USING A GREY BODY MODEL TO DETERMINE METAL CLOUD DEVELOPMENT IN EXTRASOLAR ATMOSPHERES.
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Introduction: Since the discovery of the first extrasolar planet less than 10 years ago, more than 1000 planets have been discovered orbiting other stars. The increased number of observations has also fueled an effort to model the atmospheres of these planets, especially in terms of the thermal profile, atmospheric compositions, and cloud formation.

Clouds have a large impact on their respective atmospheres, especially in influencing the planet's albedo and contributing to the energy transfer. The chemistry of a cloud, as well as the particle size, governs the reflection and absorption of radiative energy. In addition, the constituent properties of a cloud would characterize its opacity, and in the case of an optically thick cloud, would heat the atmosphere by a back-warming effect [1]. The existence of silicate clouds could alter the atmospheric chemistry and structure of an extrasolar atmosphere [2]. Therefore it is important to determine if the development of such clouds is possible within the extrasolar atmosphere and at what physical limits.

This project aims to determine a simple, one-dimensional thermal model that can be applied to extrasolar planetary atmospheres. The model will specifically be used for Hot Jupiters to determine the height of silicate and iron cloud formation, in an effort to aid in the understanding of atmospheres with metal cloud development.

Method: A simple radiative-convective model was used to determine a baseline thermal profile of an extrasolar planet. The model is largely based on that of Robinson and Catling (2012) and was intended to be applicable to several planets as a generalized model [3].

The model is determined as a function of optical depth which is then related to atmospheric pressure by

$$\boldsymbol{\tau = \tau_0 \left(\frac{p}{p_0}\right)^n} \qquad (1)$$

Where τ is optical depth, τ_0 is the grey infrared optical depth at the reference pressure p_0, and n controls the strength of the scaling and is typically a number between 1 and 2, depending on whether the atmosphere is well-mixed. Temperature is then defined as a function of pressure (and thus optical depth) with the equation:

$$\boldsymbol{\sigma T^4(\tau) = \frac{F_{net} + F_i}{2}(1 + D\tau)} \qquad (2)$$

Where F_{net} is the net solar flux, F_i is energy flux from the planet's interior, D is the diffusivity factor, and σ is the Stefan-Boltzmann constant. D for our model is set as 1.66 in agreement with the literature [3, 4].

The model is then applied to known planets using defined parameters including the luminosity, effective temperature and radius of the star, as well as planetary parameters: distance from the star, radius, equilibrium temperature and the effective temperature, which is dependent on the bond albedo.

Once the thermal profile of the planet is plotted, the saturation vapor pressure curves of both iron and enstatite ($MgSiO_3$) are overlaid to determine cloud base height. The equations for these curves are the well-known vapor pressure relations for both [1, 5, 6]. Equation 3(a,b) calculate the saturation vapor pressure for iron above and below its melting point of 1800 K, respectively. Equation 4 computes the saturation vapor pressure for enstatite.

$$\boldsymbol{e_s(Fe,\ solid) = exp\left(15.71 - \frac{47664}{T}\right)} \qquad (3a)$$

$$\boldsymbol{e_s(Fe,\ liquid) = exp\left(9.86 - \frac{37120}{T}\right)} \qquad (3b)$$

$$\boldsymbol{e_s(MgSiO3) = exp\left(25.37 - \frac{58663}{T}\right)} \qquad (4)$$

Results & Discussion: The model was successfully applied to several atmospheres. The first goal was to make sure that the model profile was the expected output. We chose extrasolar planets specifically exhibiting a wide range of effective temperatures to determine approximate temperatures at which metal clouds would be (or not) able to form. The results of these runs are presented in Fig. 1 with cloud formation possible where the vapor pressure curves intercept the planetary thermal profile. The model output was as expected, where at lower planetary effective temperatures metal clouds are only possible at lower altitudes. With increasing effective temperatures, metal clouds will form higher in the atmosphere until eventually the temperature is high enough that enstatite is unable to form, followed by iron.

