH₄-rich gas, while the tidal heating models bring up CH₄-poor gas. This is a dramatic effect in all three planets. Large K_{zz} values, driven by strong convection caused by ongoing tidal dissipation, can drive the CH₄ abundance to low values, in the range constrained by observations to date.

This strongly suggests that nonequilibrium chemistry and tidal heating conspire to drive the atmospheric abundances far from simple expectations. We should of course be a bit wary about treating the three planets as *carbon copies*, however. With no theory to guide the strength of tidal heating, Q for the planets could be quite different for all three. The expected mass fraction of H/He in WASP-107b is far larger than for GJ 3470b, for instance. Similarly, with little theory to guide vertical mixing strength, this could also be quite different among the planets, as they have quite different surface gravities. Additionally, they have been modeled with relatively simple chemical abundances (100× solar, with a solar C/O ratio), and the actual planets could readily have more complex, and different, base elemental abundances. Of note, the planet WASP-80b, about 100–150 K warmer than this trio but on a circular orbit (Triaud et al. 2015), has a Spitzer IRAC 3.6/4.5 μ m ratio in thermal emission that is similar to early T dwarfs. Triaud et al. (2015) suggest that this IRAC color could potentially be due to some CH₄ absorption in the planet’s atmosphere, which seems quite viable, as we describe in the next section.

As Morley et al. (2017a) suggested for GJ 436b, a direct sign of tidal heating would be a high thermal flux from the planet’s interior, which could be observed via a secondary eclipse spectrum or thermal emission phase curve. Future observations with JWST, including those where tidal heating are not at play, may allow for a coupled understanding of atmospheric abundances, temperature structure at a variety of depths, vertical mixing speed, and tidal heating. These three planets, all in a similar P – T space, motivate a wider investigation.

4. The Phase Space of Chemical Transitions

In the face of vertical mixing altering chemical abundances, mixing ratios in the visible atmosphere are tied to atmospheric temperatures at depth, as described in the previous section. This complicates the goal of deriving a straightforward understanding of chemical transitions. We aim to show that, even at a given metallicity and K_{zz} , this transition will depend on the cooling history (hence, mass and age) of any planet. We refer back to Figure 3, which showed models of the thermal evolution of giant planets. These model planets are all at 0.1 au from the Sun, but these cooling tracks would be correct, to within several kelvin, at closer or farther orbital distance (Fortney et al. 2007). Therefore, we can investigate, at a fixed value of T_{int} , how changing incident flux (and hence T_{eq}) does

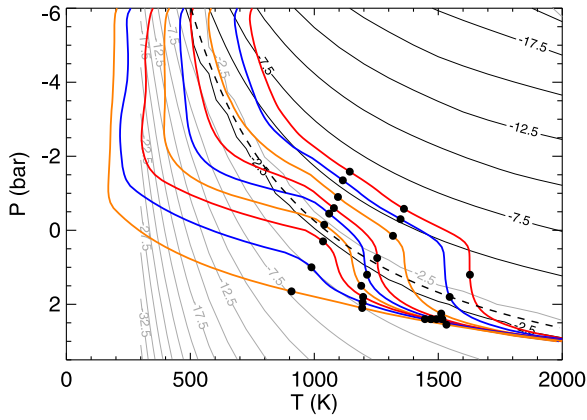


Figure 7. Atmospheric P - T profiles for old, Saturn-like planets ($T_{\text{int}} = 75$ K, $g = 10 \text{ m s}^{-2}$, assuming $10\times$ metallicity). The models are at nine incident flux levels, at 0.06, 0.07, 0.1, 0.15, 0.2, 0.3, 0.5, 1, and 2 au from the Sun. Three sets of black filled circles show the depth of vertical mixing with $\log K_{zz}$ of 4, 8, and $11 \text{ cm}^2 \text{ s}^{-1}$. At higher pressures, note that the spread between all profiles is lessened, both in temperature and in reference to the CH_4 (black) and CO (gray) abundance curves.

or does not lead to changes in chemical abundances in the visible atmosphere. We first explore carbon chemistry.

4.1. CO-CH₄ Transitions

In Section 3 we examined the CO-CH₄ boundary for specific tidally heated Neptune-class planets. Objects with tidal heating are special cases, but they certainly will be common enough that they cannot simply be ignored, when looking at general trends. But here we can examine the general trends in the absence of tidal heating, for a range of planet masses and ages. As we will see, the range of cooling histories, as well as the lack of clarity with how vertical mixing will change with planet mass, can lead to important complexities.

4.1.1. Effects of T_{eq} and Vertical Mixing

We first examine the general case of a Saturn-like exoplanet as a function of distance from a Sun-like star. Here we have chosen a $10\times$ solar atmosphere, surface gravity of 10 m s^{-2} , and $T_{\text{int}} = 75$ K, representative of a several-gigayear-old Saturn-mass exoplanet. We choose this as our “base planet” since these kinds of giant planets would be excellent targets for atmospheric characterization via transmission. Atmospheric P - T profiles are shown in Figure 7, for planets from 0.06 to 2 au. The three sets of black filled circles show quench pressures corresponding to $\log K_{zz}$ values of 4, 8, and 11. Most importantly, at lower pressures, the atmospheres diverge quite widely, owing to the factor of ~ 1100 difference in incident flux across these models.

As one looks deeper, it is apparent that profiles modestly converge as the pressure increases, followed by a dramatic “squeezing together” as the planets fall on nearly identical adiabats. This is a generic behavior for g/T_{int} pairs, and one could make a plot like this for any Jupiter-like planet, super-Jupiter, or sub-Saturn. Why this behavior occurs requires some discussion. To our knowledge this effect was first noted in Figure 3 of Fortney et al. (2007), who described the effects of these “bunched-up” deep profiles on the mass-radius relation for warm transiting giant planets, but they did not identify a cause for the similarity of the deep temperatures.

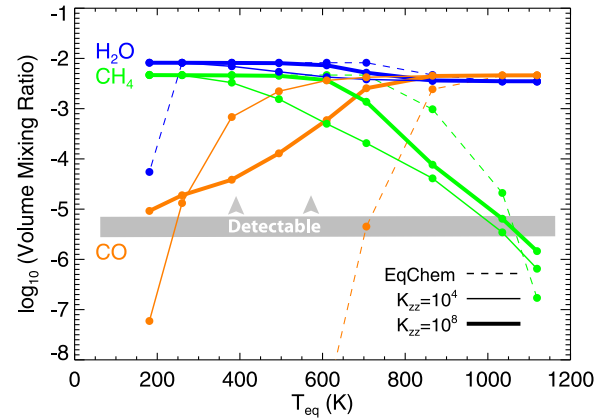


Figure 8. The nine P - T profiles from Figure 7 are plotted at nine T_{eq} values across the x-axis, with chemical abundances along the y-axis. “EqChem” gives the chemical equilibrium abundances at 1 mbar (dashed), while $\log K_{zz} = 4$ and 8 are shown as thin solid and thick solid, respectively. In equilibrium, at $T_{\text{eq}} < 800$ K, the CO mixing ratio falls off precipitously, while for $\log K_{zz} = 4$ this falloff is delayed until ~ 500 K cooler. At $\log K_{zz} = 8$ the weakening of CO is also delayed and the change in CO abundance with T_{eq} is much “shallower.” The corresponding increases in CH_4 abundance with lower T_{eq} are again “shallower” for nonequilibrium chemistry. The loss of H_2O in the coolest (equilibrium) model is due to loss of water vapor into water clouds.

A study of the gray analytic temperature profiles of Guillot (2010) suggests, via their Equation (29), a relation between the temperature (T) and optical depth τ that is a function of only three quantities: the irradiation temperature (which is directly related to T_{eq}), T_{int} , and γ , the ratio of the visible to thermal opacities. If γ is relatively constant, and at a given T_{int} value, decreasing T_{eq} cools the entire atmosphere at every τ , including the deep region that here transitions to an adiabat. However, if γ were to dramatically decrease with decreasing T_{eq} , the deep $T - \tau$ profile (analogous to our deep T - P profile) could remain nearly constant at depth with an upper atmosphere that was colder with decreasing T_{eq} . Indeed, Figure 5 of Freedman et al. (2014) shows a factor of ~ 60 falloff in γ from ~ 1400 to 700 K, due to the loss of alkali metals Na and K from the vapor phase, with γ relatively constant at hotter and colder temperatures. This 700–1400 K temperature range corresponds reasonably well to what is seen in our Figure 7 and the “middle region” of Figure 3 of Fortney et al. (2007). Therefore, we suggest that this change in visible opacity is the dominant physical effect that keeps the deep atmosphere temperatures relatively constant across this T_{eq} range. However, additional work on this point is surely needed.

