Identifying the “true” radius of the hot sub-Neptune CoRoT-24b by mass loss modelling

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ABSTRACT

For the hot exoplanets CoRoT-24b and CoRoT-24c, observations have provided transit radii $R_T$ of $3.7 \pm 0.4 R_\oplus$ and $4.9 \pm 0.5 R_\oplus$, and masses of $\leq 5.7 M_\oplus$ and $28 \pm 11 M_\oplus$ respectively. We study their upper atmosphere structure and escape applying an hydrodynamic model. Assuming $R_T \approx R_{PL}$, where $R_{PL}$ is the planetary radius at the pressure of 100 mbar, we obtained for CoRoT-24b unrealistically high thermally-driven hydrodynamic escape rates. This is due to the planet’s high temperature and low gravity, independent of the stellar EUV flux. Such high escape rates could last only for $<100$ Myr, while $R_{PL}$ shrinks till the escape rate becomes less than or equal to the maximum possible EUV-driven escape rate. For CoRoT-24b, $R_{PL}$ must be therefore located at $\approx 1.9 \sim 2.2 R_\oplus$ and high altitude hazes/clouds possibly extinct the light at $R_T$. Our analysis constraints also the planet’s mass to be $5 \sim 5.7 M_\oplus$. For CoRoT-24c, $R_{PL}$ and $R_T$ lie too close together to be distinguished in the same way. Similar differences between $R_{PL}$ and $R_T$ may be present also for other hot, low-density sub-Neptunes.

Key words: planets and satellites: atmospheres – stars: ultraviolet – hydrodynamics

1 INTRODUCTION

The CoRoT satellite detected two Neptune-size planets with transit radii $R_T$ of $\approx 3.7 R_\oplus$ and $\approx 4.9 R_\oplus$ with orbital periods of $\approx 5.11$ and $\approx 11.76$ days around an old main-sequence K1V star (Alonso et al. 2014). Radial velocity measurements led only to an upper limit of $5.7 M_\oplus$ for the hotter planet, while for the cooler, more massive planet a mass of $28 \pm 11 M_\oplus$ was obtained. From the deduced low average densities of $\lesssim 0.87$ g cm$^{-3}$ and $1.31 \pm 0.65$ g cm$^{-3}$ of CoRoT-24b and CoRoT-24c respectively, one can expect that the cores of both planets are surrounded by H$_2$-dominated envelopes. This assumption agrees well with previous studies, concluding that protoplanetal cores with masses $>1.5 M_\oplus$ and radii $\gtrsim 1.6 R_\oplus$ would hardly lose their H$_2$-envelopes under the action of the stellar high-energy flux (Lammer et al. 2014; Erkaev et al. 2015; Johnstone et al. 2014; Rogers 2013; Stökl, Dorfi, & Lammer 2013).

We aim at understanding whether the low density and large radius of the smaller planet are physically possible. In Sect.~2 and 3 we describe the applied hydrodynamic model, and present the obtained upper atmosphere structure and loss rates. In Sect.~4 we compare the results and discuss the implications of our findings. We conclude in Sect.~5.

2 MODELLING APPROACH

To study the EUV-heated upper atmosphere structure and hydrogen thermal escape rates, we apply an energy absorption and 1-D hydrodynamic upper atmosphere model described in detail in Erkaev et al. (2013, 2015, 2016) and Lammer et al. (2014). The model solves the system of hydrodynamic equations for mass,

$$\partial (\rho R^2) + \frac{\partial (R^2 \rho v)}{\partial R} = 0,$$

momentum,

$$\frac{\partial (\rho v R^2)}{\partial t} + \frac{\partial R^2 (\rho v^2 + P)}{\partial R} = -\rho R^2 \frac{\partial \phi}{\partial R} + 2PR,$$

and energy conservation,

$$\frac{\partial R^2 \left[ \frac{\rho v^2}{2} + E_T \right]}{\partial t} + \frac{\partial R^2 v \left[ \frac{\rho v^2}{2} + E_T + P \right]}{\partial R} =$$

$$-\rho c \frac{\partial \phi}{\partial R} R^2 + Q_{EUV} R^2 + \frac{\partial}{\partial R} \left[ \kappa R^2 \frac{\partial T}{\partial R} \right].$$

