The Effect of Disequilibrium Carbon Chemistry on the Atmospheric Circulation and Phase Curves of Hot Jupiter HD 189733b

Maria E. Steinrueck,1 Vivien Parmentier,2 Adam P. Showman,1 Joshua D. Lothringer,1 and Roxana E. Lupu3

1Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ, 85721, USA
2Aix Marseille Univ, CNRS, LAM, Laboratoire dAstrophysique de Marseille, Marseille, France
3BAER Institute/NASA Ames Research Center, Moffett Field, CA 94043, USA

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ABSTRACT

On hot Jupiter exoplanets, strong horizontal and vertical winds should homogenize the abundances of the important absorbers CH4 and CO much faster than chemical reactions restore chemical equilibrium. This effect, typically neglected in general circulation models (GCMs), has been suggested as explanation for discrepancies between observed infrared lightcurves and those predicted by GCMs: On the nightsides of several hot Jupiters, GCMs predict outgoing fluxes that are too large, especially in the Spitzer 4.5 µm band. We modified the SPARC/MITgcm to include disequilibrium abundances of CH4, CO and H2O by assuming that the CH4/CO ratio is constant throughout the simulation domain. We ran simulations of hot Jupiter HD 189733b with 8 CH4/CO ratios. In the more likely CO-dominated regime, we find temperature changes of ~50 K compared to the equilibrium chemistry case across large regions. This effect is large enough to affect predicted emission spectra and should thus be included in GCMs of hot Jupiters with equilibrium temperatures below 1300 K. We find that spectra in regions with strong methane absorption, including the Spitzer 3.6 and 8 µm bands, are strongly impacted by disequilibrium abundances. We expect chemical quenching to result in much larger nightside fluxes in the 3.6 µm band, in stark contrast to observations. Meanwhile, we find almost no effect on predicted observations in the 4.5 µm band, as the opacity changes due to CO and H2O offset each other. We thus conclude that disequilibrium carbon chemistry cannot explain the observed low nightside fluxes in the 4.5 µm band.

Keywords: hydrodynamics – methods:numerical – planets and satellites: atmospheres – planets and satellites: gaseous planets – planets and satellites: individual (HD 189733b) – radiative transfer

1. INTRODUCTION

Close-in extrasolar giant planets, known as hot Jupiters, are the best characterized exo-
planets to date. Due to their proximity to their host stars, they are expected to be tidally locked. This creates strong temperature contrasts between the permanent day side and the night side. For the temperature ranges of typical hot Jupiters, assuming chemical equilibrium, these temperature contrasts translate to large horizontal gradients in the abundance of methane \((\text{CH}_4)\) and carbon monoxide \((\text{CO})\), two important absorbers in the atmospheres of hot Jupiters. Carbon is preferentially found in \(\text{CH}_4\) at high pressures and low temperatures, while at low pressures and high temperatures, \(\text{CO}\) is the dominant carbon-bearing species. Most models of hot Jupiters, especially three-dimensional general circulation models (GCMs) allowing for realistic representation of opacities and the effect that chemical composition exerts on them, assume equilibrium chemistry as a basis for calculating opacities. However, the stark day-night temperature contrast also drives a vigorous atmospheric circulation, with a strong eastward equatorial jet advecting thermal energy from the day side to the night side and strong vertical mixing (e.g. Showman & Guillot 2002; Showman & Polvani 2011; Dobbs-Dixon & Lin 2008; Heng et al. 2011; Thrastarson & Cho 2011; Rauscher & Menou 2012; Perna et al. 2012; Dobbs-Dixon & Agol 2013; Parmentier et al. 2013; Mayne et al. 2014; Kataria et al. 2016; Mendonça et al. 2016). In addition, at low pressures \((\lesssim 1\, \text{bar})\), the chemical time scale at which the interconversion between \(\text{CH}_4\) and \(\text{CO}\) acts, becomes very long. Therefore, an air parcel is advected much faster than its \(\text{CH}_4\) and \(\text{CO}\) abundances can adapt to the local equilibrium values. This process, called quenching, is expected to vertically and horizontally homogenize the abundances of \(\text{CH}_4\) and \(\text{CO}\) (as well as of many other species, including \(\text{N}_2\) and \(\text{NH}_3\)) in the near-infrared photospheres (located roughly between 1 bar and 1 mbar) of hot Jupiters \((\text{Cooper & Showman 2006; Agúndez et al. 2012, 2014; Drummond et al. 2018})\).

These disequilibrium abundances can have a significant effect on the opacities and thus the radiative transfer. Including this effect in general circulation models (GCMs) could potentially impact the thermal structure and atmospheric circulation, as well as the predicted spectra and phase curves. In fact, this has been proposed as a solution for the observed discrepancy between phase curves predicted by state-of-the-art GCMs assuming equilibrium chemistry and observations with the Spitzer Space Telescope \((\text{Knutson et al. 2012})\). GCMs over-predict the night side fluxes in the Spitzer 4.5 \(\mu\text{m}\) band for the hot Jupiters HD 189733b \((\text{Knutson et al. 2012})\), HD 209458b \((\text{Zellem et al. 2014})\) and WASP-43b \((\text{Kataria et al. 2015})\). Within this wavelength bandpass, \(\text{CO}\) has a strong absorption band. For relatively cool hot Jupiters, like HD 189733b, transport-induced disequilibrium chemistry is expected to enhance the \(\text{CO}\) abundance on the night side compared to the equilibrium chemistry value \((\text{Cooper & Showman 2006; Agúndez et al. 2014})\). Knutson et al. (2012) argued that this would lead to increased opacity in the 4.5 \(\mu\text{m}\) band, such that the outgoing radiation in that band would probe higher, cooler regions of the atmosphere, decreasing the flux emitted in this band. So far, this hypothesis has not been tested quantitatively with GCMs.

In addition to changing the pressure level from which the outgoing radiation is emitted, the altered opacities can also affect the thermal structure and the atmospheric circulation in a GCM. So far, this effect has only been taken into account by Drummond et al. (2018). These authors, however, focused on HD 209458b, for which the effects of disequilibrium chemistry are expected to be weaker than for the cooler hot Jupiter HD 189733b.
The goal of this study is to quantify both of these effects of disequilibrium carbon chemistry in a GCM. We assume that the abundance ratio of CH$_4$ to CO is constant throughout the entire simulation domain. This simple approach allows us to explore a broad parameter range and to focus on the radiative effects. Our approach is motivated by the findings of previous studies: Coupling a simple chemical relaxation scheme to a GCM of HD 209458b, both Cooper & Showman (2006) and Drummond et al. (2018) found that the CO and CH$_4$ abundances are homogenized everywhere above the ~ 3 bar level. Agúndez et al. (2014) instead used a full kinetical network in a pseudo-2D framework that was able to capture vertical and horizontal transport, and included photochemistry on the day side. They found that quenching homogenized the CO and CH$_4$ abundances at pressures between ~ 1 and ~ 10$^{-4}$ bars on HD 189733b. (At lower pressures, photochemical processes destroy CH$_4$ on the day side.) While these three studies disagree on the relative importance of vertical versus horizontal quenching, all of them conclude that the abundances of CO and CH$_4$ should be homogeneous in the near-infrared photosphere, justifying our assumption.

