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Model Atmospheres for Volatile-Rich Hot Rocky Planets

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Abstract

We are building a versatile set of self-consistent atmospheric models to calculate the structure, composition, and spectra of hot rocky exoplanets in short period orbits. To date, more than 100 such hot rocky exoplanets have been confirmed, and they will form the majority of small planets in close-in orbits to be discovered by the TESS and Kepler K2 missions. These hot worlds offer the best opportunity to characterize rocky exoplanets with current and future instruments. We are using a fully non-grey radiative-convective atmospheric structure code with cloud formation combined with a self-consistent treatment of gas chemistry above the magma ocean. Being in equilibrium with the surface, the vaporized rock material can be a good tracer of the bulk composition of the planet. We are investigating both volatile-poor and volatile-rich compositions, with the volatile-poor ranging from completely depleted, to water-free (Venus-like), to containing only sulfur and halogens (Io-like). To properly account for these exotic compositions and thermodynamic regimes, we are working on a self-consistent treatment of vertical mixing, condensation, and non-ideal gas behavior. We present our preliminary results for the atmospheric structure of volatile-rich hot rocky as a function of planet-star distance. Our models will inform follow-up observations with JWST and ground-based instruments, aid the interpretation of transit and eclipse spectra, and provide a better understanding of volatile behavior in these atmospheres.

1.Introduction and Methods

Hot rocky planets in short and ultra-short orbits will offer us the first opportunities to characterize rocky planets outside our Solar System. Such targets will be scheduled among the first transit and eclipse observations for JWST. However, we currently lack a reliable set of models to guide the planning of such observations and help their interpretation.

1.1 Ultra-Short period planets

Ultra-short period (USP) planets have orbital periods of the order of a day or less [1]. They undergo strong irradiation from the host star. Their atmosphere is thought to be the result of evaporation from the hot surface and stellar processing. A few such rocky planets have measured masses and radii, which are consistent with a rocky composition, as shown in Table 1.

Table 1: USP planets with measured masses and radii

Planet	**p (days)**	**a (AU)**	**Mass (M_{Earth})**	**Radius (R_{Earth})**
Kepler 78b	0.36	0.01	1.87	1.2
Kepler 10b	0.84	0.0168	3.72	1.47
Corot 7b	0.85	0.0172	4.73	1.585
K2-106b	0.57	0.0116	8.36	1.52
HD 3167b	0.96	0.0182	5.02	1.575
K2-131b	0.37	0.0100	6.5	1.81
WASP-47e	0.79	0.0173	6.83	1.81
55 Cnc e	0.74	0.0154	6.4	1.92
K2-141b	0.28	0.0073	5.08	1.51

1.2 Equilibrium Chemistry

We are investigating a range of compositions from volatile rich to volatile poor. In the volatile-rich limit we started with the compositions of bulk silicate Earth (BSE) and continental crust (CC) from [3], and solar abundances for comparison purposes. The equilibrium abundances take into account condensation and gas-rock equilibrium. Work on other compositions, such as Venus-like and Io-like is in progress. Preliminary work shows that the atmospheres of Io-like planets will be dominated by SO2 and sulfur-bearing hazes and condensates. The inclusion of clouds and hazes in these models will be essential for reproducing these atmospheres.

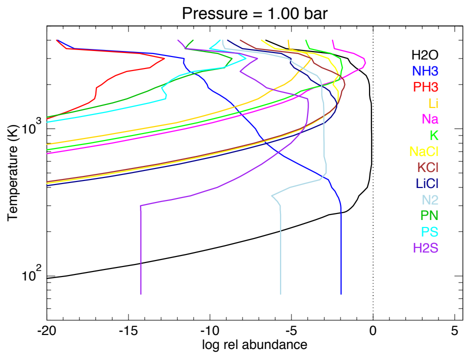

Figure 1: Plot of the most abundant species as a function of temperature at 1 bar pressure for the bulk silicate earth composition, assuming equilibrium chemistry.

