Condensate cloud formation in exoplanet atmospheres

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ABSTRACT

Clouds can have a major impact on a planet's energy balance. They can increase a planet's albedo, reflecting the parent star's radiation. They can also be strongly absorbing[1]. As such, they impact the transport of radiation, the chemistry of the atmosphere, and the planet's surface temperature[2]. In this paper, we investigate whether particular molecular species can condense to form clouds, using the Clausius-Clapeyron framework as outlined in Sanchez-Lavega et al.[6]. We will use equations 7,12,16,20, and data from tables I, II, and III from their paper to validate our implementation of their framework. We'll accomplish this using solar system planet atmospheres referenced in their paper as well as their reference exoplanet, HD209458b. Our implementation attempts to determine the possibility of Fe condensate cloud formation in WASP43b and HD189733b. If clouds are present, we attempt to determine the location of the cloud base. Our results are mixed, finding cloud formation in HD189733b, but none in WASP43b.

Introduction

In section 1, we detail the techniques used to determine whether clouds may form in an atmosphere and where the cloud base is located. In section 2, we show the results of our model applied to various solar system planets, and to the well studied exoplanet HD209458b, to validate that we get expected results from our model. Following these tests, we then apply our model to the exoplanets HD189733b and WASP43b, looking for the formation of Fe condensate clouds in their atmospheres.

1. Methods

The equations and data used in the model are taken from Sanchez-Lavega et al.[6]. We make several assumptions: There is no heat exchange, i.e. the atmosphere is adiabatic, and that the temperature decreases with altitude, $\frac{dT}{dz} < 0$, and that C_P (specific heat), g (surface gravity), and Γ_a (adiabatic gradient) are all constant. Finally, we assume that the atmosphere obeys the ideal gas law[6]: $P(T) = \rho R^* T$ where ρ is the density of the atmosphere, and $R^* = \frac{R}{\mu}$ and μ is the mean molecular weight of the atmosphere. For calculating the P-T profile of a planet's atmosphere, we use eqn.(1).[6]. And, for calculating the saturation vapor pressure of a condensible species, we use eqn.(2), divided by X_C, the volume mixing ratio, $\frac{P_V}{X_C}$.[6].

$$P(T) = P_o \left(\frac{T}{T_o} \right)^{\frac{g}{\Gamma_a R^*}} \tag{1}$$

$$ln(P_V) = ln(C) + \frac{1}{R_V} \left[-\frac{L_o}{T} + \Delta\alpha T + \frac{\Delta\beta}{2} \right] \tag{2}$$

In the Eq. 1 above, for terrestrial planets, T_o and P_o are values at the planet's surface. Whereas, for gas giants, $P_o = 1$ bar and $T_o = T(P_o)$. $\Delta\alpha$ $(Jg^{-1}K^{-1})$ and $\Delta\beta$ $(Jg^{-1}K^{-2})$ are empirically derived values. L_o (Jg^{-1}) and C (bars) are constants taken from Table II[6] in Sanchez-Lavega et al.. Finally, R_V is the ideal gas constant divided by the mean molecular weight of the condensible species. The location of the cloud base is identified graphically where the atmosphere's P-T curve and the condensate's saturation vapor pressure curves intersect, or where $P_{Cl}(T_{Cl}) = \frac{P_V(T_{Cl})}{X_C}$. Using this relation, and those below, we can calculate location of the cloud base.

$$P(T) = P_o \left(\frac{T}{T_o} \right)^{\frac{g}{\Gamma_a R^*}} \implies \quad z = \frac{-R^* T_o}{g} \ln \left(\frac{P}{P_o} \right) \tag{3}$$

Note: Values for X_c,the volume mixing ratio, and μ, the mean molecular weight of the atmosphere, and μ_{cl}, the mean molecular weight of the condensible species are taken from Tables I, II, and III in Sanchez-Lavega et al.[6].

2. Results

To validate our implementation, we applied our model to Earth, Venus, Neptune, and HD209458b. The SVP curves are in agreement with those in Sanchez-Lavega et al.[6]. Graphically, clouds form where the SVP curves intersect with the pressure-temperature curve. The main difference between their plots and ours have to do with the atmosphere P-T curves. They use actual data, whereas we use eqn.(1), taken from Sanchez-Lavega. We do apply both theoretical and actual P-T plots to Earth (Fig. 2). All code for the model can be found at: https://github.com/rschroder/exoplanet_clouds. Instructions on how to run the code are documented there. For comparison to the Sanchez-Lavega plots, see Fig. 3 in their paper here: http://www.atmo.arizona.edu/students/courselinks/fall07/atmo551a/pdf/Clouds_in_Planetary_Atmospheres_AJP_June_2004.pdf. Until very recently, *Fe*, had not been observed in exoplanetary atmospheres, in spite of its abundance.[7]. We applied our model, checking for the formation of Fe condensate clouds, to WASP43b and HD189733b, see Fig. 5 and Fig. 6. For these computations, we assumed a range of mixing ratios: $10^{-3} \rightarrow 10^{-6}$, a range expanded by several orders of magnitude from the value used in Sanchez-Lavega for HD209458b. Calculated values for g and Γ_a can be found in the captions of Fig. 5 and Fig. 6. We find the possibility of cloud formation in HD189733b, but none in WASP43b.

