Radiation Transfer through an Extended Planetary Atmosphere

K. Schnabel, Ch. Helling, P. Woitke, E. Sedlmayr

(Zentrum für Astronomie und Astrophysik, TU Berlin, Hardenbergstraße 36, D-10623 Berlin, Germany)

Correspondence to: schnabel@astro.physik.tu-berlin.de, chris@astro.physik.tu-berlin.de, woitke@astro.physik.tu-berlin.de

1 Introduction

Transits of extrasolar planets in front of their parent stars provide an interesting possibility to gain more insight into the structures of planetary atmospheres. The imposed features on the spectrum of the parent stars – which carry information about the physical and chemical conditions in the planet's atmosphere – are, however, expected to be only of the order of 1% ... 2% (Moutou et al. 2001). The outermost, exospheric layers may cover about 10% of the total planet area (Brown 2001).

In present theoretical models, the extrasolar planet atmosphere is assumed to be in hydrostatic equilibrium. Different degrees of approximation are applied, especially concerning the modeling of phase transitions associated with cloud formation (e. g. Seager & Sasselov 2000, Goukenkeuque et al. 2000, Brown 2001). A crucial point in the comparison to observations is in any case the treatment of the radiative transfer which strongly depends on the completeness of the available molecular line opacity data (Jørgensen 1994).

Compiling a line opacity data set of 25 molecules and various continuum species from the Copenhagen database and the HITRAN database (Table 1), we have constructed a simplified planetary atmosphere including an extended equilibrium chemistry for 155 molecules in order to study possibly important molecular opacity carriers and respective wavelength ranges of observational interest. Element depletion by phase transitions has been neglected so far. The influence of photochemistry, which possibly affects the very outer exosphere, as well as planetary rotation and winds are not considered.

2 Model Atmosphere

Our simplified model of a planetary atmosphere is divided into two parts:

The **inner part** ($z \le R_{\rm Pl}$) is assumed to be dominated by convection, i. e. to have a roughly adiabatic structure. The adiabatic temperature structure $T(z)$ is calculated from

$$T(z) = T_0 - \frac{c_{\rm P}^0}{\alpha} + \sqrt{\left(\frac{c_{\rm P}^0}{\alpha}\right)^2 + \frac{2\bar{\mu}g}{\alpha}(R_{\rm Pl} - z)}\ ,$$

where the ansatz for the heat capacity $c_{\rm P} = c_{\rm P}^0 + \alpha(T - T_0)$ has been guided by Jupiter's atmosphere (Lewis 1995). The mean molecular weight $\bar{\mu}$ is assumed to be constant (see Table 2).

The total hydrogen particle density $n_{<H>}$ is calculated by assuming hydrostatic equilibrium

$$n_{<H>}(z) = n_0 \left(\frac{T(z)}{T_0}\right)^{\frac{c_{\rm P}^0 - \alpha T_0}{k}} \exp\left(\frac{\alpha(T(z) - T_0)}{k}\right)\ .$$

T_0 and P_0 are the values at the planet's radius $R_{\rm Pl}$ (see Table 2) from which n_0 can be calculated by applying the ideal gas law.

The **outer region** ($z > R_{\rm Pl}$) is assumed to be isothermal ($T(z) = T_0$). The total hydrogen particle density $n_{<H>}(z)$ is calculated from

$$n_{<H>}(z) = n_0 \cdot \exp\left(-\frac{g}{kT}(z - R_{\rm Pl})\right)$$

assuming hydrostatic equilibrium and the ideal gas law. To calculate the molecular particle densities $n^{\rm k}$, chemical equilibrium is assumed. The necessary chemical data originate from the electronic version of JANAF-tables (Chase et al. 1985).