Of particular interest is that the coldest profiles are mostly in the CH_4 -dominant region at lower pressures, but along the atmospheric adiabat, as one reaches hotter layers, one finds gradually more CO. This is the “typical” case for brown dwarfs (Saumon et al. 2003; Phillips et al. 2020) and for Jupiter as well (Prinn & Barshay 1977; Lodders & Fegley 2002). However, for the hottest models, this typical trend is reversed, and when one probes quite deeply, one reaches more CH_4 -rich gas, in particular at $P > 1$ bar, where the isothermal regions are reached.

We can examine how atmospheric abundances are affected by making plots of volume mixing ratio as a function of planetary T_{eq} . Such a plot is shown in Figure 8 and includes all the profiles shown in Figure 7. The mixing ratios at 1 mbar for H_2O , CO, and CH_4 are plotted, for equilibrium chemistry and for $\log K_{zz}$ of 4 and 8. In the equilibrium chemistry case

(dashed curves), the changeover from CO dominant to CH₄ dominant is at about $T_{\text{eq}} = 850$ K. As one goes cooler, this also leads to an increase in the H₂O abundance, as oxygen is liberated from CO (and CO₂).

If we include quite sluggish vertical mixing, with $\log K_{zz} = 4$ (thin solid line), this boundary shifts dramatically left, to a much lower T_{eq} value of only 475 K. The slopes of the CH₄ and CO curves, versus T_{eq} , are both quite shallow compared to the equilibrium chemistry case, and one might readily expect both molecules to be seen from ~ 800 to 200 K. Of course, how “detectable” a molecule is depends strongly on the wavelength being investigated, the spectral resolution, and the impact on other opacity sources, like clouds. Given the nondetections of CH₄ with HST at mixing ratios of $\sim 10^{-6}$ in the Neptune-class planets (See Section 3), here we suggest $\sim 10^{-5.5}$. However, the 3.3 and 7.8 μm bands of CH₄ and the 4.5 μm band of CO are strong and could likely yield detections at lower mixing ratios, in particular at high spectral resolution.

Interestingly, a look back to Figure 7 might suggest that the $\log K_{zz} = 8$ case might be a bit less extreme in altering abundances, even though we are mixing up from even hotter layers. The modest pinching together of the P - T profiles yields a behavior in Figure 8 (solid line) that is intermediate between the two previous behaviors, with a crossover T_{eq} of 680 K. Both CO and CH₄ may be seen from $T_{\text{eq}} \sim 900$ to 400 K. The upshot here is that the value of K_{zz} in these atmospheres and its depth dependence, which is currently unknown, will have a significant effect on the atmospheric abundances as a function of T_{eq} , and a wide range of behavior is expected. As discussed later, given that K_{zz} is unlikely to be constant with altitude, more realistic mixing further complicates this picture.

4.1.2. Effects of Planet Mass at a Given Age

In the previous section we examined one particular planet, a Saturn-like object at different distances from the Sun. However, we have already discussed in some detail in the Introduction that planets of different masses are expected to have quite different cooling histories (Figure 3).

We can begin to address the question of planet mass with three disparate planet examples, with planets of 10 M_J (a super-Jupiter), 1 M_J , and 0.1 M_J (32 $M_{\oplus}$, a super-Neptune). For now we limit ourselves to the same 10 $\times$ atmospheric metallicity, so as not to change too many parameters at once. Similar to Figure 7 above, we have computed a range of atmospheric P - T profiles for these three planets, at different distances from the Sun, assuming an age of 3 Gyr and the T_{int} values from Figure 3. These profiles are shown in Figure 9. For clarity, profiles are only shown at three distances, 0.1, 0.5, and 2 au. Along each profile, colored filled circles, from lower to higher pressure, show $\log K_{zz}$ of 4, 8, and 11, respectively. The more massive the planet, the higher the surface gravity, and the higher the pressure at a given temperature, in the outer atmosphere. This, however, is reversed in the deep atmosphere and interior, as the higher-mass planets take longer to cool, so they have a higher T_{int} (333, 117, and 52 K, respectively, for the 10, 1, and 0.1 M_J models) and “hotter” (higher specific entropy) interior adiabat. The much larger scale heights for the low-gravity models mean greater physical distances for mixing, thus longer mixing times for a fixed K_{zz} , and hence lower quench pressures.

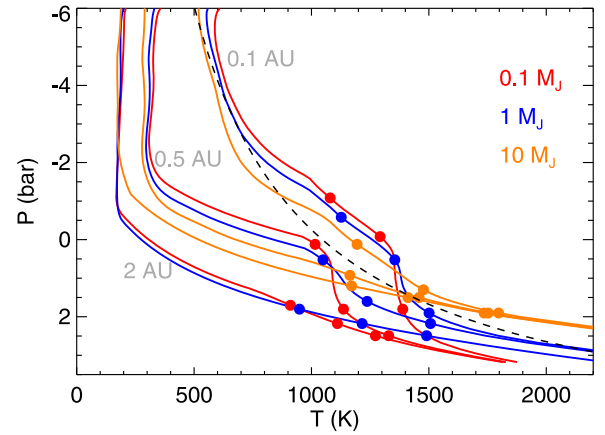


Figure 9. Atmospheric P - T profiles for 3 Gyr old planets at 0.1 (red), 1 (blue), and 10 (orange) M_J , at 10 $\times$ solar. The CO/CH₄ equal-abundance curve is in dashed black. The models are at 0.1, 0.5, and 2 au from the Sun. The color-coded filled circles show the quench pressure for $\log K_{zz} = 4, 8$, and 11. Higher-gravity models have higher-pressure photospheres, but they also have hotter interiors, which causes significant crossing of profiles. The much larger scale heights for the low-gravity models means greater physical distances for mixing, and hence lower quench pressures.

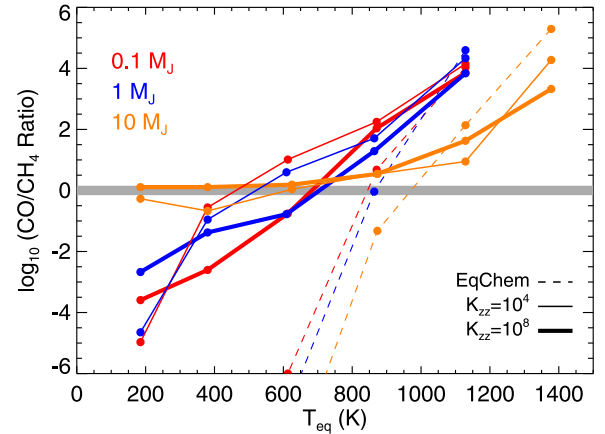


Figure 10. The log of the CO/CH₄ ratio for five values of T_{eq} for 0.1, 1, and 10 M_J model planets, where a subset of the profiles are shown in Figure 9. In equilibrium (at 1 mbar), the transition T_{eq} for CO/CH₄ = 1 (log = 0, shaded gray) is at $\sim 800, 950$, and 1150 K, from low mass to high mass. As expected, vertical mixing lessens the slopes of these curves and pushes the transition T_{eq} lower for the 0.1 and 1 M_J models. The 10 M_J model quenches from CH₄-richer gas, at high T_{eq} , which yields the opposite behavior. For all three model planets, CO and CH₄ exist together in detectable amounts for a wide swath of T_{eq} values.

What we are particularly interested in here is how the roles of surface gravity and cooling history work to dramatically change the ratio of CO/CH₄ in these atmospheres. We address this scenario in Figure 10. This abundance ratio is plotted versus planetary T_{eq} , and we will first examine the abundances for equilibrium chemistry at 1 mbar. The “transition” T_{eq} value is 950 K at 10 M_J and 850 K at 1 and 0.1 M_J . With sluggish vertical mixing ($\log K_{zz} = 4$), the story becomes more complex, however. The 10 M_J planet has a relatively hot interior adiabat, which is essentially the same for all values of T_{eq} , as seen in orange in Figure 9. For such a large value of T_{int} , the smaller values of T_{eq} become essentially irrelevant. For the lower-mass planets, the transition T_{eq} is much lower than in the equilibrium case, reaching 500 K. For more vigorous mixing ($\log K_{zz} = 8$), more CH₄-rich gas is brought up, leading to a hotter transition temperature, at 700 K.