However, coupling a chemical relaxation scheme to their GCM, Mendonça et al. (2018b) found that on WASP-43b, the CH$_4$ abundances were only homogenized horizontally but not vertically. A similar behavior is seen in the HD 209458b case of Agúndez et al. (2014) (though only for their nominal eddy diffusion profile). While there are several differences in the models and planet parameters used that could contribute to this different outcome, an important factor is the hotter day side in both of these models. A hotter day side leads to a shorter chemical time scale, allowing abundances to relax towards their local equilibrium abundances on the hottest parts on the day side (as also seen in 1D models, e.g. Tsai et al. 2018). In the case of Agúndez et al. (2014), the hotter day side at low pressures is largely due to their assumption of a thermal inversion on the day side of HD 209458b. Mendonça et al. (2018b) look at WASP-43b, for which Kataria et al. (2015) also found a larger day-night contrast and hotter day side compared to HD 209458b due to its shorter orbital period and larger gravity. Our study looks at the cooler HD 189733b, for which it is likely that abundances are quenched horizontally and vertically.

With the focus of these previous studies being on chemistry, most of them did not self-consistently calculate the radiative transfer, and thus were not able to quantify the effect of the changed opacities on the temperature structure in their model. In their GCM, Cooper & Showman (2006) used a Newtonian cooling scheme, in which the temperature relaxes towards a prescribed temperature profile at each point in the atmosphere. Like typical kinetical networks, Agúndez et al. (2014) used a prescribed background pressure-temperature profile (in this case derived from a GCM assuming equilibrium chemistry). Mendonça et al. (2018b) use a double-grey radiative transfer scheme. Only Drummond et al. (2018), whose GCM uses state-of-the-art radiative transfer with correlated k-coefficients, included the effect of the changed opacities on the temperature structure in their model. Our approach thus complements previous studies by focusing on the radiative transfer rather than on chemistry.

We choose to focus on HD 189733b. Due to its cooler temperature compared to HD 209458b and WASP-43b, disequilibrium effects are expected to be stronger on this planet. The latter two planets are hot enough that in simulations assuming equilibrium chemistry, CO is the dominant carbon species at all longitudes and latitudes (Showman et al. 2009; Drummond et al. 2018). In contrast, on the cooler HD 189733b, in
chemical equilibrium one expects that the day side is dominated by CO, while the night side is dominated by CH$_4$ (see Figure 1). HD 189733b thus occupies an interesting point in the parameter space: Regardless of the quenched CH$_4$ and CO abundances, including disequilibrium chemistry will change which of the two species is dominant on about half of the planet. The radiative effects of disequilibrium chemistry are thus expected to play a larger role than on hotter planets. In addition, unlike for HD 209458b, for HD 189733b there exist phase curve observations in multiple Spitzer bandpasses (Knutson et al. 2007, 2009; Agol et al. 2010; Knutson et al. 2012), providing stronger observational constraints.

2. METHODS

We use the SPARC/MITgcm model (Showman et al. 2009) to perform simulations of hot Jupiter HD 189733b. This model couples the two-stream, non-gray radiative transfer code of Marley & McKay (1999) to the MITgcm general circulation model of Adcroft et al. (2004) and has previously been applied to a wide range of hot Jupiters and other exoplanets (e.g., Showman et al. 2009, 2013, 2015; Parmentier et al. 2013, 2018; Lewis et al. 2010, 2014; Kataria et al. 2013, 2014, 2015).

**Figure 1.** Left: horizontal temperature maps of the reference simulation (equilibrium chemistry) at pressures of 1 mbar, 30 mbar and 1 bar, respectively. The substellar point (0° longitude, 0° latitude) is at the center of each panel. The arrows represent the velocities of the horizontal component of the wind. Right: horizontal maps of the abundance ratio of methane to carbon monoxide assuming chemical equilibrium. Methane dominated regions are magenta while carbon-monoxide dominated regions are green. The contours are evenly spaced in log space and mark $\log_{10}(\text{CH}_4/\text{CO})=(-4,-3,-2,-1,0,1, 2)$, respectively. The zero contour (corresponding to $\text{CH}_4/\text{CO}=1$) is thickened.
2.1. Dynamics

Using the MITgcm (Adcroft et al. 2004), we solve the three-dimensional global primitive equations on a cubed sphere grid. The primitive equations are valid for stably stratified shallow atmospheres. Horizontal noise is smoothed with a fourth-order Shapiro filter (Shapiro 1970).

We assume a gravity of \( g = 22.86 \text{ m s}^{-2} \), a planetary radius of \( 7.9559 \cdot 10^7 \text{ m} \) and a rotation period equal to the orbital period of 2.22 days, as the planet is assumed to be in synchronous rotation. We use a value of \( c_p = 1.3 \cdot 10^4 \text{ J kg}^{-1} \text{ K}^{-1} \) for the specific heat capacity and \( \kappa = R/c_p = 2/7 \), where \( R \) is the specific gas constant. These values are appropriate for hydrogen dominated atmospheres. Our simulations use a horizontal resolution of C32, which is roughly equivalent to a resolution of 128x64 on a longitude-latitude grid. The pressure spans from 200 bars to 2 \( \mu \)bar and is resolved by 53 vertical levels. We use a timestep of 25 s, run the simulations for 400 days and then average over the last 100 days.

2.2. Radiative transfer

The radiative transfer code in our model is based on the plane-parallel code of Marley & McKay (1999). This code was originally developed to study Titan’s atmosphere (McKay et al. 1989) and has since been applied to Uranus (Marley & McKay 1999), brown dwarfs (Burrows et al. 1997; Marley et al. 1996, 2002) and hot Jupiters (Fortney et al. 2005, 2008; Showman et al. 2009). The code uses the delta-discrete ordinate method (Toon et al. 1989) for the incident stellar flux, while the thermal flux is calculated using the two-stream approximation. Molecular opacities are treated using the correlated k-method (e.g. Goody & Yung 1989): In each frequency bin, the opacity information from line-by-line calculations using as many as 10,000 to 100,000 frequency bins is turned into a cumulative distribution of opacities, which is then described by 8 k-coefficients. We use 11 frequency bins spanning from 0.26 \( \mu \)m to 325 \( \mu \)m (see Kataria et al. 2013). The correlated-k method is the most sophisticated and accurate treatment of opacities in GCMs of exoplanets to date and is used both in the SPARC/MITgcm and in the adaptation for hot Jupiter of the UK MetOffice model (Amundsen et al. 2016).