Because the influence of the Roche Lobe can not be neglected, we consider also the energy $\phi$ per unit mass of a test particle in the ecliptic plane.
\[ \phi = -G \frac{M_{\text{pl}}}{R} - G \frac{M_{\text{at}}}{d - R} - G \frac{(M_{\text{pl}} + M_{\text{at}})}{2d^3} a^2 + \text{const}, \]

where \( G \) is Newton’s gravitational constant, \( M_{\text{pl}} \) is the planetary mass, \( a \) is the distance from a given point to the center of mass, \( M_{\text{at}} \) is the stellar mass and, \( d \) is the distance between the star and the planet. In the equations above, \( R \) is the planetocentric distance, \( t \) is the time, \( T \) the atmospheric temperature, \( Q_{\text{EUV}} \) is the EUV volume heating rate, \( \rho \) the atmospheric mass density, \( v \) the gas flow velocity, \( P \) the atmospheric pressure, and \( \kappa = 4.45 \times 10^{-4} (T/1000)^{0.7} \text{erg cm}^{-1} \text{s}^{-1} \text{K}^{-1} \) is the thermal conductivity (Watson, Donahue, & Walked 1981). The thermal energy \( E_T \) of the atmospheric particles per unit volume can then be written as,

\[ E_T = \left[ \frac{3}{2} (n_{\text{H}} + n_{\text{H}^+} + n_e) + \frac{5}{2} (n_{\text{H}_2} + n_{\text{H}_2^+}) \right] kT, \]

with \( k \) being the Boltzmann constant and \( n_{\text{H}}, n_{\text{H}^+} \) neutral particle and \( n_{\text{H}_2^+} \) ion densities. The continuity equations for these number densities are solved as described in Erkaev et al. (2016). To calculate \( Q_{\text{EUV}} \), we adopt the average EUV photoabsorption cross sections \( \sigma_{\text{EUV}} \) of \( 5 \times 10^{-18} \text{cm}^2 \) and \( 3 \times 10^{-18} \text{cm}^2 \) for H atoms and H2 molecules, respectively, in agreement with what is provided by experimental and theoretical data (Bates, Massey, & Amdur 1962; Murray-Clay, Chiang, & Murray 2009; Erkaev et al. 2013; Lammer et al. 2014; Erkaev et al. 2015), scaled proportionally to the EUV luminosity of \( 3 \times 10^{22} \text{erg s}^{-1} \) of the two model curves with the transmission function of the CoRoT filter at the center of the wavelength span covered by the filter, which is indicated by the horizontal bars.

To estimate the EUV (10-92 nm) luminosity of CoRoT-24, we consider a stellar rotation period of 27.3 days (Alonso et al. 2014). Using the scaling laws of Wright et al. (2011) and a \( \beta \) (the power-law index correlating the Rossby number at saturation and the X-ray flux; see Eq. 4 of Wright et al. 2011) of \( \beta = -2.18 \), we obtain \( L_X = 4.51 \times 10^{26} \text{erg s}^{-1} \), hence \( L_{\text{EUV}} = 3.82 \times 10^{29} \text{erg s}^{-1} \) (Sanz-Forcada et al. 2011). Therefore, we adopted EUV fluxes of \( 4330 \text{erg s}^{-1} \text{cm}^{-2} \) and \( 1410 \text{erg s}^{-1} \text{cm}^{-2} \) for CoRoT-24b and CoRoT-24c, respectively. For comparison, the X-ray luminosity of HD189733, which has similar parameters to CoRoT-24 is \( L_X = 2.95 \times 10^{29} \text{erg s}^{-1} \) (Schmitt & Liefke 2004). By using instead the other value of \( \beta = -2.7 \) given by Wright et al. (2011), we obtain \( L_X = 1.27 \times 10^{27} \text{erg s}^{-1} \).

The 1-D simulations also include the effects of ionization, dissociation, and recombination. The photoionization cross sections, the dissociation and recombination coefficients, the continuity equations for the number densities of the atomic hydrogen atoms and ions, and those for the neutral and ionized molecules were taken from Yelle, Anderson, & Watson (2001) and Erkaev et al. (2016) and scaled proportionally to the EUV fluxes derived for each planet. The electron density is determined from the quasi-neutrality condition.