3 Radiative Transfer Model

The flux of the star-planet-system is calculated according to Eq. (1) neglecting interstellar absorption and assuming isotopic scattering inside the planetary atmosphere. The variables have their usual meaning in the (p, s) coordinate system. The transport coefficients (κ_ν, ϵ_ν, σ_ν) are calculated by assuming LTE. The incident stellar radiation field $I_\nu^\star$ is approximated by a blackbody.

$$\begin{aligned} F_\nu(r) &= \left(\frac{\pi R_\star^2 - \pi p_{\max}^2}{d^2}\right) I_\nu^\star \\ &+ \frac{2\pi}{d^2}\left[\int_{p_{\min}}^{p_{\max}}\left(I_\nu^\star\, {\rm e}^{-\tau_{\max}} + \int_0^{\tau_{\max}} S_\nu(\tau_\nu)\, {\rm e}^{-\tau_\nu} d\tau_\nu\right) p\, dp\right] \\ &+ \frac{2\pi}{d^2}\int_0^{p_{\min}}\int_0^{\tau_{\max}} S_\nu(\tau_\nu)\, {\rm e}^{-\tau_\nu}\, d\tau_\nu\, p\, dp \end{aligned} \qquad (1)$$

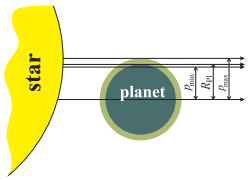

Fig. 1: Geometry of the star-planet-system.

Parameters:

star's effective temperature $T_{\rm eff}$	6000 K
stellar radius $R_\star$	8.352E+10 cm
planet's gravitational acceleration g	8.7E+2 cm s^{-2}
planet's radius $R_{\rm Pl}$	1.0E+10 cm
pressure at the planet's radius P_0	0.5 bar
temperature at the planet's radius T_0	1000 K
mean molecular weight $\bar{\mu}$	2.2 amu
C/O ratio in the planet's atmosphere	0.43
distance earth – parent star d	47 pc

Table 1: Model input parameter for the parent star HD 209458 and its transit planet HD 209458 b (for references see Schnabel 2001).

Database: The spectroscopic data for the calculation of the absorption coefficient have been adopted from the HITRAN 96 database and the Copenhagen database (Table 2) for line and continuum species. The partition functions for most of the molecules used in this work are taken from the HITRAN update 10/98, except for O_2 (Irwin 1988), H_2S (Irwin 1981), and HO_2 (HITRAN 96).

HITRAN 96		Copenhagen	
mol.	spectral range [cm^{-1}]	mol.	spectral range [cm^{-1}]
CO_2	442.0 - 9648	CO	910 – 6416
O_3	4.005 - 4061	TiO	2988 – 24.498
N_2O	4.190 - 5131	SiO	805 – 4872
CH_4	4.018 - 6184	H_2O	800 – 24988
O_2	1.213 - 15930	CH	333 – 44977
NO	5.009 - 3966	CN	670 – 36798
SO_2	4.004 - 4093	C_2	670 – 36798
NO_2	4.011 - 2938	C_3	800 – 13889
NH_3	4.675 - 5295	HCN	800 – 13889
HNO_3	4.000 - 1770	C_2H_2	800 – 12000
OH	4.601 - 9997	H_2-H_2(cia)	800 – 21998
H_2CO	4.001 - 2999	H_2-He(cia)	800 – 21998
N_2	1923.0 - 2625		
H_2S	4.992 - 2994		
HO_2	4.001 - 3676		

SCATTERING: Thomson, Rayleigh (H I, He I, H_2)
CONT. OPACITIES: C I, Mg I, Al I, Si I, H I , H^-

Table 2: Spectral range of the HITRAN 96 molecules (left; Rothman et al. 1998) and of the Copenhagen database (right; sampled data; see e.g. Helling 1999), cia = collision induced absorption.

4 Results

Particle Densities: Figure 2 depicts the particle densities of the important opacity species. At the inner edge of the model H_2O, CO, N_2 and SiO are most abundant. Further important molecules are CO_2, TiO, CH_4 and OH in decreasing abundance.

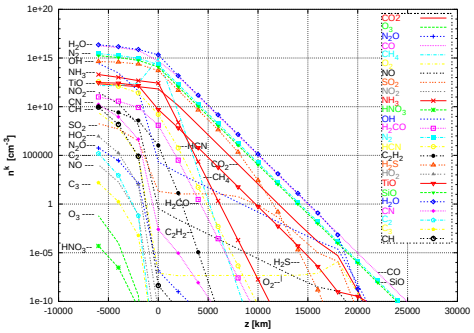

Fig. 2: Particle densities $n^k(z)$ in the atmospheric range $9.4 \cdot 10^4$km $< z + R_{\rm Pl} < 1.3 \cdot 10^5$km of the planet's atmosphere. $z = 0$ corresponds to $R_{\rm Pl}$.