Table 1
Guide to Model Parameters

Figure	T_{eq} (K)	T_{int} (K)	M_J	g (m s^{-2})	m	Age (Gyr)
1	710	60, 100, 200, 300, 400	1	25	$10\times$	
4, 23	710	52, 77, 117, 182, 333	0.1, 0.3, 1, 3, 10	5.8, 9.8, 24, 65, 225	$10\times$	3
7, 13	1120 to 180	75	0.3	10	$10\times$	3
9, 15	870, 380, 180	52, 117, 333	0.1, 1, 10	5.8, 24, 225	$10\times$	3
11, 17	710	501, 383, 283, 212, 156, 117, 84	1	13, 16, 19, 21, 23, 24, 26	$3\times$	0.01, 0.03, 0.1, 0.3, 1.0, 3.0, 10.0
19	870, 380	52, 117, 333	0.1, 1, 10	5.8, 24, 225	1, 3, $50\times$	3

Note. In each figure, a range of planetary models is considered explored across different planetary parameters. The metallicity factor m is defined as $m = 10^{[\text{Fe}/\text{H}]}$.

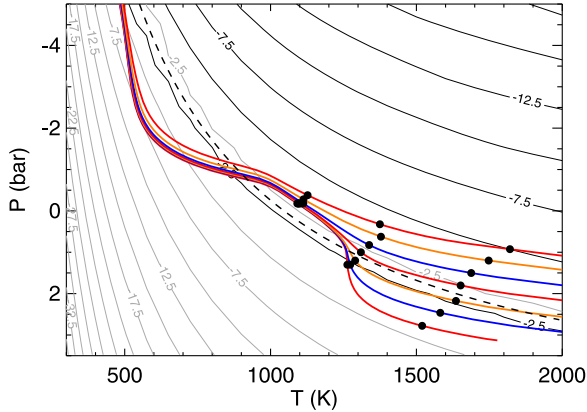


Figure 11. Atmospheric P - T profiles for a $1 M_J$ planet at 0.15 au from the Sun, assuming $3\times$ solar metallicity. Seven ages, every half dex from 10 Myr to 10 Gyr, with seven values of T_{int} (501, 383, 283, 212, 156, 117, and 84 K) are shown. The planetary surface gravity also changes among the models. The three collections of black filled circles show quench pressures for $\log K_{zz} = 4$, 8, and 11. At depth, hotter profiles are clearly CO-rich, while cooler profiles are CH_4 -rich.

4.1.3. Effects of Planet Age at a Given Mass

Up until this point, we have examined “old” planetary systems that to date make up the vast majority of the transiting population. However, studying younger transiting planets to better understand evolutionary histories is extremely important. First, this would yield connections to the directly imaged self-luminous planets, which are predominantly young (Bowler 2016). Second, understanding atmospheric abundances as a function of planet age would give us new insight into planetary thermal evolution. Third, since parent stars are much more active when they are young, high X-ray and ultraviolet fluxes for young systems could drive quite interesting photochemistry.

In the absence of tidal heating giant planet interiors inexorably cool as they age, meaning cooler interior adiabats and lower T_{int} values. In the face of vertical mixing, we should expect atmospheric abundances to change then as well. We also note here that Table 1 may prove a useful guide to the range of atmosphere models and figures in the paper. We examine the effect on a range of P - T profiles for a Jupiter-like example ($1 M_J$, $3\times$ solar) at 0.15 au in Figure 11. The values of T_{int} are taken from every half dex in planetary thermal evolution from an age of 10 Myr to 10 Gyr, yielding seven models from T_{int} of 501 to 84 K. For moderately irradiated planets like these, the cooling of the interior has little effect on the upper atmosphere (Sudarsky et al. 2003), but we should expect quite different atmospheric abundances when including vertical mixing. The

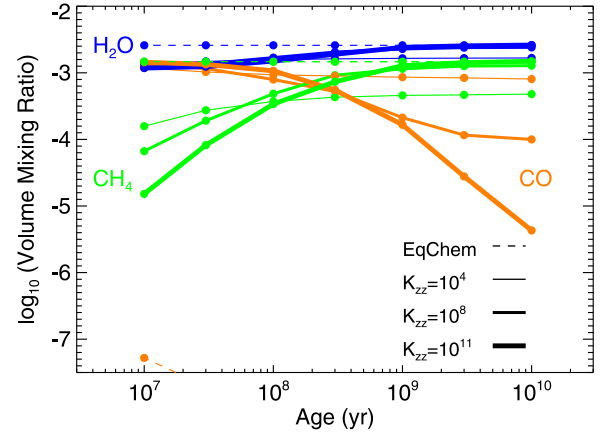


Figure 12. Atmospheric abundances at 1 mbar as a function of planetary age, for the P - T profiles shown in Figure 11. In equilibrium (dashed), the cooling of the planet’s interior has *no effect* on the atmospheric abundances, as the temperatures of the upper atmosphere are essentially constant, and the atmosphere could be CH_4 -rich and quite CO-poor. Modest vertical mixing ($\log K_{zz} = 4$) yields a much higher CO/ CH_4 ratio, but abundances that again are essentially constant with time. More vigorous mixing, from higher quench pressures, samples a much wider range of CO and CH_4 abundances. As the interior cools off, the atmosphere transitions from CO-rich to CH_4 -rich.

three sets of black filled circles in Figure 11 show $\log K_{zz}$ of 4, 8, and 11.

In Figure 12 we examine the corresponding chemical abundances for equilibrium and the three values of vertical mixing strength, as a function of planetary age. In equilibrium at 1 mbar, the atmosphere is CH_4 dominated, and the CO mixing ratio is nearly off the bottom of the plot. However, even very modest vertical mixing ($\log K_{zz} = 4$, thin lines) changes the picture. The atmosphere becomes modestly CO dominated, and we lose essentially all sensitivity to the deeper atmosphere of the planet—the abundances depend very little on T_{int} . However, with more vigorous vertical mixing, we see a picture emerge that has much in common with our understanding of nonequilibrium chemistry in brown dwarfs. Higher T_{int} values and hotter interiors lead to more CO and less CH_4 . The plot shows a changeover from CO dominated to CH_4 dominated at ~ 200 Myr, at a T_{int} value of ~ 250 K. Again, this is generic behavior, as more massive objects would transition later in life (but at higher T_{int} values given their higher-pressure photospheres and the positions of the CO and CH_4 iso-composition curves), and less massive objects earlier (but at higher T_{int} values, given their lower-pressure photospheres). While we expect that building up a large sample of atmospheric spectra size as a function of planetary age will be a challenge, it will be rewarding to have a statistical sample to compare to the typical

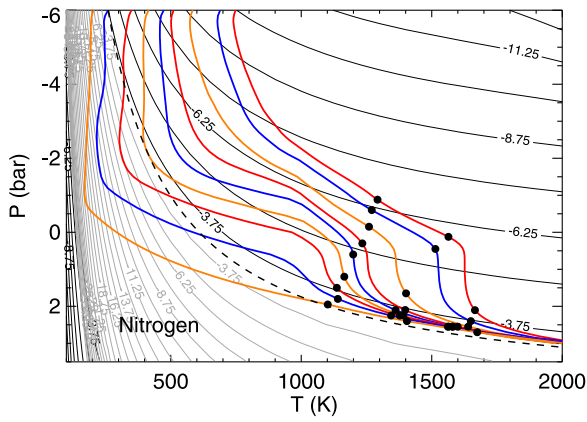


Figure 13. Atmospheric P - T profiles for old, Saturn-like planets ($T_{\text{int}} = 75$ K, $g = 10 \text{ m s}^{-2}$, assuming $10\times$ metallicity). The models are at nine incident flux levels, at 0.06, 0.07, 0.1, 0.15, 0.2, 0.3, 0.5, 1, and 2 au from the Sun. Three sets of black filled circles show the nitrogen quench pressure for $\log K_{zz}$ of 4, 8, and $11 \text{ cm}^2 \text{ s}^{-1}$. At higher pressures, note that the spread between all profiles is lessened, both in temperature and in reference to the NH_3 (black) and N_2 (gray) abundance curves.

several-gigayear-old systems. This could yield important insights into planetary cooling history and the vigor of vertical mixing with age.

4.2. N_2 - NH_3 Transitions

Nitrogen chemistry is predominantly a balance between N_2 and NH_3 and has been explored and validated in the brown dwarf context (e.g., Saumon et al. 2000, 2003; Cushing et al. 2006; Hubeny & Burrows 2007; Zahnle & Marley 2014). N_2 is favored at high temperatures (and low pressures), while NH_3 is favored at low temperatures (and high pressures). The transition from N_2 to NH_3 at cooler temperatures has a similar character to that of CO converting to CH_4 , but it occurs at lower temperatures. Understanding nonequilibrium nitrogen chemistry in brown dwarfs has typically been hampered by two constraints. The first is that N_2 , with no permanent dipole, has no infrared absorption features, unlike CO . The second is that NH_3 iso-composition curves have slopes that lie nearly along interior H/He adiabats, meaning that one typically cannot assess a given atmosphere’s quench pressure, as all pressures along the adiabat correspond to nearly the same NH_3 mixing ratio.