The upper boundary of the simulation domain is set at the Roche lobe of \( 24 R_{\oplus} \) and \( 7.17 R_{\oplus} \) for CoRoT-24b and 24c, respectively. The hydrodynamic model can be applied when enough collisions occur, which is the case if Knudsen number \( Kn = \lambda / H < 0.1 \) (Volkov et al. 2011), where \( \lambda \) is the mean free path and \( H \) is the local scale height. This Knudsen criterion is fulfilled within the calculation domain. For all calculations we considered a heating efficiency of 15% (Shematovich et al. 2014). We set the lower boundary of the simulations at \( R_{\text{pl}} \), where we assume a temperature equal to the planetary equilibrium temperature \( T_{\text{eq}} \). Here we also assume an H2 number density corresponding to an atmospheric pressure of 100 mbar, which is near the level where the tangential optical depth \( \tau = 1 \) for most transparent continuum bands (Brown 2001; Lopez & Fortney 2014).

To prove the validity of this assumption we use a radiative-transfer transmission-spectrum model4 for a solar composition atmosphere and the \( T-P \) profiles obtained from the hydrodynamic code extended with isothermal hydrostatic profiles at high pressures, assuming two different planetary radii (see Sect. 3). The main contribution to the absorption comes from H2 Rayleigh scattering (\(<600 \text{ nm} \)), alkali lines (Na and K; \( 500-800 \text{ nm} \)), H2-H2 collision-induced absorption (\( >600 \text{ nm} \)), and H2O (\( >900 \text{ nm} \)). CoRoT’s observing band covers the range 350–1000 nm, with the effective wavelength at \( \approx 690 \text{ nm} \). Figure 1 shows that \( \tau \approx 1 \) lies at a pressure of \( \approx 60-70 \text{ mbar} \), but this is for a slant geometry (transmission) and therefore in a radial geometry the pressure at \( R_T \) is slightly higher than the average pressure probed by transmission spectroscopy. Differences of a factor of 10 in metallicity do not affect this result.

We run a consistency check of the adopted hydrodynamic code by comparing the calculated H loss rates with those of the well studied hot-Jupiter HD 209458b, for which upper atmosphere hydrodynamic modelling has been performed by several groups. If we assume similar planetary and atmospheric parameters at the lower boundary (Koskinen et al. 2013) we obtain a mass-loss rate of \( \approx 7 \times 10^{-7} \text{g s}^{-1} \), which agrees well with what previously derived by several other authors (4–7 \times 10^{-7} \text{g s}^{-1}; Yelle 2004; Garcia Muñoz 2007; Koskinen et al. 2013; Khodachenko et al. 2015).

3 RESULTS
3.1 Thermal outflow

For the first set of calculations, we assumed that \( R_T = R_{\text{pl}} = 3.7 R_{\oplus} \) for CoRoT-24b and 4.9 \( R_{\oplus} \) for CoRoT-24c. The points show the integral of the convolution of the two model curves with the transmission function of the CoRoT filter at the center of the wavelength span covered by the filter, which is indicated by the horizontal bars.

Figure 1. Atmospheric pressure as a function of wavelength at which a solar metallicity clear (i.e., without clouds and hazes) atmosphere of a planet becomes opaque, hence where \( \tau \approx 1 \). Calculations have been done for two planetary radii and a planetary mass of 5.7 \( M_{\oplus} \). The points show the integral of the convolution of the two model curves with the transmission function of the CoRoT filter at the center of the wavelength span covered by the filter, which is indicated by the horizontal bars.