1.2 Molecular Opacities

We have vastly increased our already large opacity database by adding new molecules with line lists computed by the ExoMol group. These are: AlO, CS, CaO, KCl, LiH, NaCl, PO, PS, CH, CN, CP, NH, NaH, PN, ScH, and TiH. For our conditions, the most important will be NaCl and KCl. The H2O and CH4 opacities are shown for comparison.

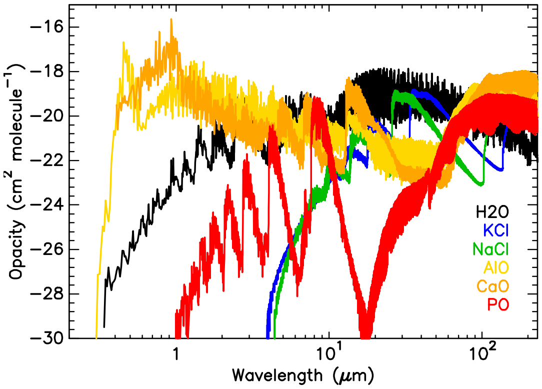

Figure 2: Opacity calculations for several new species. NaCl and KCl are abundant species in our context, and H2O is shown for comparison.

2.Results

2.1 Radiative-Convective Equilibrium Models

Using our well-tested radiative-convective equilibrium code [3],[4],[5] we ran models for these three compositions, at decreasing separation between the planet and the star. We build 1D models for a planet similar to Kepler 78b: g=13 m/s2, around a 5100 K star (BT-settl model with log g=4.5), with surface pressure from 1 to 100 bar. We vary the distance from the star from 0.05 to 0.01 AU to follow the changes in atmospheric structure. These preliminary models do not include clouds and hazes. We calculate the abundance profiles by interpolating the equilibrium chemistry tables on the new pressure-temperature profiles. The solar composition will produce a case similar to a hot Jupiter, up to the surface boundary conditions.

In all cases (for all three compositions) we note a turnover of the pressure-temperature profiles around 0.011 AU from the star. This is similar to the finding for hot Jupiters in [6] (two families , as a function of stellar irradiation). The strong thermal inversion in the upper atmosphere could be due to a new absorber at these temperatures, but this effect might be mitigated by photochemistry. We will address this aspect in future work.

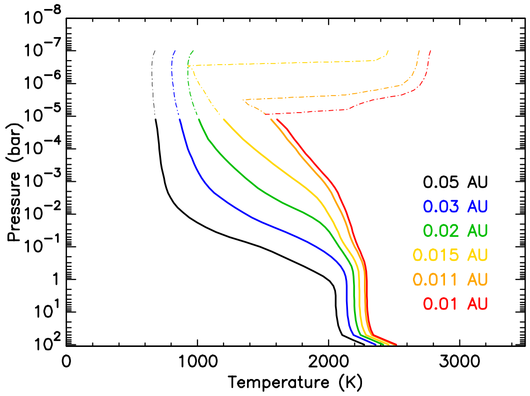

Figure 3: Pressure-temperature profiles for the BSE compositions at various distances from the star.

2.2 Abundances profiles

Using the abundance profiles corresponding to the equilibrium structure, we select the strongest absorbers by multiplying the abundances with the opacities at 2000 K and 0.1 and 1 bar. These will be representative for the hottest planets, closest to the star. Methane will start to dominate as the models approach 1000 K. The first eight highest contributors are selected.

The figures below show a comparison between the vertical molecular abundance profiles for the BSE composition at 0.05 AU and 0.01 AU, respectively. While these atmospheres are dominated mostly by water and CO2, we note other dominant species, such as K, Na, HCl, HF, NaCl, and SO2. These profile will be further affected by vertical mixing and photochemistry.