However, in some sense irradiated planets have the advantage of having relatively more isothermal P - T profiles, which can remain nonadiabatic to pressure of ~ 1 kbar. And, if these predominantly radiative atmospheres have K_{zz} values less than their mostly convective brown dwarf cousins, then it may be these more isothermal radiative parts of the atmosphere where one may quench the chemistry. We can examine this with the same Saturn-like P - T profiles we first examined in Figure 7. These profiles, but now with quench pressures for N_2 - NH_3 chemistry (Zahnle & Marley 2014), are shown in Figure 13.

Underplotted in black are curves of constant NH_3 abundance, falling off at higher temperature and lower pressure. Underplotted in gray are curves of constant N_2 abundance, falling off at lower temperature and higher pressure. A detailed look at Figure 13, compared to Figure 7, shows that the NH_3 iso-composition curves are more “spread out” than similar curves for CH_4 , suggesting a more gradual change in nitrogen

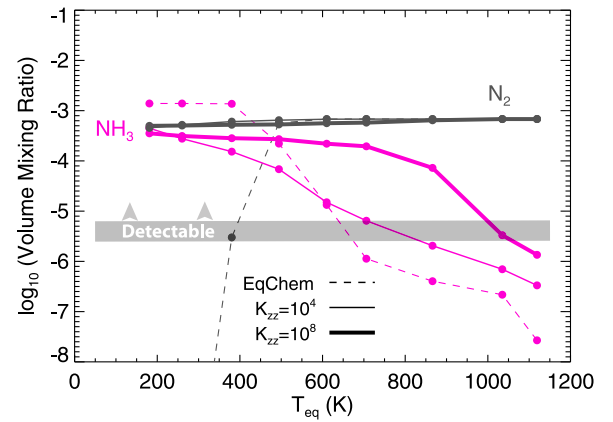


Figure 14. The nine P - T profiles from Figure 13 are plotted at nine T_{eq} values across the x -axis, with chemical abundances along the y -axis. “EqChem” gives the nitrogen chemical equilibrium abundances at 1 mbar (dashed), while $\log K_{zz} = 4$ and 8 are shown as thin solid and thick solid curves, respectively. In equilibrium, at $T_{\text{eq}} \sim 480$ K, the N_2 and NH_3 mixing ratios cross over, while for all models with vertical mixing, this crossover does not happen. The more vigorous the vertical mixing, generally, the higher the NH_3 mixing ratio, except for the coldest models.

chemistry, with temperature, than for carbon. As the chemical conversion times for $\text{N}_2 \rightarrow \text{NH}_3$ are longer than for $\text{CO} \rightarrow \text{CH}_4$, the corresponding quench pressures for $\log K_{zz} = 4, 8$, and $11 \text{ cm}^2 \text{ s}^{-1}$ are at somewhat higher pressures. While for vigorous mixing ($\log K_{zz} = 11$) all profiles converge to the same quench pressure (and hence changes in T_{eq} across this range would yield no change in the NH_3 abundance), there are broad ranges of N_2 and NH_3 mixing ratios for the $\log K_{zz} = 4$ and $K_{zz} = 8$ cases.

Figure 14 shows the mixing ratios of N_2 and NH_3 as a function of planetary T_{eq} . Equilibrium chemistry (at 1 mbar) shows a crossover from N_2 dominant to NH_3 dominant at around 475 K. However, even sluggish vertical mixing keeps all of these atmospheres N_2 dominant, while also increasing the NH_3 mixing ratio for all T_{eq} values > 600 K. More vigorous mixing ($\log K_{zz} = 8$) further flattens the slope of the NH_3 curve, leading to relatively abundant NH_3 at essentially all T_{eq} values, as expected from the grouping of most of the $\log K_{zz} = 8$ black filled circles in Figure 13. Across the entire phase space, the NH_3 mixing ratios are similar to those of CH_4 (see Figure 8) and are actually even *higher* for NH_3 than for CH_4 for the higher T_{eq} values. This suggests that onset of detectable CH_4 in these planets should be accompanied by NH_3 as well—one will not need to wait for particularly cold temperatures, compared to the brown dwarfs. For those interested in determining the relative abundances of C, N, and O, to compare to Jupiter’s values (Wong et al. 2004), we note that in these models NH_3 never becomes the dominant nitrogen carrier compared to N_2 , such that the nitrogen abundance determined from NH_3 would only be a lower limit.

4.2.1. Effects of Planet Mass at a Given Age

Previously, in Section 4.1.2 and Figures 9 and 10, we investigated the role that surface gravity and cooling history have for the planets. Here we examine the same profiles, but for nitrogen chemistry. Figure 15 shows these sample P - T profiles for the 0.1, 1.0, and $10 M_J$ planets, with $\log K_{zz} = 4, 8$, and 11. Compared to the carbon example from Figure 9, the quench pressures are higher. For the high-gravity ($10 M_J$) planet in

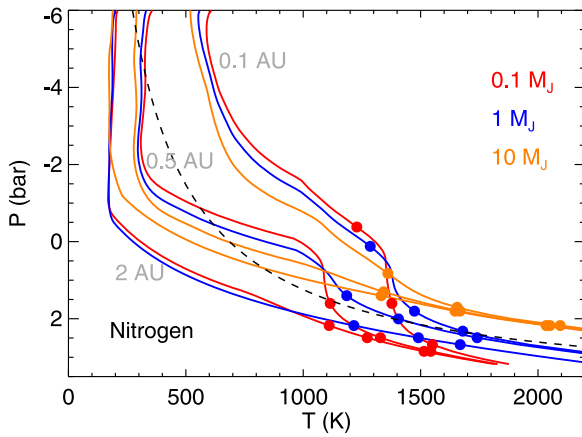


Figure 15. Atmospheric P - T profiles for 3 Gyr old planets at 0.1 (red), 1 (blue), and 10 (orange) M_J , at $10\times$ solar. The N_2/NH_3 equal-abundance curve is shown in black. The models are at 0.1, 0.5, and 2 au from the Sun. The color-coded filled circles show the nitrogen quench pressure for $\log K_{zz} = 4, 8$, and 11. Higher-gravity models have higher-pressure photospheres, but they also have hotter interiors, which causes significant crossing of profiles. The much larger scale heights for the low-gravity models means greater physical distances for mixing, and hence lower quench pressures. Compared to Figure 9, the nitrogen chemistry quench pressures are at higher pressures than for carbon chemistry. For high-gravity and/or cool models, the quench pressure is near or within the deep atmosphere adiabat.

particular, the quench pressure is within the deep atmosphere adiabat for $\log K_{zz} = 8$ and 11, and near it for $\log K_{zz} = 4$. We might expect that the NH_3 abundance will change little with K_{zz} , similar to a brown dwarf case (Zahnle & Marley 2014). The deeper one probes, the closer one comes to these adiabats, which lie nearly parallel to curves of constant NH_3 abundance. Instead, the NH_3 mixing ratio is in some sense a probe of the current specific entropy of the adiabat, which could prove useful in constraining thermal evolution models.

We can examine the N_2/NH_3 ratio as a function of T_{eq} for these three planets in Figure 16. The crossover T_{eq} for nitrogen chemistry, in equilibrium, would be ~ 550 K at $10 M_J$, 500 K at $1 M_J$, and 475 K at $0.1 M_J$. However, even modest vertical mixing dramatically changes this picture. As the T_{eq} decreases, the quench pressure falls near or into the deep atmosphere adiabat, even at low gravity. On Figure 15 this manifests as the N_2/NH_3 ratio asymptoting to values that depend solely on the specific entropy of the adiabat, as one might have expected for the specific cases investigated for the Saturn-like planet in Figure 14. Much like the brown dwarfs, at cool temperatures (and especially at high surface gravity) planets here are insensitive to K_{zz} .

4.2.2. Effects of Planet Age at a Given Mass

Previously in Section 4.1.3 and Figures 11 and 12 we found that planet age, and hence the cooling history and specific entropy of the interior adiabat, can have dramatic effects on the carbon chemistry. Young planets would have quite different abundances (richer in CO) than older planets at the same T_{eq} , all things being equal. We can investigate the role of cooling history on the nitrogen chemistry with these same profiles. In Figure 17 we plot the $1 M_J$ profiles from 10 Myr to 10 Gyr, this time with the nitrogen quench pressures labeled. The figure is quite similar to Figure 11, but with higher quench pressures, at hotter temperatures. At $\log K_{zz} = 4$, the levels are in the radiative part of the atmosphere but are relatively pinched together. At $\log K_{zz} = 8$ and 11, we find all quench pressure in or very near the deep atmosphere adiabats.