In order to combine the opacities from different species within the atmosphere, we employ the approach of pre-mixed opacities, meaning that the k-coefficients of the mixture are derived from line-by-line opacities that are calculated for a mixture with specified chemical abundances that are specified functions of temperature and pressure (typically derived from equilibrium chemistry). This approach is fast and accurate. We use the equilibrium chemistry abundances for solar metallicity of Lodders & Fegley (2002) and Visscher et al. (2006) with the modifications for CH\(_4\), CO and H\(_2\)O described in section 2.3 and the opacities of Freedman et al. (2008) including the updates of Freedman et al. (2014). Note that the updated opacities result in changes in the thermal structure and the resulting equilibrium chemistry phase curve compared to Showman et al. (2009) and Knutson et al. (2012) (see Section 4.2). The disadvantage of this method is that it leaves little flexibility for varying abundances due to disequilibrium chemistry. However, alternative methods combining the k-coefficients of individual species on the fly come at a much higher computational cost and are thus impractical when coupled to GCMs (as discussed in Amundsen et al. 2017). To explore the effect of disequilibrium abundances, we thus take advantage of the fact that due to strong horizontal and vertical mixing, the disequilibrium abundances of CH\(_4\) and CO are expected to be close to constant throughout the photosphere, as further detailed in section 2.3.
To obtain spectra and phase curves, we post-process our simulation output using the same plane-parallel two-stream radiative transfer code as used in our full 3D simulations, but adopting 196 wavelength bins instead of 11 to yield improved spectral resolution. Given the time-averaged temperature structure from the GCM at a particular time, we calculate the outgoing flux in the line of sight to the observer for each atmospheric column. The fluxes are then combined into a weighted average across the disk to give the total flux received at a particular observing vantage point and at a particular time during the orbit. We do this calculation at many orbital phases (throughout which the Earth-facing hemisphere shifts in longitude) to assemble full orbit phase curves at wavelengths of interest. This method is similar to the method described in Fortney et al. (2006), Showman et al. (2009) and Parmantier et al. (2016) and naturally takes into account limb darkening of the planet. We use a NextGen spectrum (Hauschildt et al. 1999) for HD 189733, a stellar radius of 0.805 \( R_\odot \) (Boyajian et al. 2015) and a planet-to-star radius ratio \( R_p/R_\star = 0.0145 \).

2.3. Disequilibrium chemistry

All previous studies of hot Jupiters using the SPARC/MITgcm utilized k-coefficient tables calculated assuming equilibrium chemistry. To explore the effect of transport-induced disequilibrium carbon chemistry, in this study we instead assume that the CH\(_4\) to CO ratio is quenched to a constant value throughout the entire atmosphere. This assumption is a good approximation at pressures lower than roughly 1 to 10 bars, as shown by Cooper & Showman (2006), Agúndez et al. (2014) and Drummond et al. (2018). At higher pressures, the chemical timescale becomes shorter than the mixing time scale and the approximation of a constant quenched value breaks down. Since this study is a first exploration of the effects of disequilib-
emission spectra that we are interested in or the
temperatures in the regions probed by broad-
band emission.

The net reaction that converts CH$_4$ to CO and
vice versa is

$$\text{CH}_4 + \text{H}_2\text{O} \rightleftharpoons \text{CO} + 3\text{H}_2.$$ (1)

Together with the CH$_4$ and CO abundances, the
water abundance thus changes as well. We take
this effect into account by adjusting the water
abundance such that the total number of oxy-
gen atoms present in water and CO is conserved.
The C/H and O/H ratios thus remain at solar
values, consistent with our general assumption
of solar elemental abundances. We leave the
abundance of CO$_2$ unchanged from its equilib-
rium chemistry value, as it is not the dominant
carbon species in either equilibrium or disequi-
librium chemistry and deviations from equilib-
rium chemistry are expected to remain moder-
ate compared to CH$_4$ (Agúndez et al. 2014).

The quenched CH$_4$/CO ratio predicted by
chemistry models depends on the assump-
tions about the strength of vertical mixing
(parametrized through the eddy diffusion co-
efficient $K_{zz}$) as well as the reaction rates, some
of which are not well-known in the pressure and
temperature range encountered in hot Jupiter
atmospheres. A variety of different 1D and
pseudo-2D thermochemical kinetics models of
HD 189733b find CH$_4$/CO ratios roughly be-
tween 0.001 and 0.5 (Moses et al. 2011; Visscher
& Moses 2011; Agúndez et al. 2014; Drummond
et al. 2016). However, CH$_4$/CO ratios larger
than one might also be possible if vertical mix-
ing is very strong (Tsai et al. 2018). GCM
simulations with simplified chemical schemes
have focused on the hotter HD 209458b and
find CH$_4$/CO ratios $\sim$ 0.01 (Cooper & Show-
man 2006; Drummond et al. 2018). We thus
choose to treat the CH$_4$/CO ratio as a free pa-
rameter and perform 8 simulations varying this
ratio from 0.001 to 100 as well as a reference
simulation assuming equilibrium chemistry. Al-
though kinetics models favor CH$_4$/CO ratios
$< 1$, we include the full range for completeness.

To illustrate the changes in opacity, the result-
ning near-infrared opacities for different CH$_4$/CO
ratios at a typical photospheric pressure and
temperature are shown in Figure 2. The plotted
opacities represent the bin-averaged opacity
for each of the 196 wavelength bins used for the
postprocessing averaged over the inverse of the
opacity. This kind of average is a good way of
representing the effects on the broadband emis-
ion. Note that the average is only used for
illustration in the figure—in the radiative trans-
fer in the GCM and for post-processing we use
the correlated-k method instead (with 11 and
196 bins, respectively). It is obvious from Fig-
ure 2 that for a higher CH$_4$/CO ratio, the opacity
significantly increases for almost all wave-
lengths in the near and mid-IR. This is mainly
because CH$_4$ has many broad absorption bands
in the near- and mid-infrared while CO only
has a few narrow absorption bands. On top of
that, with increased CH$_4$, the water abundance
also increases by a factor of $\sim$ 2. Similar to
CH$_4$, water has many broad absorption bands.
The only spectral region in which the opacity
decreases for high CH$_4$/CO ratios is near the
CO absorption band centered around 4.7 $\mu$m.
Even in this region, the opacity decreases only
by a factor of $\sim$ 2, much less than it increases
at most other wavelengths. This is likely be-
cause the water feature centered around 6.3 $\mu$m
contributes significantly to the total opacity in
this region. Since for every CO molecule that is
removed, a water molecule is added, these two
changes in opacity partially offset each other in
this region.