At the outer edge CO, N_2 and SiO are most abundant, followed by TiO, H_2O, CO_2, OH and O_2.

Spectral Flux: Figure 3 depicts the subtracted logarithmic fluxes with (WPL) and without (WOPL) the transitting planet. The highest values correspond to the deepest planetary absorption lines. The lowest values correspond to the effect of the plant's continuum absorption, partially obscuring the star during the transit.

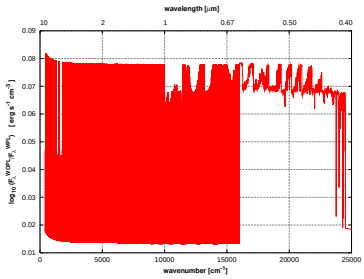

Fig. 3: Subtracted logarithmic fluxes $\log(F_\lambda^{\rm WOPL}/F_\lambda^{\rm WPL})$ (WPL = with planet, WOPL = without planet). The line dominated part of the spectrum up to 25.000 cm^{-1} is shown.

The blue part of the spectrum from 10.000 cm^{-1} to 25.000 cm^{-1} (0.4 μm to 1 μm) is mainly affected by H_2O, TiO, and O_2. The red part (< 10.000 cm^{-1}) is strongly influenced by H_2O, TiO, OH, CO_2, whereby H_2O from 900 cm^{-1} to 20.000 cm^{-1}, TiO from 5.900 cm^{-1} to 24.300 cm^{-1}, OH absorbs mainly in the range from 2.200 cm^{-1} to 10.000 cm^{-1} and CO_2 from 450 cm^{-1} to 9.300 cm^{-1}.

mol.	wavenumber [100 cm^{-1}]	wavelength [μm]	spectral characteristic
H_2O	9 ... 200	0.5 ... 11	wealth of weak lines
TiO	59 ... 240	0.4 ... 1.7	weak bands
OH	23 ... 100	1.0 ... 4.4	wealth of weak lines
CO_2	4.5 ... 93	1.1 ... 2	absorption bands
CO	20, 41, 61	4.9, 2.4, 1.63	band system
SiO	9, 23, 36, 48	11, 4.4, 2.7, 2	band system
O_2	16 ... 160	0.6 ... 6.3	narrow, significant absorption bands

Table 3: Strongest molecular absorption characteristics during the planet transit.

5 Summary

- The evaluation of the particle densities and cross sections suggest that H_2O, TiO, OH, CO_2, CO, SiO, and O_2 are the main molecular contributors to the total opacity of the planetary atmosphere in the outer region which is optically thin in the continuum.
- The line dominated part from 10.000 cm^{-1} to 25.000 cm^{-1} of the transit spectrum is mainly influenced by the three molecules H_2O, TiO, and O_2.
- In spite of its low particle density, it is surprising that O_2 is observable in the transit spectrum. These spectral features undoubtedly originate from the planetary, but not from the stellar atmosphere.
- The strength of the imposed molecular features on the spectrum during the transit, according to our model, are expected to be as large as 3% ... 6% for the considered giant gas planet.

6 Discussion

A simplified planetary model atmosphere has been constructed (compare Brown 2001) for which a radiative transfer along discrete rays has been carried out applying an extended opacity data set of 25 molecules and various continuum species.

Brown (2001) argue that H_2O, CO and CH_4 absorption features should appear from a model atmosphere comparable to ours. Hubbard et al. (2001) favor H_2O as dominating opacity species. Our work suggests H_2O, TiO, OH, CO_2, CO, SiO, and O_2 which is in reasonable agreement with other works despite the comparable roughness of our present planetary model atmosphere. The discrepancies regarding CH_4 are probably a consequence of the different planetary structures assumed, but may also be a result of different opacity data. CH_4 would be much more abundant in our model, if we had assumed a smaller value for T_0. Only a very limited number of molecular opacity species is considered in other works which is likely to be the cause for their negative results regarding molecules like TiO, SiO, CO_2. One might notice that CH_4, O_2, CO_2, and H_2O are suggested to be biomarker gases (Schindler & Kasting 2000).

The outer radius of our model planetary atmosphere is about 30% larger than the planet itself which compares approximately with Brown (2001).

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