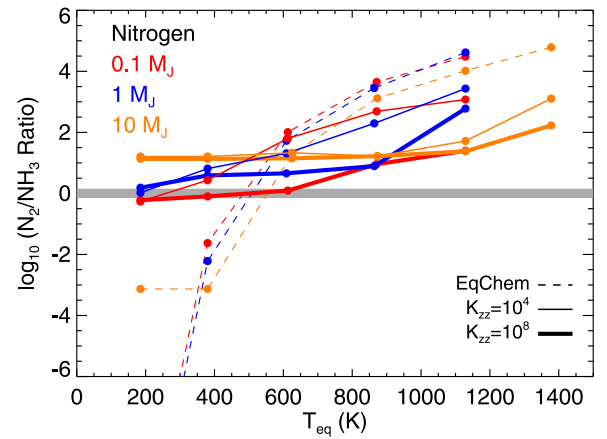


Figure 16. The log of the N_2/NH_3 ratio for five values of T_{eq} for 0.1, 1, and 10 M_J model planets, where a subset of the profiles are shown in Figure 15. In equilibrium (at 1 mbar), the transition T_{eq} for $CO/CH_4 = 1$ ($\log = 0$, shaded gray) is at $\sim 420, 530$, and 600 K, from low mass to high mass. This is ~ 400 – 500 K colder than the carbon chemistry transitions shown in Figure 10. However, vertical mixing essentially flattens the slopes of these curves, as one quenches from high-pressure regions that lie on nearly the same adiabat, as shown in Figure 15. For all three model planets, NH_3 exists in detectable amounts for a wide swath of T_{eq} values.

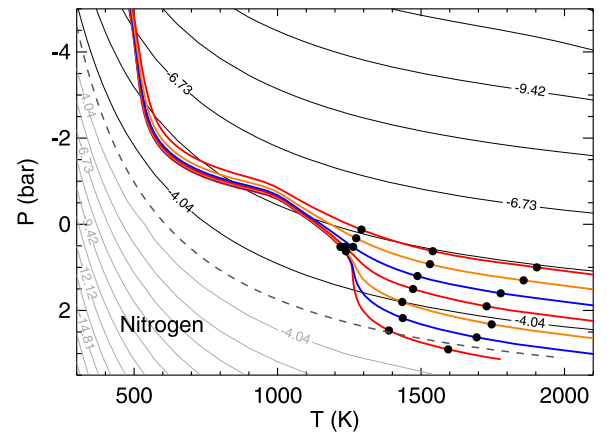


Figure 17. Atmospheric P - T profiles for a $1 M_J$ planet at 0.15 au from the Sun, assuming $3\times$ solar metallicity. Seven ages, every half dex from 10 Myr to 10 Gyr, with seven values of T_{int} (501, 383, 283, 212, 156, 117, and 84 K, from Figure 3) are shown. The three collections of black filled circles show nitrogen quench pressures for $\log K_{zz} = 4, 8$, and 11. At depth, all profiles are within the N_2 -rich region of P - T space, and the adiabats lie parallel to curves of constant NH_3 abundance.

The effects on the atmospheric mixing ratios of N_2 and NH_3 , shown in Figure 18, are quite straightforward but different from that found for the carbon chemistry in Figure 12. In equilibrium at 1 mbar, as the atmosphere changes negligibly in temperature, the NH_3 mixing ratio (dashed line) changes little with age. The same is true at $\log K_{zz} = 4$, albeit at a higher NH_3 abundance. Since both the $\log K_{zz} = 8$ and 11 quench pressures sample the deep adiabat, which are nearly parallel NH_3 abundance curves, we find essentially the same behavior of mixing ratio as a function of age, independent of (high) K_{zz} . This is essentially the same as the well-understood brown dwarf behavior.

4.3. Effect of a Mass–Metallicity Relation on Carbon and Nitrogen

So far we have aimed, as much as possible, to investigate the physical and chemical effects of only altering one or two

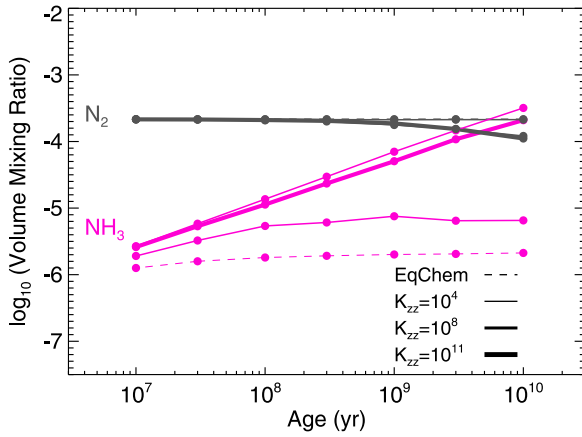


Figure 18. Atmospheric N_2 and NH_3 abundances at 1 mbar as a function of planetary age, for the P - T profiles shown in Figure 17. In equilibrium (dashed), the cooling of the planet’s interior has almost no effect on the atmospheric abundances, as the temperatures of the upper atmosphere are essentially constant, and the atmosphere would be N_2 -rich. Modest vertical mixing ($\log K_{zz} = 4$) yields a slightly higher NH_3 abundance, but still essentially constant with time. More vigorous mixing, from higher quench pressures ($\log K_{zz}$ or 8 and 11), samples progressively more NH_3 -rich gas. However, there is little sensitivity in these models.

quantities at a time, including distance from the Sun, surface gravity, and T_{int} . Atmospheric metallicity will also play an important role in altering these boundaries. This chemistry has certainly be explored before, or a very wide range of compositions (e.g., Moses et al. 2013). In this section we attempt to explore a composition phase space, but in a narrower sense.

It is strongly suggested from the bulk densities of transiting giant planets that there is a bulk “mass–metallicity relation” for the planets (Thorngren et al. 2016), with the lower-mass giant planets being more metal-rich. The effect of such a relation at atmospheric abundances is not yet clear (Kreidberg et al. 2014; Wakeford et al. 2017; Welbanks et al. 2019), but there is such a relation in the solar system for carbon (e.g., Atreya et al. 2016) and from standard models of core accretion planet formation theory, albeit with a large spread (Fortney et al. 2013).

For both the carbon and nitrogen chemistry discussed in Sections 4.1.2 and 4.2.1, for the three planet masses at $10\times$ solar, we can examine how an increasing metallicity with lower planet masses may alter the previously examined trends. Figure 19 shows P - T profiles for planets at 0.5 and 2 au from the Sun, with the top panel showing carbon quench pressures and the bottom panel showing nitrogen quench pressures. The profiles themselves differ somewhat from those shown in Figures 9 and 15, as the models here use $50\times$ solar ($0.1 M_J$), $3\times$ solar ($1 M_J$), and $1\times$ ($10 M_J$). Since the plots use three different metallicities, we also show three different CO/CH_4 equal-abundance curves (dashed).

Compared to our previous investigations into chemistry at $10\times$ solar metallicity (Figures 10 and 16), the two panels in Figure 20 show a much wider range of behavior. At higher metallicity, the cooler models “hang on” to CO and N_2 to much cooler T_{eq} values. In equilibrium the carbon transitions would occur between 1100 and 700 K in these models. Even sluggish vertical mixing shows a large impact. For instance, with more vigorous mixing ($\log K_{zz} = 8$), these three transition T_{eq} values are ~ 1100 , 800, and 450 K.

