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Radiative equilibrium models of "hot Jupiters"

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Abstract. We present an extension of our equilibrium model, initially applied to 51 Peg b (Goukenleuque et al. 2000), to other irradiated extrasolar planets with different orbital distances (up to 1 AU). The model yields the mean atmospheric thermal structure and predicts the reflected spectral flux as well as the thermal flux emerging from such planets, in the visible and in the infrared wavelength ranges.

1. Introduction

The 1-M_J planets considered here, at orbital distances ranging from 0.05 to 1 AU, are assumed to circularly orbit a solar-type star which irradiates them. The planet's internal energy is neglected. The atmosphere of our models is limited at the bottom by an opaque cloud. Above the cloud deck, atmospheric opacity is provided by the collision-induced continuum of H_2-H_2 and H_2-He and by the rovibrational transitions from the gaseous species H_2O, CO, CH_4 and NH_3. The vertical distribution of all compounds is calculated assuming thermochemical equilibrium in each atmospheric layer and solar elemental abundances.

2. Thermal structures and spectra

2.1. Temperature profiles

Figure 1 shows the solution temperature profiles of the model for a planet at 0.05, 0.23, 0.5 and 1 AU. Since there is no condensible likely to form a cloud between 900 and 1500 K, the atmosphere is supposed to be clear down to 30 bar for planets larger orbital distances. In this case we assume that cloud condensation only occurs at deeper levels.
Unlike the giant planets of the Solar System, the atmospheres of these planets have no temperature inversion. However, heating from the stellar UV radiation (not included in the model) might result in a temperature inversion in the upper layers (above $\sim 10^{-4}$ bar). Except for the most distant planet of this sample, the atmosphere is subadiabatic over the whole grid of pressure, which fully validates the hypothesis of radiative equilibrium. At 1 AU, the temperature

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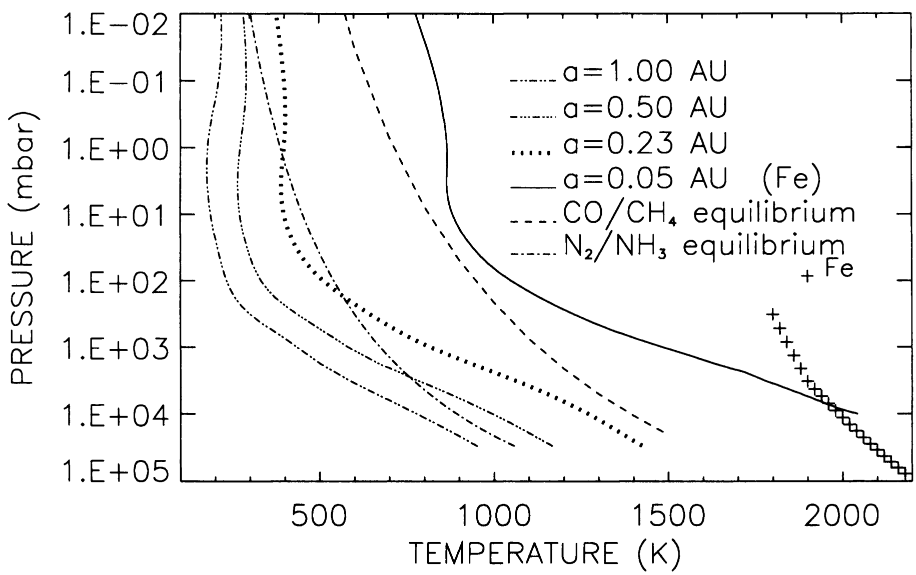

Figure 1. Solution temperature profiles for a 1-M_J planet orbiting a solar-type star at 0.05, 0.23, 0.5 and 1 AU.

profile exhibits a convective zone around 500 mbar.

In 51 Peg b, the most abundant carbon-bearing molecule is carbon monoxide, the methane mixing ratio reaching at most 8×10^{-5} around 30 mbar. The scheme is quite different for the further planets, and, CH_4 is fully dominant at 0.23 AU and beyond. Atmospheric temperatures for 51 Peg b prohibit its presence in significant amount. On the contrary, the farther planets have an atmosphere cold enough to allow NH_3 to dominate over N_2, above the $\sim$ 200-mbar level at 0.23 AU, and above the $\sim 2 \times 10^3$-mbar level at 1 AU.

2.2. Spectra

The reflected spectrum and the thermal emission spectrum are displayed for planets at 0.23 and 1 AU in Fig. 2. For 51 Peg b, the reflected flux is due, in part, to the Fe cloud whose albedo varies with wavelength. For the other planets it only results from Rayleigh-scattered radiation (mainly by H_2 and He).

Table 1. Bond albedo A_{BOND} and effective temperature T_{EFF} derived from the spectra.

ORBIT (AU)	CLOUD	P_{CLOUD} (bar)	A_{BOND}	T_{EFF} (K)
0.05	Fe	10	0.25	1234
0.23	R=0	30	0.32	565
0.50	R=0	30	0.32	383
1.00	R=0	30	0.32	277

R refers to the reflectance

Absorption by water vapor dominates the thermal spectrum for all planets. Synthetic spectra for all planets show a pronounced window at 4 μm (2500 cm^{-1}). As orbital distance increases, the peak flux at 10-20 μm (500-1000 cm^{-1}) is increasingly significant compared with the 4-μm window.

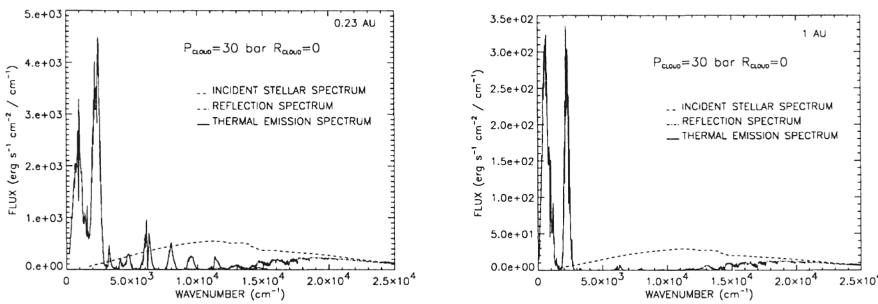

Figure 2. Stellar reflected and thermal spectra of a planet orbiting at 0.23 and 1 AU.

CH_4 absorption at 3.3 μm occurs in all planets. The 7.7-μm (1300 cm^{-1}) signature is visible in planets colder than 51 Peg b as the Planck function is shifted to longer wavelengths and the CH_4 abundance is larger. In these colder planets, NH_3 signature can be seen at 10.5 μm (950 cm^{-1}).

Finally, the Bond albedos and the effective temperatures derived from these spectra are gathered in Table 1. Similar values of the Bond albedos are found for the farthest three planets studied here. Bond albedos and effective temperature at 0.05 AU depend on the location of the cloud in the atmosphere and its optical properties.

3. Conclusion

Ultraviolet stellar radiation may penetrate as deep as 0.3 bar, as in Jupiter, and photodissociate NH_3, therefore inducing ammonia photochemistry in this region. Methane and water vapor are also expected to undergo photolysis but only in the high atmosphere. Because the close-in EGPs are within 1 AU of their respective parent stars the flux in the ultraviolet is high and the photochemical lifetimes of such species as CO, CH_4, H_2O, NH_3, etc. are short in their upper atmospheres and it is likely that photochemical equilibrium is the controlling process. Hence current thermochemical models might not predict the abundances and distribution of these species and their photochemical daughter products accurately. A detailed examination of the photochemical processes of these chemical species is needed to improve the model.

References

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