3. RESULTS

3.1. Reference simulation: equilibrium
chemistry case
First, we give a brief overview of the reference simulation, which assumes equilibrium chemistry. The left column of Figure 1 shows the temperature and horizontal wind velocities at pressures of 1 mbar, 30 mbars and 1 bar. The pressure levels in the figure are chosen such that the lowest pressure level shown (1 mbar, uppermost panel) is slightly above the photosphere at most infrared wavelengths, while the highest pressure level (1 bar, lowermost panel) is somewhat below the photosphere at most infrared wavelengths. The temperature and wind patterns are typical for a hot Jupiter: The simulation exhibits a large day-night temperature contrast, especially at low pressures, and a superrotating (eastward) equatorial jet. The hottest point is shifted east with respect to the substellar point. The coldest regions in the simulation are east of the antistellar point at roughly 40° to 50° latitude, at the center of two large gyres.

At low pressures, where the radiative time scale is short compared to the dynamical time scale, the temperature difference between day and night side is largest. In addition to the jet, there is a strong day-to-night flow. As pressure increases and the radiative timescale becomes longer, the eastward equatorial jet dominates more over the day-to-night flow. At a pressure of 1 bar, the equatorial jet efficiently transports heat from the day side to the night side and longitudinal temperature differences along the equator are small. Winds at mid-latitudes are much smaller than at lower latitudes. The cold spots associated with the night side gyres are still several hundred K colder than the equatorial regions.

The ratio of the equilibrium chemistry abundances of CH₄ to CO is plotted in the right column of Figure 1. In chemical equilibrium, CH₄ is the dominant carbon species at high pressures and low temperatures, while carbon preferentially forms CO at low pressures and high temperatures. On isobars, abundances thus directly follow the temperature pattern. On the day side, CO is the prevailing carbon species and is up to 5 orders of magnitude more abundant than CH₄. At most locations of the night side, the abundances of both species become more even, with CH₄ prevailing. Methane abundances peak at the night side cold spots at mid-latitudes. As with temperature gradients, the abundance gradients become much less pronounced deeper in the atmosphere: While the abundance ratios span over 7 orders of magnitude at the 1 mbar level, they differ by less than 3 orders of magnitude at the 1 bar level.

3.2. Simulations with quenched abundances: Thermal structure

In response to the different opacities, the thermal structure changes in the simulations with disequilibrium chemistry compared to the reference case. We consider two of the quenched simulations, CH₄/CO=0.01 and CH₄/CO=100, in detail to illustrate these changes for the CO dominated and the CH₄ dominated regime. Figure 3 shows the temperature difference with respect to the reference case on isobars. Vertical pressure-temperature profiles from these two simulations along with the reference simulation are plotted in Figure 4.

In the CO dominated regime (the regime favored by kinetics models), the day side is cooler compared to the equilibrium case, while the temperature of the night side cold spots increases. Temperatures also drop at high latitudes, especially on the night side. All of these effects can be seen in the left column of Figure 3. In the particular case shown (CH₄/CO=0.01), day side temperatures drop by about 50 K throughout most of the photosphere. This is also evident in the pressure-temperature profiles near the substellar point (upper left panel of Figure 4). A closer look at the pressure-temperature profiles reveals that the vertical temperature gradient is slightly larger compared to the equilibrium chemistry case near
the substellar point, but slightly smaller at the antistellar point. This is likely because on the day side, greenhouse gases (CH$_4$, H$_2$O) are added compared to the equilibrium composition while on the night side greenhouse gases are taken away. The CH$_4$/CO=0.001 simulation (not shown) displays very similar changes in thermal structure, but with a somewhat larger amplitude.

Our interpretation for why the day side is cooler is related to energy-balance: The changes in opacity lead to only slight changes in albedo, so for all the CH$_4$/CO ratios considered, the total amount of absorbed starlight is nearly the same. Since the simulations achieve an approximate energy balance (energy gained equals energy lost), this means that the total IR energy radiated to space (from the entire planet) is also nearly the same regardless of the CH$_4$/CO ratio. Compared to equilibrium chemistry, the overall infrared opacity decreases on the night side. Therefore, the radiation on the night side escapes to space from deeper levels, where the atmosphere tends to be hotter, leading to a larger flux being radiated away. As a consequence, less energy is returned to the day side and the day side cools, which in turn leads to a dayside radiating less IR flux.

In the (less likely) CH$_4$ dominated case, the temperature changes are more striking: Below
Figure 4. Pressure-temperature profiles. The equilibrium chemistry simulation is shown in blue, the CH$_4$/CO=0.01 simulation in green and the CH$_4$/CO=100 simulation in magenta. The shaded grey region indicates pressure ranges for which the simulation has not converged due to the long radiative timescale in deep layers of the atmosphere. Coincidentally, our assumption of a constant quenched CH$_4$/CO ratio breaks down at roughly a similar pressure. Upper left: Profiles within 10° of the substellar point. Upper right: Profiles within 10° of the antistellar point. Lower left: Profiles within ±2° of the evening terminator. Lower right: Profiles within ±2° of the morning terminator.

roughly the 10 mbar level, temperatures are significantly hotter at almost all longitudes and latitudes. In the CH$_4$/CO=100 simulation, the temperature difference with respect to the reference simulation reaches 200 to 300 K at the 1 bar level in the equatorial region (see right column of Figure 3). In this simulation, the location of the night side cold spots shifts to slightly higher latitudes. In Figure 3, this is visible in the center right panel as the light blue regions and in the upper right panel as the two small deep purple regions at ≈ ±50° latitude in conjunction with two orange regions at lower latitudes.
At the 1 mbar level, temperatures are similar or slightly colder compared to the reference simulation. Looking at the temperature profiles in Figure 4, it is obvious that the temperature gradient between 1 mbar and 1 bar is steeper in the CH$_4$ dominated case than for the other simulations at all four locations shown, signifying a stronger greenhouse effect. Given that in the CH$_4$ dominated case the abundances of the greenhouse gases methane and water are enhanced compared to equilibrium chemistry at any location other than the night side mid-latitude cold spots, this behavior is expected.

3.3. Phase Curve Predictions and Comparison with Observations

We post-process the GCM results as described in Section 2.2 to obtain phase curves and emission spectra and compare them to the available observational data (Figure 5). In short, the fit with respect to the observational phase curve worsens substantially in the 3.6 $\mu$m band for all quenched ratios while the changes in the 4.5 $\mu$m band are negligible in the expected CO dominated case and lead to a worse fit in the CH$_4$ dominated regime.

