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A large grid of super-Earth upper atmosphere models and its application to planetary evolution

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Abstract

The NASA Kepler mission revealed the existence of a large variety of planets very different from what we know from the Solar System. Among them a large number of planets was found in the range between Earth and Neptune (e.g. [1]), with a large spread in average densities (e.g. [2-4]). These planets are easier to detect and characterize in comparison to Earth-like planets, making them primary targets for a number of upcoming missions such as CHEOPS [5], TESS [6], JWST [7], PLATO [8], and ARIEL [9].

As part of the work carried out in support to the scientific preparations for the CHEOPS mission, we have assembled a large grid of upper planetary atmosphere models covering super-Earths hosting hydrogen-dominated atmospheres and orbiting early M- to late F-type main-sequence stars. The planetary mass ranges between 1 and 39 Earth masses (up to twice Neptune mass), while the radii cover the 1 to 10 Earth radii (up to 2.5 Neptune radius) range. The equilibrium temperature of the planets spans from 300 to 2000 K. For each stellar mass, we considered three distinct values of the high-energy (XUV) stellar fluxes, which cover roughly the interval from a chromospherically active to a quiet star.

The base physical model is an upgraded version of the model from [10], that is a 1D hydrodynamic model of an XUV-heated atmosphere accounting for hydrogen dissociation, recombination and ionization, Lα- and H_3^+-cooling, and X-ray heating. The boundaries are the planet photosphere and Roche lobe. To allow the computation of a large grid, the XUV stellar spectrum is simplified to two wavelength points: 60 nm and 5 nm for the emission in the extreme ultraviolet (EUV) and X-ray spectral ranges, respectively.

The grid of models consists of about 7000 points and provides the height profiles of the main atmospheric parameters, namely temperature, velocity, bulk density and hydrogen species fractions, from which we compute the atmospheric escape rates and other relevant quantities. We further developed an interpolation routine allowing one to obtain the output of the model grid for any planet lying inside the grid boundaries.

We coupled the interpolation routine with a planetary structure code providing the atmospheric mass fractions for any given planet on the basis of the system parameters and basic assumptions [13]. By employing the two codes, we compute planetary atmosphere evolution tracks for a number of known planets. We further employ the MESA Isochrones and Stellar Tracks (MIST; [11]) to account for changes of stellar temperature, radius (controlling the planetary equilibrium temperature), and bolometric luminosity (involved in the computation of the stellar XUV flux [12]).

We present the modelling scheme, the code upgrades, the model grid, and the interpolation routine. We further show how the current lack of a hydrogen-dominated atmosphere for close-in, high-density super-Earths can be the result of atmospheric escape. We finally apply our simple atmospheric evolution scheme to planets hosting a hydrogen-dominated atmosphere showing how it can lead to further constraining important planetary and stellar properties.

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