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The future of Jupiter-like planets around Sun-like stars: first steps

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Abstract. Planets that orbit low- to intermediate mass main sequence (MS) stars will experience vigorous star-planet interactions when the host star evolves through the giant branches, including the asymptotic giant branch (AGB) phase, due to extreme luminosities and stellar outflows. In this work, we take the first steps towards understanding how a planet's temperature profile and chemical composition is altered when the host star evolves from the MS to the AGB phase. We used a 1D radiative transfer code to compute the temperature-pressure profile and a 1D chemical kinetics code to simulate the disequilibrium chemistry. We consider a Jupiter-like planet around a Solar-type star in two evolutionary stages (MS and AGB planet) by only varying the stellar luminosity. We find that the temperature throughout the AGB planet's atmosphere is increased by several hundreds of Kelvin compared to the MS planet. We also find that CO joins H_2O and CH_4 as a prominent constituent in the AGB planet's atmospheric composition.

Keywords. stars: AGB and post-AGB, Planets and satellites: gaseous planets, Planets and satellites: atmospheres

1. Introduction & Methods

The majority of discovered planets orbit low- to intermediate mass main sequence (MS) stars. Star born with masses between 0.8 and 8 $M_\odot$ evolve through the asymptotic giant branch (AGB) phase towards the end of their lifetime. AGB stars are cool, luminous giants that have developed a stellar outflow with mass loss rates upwards from $10^{-8}\,M_\odot yr^{-1}$ with luminosities around $10^3 - 10^4\,L_\odot$. Spiegel & Madhusudhan (2012) showed that Jovian planets around AGB stars (AGB planets henceforth) at orbits of several AU will receive irradiation levels comparable to hot Jupiters, which will increase the planetary temperatures to over ~ 1000 K. The question then arises how the AGB planet's temperature-pressure profile and chemical composition will adjust to these increased irradiation levels. A higher incident stellar flux will strengthen photochemical processes in the atmosphere, which are known to drive the chemical composition of MS hot Jupiters out of equilibrium (Baeyens et al. 2022). In this work, we asses how the thermal profile and chemical composition of a Jupiter-like planet is affected when it is irradiated by a MS and AGB solar-type star. We consider a $1\,M_J$ gaseous planet at an orbital distance of 5 AU from a $1\,M_\odot$ MS star (MS planet henceforth) and keep these parameters fixed when examining the AGB planet. The stellar luminosity is changed from $1\,L_\odot$ to $3 \times 10^3\,L_\odot$, the effective temperature from 5700 K to 4000 K and the stellar radius from $1\,R_\odot$ to $100\,R_\odot$. We use the one-dimensional radiative transfer package petitCODE (Mollière et al. 2015) to compute a thermal structure under radiative-convective equilibrium, starting from an atmosphere with a solar elemental gas mixture. (for more details, see Sect 2.1 of Baeyens et al. (2021)). We use the one-dimensional chemical kinetics model of Agúndez et al.

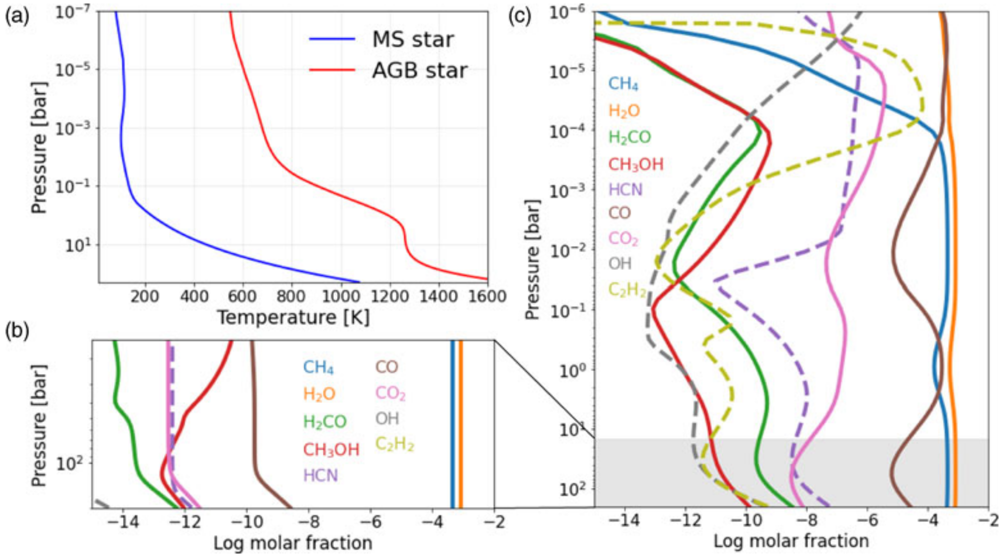

Figure 1. *a)* Temperature-pressure profile of the Jupiter-like planet considered in the work with a MS (blue) and AGB host star (red). *b)* Molar fractions of species in the deep atmosphere of the MS planet. *c)* Molar fractions of species in the atmosphere of the AGB planet. The shaded area indicates the pressure range that was probed for the MS planet.

(2014) with a chemical network of Venot et al. (2020) to compute the molecular composition. To compute the photochemical rates, we use the solar spectral energy distribution (SED, see Baeyens et al. (2022)) and scale it accordingly.

2. Results

Below ~ 1 bar, the MS planet's temperature (Fig. 1a) remains below 200 K, which does not allow the chemistry code to compute molar fractions. Therefore, we constrain the pressure range to the deepest layers in the chemistry model (Fig. 1b). H_2O and CH_4 are the most abundant species, with the latter being the expected dominant carbon-bearing molecule in cooler planets (Lodders & Fegley 2002). In general, we compute very similar quantities of H_2O, CH_4, CO, and CO_2 as Visscher et al. (2010), who modelled Jupiter's atmosphere. The AGB planet exceeds a temperature 500 K throughout the entire simulated pressure range. The distribution of constituents (Fig. 1c) is showing a complex pattern owing to hot temperatures in the middle/deep layers and intense photochemistry in the upper regions. The main difference with the MS planet is the enhancement in CO, which becomes a dominant constituent. The upper layers experience photodissociation as, for example, CH_4 is substantially depleted below ~ 0.1mbar. Finally, we note that we are most likely overestimating the XUV flux of the AGB star by scaling the solar SED with the luminosity of the considered AGB star, as AGB stars generally emit less XUV flux relative to the radiated black body flux (Montez et al. 2017).

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