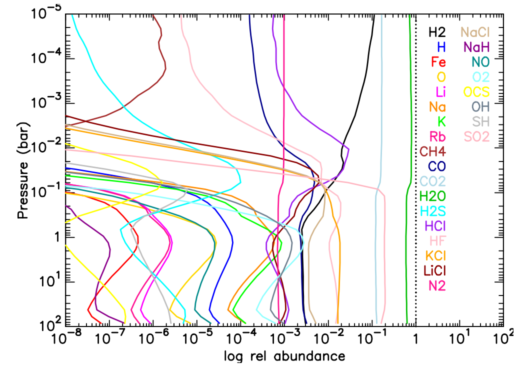

Figure 4: Molecular abundances for the BSE composition at 0.05 AU from the star

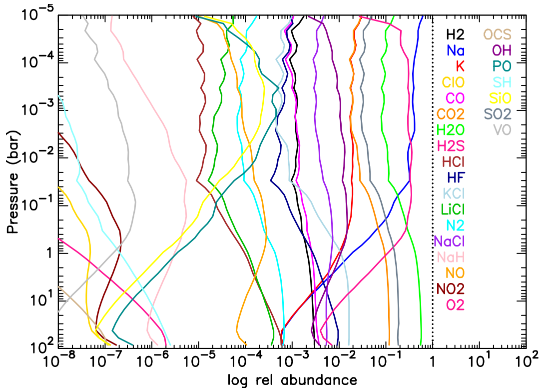

Figure 5: Molecular abundances for the BSE composition at 0.01 AU from the star

2.3 Thermal emission and secondary eclipse spectra

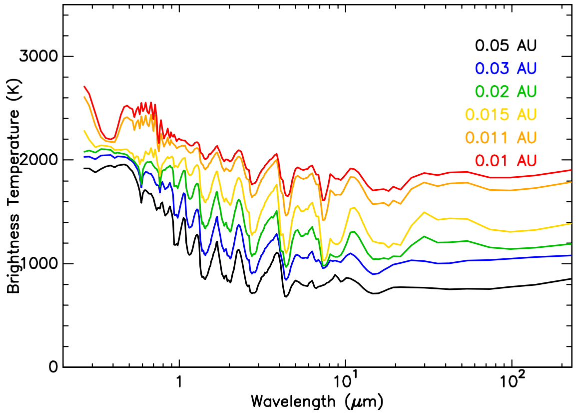

Figure 6: Thermal emission for the Bulk Silicate Earth composition as a function of distance from the host star.

The thermal emission of the planets results as a by-product of our radiative-convective equilibrium model. Due to calculation speed constraints in this iterative code, the radiative transfer treatment uses the correlated-k coefficients method with 196 windows from 0.25 to 200 microns, which results in a low-resolution spectrum. A high resolution version can be calculated using a line-by-line code.

We calculate the secondary eclipse depths assuming the radii for the Kepler 78 system. Work on the transit spectra is in progress.

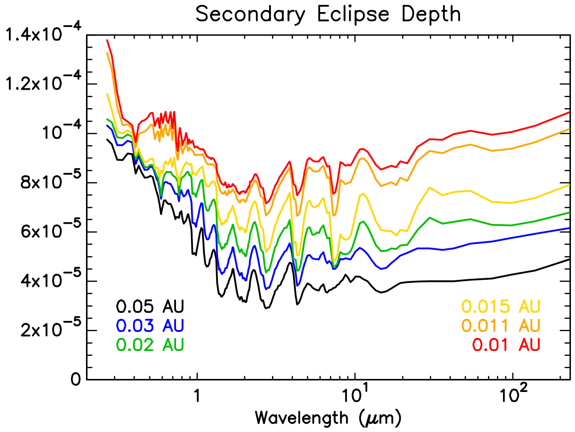

Figure 7: Secondary eclipse spectra for the Bulk Silicate Earth composition as a function of distance from the host star.

3. Summary and Future Work

We present a series of models for volatile-rich hot rocky planets, as a function of distance from the host star. We have investigated three possible compositions, namely solar, bulk silicate earth, and continental crust. The solar composition is taken as a reference case, where we recover the known results for hot Jupiters, with some extra opacity sources. In all cases we wind a turn-over of the pressure-temperature profile when the planet is at 0.011 AU or closer to the star. This change could be due to a new absorber becoming important in the upper atmosphere, and has a detectable signature in both thermal emission and secondary eclipse spectra. we are working on refining these models by taking into account photochemistry, clouds and hazes, and the possibility of disequilibrium chemistry.

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