CINECA INA17_C2BB0: report and preliminary results

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July 20, 2018

1 Scientific Rationale

The search for exoplanets is a new-born field of astrophysics, whose importance can be hardly overstated. Currently, more than 5000 planets (or candidates) have been discovered and even more are expected in the near future with the launch of new generation space facilities. In this framework, where new data are about to come and need to be analyzed, a theoretical approach via numerical computation becomes mandatory, in order to plan and develop observational protocols, identify peculiar cases, and have hints about some of the phenomena only partly understood.

The project focuses on Super Earths (rocky planets whose mass is in the 1-10 Earth masses range, and whose radius is in the 0.8-2 Earth radii range), a class of planets that is absent in our Solar System. This is particularly interesting from the perspective of planet formation theory, as more and more Super Earths are being observed to orbit stars in the Milky Way. Their characterization could thus place constraints on the formation of the Solar System itself, and could question the robustness of currently accepted formation theories. Super Earths are predicted to have large surface gravities and are likely to exist in a wide range of atmospheres: some of them could retain a thick H-rich atmosphere, others could have a stronger resemblance to Earth, or show a large abundance of complex molecules in their atmospheres. Many Super Earths are also predicted to be potentially habitable planets, as they were found to float in the habitable zone of their host star.

2 Current Project Status

Researchers and PhD students belonging to an Italian collaboration among the Observatories of Padua, Palermo, and Cagliari built from scratch a 1D structure code which accounts for both radiative transfer and convective adjustment. We chose to call it `MAGRATHEA` to quote Douglas Adams's *Hitchhikers Guide to the Galaxy*, in which the ancient planet Magrathea is considered the home of the industry of "custom-made planet building". This is, in a sense, what our code is supposed to do when it will be fully developed.

The radiative subroutine `ExART` can calculate up and down fluxes at each atmospheric layer using absorption spectra previously adapted via k distribution method. The only input it requires is a set of 14 values, each one representing the radiation of the host star integrated in the 14 bands where the k distributions are calculated. The k distribution approach is fast, flexible, and generally accurate. It reduces by orders of magnitude the computational time and the volume of data that it is usually occupied by a whole set of absorption spectra, necessary in order to retrieve the fluxes at each layer of the atmosphere. This technique also allows the radiative code to equally consider input absorption spectra at various pressures.

The thermo-convective subroutine `THERMOCON` was written to manage convective adjustment, following the approach proposed originally by Manabe and coworkers in 1964 [1], and it is coupled to the radiative counterpart. At present time, this code allows to model cloud-free atmospheres spanning a wide range of parameters, such as pressure, temperature, and stellar irradiation.

3 CINECA Runs

For the six months' time during which the project INA17_C2BB0 was running on MARCONI cluster, the group worked on many issues:

- The restore feature, so that each model could restart from one of the latest steps when the job had to be re-runned after exceeding the wall-clock time defined by the queuing system;
- An MPI parallelization of the code, in order to run multiple models at the same time;
- The possibility to run variable chemistry models that allowed the update of water vapor abundance at each time-step; fixed chemistry models, where the chemical composition of the atmosphere does not change throughout the various iterations, could be also run.

The ongoing work done on the code itself allowed us to run a wide variety of models, that could be grouped in:

- A grid of 2400 fixed chemistry models (hereafter `G2400_CF`), compiled by taking all combinations of the input parameters reported in Table 1. This grid was computed with the serial version of the code. Each model ran on a single CPU, for a maximum of 20 simultaneous jobs. The total grid was completed in about a month's time, with about 450 Core/hours consumed per day.

Parameters	Number	Notes/Values
Tstar (K)	8	2500, 3000, 3500, 4000, 4500, 5000, 5500, 6000
Planetary Mass ($M_\oplus$)	5	0.1, 0.5, 1, 5, 10
Distances (AU)	4	From 0.8 S_{maxg} to 1.2 S_{rg}
Density (to define radius)	1	Earth-like
CO2 VMR	5	0.0001, 0.001, 0.01, 0.1, 0.9
Atmospheric Mass Factor	3	0.1, 1, 10 times the mass of Earth's atmosphere
Albedo	1	0.3

Table 1: Information about every parameter we chose to vary in the grids `G2400_CF` and `G2400_CV`.