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1. https://github.com/exosports/BART
Table 1. Results of the hydrodynamic simulations for CoRoT-24b with $M_{PL} = 5.7 M_{\oplus}$, $T_{eq} = 1070\, \text{K}$, and $R_{PL} = R_{100 \text{ mbar}}$ ranging between 1.7 and 3.7 $R_{\oplus}$. The table lists the planetary densities $\rho_{PL}$ in $\text{g cm}^{-3}$, hydrodynamic $L_{HY}$ and energy-limited $L_{EN}$ escape rates in $\text{s}^{-1}$ and their ratio ($L_{HY}/L_{EN}$).

| $R_{PL}$ | $\rho_{PL}$ | $L_{HY}$ [$\text{s}^{-1}$] | $L_{EN}$ [$\text{s}^{-1}$] | $L_{HY}/L_{EN}$ |
|---------|-------------|---------------------------|---------------------------|-----------------|
| 3.7     | 0.62        | $2.0 \times 10^{36}$     | $5.3 \times 10^{34}$     | 37.7            |
| 3.5     | 0.73        | $1.3 \times 10^{36}$     | $4.8 \times 10^{34}$     | 27.1            |
| 3.0     | 1.16        | $1.8 \times 10^{35}$     | $1.9 \times 10^{34}$     | 9.5             |
| 2.5     | 2.01        | $2.6 \times 10^{34}$     | $1.0 \times 10^{34}$     | 2.6             |
| 2.2     | 2.94        | $6.0 \times 10^{33}$     | $6.0 \times 10^{33}$     | 1.0             |
| 2.0     | 3.92        | $2.3 \times 10^{33}$     | $5.0 \times 10^{33}$     | 0.46            |
| 1.7     | 6.38        | $4.4 \times 10^{32}$     | $2.7 \times 10^{33}$     | 0.16            |

24c. The equilibrium temperatures $T_{eq}$ of CoRoT-24b and 24c are $1070\pm140\, \text{K}$ and $850\pm80\, \text{K}$, respectively (Alonso et al. 2014). Because these temperatures are cooler than the H$_2$ thermal dissociation temperature ($\approx 2000\, \text{K}$), H$_2$ is the dominant species near the 100 mbar level. Above the altitude level where dissociation takes place, H atoms become the main species and can escape from the planet’s gravitational well. The solutions of our model runs are quasi-stationary with slow time variations of the atmospheric parameters.

For CoRoT-24b and CoRoT-24c, the hydrodynamic model gives H escape rates of $\approx 2.0 \times 10^{36} \, \text{s}^{-1}$ ($3.35 \times 10^{12} \, \text{g s}^{-1}$) and $\approx 8.0 \times 10^{33} \, \text{s}^{-1}$ ($1.34 \times 10^{10} \, \text{g s}^{-1}$), respectively. Under the assumption that the 100 mbar level lies near the observed transit radius, the high thermally driven hydrodynamic outflow obtained for CoRoT-24b is caused by the combination of the planet’s high temperature and low gravity, independent of the stellar EUV flux. This happens because for hot, low-gravity planets the thermal energy $E_T$ shown in Eq. 6 for a large fraction of the particles in the upper atmosphere is of the order of or larger than the potential energy. As a consequence, the atmosphere flows upwards, even without the need of an additional external energy source, such as the stellar EUV flux. In this case, the stellar EUV flux is not the main driver of the atmospheric escape. This is similar to the so-called “boil-off” evaporation regime of very young planets (Owen & Wu 2013).

The high escape rate obtained for CoRoT-24b could in principle last for $<100\, \text{Myr}$ (see Sect. 3.2), which is inconsistent with the old age of the system: with the exception of very young planets, the escape rate can only be less than or equal to the maximum possible EUV-driven H escape rate, which can be analytically estimated with the energy-limited formula (e.g., Watson, Donahue, & Walker 1981; Erkaev et al. 2007; Lammer et al. 2009; Luger et al. 2013).

$$L_{EN} = \frac{\pi \eta R_{PL} R_{EUV}^2 E_{UV}}{G M_{PL} m_h K},$$

where $\eta$ is the heating efficiency, $E_{UV}$ is the stellar EUV flux, $R_{EUV}$ is the effective radius where the EUV energy is absorbed in the upper atmosphere (Erkaev et al. 2013, 2014), and $m_h$ is the mass of the H atom. The factor $K$ takes into account Roche lobe effects (Erkaev et al. 2007).

By applying this formula to CoRoT-24b and CoRoT-24c, we obtain escape rates of $5.3 \times 10^{34} \, \text{s}^{-1}$ ($8.9 \times 10^{10} \, \text{g s}^{-1}$) and $5.5 \times 10^{33} \, \text{s}^{-1}$ ($9.2 \times 10^{8} \, \text{g s}^{-1}$), respectively. For the hotter and less massive sub-Neptune CoRoT-24b, the escape rate based on the hydrodynamic model of $L_{HY}$ is $\approx 40$ times higher than $L_{EN}$ obtained from Eq. 6 while for the more massive and cooler planet, CoRoT-24c, $L_{HY}$ is consistent with $L_{EN}$, within the expected uncertainties.