In the 3.6 $\mu$m band, the phase curve amplitude decreases for all quenched simulations compared to equilibrium chemistry. A similar, but less drastic behavior can be seen in the 8 $\mu$m band. This behavior is expected for wavelength regions with strong methane absorption bands, including these two band passes: In equilibrium chemistry, the outgoing radiation on the day side, where there is little methane, probes deeper, hotter layers while on the night side, where more methane is present, the radiation is emitted from higher, cooler layers. Thus the temperature varies more strongly from day to night on the photosphere in these bands (which differs in pressure from day to night) than it does on isobars. This enhances the day-night contrast of the phase curve relative to what would occur if the photosphere were at constant pressure (see also Dobbs-Dixon & Cowan 2017). When assuming a constant methane abundance throughout the atmosphere, however, regardless of the exact value, the outgoing radiation emerges from similar pressure regions everywhere on the planet and the phase curve amplitude decreases. Consistent with this picture, the day side fluxes from the CH$_4$/CO=0.01 simulation are relatively close to those from the equilibrium chemistry simulation, while the night side fluxes from the CH$_4$ dominated simulations match those from equilibrium chemistry at the flux minimum.

In the 4.5 $\mu$m band, the night side fluxes are similar to or higher than the value from the equilibrium chemistry simulation for all quenched values. At first, this seems surprising, given that Knutson et al. (2012) base their argument for disequilibrium chemistry almost entirely on the fact that equilibrium chemistry models over-predict the 4.5 $\mu$m night side fluxes, arguing that adding CO on the night side will shift the photosphere in this band to a higher, colder atmospheric layer and thus decrease the flux. However, they ignore that when changing the CO abundance through quenching, the water abundance should also change. Water has significant opacity in the 4.5 micron band as well. Averaged across the band, its molecular absorption cross section is comparable to that of CO (see e.g. Figure 5 in Fortney et al. (2006) or Figures 2 and 3 in Sharp & Burrows (2007)). For each CO molecule added, an H$_2$O molecule is removed (assuming metallicity is held constant), and the resulting changes in opacity in the 4.5 micron band due to CO and H$_2$O largely offset each other (see also Section 2.3 and Figure 2). The changes in the 4.5 micron phase curve are thus mainly due to the change in thermal structure and not due to a change of the photospheric level. In the hotter CH$_4$ dominated case, the flux increases at all phase angles in this band. In the CO dominated
Figure 5. Phase curves predicted from our models and available observational data in the Spitzer 3.6, 4.5, 8 and 24 micron bands. The green dash-dotted line represents the CH$_4$/CO=0.01 simulation, the light pink solid line CH$_4$/CO=1, the magenta dashed line CH$_4$/CO=100 and the thick dotted blue line the reference simulation. The observational data (light blue circles) are the same as in Fig. 12 in Knutson et al. (2012) and are taken from Knutson et al. (2012) (3.6 and 4.5 µm), Knutson et al. (2007, 2009); Agol et al. (2010) (8 µm) and Knutson et al. (2009) (24 µm).

We now examine trends in the phase curve properties with the quenched ratio. Two factors control how the phase curve in the quenched case differs from the the equilibrium chemistry case. First, the change in opacities directly impacts the thermal structure of the planet, as discussed in Section 3.2. Second, the change in opacities causes the photospheric level to shift upwards or downwards. As a result, the outgoing radiation probes cooler or hotter layers. This change in the location of the photosphere can also be studied by postprocessing the output of GCM simulations assuming equilibrium chemistry with quenched opacities instead of self-consistently including quenched
opacities in the GCM. It is thus of significant interest to examine the relative importance of both of these factors in shaping the predicted phase curve. If it turned out that the change in the thermal structure had only a small effect on the phase curve, modelers could restrict themselves to including disequilibrium chemistry in the postprocessing of the GCM output, which is simpler and computationally less expensive. In addition to computing the phase curves from the simulations with disequilibrium chemistry (self-consistent opacities), we thus also computed phase curves by postprocessing the output from the equilibrium chemistry simulation with quenched opacities.

Figures 6 to 8 show trends in secondary eclipse depth, phase curve offset and phase curve amplitude, respectively, with the quenched ratio for phase curves obtained from both simulations with self-consistent opacities and from the equilibrium chemistry simulation postprocessed with quenched opacities. If both curves align, the change is dominated by the shift in the photosphere pressure. If there are large discrepancies between the postprocessed and the self-consistent GCM phase curves, the change in thermal structure plays an important role.

In the 3.6 and 8 µm bands, which include strong methane absorption features, the phase curve amplitude increases with increasing methane abundance (Figure 8, while the phase curve offset and the secondary eclipse flux decrease (Figures 7 and 6, respectively). This is expected as the photosphere in these bands shifts to higher levels of the atmosphere with stronger day-night contrasts. All of these trends flatten once CH4 starts to dominate over CO. The phase curve amplitudes from the postprocessed simulations closely match the ones with self-consistent opacities, indicating that the change of the photospheric level is the dominant cause for this trend. For the phase curve offset, the direction of the trend is similar; however, the trend is weaker in the post-processed only points, indicating that the change in thermal structure significantly contributes to the trend.

In the 4.5 µm band, secondary eclipse flux, phase curve offset and phase curve amplitude from the postprocessed-only simulations are close to the equilibrium value, indicating that the location of the photosphere changes only marginally. In the simulations with self-consistent opacities, however, the secondary eclipse flux is increasing with increased methane abundance, in line with the hotter temperatures in the simulation described in Section 3.2. The phase curve offset also decreases with increasing CH4 in the CO dominated regime. The phase curve amplitudes stay similar.

In the 24 µm band, there are no trends in secondary eclipse and phase curve amplitude. For the phase curve offset, the simulations with self-consistent opacities replicate the same decreasing trend as in other wavelength bands, as would be expected for a trend due to a change in thermal structure.

3.5. Emission spectra

To move beyond a discussion restricted to the Spitzer bands, we plot the predicted emission spectra of the day side (Figure 9) and night side (Figure 10) for the CO-dominated simulations. We focus on our CH4/CO < 1 cases as these are expected to be more likely for the temperature range of HD 189733b. Even though we found in the previous subsections that the disequilibrium chemistry cases from our model do not match existing observations, it is instructive to look at the effect of disequilibrium chemistry on the emission spectra. The findings could also be applied to other planets in a similar temperature regime.