- The same grid of 2400 models we did in G2400_CF, but varying the chemistry (hereafter G2400_CV). This grid was computed with the parallelized version of the code: this improved the computational speed and subsequently the fulfillment of all grid points, which required a couple days' time.
- A grid of 15840 fixed-chemistry models (hereafter G15840_CF), compiled by taking all combinations of the input parameters reported in Table 2. This grid was computed with the parallelized version of the code in a week's time.

Parameters	**Number**	**Notes/Values**
Tstar (K)	11	Every 300 K from 3000 to 6000 K
Planetary Mass ($M_\oplus$)	4	0.1, 1, 5, 10
Distances (AU)	4	From 0.8 S_{maxg} to 1.2 S_{rg}
Density (to define radius)	1	Earth-like
CO2 VMR	5	0.0001, 0.001, 0.01, 0.1, 0.9
Atmospheric Mass Factor	3	0.1, 1, 10 times the mass of Earth's atmosphere
Albedo	3	0.1 0.3 0.7
Humidity	2	Dry - wet (and fixed)

Table 2: Information about every parameter we chose to vary in the grid G15840_CV.

Among all sets of models, a small percentage (about 6 – 10%) showed some kind of errors that prevented convergence and were excluded from the main analysis. These models were nevertheless studied to understand the various problems the code encountered, in order to be able to eventually solve or discuss them.

The possibility to run these models on CINECA clusters by means of the MoU CINECA-INAF allowed us to retrieve a large amount of data that could eventually lead to some interesting conclusions for what concerns physical, chemical and statistical properties of the probable atmospheres hosted by Super-Earths.

4 Analysis

The analysis of the results is still ongoing. We focus on both physical features of specific models, as well as global features of the grids by using neural networks in order to look for any regularity within the models.

For what concerns the physical features of the models, we are trying to reach the following goals:

1. We would like to understand under which conditions a terrestrial planet could be habitable at its surface. Therefore, we are particularly interested in the physical conditions at the ground level. This could potentially allow us to determine the impact of the greenhouse gases on the ground temperature of a planet (see e.g. Figure 1);
2. We would like to study the profile of the atmosphere, in order to better understand the physical and chemical processes involved in the various layers. From an observational

point of view, these profiles could be interesting for other retrieval models and for the analysis of future transmission spectra. We should be able to observe a change in the behavior of the profile with the variation of the input parameters: not only the ground temperature could be effected by them, but also the height of the tropopause and of the stratosphere, if any (see e.g. Figure 2).

5 Papers in preparation

This model run provides us with the bases of a new project, which still needs to be properly tested and analyzed. Our group should submit at least two papers that will involve the analysis of these datasets. We provide here the provisional titles:

1. Paper I: *Radiative-convective models of exoplanetary atmospheres around low-mass stars* - Giambattista Aresu, Eleonora Alei, Daniele Locci, Antonino Petralia, Cesare Cecchi-Pestellini, Giuseppina Micela, Riccardo Claudi, Angela Ciaravella - To be submitted to *Monthly Notices of the Royal Astronomical Society*;

2. Paper II: *Retrieval of physical and statistical properties of Super Earths atmospheres via 1D cloud-free radiative-convective models* - Eleonora Alei, Antonino Petralia, Giambattista Aresu, Daniele Locci, Riccardo Claudi, Cesare Cecchi-Pestellini, Giuseppina Micela, Angela Ciaravella - To be submitted to *The Astrophysical Journal Supplement Series.*

References

[1] S. Manabe, R. F. Strickler, S. Manabe, and R. F. Strickler. Thermal Equilibrium of the Atmosphere with a Convective Adjustment, 1964.