We can examine the N_2/NH_3 ratio as a function of T_{eq} for these three planets in Figure 19. The crossover T_{eq} for nitrogen

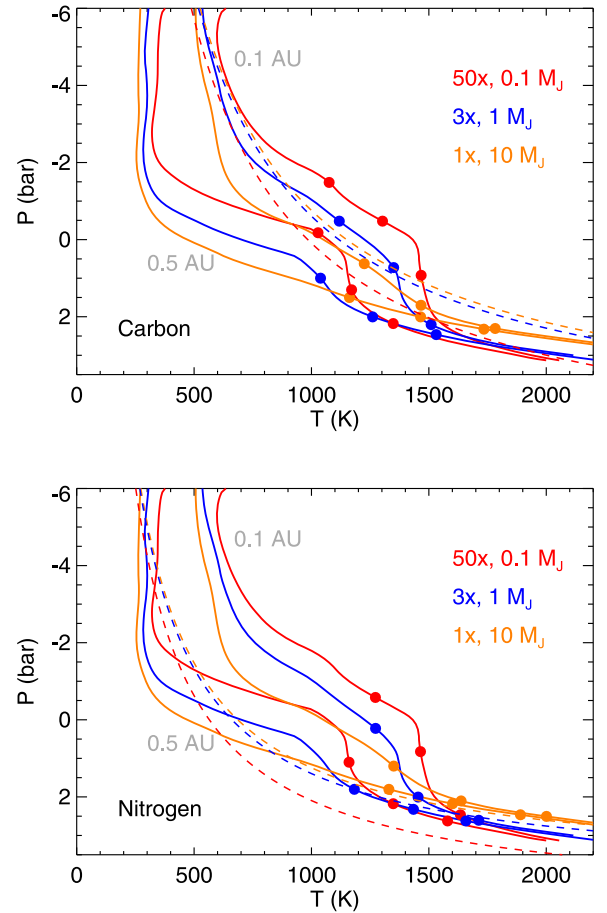


Figure 19. Atmospheric P - T profiles for 3 Gyr old planets at 0.1 (red, $50\times$), 1 (blue, $3\times$), and 10 (orange, $1\times$) M_J . The CO/CH_4 (top) and N_2/NH_3 (bottom) equal-abundance curves at these three metallicity values are shown in dashed curves with the same three colors. The models are at 0.1 and 0.5 au from the Sun. The color-coded filled circles show the quench pressures for $\log K_{zz} = 4, 8$, and 11 for carbon (top panel) and nitrogen (bottom panel). The nitrogen chemistry quench pressures are at higher pressures than for carbon chemistry. For high-gravity and/or cool models, the quench pressure is near or within the deep atmosphere adiabat, in particular for nitrogen.

chemistry, in equilibrium, would be ~ 600 K at $10 M_J$, 530 K at $1 M_J$, and 420 K at $0.1 M_J$. However, even modest vertical mixing dramatically changes this picture. As the T_{eq} decreases, the quench pressure falls near or into the deep atmosphere adiabat, even at low gravity. On Figure 15 this manifests as the N_2/NH_3 ratio asymptoting to values that depend solely on the metallicity and the specific entropy of the adiabat, as one might have expected for the specific cases investigated for the Saturn-like planet in Figure 14.

4.4. Putting It Together: The Onset of CH_4 and NH_3

We can summarize, at least for the “old” 3 Gyr planets that have been the baseline for many of calculations, the expected rise of detectable CH_4 and NH_3 abundances. It is by now well understood that for the atmospheres of brown dwarfs the onsets of CH_4 and NH_3 are well separated in T_{eff} -space. Indeed, the rise of near-infrared CH_4 and NH_3 defines the T and Y spectral classes, at ~ 1300 and ~ 600 K, respectively (Kirkpatrick 2005; Stephens et al. 2009; Line et al. 2017), although the much stronger mid-IR bands can appear at 1700 K (CH_4 at $3.3 \mu\text{m}$) and 1200 K (NH_3 at $10.5 \mu\text{m}$).

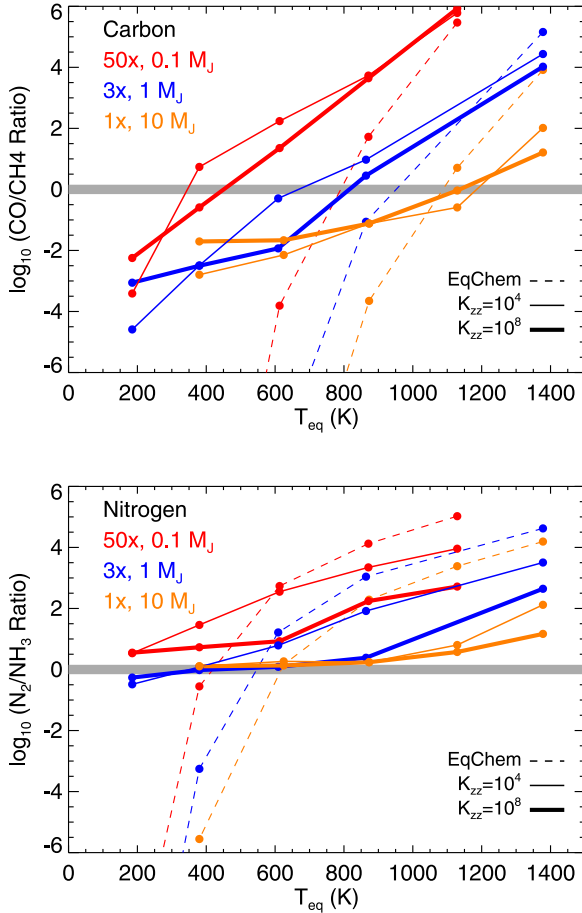


Figure 20. The log of the CO/CH₄ ratio (top panel) and N₂/NH₃ ratio (bottom panel) for five values of T_{eq} for 0.1, 1, and 10 M_J model planets, where a subset of the profiles are shown in Figure 19. In equilibrium (at 1 mbar), the transition T_{eq} for N₂/NH₃ = 1 (log = 0, shaded gray, bottom panel) is at ~ 420 , 530, and 600 K, from low mass to high mass. This is ~ 400 –500 K colder than the carbon chemistry transitions in the top panel. For nitrogen in particular, vertical mixing essentially flattens the slopes of these curves, as one quenches from high-pressure regions that lie on nearly the same adiabat, as shown in Figure 19. For all three model planets, NH₃ exists in detectable amounts for a wide swath of T_{eq} values.

However, significantly different P – T profiles of irradiated giant planets lead to much different behavior. This is shown in Figure 21, both for planets at a fixed 10 $\times$ solar metallicity (top panel) and for planets that use the notional mass–metallicity relation (bottom panel), with both panels using log K_{zz} of 8. For the higher-gravity planets with a large thermal reservoir in their interior, the giant planet behavior is at least similar to that of brown dwarfs, with CH₄ coming on for T_{eq} a few hundred kelvin hotter for the 1 $\times$ solar case at 10 M_J (bottom panel). However, beyond that example, a different and richer behavior, driven mostly by the altered temperature structure of irradiated planets, is seen. For all other example planets in both panels, CH₄ and NH₃ onset is at a similar T_{eq} , and at the higher metallicities (bottom panel) NH₃ can arise at *warmer* T_{eq} values than CH₄.

Figure 21 is in some ways the central prediction of the paper, albeit for a relatively constrained example, as we describe at some length in the Discussion section. The oddly shaped and radiative P – T profiles lead to an expectation of significantly different behavior from that already known for brown dwarfs.

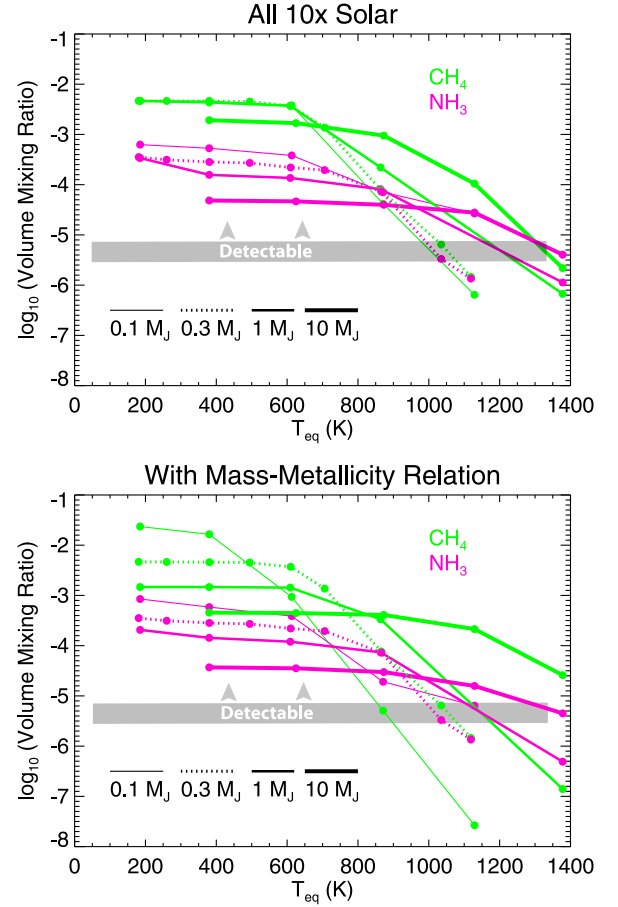


Figure 21. The log of the CH₄ and NH₃ mixing ratios as a function of T_{eq} for models at 0.1, 0.3, 1, and 10 M_J model planets at an age of 3 Gyr. The top panel shows calculations where 10 $\times$ solar abundances are used for all models, while the bottom panel assumes the mass–metallicity relation (50, 10, 3, and 1 $\times$ solar) for the four masses, respectively. For the range of models, and unlike in brown dwarfs, the onset of NH₃ is nearly coincident with the onset of CH₄, and for the lower masses ($< 0.3 M_J$), NH₃ onset occurs for warmer T_{eq} values than CH₄. In this figure log K_{zz} = 8 is assumed.