In general, the day side fluxes from the quenched simulations are lower than the fluxes from the reference case, while the night side fluxes from the quenched simulations are signif-
Figure 6. Secondary eclipse depths for different quenched CH$_4$/CO ratios. Values from the GCM simulations including the quenched opacities are shown as blue crosses connected by a solid line, while values obtained from postprocessing the equilibrium chemistry simulation are shown as orange crosses connected by a dashed line. The equilibrium value is indicated by the dashed grey line and the observed values from Knutson et al. (2012) are shown as a solid black line with the 1σ errors shaded in grey.

significantly higher than for the reference case. This is consistent with the change in energy balance mentioned in Section 3.2.

The quenched day side emission spectra deviate moderately from the equilibrium chemistry spectrum. The difference is largest in the water absorption bands between 1 and 2 µm for the CH$_4$/CO=0.001 spectrum (up to -30%) and largest near the 3.3 µm methane absorption band for the CH$_4$/CO=0.01 and 0.1 spectra (up to -20% and -40%, respectively). In the CH$_4$/CO=0.1 spectrum, methane absorption bands clearly show up.

In the night side spectra, for CH$_4$/CO=0.001 and 0.01 there are large differences compared to the equilibrium chemistry case, especially in the methane absorption bands. The largest flux difference can be found near the 3.3 µm methane band (up to 170% and 90%, respectively), but the 2.3 µm (up to 110% and 90%) and 7.7 µm (up to 60% and 40%) methane bands also show substantial flux differences. For the CH$_4$/CO=0.1 case, the difference to equilibrium chemistry is in general much smaller and the largest difference can be seen in the water absorption bands between 1 and 2 µm. In the region around 4.5 µm, the differences from the equilibrium chemistry case are small for all three quenched ratios, reinforcing our previous conclusion that this wavelength region is not suitable for detecting disequilibrium chemistry on the night sides of hot Jupiters.
Figure 7. Eastward offsets of the maximum flux with respect to secondary eclipse for different quenched CH$_4$/CO ratios. Values from the GCM simulations including the quenched opacities are shown as blue crosses connected by a solid line, while values obtained from postprocessing the equilibrium chemistry simulation are shown as orange crosses connected by a dashed line. The equilibrium value is indicated by the dashed grey line and the observed values from Knutson et al. (2012) are shown as a solid black line with the 1σ errors shaded in grey.

The fact that disequilibrium chemistry mainly affects spectral regions with CH$_4$ bands, as well as H$_2$O bands, raises the question how the spectral signatures of disequilibrium chemistry can be distinguished from the spectral signatures of increased or decreased CH$_4$ and H$_2$O abundances in equilibrium chemistry due to a non-solar C/O or C/H ratio. While for a single secondary eclipse or night side emission spectrum, these scenarios may look similar, we expect that the combination of a secondary eclipse and night side emission spectrum would be able to discriminate between these scenarios.

3.6. Simulated JWST spectra

In order to determine whether the CH$_4$/CO ratio can be distinguished with future observations, we simulated JWST observations of HD 189733b using PandExo (Batalha et al. 2017). PandExo is a noise simulator that uses the Space Telescope Science Institute’s exposure time calculator, Pandeia (Pontoppidan et al. 2016). Using PandExo, we find that in many NIRSpec and NIRISS observing modes the detector becomes saturated due to HD 189733b’s brightness (J=6.07). We therefore simulate data for two of NIRCam’s grisms, F322W2 (2.413-4.083 µm) and F444W (3.835-5.084 µm), and MIRI Low-Resolution Spectroscopy (LRS) (5-12 µm). These three modes all remain be-
low 80% full well saturation across the detector. The NIRCam grisms utilize the 64 x 2048 pixel subarray to reduce readout times. MIRI LRS uses a dedicated slitless prism subarray region.

Each instrument mode was simulated assuming only a single eclipse with equal time in eclipse as out of eclipse. We also assume a 40 PPM noise floor, which is similar to the noise floors found in WFC3 on HST (Kreidberg et al. 2014). We simulated data for different CH$_4$/CO ratios and for equilibrium chemistry. Observations were simulated for both the day side and the night side. Since PandExo only models eclipses and transits and not phase curves, the planet’s night side spectrum was given to PandExo as if it were the planet’s day side since the expected noise should be the same, except for the reduced brightness of the planet’s night side. We plot the results for the CO dominated simulations in Figure 11 in terms of the difference to the equilibrium chemistry model. We also include the simulated observations for the equilibrium chemistry case to give a sense of the expected residuals. Note that the scale on the y-axis is different in each panel. For better orientation, the regions shown in each panel are indicated with grey boxes in Figures 9 and 10.

Figure 8. Normalized phase curve amplitudes, defined as $A = 1 - F_{\text{min}}/F_{\text{max}}$, for different quenched CH$_4$/CO ratios. Values from the GCM simulations including the quenched opacities are shown as blue crosses connected by a solid line, while values obtained from postprocessing the equilibrium chemistry simulation are shown as orange crosses connected by a dashed line. The equilibrium value is indicated by the dashed grey line and the observed values from Knutson et al. (2012) are shown as a solid black line with the 1σ errors shaded in grey. Note that for the 8 µm band there is no observed value, as observations in this band did not cover the night side.
Figure 9. Predicted day side emission spectra, as would be observed at secondary eclipse. The ratio of the planet flux to the stellar flux is plotted in the top panel. The bottom panel shows the relative difference of the flux in each of the quenched simulations to the flux in the equilibrium chemistry simulation. The regions plotted in panels a and b of Fig. 11 are indicated with gray boxes. The dashed black lines at the bottom indicate the filter sensitivity profiles of the Spitzer 3.6 $\mu$m, 4.5 $\mu$m, 8 $\mu$m and 24 $\mu$m bands.

In secondary eclipse, all quenched cases can be distinguished from the disequilibrium chemistry case in all three observing modes. The different CH$_4$/CO ratios 0.1, 0.01 and 0.001 can also clearly be distinguished from each other. With MIRI LRS, the fluxes in the CH$_4$/CO=0.01 and 0.001 cases are relatively close to each other, but can still be distinguished from each other at greater than 5$\sigma$ confidence.

Looking at night side emission spectra, the relative deviations from the equilibrium chemistry spectra are much larger. The CH$_4$/CO=0.01 and 0.001 can easily be distinguished from equilibrium chemistry in all three observing modes. The night side fluxes of the CH$_4$/CO=0.1 case are in general much closer to the equilibrium chemistry case in the wavelength ranges covered by these observing modes, but still can
Figure 10. Same as Fig. 9 but for night side emission spectra, as would be observed right before or after transit.

be distinguished from disequilibrium chemistry. With the NIRCam F322W2 grism and MIRI LRS, it is possible to distinguish the three shown CH$_4$/CO ratios from each other as well. With simulated data from the NIRCam F444W grism, it is still possible to tell the different CH$_4$/CO ratios apart from each other, but differences between the quenched ratios are only evident at wavelengths shorter than 4 µm, at the very edge of the wavelength range of this grism. Thus, it may not be the first choice for observing disequilibrium chemistry.