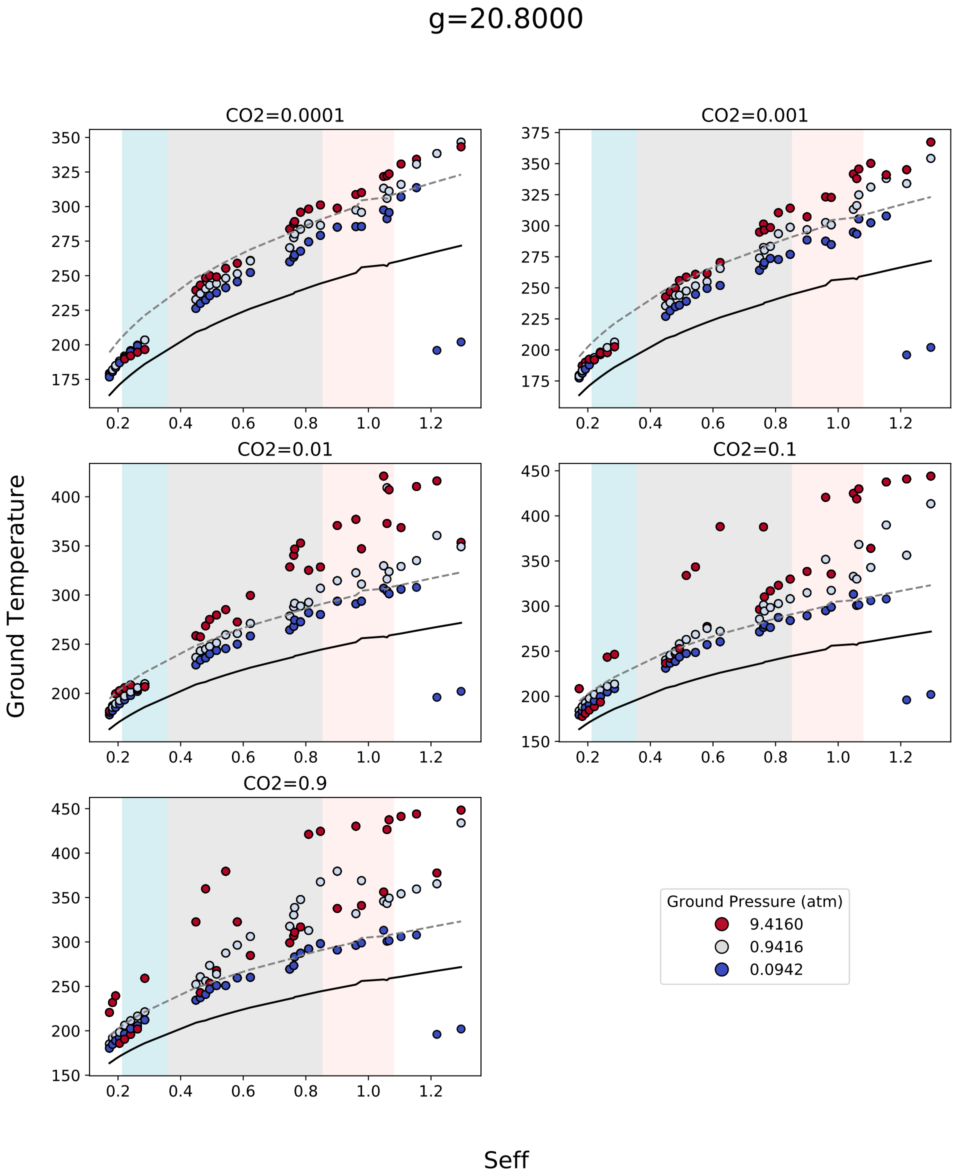

Figure 1: 5 $M_\oplus$ Super Earth with various atmospheric masses and orbiting at various distances around different stars. The five panels represent the behavior of the ground temperature with respect to the stellar constant at the top of atmosphere, where the atmosphere is composed by nitrogen, water vapor and various values of carbon dioxide abundance (in the subtitles). The black line represents the theoretical equilibrium temperature, while the gray dashed line represents the greenhouse temperature. The colors of the dots represent the mass of the atmosphere (and thus the pressure): in red, high mass/pressure, in white, medium mass/pressure, in blue, low mass/pressure. The blue shaded region is the habitable zone for the coolest star considered ($T = 2500$ K); the pink shaded region is the habitable zone for the hottest star considered ($T = 6000$ K).