4.5. Cloud Formation and Cold Traps

A lesson well learned from observations of transiting planet atmospheres to date is that clouds and hazes can readily obscure molecular absorption features. This has typically been thought of as a hindrance. However, early work in this field suggested that the atmospheres of giant planets could potentially be classified based on the presence or absence of clouds (Marley et al. 1999; Sudarsky et al. 2000, 2003). In the end, it seems likely that some mixture will be true—in some ways clouds will help us understand temperature structures and transport in these atmospheres, but they will also obscure features due to atoms and molecules.

However, it seems clear that the role of clouds will not be a simple function of T_{eq} , as cloud condensation curves can be crossed at a variety of pressures. At a low pressure, perhaps little condensable material will exist. At a high pressure, perhaps all cloud material in an optically thick cloud will be below the visible atmosphere. These effects will depend on the shape of the atmospheric P – T profile, and hence on the specific entropy of the adiabat (which depends on planet mass and age), in addition to the role of atmospheric metallicity (more metals means more cloud-forming material), and even the spectral

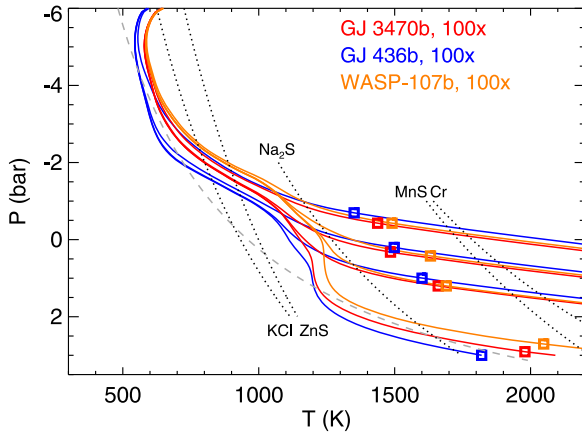


Figure 22. Atmospheric P - T profiles for planets GJ 436b, GJ 3470b, and WASP-107b, all at $100\times$ solar abundances, taken from Figure 5. Black dashed curves are for cloud condensation for various elements from Morley et al. (2012). For each planet, four interior adiabats are shown, for the case of no tidal heating (coolest), and $Q = 10^6$, 10^5 , and 10^4 , from cooler to warmer. Colored squares show the RCB depth. Tidal heating can push cloud formation of Na_2S , MnS , and Cr out of the deep atmosphere, into the visible atmosphere.

type of the parent star, which can also alter profile shapes, as discussed below.

In some ways this topic is beyond the scope of the paper, which is focused on 1D models, but we can motivate that there will be a diversity in behavior at a given planetary T_{eq} with plots that focus on P - T profiles and condensation curves. First, we will examine our trio of warm Neptunes, GJ 436b, GJ 3470b, and WASP-107b. In Figure 22 we replot the same P - T profiles from Figure 5, with chemical information removed, but now including RCB depths with squares, and condensation curves for potential cloud-forming materials. These “cooler” clouds, for planets cooler than the hot Jupiters, have been studied in Morley et al. (2012, 2013). Note, however, that Gao et al. (2020) have suggested that most of these cloud species (save KCl) may not nucleate and form. Lee et al. (2018) suggest that Cr , KCl , and NaCl (instead of Na_2S) will form across this temperature range. These predictions can be corroborated by future detailed spectroscopic observations of brown dwarfs and planets.

The KCl and ZnS cloud bases move little with or without tidal heating, as the upper atmospheres change little. The Na_2S cloud base, however, can move dramatically. Without tidal heating, the cloud base would be ~ 300 bars in all three planets. However, for tidal heating with $Q = 10^4$, the Na_2S cloud base moves to ~ 0.1 bars, in the visible atmosphere. A similar effect is seen for MnS and Cr .

We have previously investigated generic Saturn-like-planet P - T profiles at 0.15 au from the Sun. Figure 23 shows the same profiles that were explored in Figure 4, but now with a focus on RCBs and cloud condensation, rather than chemical abundances. The interface between these profiles and condensation depends strongly on surface gravity. For instance, the denser, higher-pressure photosphere of the highest-gravity models yields a detached convective zone near 0.2 bars, coincidentally at the region of ZnS and KCl clouds, which is not seen in the lower-gravity models. Potentially more vigorous mixing here could lead to thicker clouds and larger particle sizes. If these profiles were calculated at greater orbital distances, yielding cooler atmospheres, all would develop this detached convective zone (Fortney et al. 2007). The Na_2S case is also interesting for

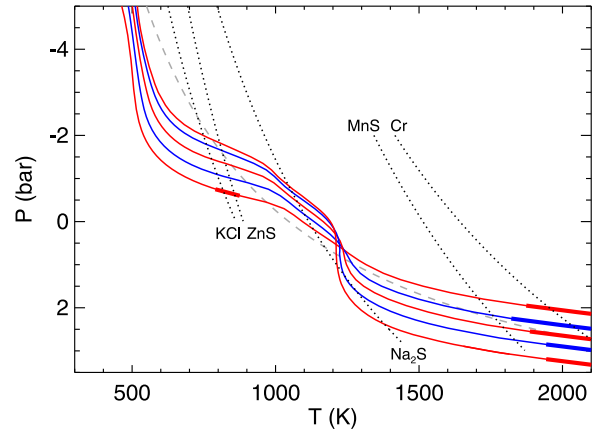


Figure 23. Model P - T profile for a $10\times$ solar atmosphere at 0.15 au from the Sun. The five profiles from Figure 4 show (alternating red and blue) five values of T_{int} , at 52, 77, 117, 182, and 333 K, with respective surface gravities $g = 5.8, 9.8, 24, 65$, and 225 m s^{-2} . Thicker parts of the profiles show convective regions. Note that the specific entropy of the deep atmosphere adiabat can move the location of the Na_2S cloud into the visible atmosphere (base at 1 bar for the highest-gravity model) or a depth (base at 300 bars in the lowest-gravity model). The high-gravity model also has a detached convective zone (coincidentally) at the location of ZnS and KCl condensate formation.

these profiles. The cloud base is found in the deep atmosphere for the two higher-gravity models, but at a few tenths of a bar in the three lower-gravity models. This clearly shows that at a given T_{eq} the depth of cloud formation can be significantly impacted by the temperature of the deep atmosphere, which is mitigated by the interior cooling. One could readily imagine other examples where the cloud formation depth is affected by planetary age, at a given mass, as is seen in brown dwarfs and self-luminous imaged planets.

5. Discussion

We wish to stress that the calculations shown here are only a starting point, and we have considered only what we believe will be the first-order effects. In the interest of brevity we have not considered several additional factors that could or will play important roles in further altering predicted temperature structures and atmospheric abundances. We describe these here:

1. We have elected not to self-consistently recalculate the atmospheric P - T profiles for each value of K_{zz} . The altered atmospheric abundances in turn alter the radiative-convective equilibrium profile, as has been explored by several authors, with and without stellar irradiation (Hubeny & Burrows 2007; Drummond et al. 2018a; Phillips et al. 2020). In particular, Drummond et al. (2018a), for HD 189733b and HD 209458b, found differences in the P - T profile of up to 100 K. For the arguments presented here, tripling or quadrupling the number of plotted P - T profiles (one for every K_{zz}) would distract from the main point, particularly given the large uncertainty today in the K_{zz} profiles. Additionally, including the cloud species discussed here would alter P - T profiles and chemical transitions (Molaverdikhani et al. 2020).
2. We have assumed a constant value of K_{zz} with height. Mixing-length theory is an important guide to K_{zz} in convective regions, but it is not yet clear how K_{zz} transitions at the RCB, in particular given the 3D nature of atmospheric mixing. Three-dimensional GCM runs

may be a guide for particular planets of interest. Work to date has suggested that as one moves deeper, to higher pressures in the radiative regions, K_{zz} should decrease. This may lead to a “quench bottleneck” of less vigorous mixing just above the RCB.