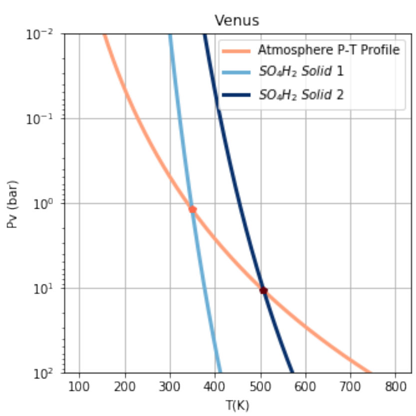

Figure 1. The SVP curves for SO_4H_2 with different mixing ratios. One at 67 km above the surface, at 349 K and 1.2 bar. The other at 33 km above the surface at 508 K and 10.8 bar.

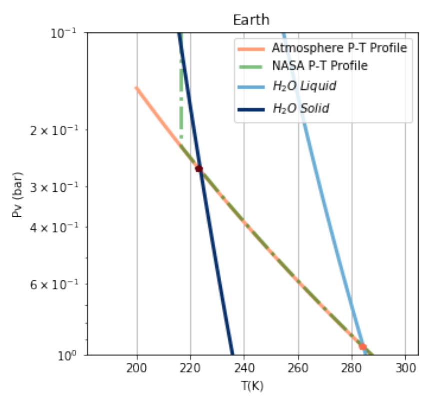

Figure 2. The SVP curves for different phases of H_2O. One at 0.61 km above the surface, at 284 K and 0.94 bar. The other at 11 km above the surface at 223 K and 0.264 bar. Note: the green dashed line is P-T data from NASA.

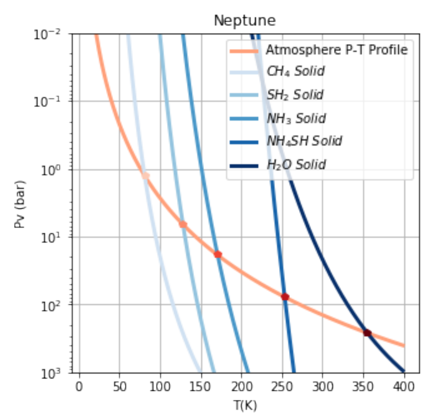

Figure 3. CH_4 at -5.5 km, 81 K, 1.2 bar. SH_2 at -46 km, 128 K, 6.5 bar. NH_3 at -71 km, 170 K, 18 bar. NH_4SH at -107 km, 253 K, 77 bar. H_2O at -137 km, 355 K, 261 bar. Note: $T_o = T_{eq}$

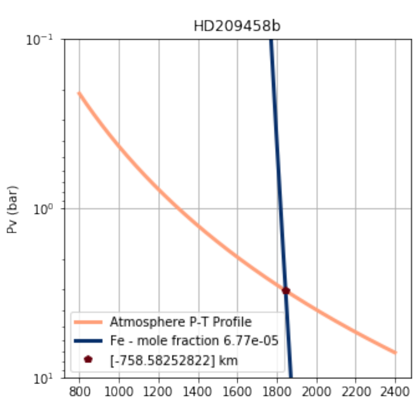

Figure 4. Our model reproduces the result from Sanchez-Lavega for HD209458b. Note: Values for g and Γ_a are taken from Tables I, II, III[6]

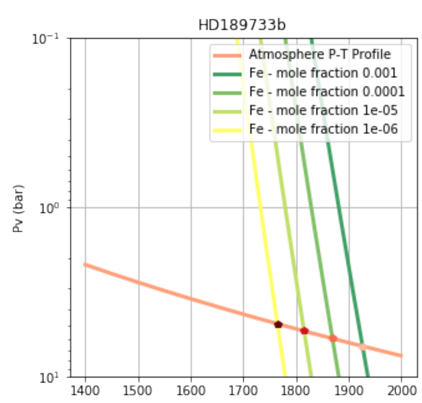

Figure 5. Model applied to *Fe* over a range of mixing ratios, resulting in *Fe* condensate clouds forming from z= -380 km to -400 km. Note: $g = 21.85\frac{m}{s^2}$ and $\Gamma_a = \frac{g}{C_P} = 1.514\frac{K}{m}$

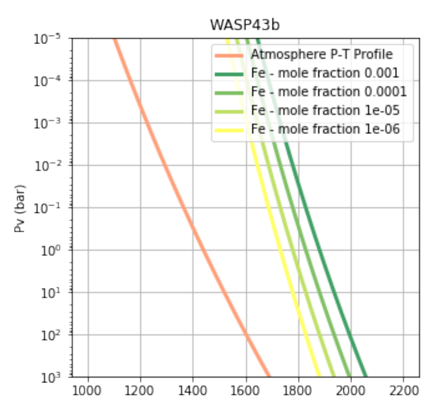

Figure 6. Model applied to *Fe* over a range of mixing ratios, resulting in no *Fe* condensate clouds forming. Note: $g = 47.3\frac{m}{s^2}$ and $\Gamma_a = \frac{g}{C_P} = 0.264\frac{K}{m}$