Figure 2 shows the $L_{HY}/L_{EN}$ ratio as a function of planetary radius and mass and indicates that, assuming $M_{PL} \approx 5.7 M_{\oplus}$ and $R_{PL}$ ranging between 1.7 and 3.7 $R_{\oplus}$, the condition $L_{HY}/L_{EN} \leq 1$ is reached for planetary radii smaller than $2.2 R_{\oplus}$. In this work, the transit radius of CoRoT-24b is the main observational uncertainty, but it has however no impact on the results: the $L_{HY}/L_{EN} \leq 1$ relation is fulfilled for $R_{PL} < 2.2 R_{\oplus}$, regardless of the observed radius and its uncertainty. Our simulations at larger masses show that the transit radius lies close to the 100 mbar level for $M_{PL} > 8 M_{\oplus}$.

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According to formation and structure models of hot ($T_{eq} \approx 1000\, \text{K}$) sub-Neptunes (e.g., Rogers et al. 2011), the transit radius would correspond to an atmospheric mass fraction $f \approx 0.04$, hence an atmospheric mass $M_{AT}$ of...
\[ \approx 1.36 \times 10^{27} \text{g} \]

By assuming a core mass of \( 5.7 M_\oplus \) for CoRoT-24b, from the escape rates given in Table 1, one can also roughly estimate the evolution of atmospheric mass with time. Atmospheric masses corresponding to the radii given in Table 1 were estimated from the 1000 K structure models of Rogers et al. (2011). As one can see in Fig. 3, an atmospheric mass above 2.2 \( R_\oplus \) corresponding to a radius of 3.7 \( R_\oplus \) would be lost within 100 Myr due to the high thermally-driven escape rates, in agreement with the results of Owen & Wu (2016). Because of the short time period in which the mass-loss rates are exceptionally high and the corresponding fast shrinking of the planet radius, the 100 mbar level of CoRoT-24b must be located much deeper in the atmosphere, compared to the position of \( R_T \).

4 DISCUSSION

Thermally driven hydrodynamical mass loss could occur at the first stages of planetary evolution (Owen & Wu 2016), but is unlikely to occur for older planets because, as shown in Fig. 3, the atmosphere structure would be modified in a short time. It is also not possible that CoRoT-24b is the remnant of a more massive planet (e.g., hot-Jupiter or hot-Saturn), because the escape rates of such massive objects are not high enough to affect significantly the planet's mass over the main-sequence lifetime of the host star (Yelle 2004).

Both escape rates, i.e., \( L_{HY} \) and \( L_{EN} \), depend on the adopted EUV flux and heating efficiency \( \eta \). For this reason we tested the effect of a higher/lower EUV flux or \( \eta \) on the results. A different EUV flux affects both \( L_{HY} \) and \( L_{EN} \) rates in a similar, though not identical, way. A variation of a factor of \( \approx 2 \) in the EUV flux would lead to a variation on the \( L_{HY}/L_{EN} \) ratio of \( \approx 0.3 \), which in terms of planetary radius corresponds to \( < 0.1 R_\oplus \). Variations in \( \eta \) also affect both escape rates. In this case we estimate that a factor of \( \approx 2 \) difference in the heating efficiency would lead to a variation on the planetary radius of \( < 0.1 R_\oplus \). From the comparison of the escape rates of the hot-Jupiter HD 209458b described in Sect. 2 we expect that the use of a different hydrodynamic code would lead to mass-loss rates consistent with those presented here within a factor of \( \approx 2 \), which, in terms of the derived planetary radius of CoRoT-24b, corresponds to \( \approx 0.1 R_\oplus \). We further tested the effect of varying \( T_{eq} \) (1070±140 K, Alonso et al. 2014), finding that variations in \( T_{eq} \) up to 200 K have a negligible impact on the results.