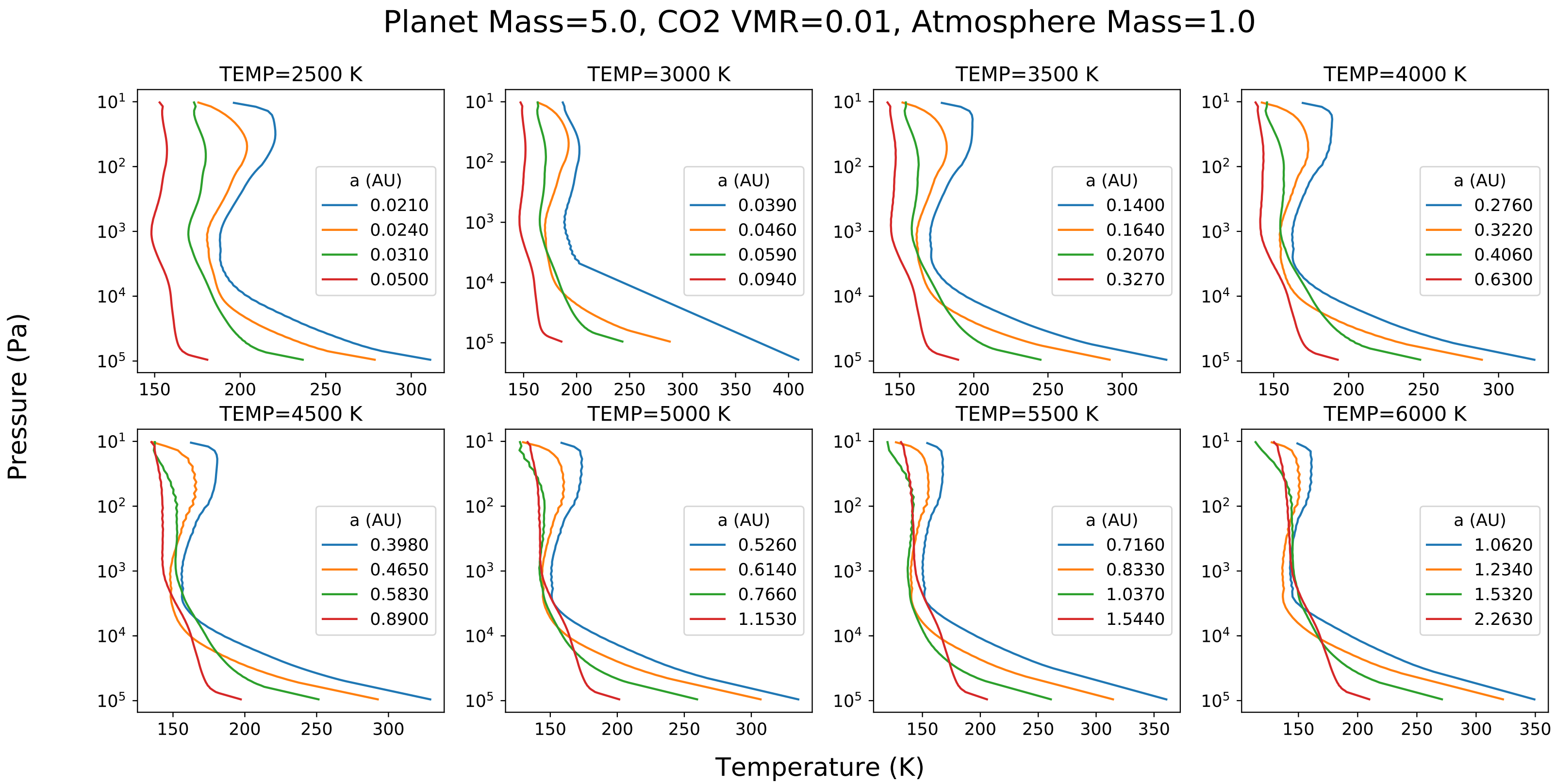

Figure 2: Atmospheric P-T profile of a $5M_{\oplus}$ Super Earth with $VMR_{CO2} = 10^{-2}$ and $M_{atm} = 1$ that orbits different stars (whose temperature is written on the subtitle of each subplot) at different distances (semi-major axes on legend).