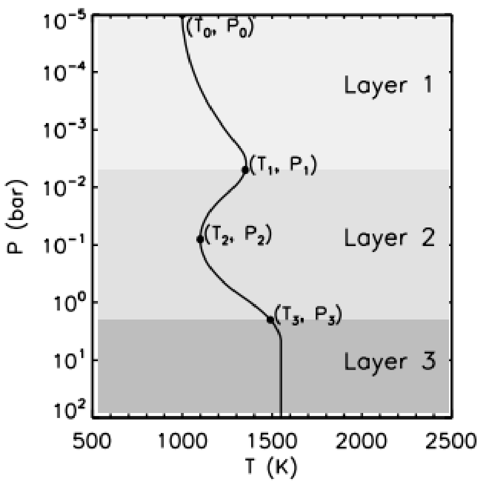

Figure 7. Figure taken from Madhusudhan and Seager[5]

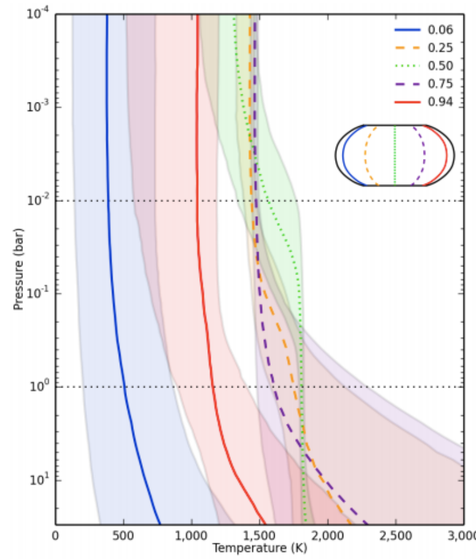

Figure 8. Figure taken from Stevenson et al.[8]

3. Conclusions

Our model made several assumptions that require further exploration. We assumed constant g, constant C_P, and an adiabatic pressure-temperature profile. It would be interesting to see what impact including gravity's dependence on height, and the specific heat's dependence on temperature would have on this model. The assumption of a purely adiabatic pressure-temperature profile did produce positive results when applied to our solar system planets, but such an assumption seems dubious. Madhusudhan and Seager[5] suggest a different, parametric, approach for modeling an atmosphere's P-T profile (see Fig. 7). For WASP43b, we did not find cloud formation. Here, our pressure-temperature profile appears somewhat supported to that found by Stevenson et al.[8](see Fig. 8). Finally, the nature of our investigation is highly speculative given the lack of constraints on the presence of Fe in WASP43b and HD189733b.

References

1. Seager, S., *Exoplanet Atmospheres: Physical Processes*, Princeton University Press, 1st edition, 2010.

2. Marley, M., Ackerman, S, Cuzzi, J., Kitzmann, D., *Clouds and Hazes in Exoplanet Atmospheres*, Comparative Climatology of Terrestrial Planets, University of Arizona Press, p.367-391, 2013.

3. Ackerman, S, Marley, M., *Precipitating Condensation Clouds in Substellar Atmospheres*, The Astrophysical Journal, 2001.

4. Crossfield, I., *Observations of Exoplanet Atmospheres*, Publications of the Astronomical Society of the Pacific, Volume 127, Number 956, 2015.

5. N. Madhusudhan, S. Seager, *A Temperature and Abundance Retrieval Method for Exoplanet Atmospheres*, The Astrophysical Journal, 707:24–39, 2009 December 10.

6. Sanchez,-Lavega, A., Perez-Hoyos, *Clouds in Planetary Atmospheres: A Useful Application of the Clausius-Clapeyron Equation*, American Association of Physics Teachers., DOI: 10.1119/1.1645279, 2003.

7. H. Jens Hoeijmakers, David Ehrenreich, Kevin Heng, Daniel Kitzmann, Simon L. Grimm, Romain Allart, Russell Deitrick, Aurélien Wyttenbach, Maria Oreshenko, Lorenzo Pino, Paul B. Rimmer, Emilio Molinari Luca Di Fabrizio, *Atomic iron and titanium in the atmosphere of the exoplanet KELT-9b*, ANaturevolume 560, pages453–455, 2018.

8. Kevin B. Stevenson, Jean-Michel Désert, Michael R. Line, Jacob L. Bean, Jonathan J. Fortney, Adam P. Showman, *Thermal structure of an exoplanet atmosphere from phase-resolved emission spectroscopyter's cloud bands and decks 2. Distribution and motion of condensates*, Science, Vol. 346, Issue 6211, pp. 838-841 2014.