Our intent in presenting these simulated observations is to demonstrate the need of including disequilibrium chemistry when interpreting future observations with JWST and to guide observers in which regions to look for signatures of disequilibrium carbon chemistry. However, it would be premature to conclude that one would be able to determine the CH$_4$/CO ratio, as other factors not considered in this work can influence the results of GCM simulations and the emission spectra, including clouds, metallicity, C/O ratio and atmospheric drag (see Section
4. DISCUSSION

4.1. Importance of including disequilibrium chemistry in GCM

In their study of HD 209458b, Drummond et al. (2018) find that the effect of transport-induced disequilibrium chemistry on the temperature structure and winds is \(\sim 1\%\) relative to otherwise similar models with chemical equilibrium. In contrast, in our simulations of HD 189733b we find an effect on the temperature of up to \(\sim 5\%\) across large regions \((\sim 10\%\) in very localized regions\) when assuming realistic values of the quenched CH\(_4/CO\) ratio. This raises the question of why we find this effect to be so much larger. The answer lies in the cooler temperature of HD 189733b. On the hotter HD 209458b \((\text{equilibrium temperature } T_{eq} \approx 1450 \text{ K})\), CO remains the dominant species even on the night side in both equilibrium and disequilibrium chemistry. The change in opacity due to disequilibrium chemistry is thus less drastic. In contrast, on the cooler HD 189733b \((T_{eq} \approx 1200 \text{ K})\) the night side is cold enough that with equilibrium chemistry, CH\(_4\) becomes

Figure 11. Simulated JWST observations for NIRCam (left panels) using the F322W2 (circles) and F444W (squares) grisms and MIRI LRS (right panels, triangles). Plotted is the difference to the flux predicted by the equilibrium chemistry model, binned to a spectral resolution of \(R \approx 50\), with 1\(\sigma\) error bars.
the dominant species on a significant fraction of the night side. In disequilibrium chemistry, however, CO is expected to be the dominant species everywhere at pressures below 1 bar. Thus, when including disequilibrium chemistry in the radiative transfer, for most of the night side the dominant carbon species switches from CH\(_4\) to CO, significantly changing the opacities. With this switch between CH\(_4\) and CO as dominant species, the H\(_2\)O abundance changes by a factor of about two as well, further affecting the opacities. For planets much cooler than HD 189733b, even the day side becomes CH\(_4\) dominated in both equilibrium and disequilibrium chemistry. Regardless of exact disequilibrium abundances, the dominant species remains the same as in equilibrium chemistry on these planets. For this situation, we would thus again expect a smaller effect on the opacities and thus on the resulting temperatures and circulation.

Therefore, we expect that including the effect of disequilibrium carbon chemistry on the opacities in the GCM is most important for planets for which equilibrium chemistry predicts a CO dominated day side but a CH\(_4\) dominated night side. Assuming solar metallicity, the equilibrium abundance of CH\(_4\) becomes comparable to the CO abundance on the coldest regions of the night side for planets with equilibrium temperatures below \(\sim 1300\) K (Kataria et al. 2016, Fig. 7, taking the morning terminator profiles to be representative of the coldest regions of the planet). This demarcates the upper boundary of the regime in which we expect disequilibrium carbon abundances to be important in GCMs. The colder end of this regime has been less explored by GCMs. Based on 1D models, for solar composition the day side is expected to transition from CO-dominated to CH\(_4\)-dominated roughly at equilibrium temperatures around 700 K, with the transition occurring at slightly higher temperatures in equilibrium chemistry and at slightly lower temperatures in disequilibrium chemistry (Moses et al. 2013b; Venot et al. 2014; Miguel & Kaltenegger 2014). We thus expect that it is important to include disequilibrium CH\(_4\) and CO abundances in GCMs of hot Jupiters for planets with equilibrium temperatures between \(\sim 600\) K and 1300 K, assuming solar abundances. As the temperature of the transition between CH\(_4\) and CO strongly depends on the metallicity and C/O ratio, this temperature range may change depending on atmospheric composition. Future work spanning a range of planets is necessary to test this prediction. This could include both simulations coupling a chemical scheme to a GCM similar to Drummond et al. (2018) and Cooper & Showman (2006) and simulations with a simpler approach comparable to ours.

While we expect these findings to qualitatively also apply to atmospheres with moderate deviations from solar metallicity and C/O ratio, our conclusions may not apply to planets with C/O ratios >1. In that case, the composition changes drastically and the abundances of CH\(_4\) and HCN can become comparable to CO for both equilibrium chemistry and disequilibrium chemistry even on the day sides of planets with temperatures comparable to HD 189733b or hotter (Moses et al. 2013a). However, up to date no planet atmosphere has been shown to have a C/O ratio >1 (Benneke 2015).

4.2. Other factors impacting the predicted phase curves

As discussed in Section 3.3, disequilibrium carbon chemistry barely affects the 4.5 \(\mu\)m phase curve while significantly decreasing the phase curve amplitude in the 3.6 \(\mu\)m band, thus worsening the fit of the 3.6 \(\mu\)m phase curve to observations. Among the simulations we ran for this paper, the equilibrium chemistry simulation actually matches the data better than any of the disequilibrium chemistry simulations. At this point, we would like to note that the equilibrium chemistry phase curve in this pa-
per somewhat differs from the solar metallicity (equilibrium chemistry) phase curve presented in Showman et al. (2009) and Knutson et al. (2012). This is due to updates of the opacities (Freedman et al. 2014) and planetary and stellar parameters. In general, in all wavelength bands, the phase curve amplitude increases and the phase curve offset decreases slightly with the updated opacities. With these changes, the issue of the model overpredicting the night side fluxes in the 4.5 µm band is somewhat mitigated and difference in phase curve offset becomes the more dominant discrepancy between observations and the solar metallicity equilibrium chemistry model.

Our finding that the phase curve from the equilibrium chemistry simulation matches the observational phase curve better than the ones assuming disequilibrium chemistry is in agreement with Dobbs-Dixon & Cowan (2017) who find that based on their GCM the phase curve data are consistent with equilibrium chemistry. Does this mean that the atmosphere of HD 189733b is in chemical equilibrium? Based on the theoretical understanding of chemical kinetics and atmospheric dynamics, this is highly unlikely. It is much more likely that other processes that our model does not take into account are responsible for the shape of the phase curve. A likely explanation is the presence of clouds on the night side of HD 189733b. Cloud microphysics models (Lee et al. 2015; Powell et al. 2018) and GCM simulations including clouds with varying levels of complexity (e.g. Parmentier et al. 2016; Oreshenko et al. 2016; Lee et al. 2016; Lines et al. 2018) show that in the atmospheres of hot Jupiters there exist a variety of species that may condense to form clouds on the night side. An optically thick cloud deck on the night side would block the emission from hotter, deeper layers in the atmosphere, thus reducing the flux emitted on the night side over a broad range of wavelengths.