On the basis of planetary formation models calculated for planets in the 1–10 \( M_\oplus \) range, one can estimate the core radius \( R_c \) of a planet on the basis of its mass if \( M_{PL} \approx M_c \) as \( R_c \approx M_{PL}^{0.27} \left( M_c \right)^{-0.3} \), depending upon the exact composition (Valencia, O'Connell, & Sasselov 2006). Taking into account that \( R_{PL} \), hence the 100 mbar level, cannot be too close to \( R_c \) (the planet needs sufficient atmosphere to produce the observed \( R_T \)), from Fig. 2 it follows that CoRoT-24b should have a minimum mass of \( \approx 5.0 M_\oplus \), with a core radius in the \( \approx 1.55–1.68 R_\oplus \) range and \( R_{PL} \) at the 100 mbar level in the \( \approx 1.9–2.2 R_\oplus \) range. These values yield an average density of 2.9–4.6 g cm\(^{-3}\). The mass contained between \( R_{PL} \) and \( R_T \) is \( 7.5 \times 10^{-5} \) of \( M_{PL} \). We conclude therefore that, accounting for the uncertainties on \( R_T \), the “true” radius \( R_{PL} \) of CoRoT-24b is \( \approx 30-60\% \) smaller than the one measured by the transit. For the solar system gas giant planets, \( R_{PL} \) is by definition set at the 1 bar pressure level. By setting this pressure level at \( R_{PL} \) and following the same procedure described in Sect. 2, we obtained again that \( R_{PL} \) would be about 2.2 \( R_\oplus \) (see Fig. 2).

Figure 4 compares the temperature and pressure profiles of CoRoT-24b, considering a \( R_{PL} = 2.2 R_\oplus \) and a \( M_{PL} \)
of 5.7 $M_\oplus$, and CoRoT-24c. In the case of CoRoT-24b, the atmosphere is hydrostatic near $R_{PL}$, while it becomes hydrodynamic and cools adiabatically above 5 $R_\oplus$. For the cooler and more massive planet, CoRoT-24c, the atmosphere is hydrostatic above $R_T$ and the temperature increases up to 3000 K due to the EUV heating. Above 10 $R_\oplus$ the atmosphere cools adiabatically. For CoRoT-24b, Fig. 4 shows that assuming $R_{PL} = 2.2 R_\oplus$ and $M_{PL} = 5.7 M_\oplus$, $R_T$ lies near the 1–10 $\mu$bar pressure level. As one can see from Fig. 4 the absorption at the level of the transit radius cannot be caused by H$_2$ Rayleigh scattering and the alkali lines are too narrow to produce broad-band absorption. At such a high altitude, absorption could be for example produced by clouds, though cloud formation models based on TiO$_2$ calculated for HD 189733b ($T_{eq}$ similar to that of CoRoT-24b) suggest formation pressures of about 0.1 mbar [Lee et al. 2013].

5 CONCLUSIONS

By comparing the escape rates obtained from a hydrodynamic code with the maximum possible EUV-driven escape rate calculated from the energy-limited formula, we discovered that for the H$_2$-dominated close-in sub-Neptune CoRoT-24b the planetary radius, by definition set at the 100 mbar pressure level, is 30-60% smaller than the observed transit radius. Additional considerations on the range of possible planetary core radii allowed us to constrain the most likely values of the planetary mass and radius to lie in the range 5.0–5.7 $M_\oplus$ and 1.9–2.2 $R_\oplus$, respectively.

The Kepler satellite has discovered several similar, low-density “sub-Neptunes” and it is very likely that the transit radii measured for the vast majority of these planets also differs from the true planetary radius, therefore introducing a systematic bias in the measured radii. This has dramatic implications for example in the determination of the mass-radius relation (e.g., Petigura, Howard, & Marcy 2013; Weiss & Marcy 2013; Lopez & Fortney 2014) and for planet population synthesis studies (e.g., Beaugé & Nesvorny 2013). Our results may also help explaining some of the discrepancies discovered between the planet radius distribution observed by Kepler and that derived from population synthesis models (Jin et al. 2014). This has also profound implications for our understanding of the structure of the large number of transiting low-mass exoplanets expected to be observed and discovered in the near future by the CHEOPS, TESS, and PLATO space missions and characterized by JWST.

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