3. Our models are 1D; however, 3D effects have been shown to be important in understanding atmospheric abundances. As has previously been demonstrated (Cooper & Showman 2006; Agúndez et al. 2014; Drummond et al. 2018b, 2020), nonequilibrium chemistry is affected by day–night temperature differences in addition to vertical mixing. Day–night effects *may* be minimized for these relatively cooler planets, compared to the hot Jupiters, as day–night temperature differences are expected to be more modest at cooler temperatures (Lewis et al. 2010; Perez-Becker & Showman 2013).
4. Nonsolar ratios of elemental abundance ratios are likely to occur. As has been extensively modeled over the past decade, planet formation processes can drive atmospheres toward higher or lower C/O ratios, depending on the formation location and the relative accretion of solids and gas (e.g., Öberg et al. 2011; Madhusudhan et al. 2014; Mordasini et al. 2016; Espinoza et al. 2017). More recently, the role of the nitrogen N_2 ice line as a site of planet formation (Piso et al. 2016; Bosman et al. 2019; Öberg & Wordsworth 2019) and altered N/O and N/C ratios in giant planet atmospheres (Cridland et al. 2020) has been investigated. Previous radiative–convective atmospheric calculations have shown that an altered C/O ratio can alter P – T phase space of major chemical transitions (e.g., Madhusudhan et al. 2011a; Mollière et al. 2015).
5. Photochemistry will further alter atmospheric abundances. The nonequilibrium abundances that we find, based on timescale arguments, are merely the “raw materials” for further chemical reactions (Zahnle et al. 2009a, 2009b; Moses et al. 2011, 2013; Venot et al. 2020). It is well known that CH_4 in the solar system can be readily photolyzed, and the destruction of CH_4 may make it less easily observed, while increasing the abundances of other hydrocarbons, along with photochemical hazes. We note that signs of hazes may already be seen in the transmission spectra of the cool transiting giant planet population (Gao et al. 2020).
6. A range of parent star spectral types will be relevant across the planetary population. Moving from hot stars to cool stars, the peak of the stellar spectral energy distribution moves to redder wavelengths, and the temperature of the incoming radiation field is more similar to that of the planetary atmosphere, leading to more isothermal temperature structure (Mollière et al. 2015), as shown in Figure 24. The range from hotter to cooler parent stars certainly spans at least the range from F to M. Temperature differences of ~ 150 K are seen at 1–100 bars, the relevant quench pressures for $\log K_{zz} = 8$, which straddles the CO/ CH_4 equal-abundance curve. Interestingly, this could be a very nice probe of K_{zz} , as for this example, at much lower and much higher K_{zz} values, the profiles converge back to similar CO/ CH_4 abundances.
7. A range of planetary eccentricities can impact the timescale arguments made here, as well as drive tidal heating. The thermal response of the planetary atmospheric temperatures,

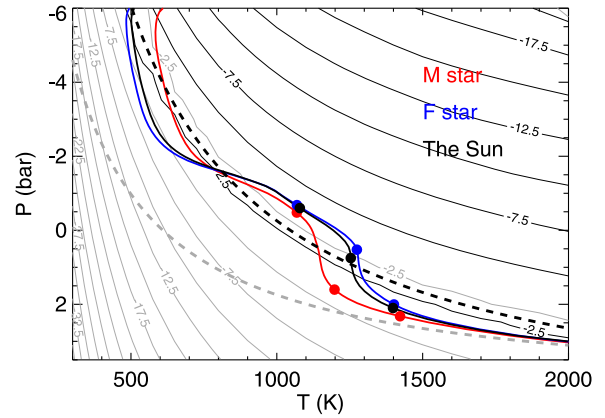


Figure 24. Atmospheric P – T profiles for three planets with the same incident stellar flux. For the profile in black, the planet is at 0.15 au. In red is a profile with the GJ 436b parent star (type M2.5), while in blue it is the WASP-17b parent star (type F4). Here $\log K_{zz}$ values of 4, 8, and 11 are shown as the top, middle, and bottom sets of colored filled circles, respectively. Large temperature differences are particularly seen at 1–100 bars, the relevant quench pressures for $\log K_{zz} = 8$, which straddles the CO/ CH_4 equal-abundance curve (dashed black). The N_2/NH_3 equal-abundance curve is shown in dashed gray, for reference.

and hence chemistry, depends on the planetary orbit. The timescale over which the atmosphere heats up and cools off owing to the eccentric orbit will compete with the timescales t_{mix} and t_{chem} that we have explored here. This idea was previously explored for highly eccentric hot Jupiters by Visscher (2012), but a new study that focuses on cooler planets appears to be warranted. Tidal heating from the interior, as shown for planets GJ 436b, GJ 3470b, and WASP-107b in Section 3, should be a relatively common process, particularly for the “in-between” planets that are not so close that they will have circularized quickly, and are not so far that tides do not affect the energy budget. Tidal heating should then be investigated for any particular target of interest. Assessing the eccentricity of a given planet may be difficult, if radial velocity data is sparse, or if a secondary eclipse is not detected.

8. The radius-inflation mechanism that affects hot Jupiters may still operate in the cooler planets we investigate here. Since Thorngren & Fortney (2018) and Thorngren et al. (2019) found no strong evidence for the mechanism affecting planets cooler than $T_{\text{eq}} < 1000$ K, we have used standard thermal evolution models that lack additional heating. However, modest additional internal heating could warm the deep atmosphere, with only small effects on the observed radius versus incident flux distribution, which would be currently undetectable in the planetary population. And any “residual” radius-inflation power could be important for the Saturn- and Neptune-class planets, whose interiors would be expected to cool off significantly in the absence of additional power. This would lead to lower CH_4/CO and NH_3/N_2 ratios at a given T_{eq} , compared to our calculations, and could be an important probe of temperatures in the deeper atmosphere.

6. Conclusions

Through a straightforward implementation of 1D radiative–convective model atmospheres and nonequilibrium chemistry,

we have shown that atmospheric abundances of C-, N-, and O-bearing molecules in warm transiting planets will show a diverse and complex behavior. This behavior will depend strongly on the cooling history of the planet, such that a planet's mass, age, parent star spectral type, and any ongoing tidal dissipation can lead to atmospheric abundances that differ from planet to planet at the same level of incident stellar flux.

Nonequilibrium chemical abundances may then serve as a tool to probe the deeper atmosphere, similar to work recently begun for very cool brown dwarfs (Miles et al. 2020). For the three Neptune-class planets discussed in Section 3 (GJ 436b, GJ 3480b, and WASP-107b), we suggest that ongoing eccentricity damping tidally heats the deep atmospheres of the planets. This raises temperatures by several thousand degrees and drives strong convective mixing, which dramatically decreases the CH₄/CO ratio in the visible atmosphere. This may play the dominant role in understanding their observations to date.

The more isothermal shape of P - T profiles in irradiated planets, compared to brown dwarfs, leads to the expectation that planetary behavior will differ strongly compared to brown dwarfs. Perhaps most strikingly, the onset of detectable CH₄ and then NH₃ should occur at very similar T_{eq} values, and for the Saturn masses and below, a reversal compared to brown dwarf behavior, where NH₃ is seen at warmer temperatures than CH₄. We have also shown that N₂ will dominate over NH₃ over a wide range of temperatures and ages, such that bulk nitrogen abundances determined from NH₃ will only be lower limits.

To discover the underlying physical and chemical trends for these atmospheres, it would likely be the most straightforward to look for *trends at a given mass and age*. For instance, in mature planetary systems (say, Gyr+), the Jupiter-mass planets around Sun-like stars at $T_{\text{eq}} < 1000$ K would all be expected (barring tidal heating) to have T_{int} values of ~ 100 K. One could expect to see a trend of increasing CH₄ abundance with lower T_{eq} , with CH₄ becoming dominant at 800 K, as in Figure 10. Note, however, that this potential trend could readily be disguised by mixing planets with a range of masses into one's sample, as shown in that same figure. We reiterate that it is not yet known how diverse the atmospheric metallicities of those planets may be, and how that may change with planetary mass, which would also add scatter to any trend.

While retrievals to constrain atmospheric abundances and temperature structures (see Madhusudhan 2018, for a review) are likely up to the task for determining abundances in planetary transmission and emission, these findings can only properly be interpreted *within the context of the physical characteristics of the planet and its environment*. In particular, since we find that T_{int} can play a significant role in altering abundances, retrievals that utilize deep atmospheric temperatures that are guided by thermal (and/or tidal) evolution models and aim to retrieve the quench pressure depth in addition to molecular mixing ratios may yield the most robust results. The role of planetary structure modeling, thermal evolution modeling, and physics-driven 1D and 3D models, to complement retrieval, are essential to interpreting observations.

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