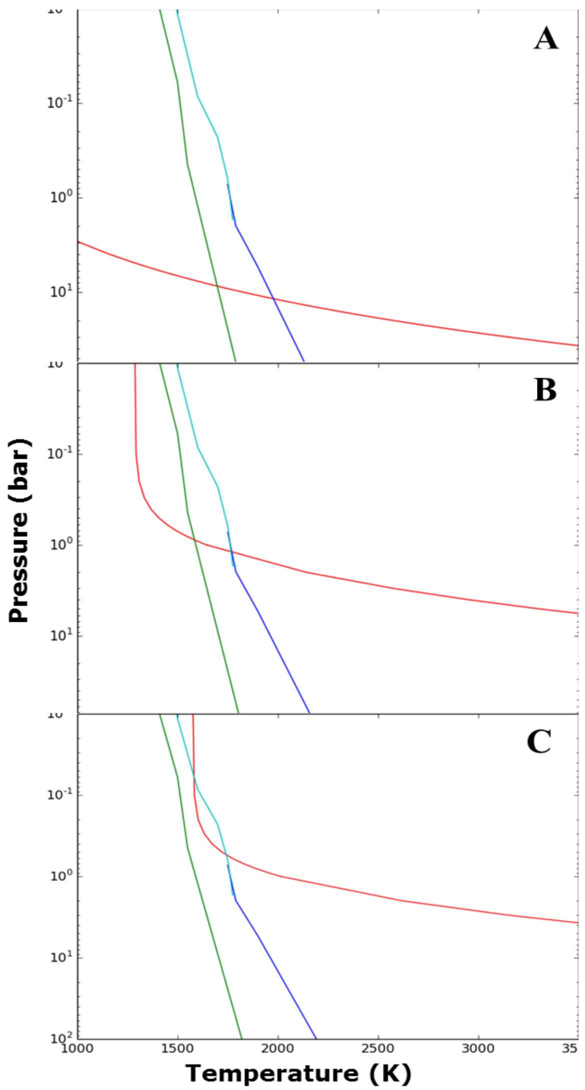

Figure 1. Thermal profile (red) and vapor pressure curves for enstatite (green) and iron (blue) for three planets. Gj-436b (A) with an effective temperature of 604 K, Corot-19b (B) with an effective temperature of 1531 K, and Hat-P-23b (C) with an effective temperature of 1876 K.

The model was applied to planet HD 209458b, as this planet has been studied extensively thus providing possible comparisons. HD 209458b has an effective temperature of 1397 K. The model showed that while the temperature profile does not match previous models at the highest and lowest pressures, the reference values are correct. Additionally, the temperatures and pressures that iron and enstatite clouds are expected to form at are accurate within approximately 10 bar. The results of this model can be found in Fig. 2.

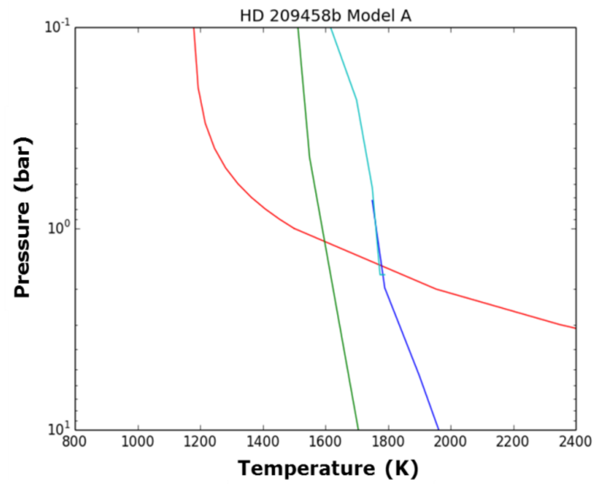

Figure 2. Thermal profile (red) and vapor pressure curves for enstatite (green) and iron (blue) for HD 209458b.

Conclusion: A simple one-dimensional radiative-convective model was created based on the model of Robinson and Catling (2012) [3]. The model was developed in order to determine if and where metal condensates would form in an extrasolar atmosphere. The model meets preliminary expectations in terms of cloud depth based on the planet's effective temperature (Fig. 1).

The next steps for this project include further refinement of the model parameters as well as application to additional extrasolar planets. Initially, we will attempt to further constrain our model to agree with those already published on well-known extrasolar planets. Additionally, cloud chemistry of compounds other than enstatite and iron, as well as cloud heights will be quantified.

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