Clouds present only on the night side of the planet would therefore increase the amplitude of the phase curve. Mendonça et al. (2018a) include a simple parametrization of night side clouds in their GCM simulations of WASP-43b and study the effect on the spectra and phase curves. They are able to match the spectrally resolved HST WFC3 phase curve from 1.1-1.7 µm and the Spitzer 3.6 µm phase curve quite naturally. This demonstrates both the importance of including the effect of night side clouds and the potential of clouds to explain the low observed night side fluxes on several hot Jupiters. However, the effect of clouds on spectra depends on many unknown properties such as cloud top pressure, composition and latitudinal and longitudinal distribution and more theoretical and observational work is necessary. Furthermore, to match the 4.5 µm phase curve, Mendonça et al. (2018a) include additional CO$_2$ compared to the equilibrium chemistry abundance on the night side. There is no clear theoretical motivation for additional CO$_2$ on the night side—in contrast, Agúndez et al. (2014) find that disequilibrium chemistry tends to reduce the CO$_2$ abundance on the night sides of HD 209458b and HD 189733b compared to equilibrium chemistry. Mendonça et al. (2018b) find that disequilibrium chemistry reduces the CO$_2$ abundance on the night side in the C/O=0.5 case but increases it in the C/O=2 case. They conclude that the changes in CO$_2$ due to disequilibrium chemistry cannot resolve the remaining discrepancy in the 4.5 µm band.

Especially on relatively cool planets such as HD 189733b, clouds need not be restricted to the night side. An optically thick cloud deck extending into parts of the day side or even covering the entire planet is another plausible possibility (e.g., Parmentier et al. 2016; Roman & Rauscher 2018). Using a simple, constant particle size cloud scheme that includes radiative feedback, Roman & Rauscher (2018) find that
their cloud distribution (covering large fractions of the day side) results in a larger phase amplitude and lower phase offset than in the cloud-free case. They stress the role of cloud radiative feedback in shaping the phase curve. However, it is likely that a realistic distribution of clouds over the planets is not uniform in particle size and density (Lee et al. 2016; Lines et al. 2018), potentially resulting in a much more complex effect on the phase curve (Lines et al. 2018).

In addition to clouds, several other parameters not explored in this study can significantly impact the phase curves, including non-solar metallicities and C/O ratios and atmospheric drag. Independent of these factors, there are also moderate uncertainties associated with the numerical model, most notably the uncertainty in the opacities of some species which are not well-known at high temperatures. In this context, we would like to remind the reader that the simulations presented are pure forward models and we make no attempt to fit the observational data. The general trends observed in this paper thus are much more important and meaningful than specific predictions for the emitted flux or other observable quantities.

5. CONCLUSION

We have included the radiative effect of transport-induced disequilibrium CH$_4$, CO and H$_2$O abundances in a GCM to study the effect on the atmospheric circulation, phase curves and emission spectra. We have assumed that the ratio of CH$_4$ to CO is constant throughout the entire simulation (an assumption that is expected to be well fulfilled at pressures between $\sim 10^{-4}$ bars and 1 bar) and treat the CH$_4$/CO ratio as free parameter. The water abundance is updated accordingly, such that the total number of oxygen atoms is preserved. We ran simulations of hot Jupiter HD 189733b with eight different quenched CH$_4$/CO ratios.

We find that in the CO dominated case, which is the case favored by chemical kinetics models, the temperature changes locally by up to 100 K, with cooler temperatures compared to equilibrium chemistry on the day side and warmer temperatures on part of the night side. In the less plausible CH$_4$ dominated case, the addition of greenhouse gases leads to hotter temperatures everywhere at pressures higher than a few tens of mbars. When comparing the predicted phase curves from GCM simulations including disequilibrium CH$_4$ and CO abundances to phase curves obtained from an equilibrium chemistry GCM simulation that has been post-processed assuming quenched CH$_4$/CO abundances, we find that the eastward offset of the phase curve maximum can differ by up to 10$^\circ$.

We thus conclude that it is important to self-consistently include the effect of disequilibrium abundances of CH$_4$ and CO on the opacities in GCMs rather than including disequilibrium abundances only in the post-processing while continuing to use opacities based on equilibrium chemistry abundances in the GCM. This is in contrast to Drummond et al. (2018) who find in their study of HD 209458b that the effect of radiative feedback of disequilibrium abundances on the temperature and wind fields is only $\sim 1\%$. These seemingly conflicting results can be understood when considering the difference in the equilibrium temperatures of the planets: On the hotter HD 209458b, the CH$_4$ remains low compared to the CO and H$_2$O abundances in both equilibrium and disequilibrium chemistry even on the night side. In contrast, on the cooler HD 189733b, the night side is cool enough to be dominated by CH$_4$ in equilibrium chemistry. Including disequilibrium chemistry thus changes the dominant carbon species on half of the planet, resulting in much larger changes.

Furthermore, we show that disequilibrium CH$_4$ and CO abundances have only a small effect on the Spitzer 4.5 $\mu$m phase curve despite CO having a prominent absorption band
within this wavelength band. This is because the change in opacity due to CO is offset by a change in water opacity in the opposite direction. In wavelength regions dominated by CH$_4$ opacity, including the Spitzer 3.6 µm and 8 µm bands, the phase curve amplitude decreases significantly, resulting in a much worse fit to the observed Spitzer 3.6 µm and 8 µm phase curves. We thus conclude that disequilibrium carbon chemistry cannot explain the observed low night side fluxes in the 4.5 µm band, in contrast to the interpretation of Knutson et al. (2012). Other effects, for example night side clouds, must be responsible for the observed shape of the phase curve.

While disequilibrium chemistry does not explain existing observations of HD 189733b, it may be detectable on other hot Jupiters with a similar equilibrium temperature. Therefore, we examine the effect of disequilibrium carbon chemistry on emission spectra and simulated JWST observations. We find that in the expected CO dominated regime, spectral regions dominated by methane absorption bands are most suitable to observe disequilibrium abundances. Assuming that the spectral signatures of disequilibrium carbon chemistry are not obscured by clouds or other effects not considered in our model, it will be possible to distinguish between different quenched ratios with JWST in both secondary eclipse and phase curve observations.

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