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The Kompot Code: first-principles upper atmosphere modelling and the evolution of planetary atmospheres

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Abstract

Understanding the physical structures of planetary atmospheres under a variety of conditions is necessary for understanding atmospheric evolution and the roles of escape to space. We present here The Kompot Code, which calculates the thermal, chemical, and hydrodynamic structures of planetary atmospheres for arbitrary conditions. The model is 1D and attempts to take into account all of the major physical processes that influence the structure of the atmosphere. We demonstrate how this model can be applied to a range of planets with different atmospheric compositions and inputs from the central star.

1. Introduction

The physical properties of a planet's upper atmosphere are crucially dependent on a large number of factors. These include the planet's mass, the chemical composition of the atmosphere, the planet's orbital distance from the central star, and the magnetic activity level of the star. To properly take into account all of these factors, models that include as many of the relevant physical processes as possible are needed. The most important physical processes include hydrodynamic expansion and contraction of the gas, chemistry, including photoreactions and ion chemistry, diffusion processes such as eddy and molecular diffusion, heating of the gas by stellar X-ray, UV, and IR radiation, and the transport of heat within the atmosphere by conduction and energy exchanges between different components of the gas. Much work is still needed for models that combine such processes in complete and self-consistent ways, both in developing such models and in applying them to a range of planetary cases.

2. The Kompot Code

We have developed The Kompot Code (Johnstone et al. submitted), which applies the physical processes listed above to planets with arbitrary properties. In all cases, we have attempted to model these processes from first-principles physical considerations, as much as is practical, though much improvement to the model is planned for future work. The model is 1D and and extends from some altitude in the middle atmosphere to the exobase, as shown in Fig. 1. We have validated our model by applying it to the cases of modern Earth and Venus and found good agreement for both the thermal and chemical structures.

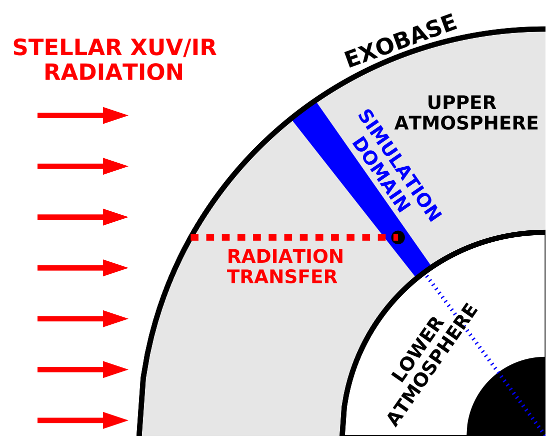

Figure 1: Figure showing the computational domain calculated by The Kompot Code. The domain extends from an arbitrary location in the middle atmosphere to the exobase and can be at any angle relative to the incoming radiation.

The code models the gas as three components, i.e. neutrals, ions, and electrons, with their own separate temperatures. The chemical network used contains 63 species, including 30 ion species, and 503 reactions, including 56 photoreactions and 7 reactions involving impacts with non-thermal photoelectrons. The two stellar inputs are the XUV (i.e. X-ray and ultraviolet)

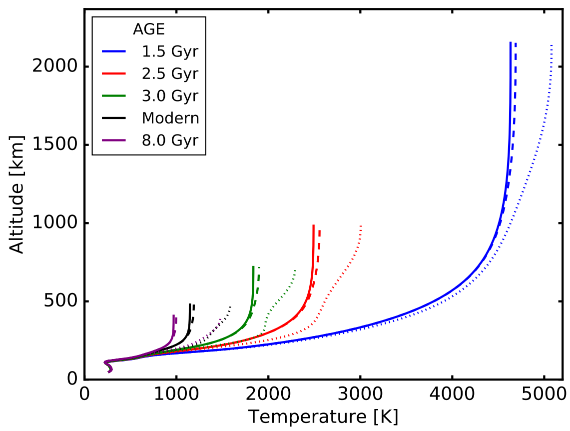

Figure 2: Figure showing the structure of the Earth's upper atmosphere at different ages from Johnstone et al. (submitted). In all cases, the lower atmospheric properties are assumed to be equal to those of the modern Earth and the only difference has been the input XUV spectrum of the Sun.

field between 1 and 400 nm, and the IR field between 1 and 20 μm. In addition, we calculate the spectrum of non-thermal photoelectrons created by photoionisation reactions. The heating of the gas takes place due to a range of processes: these are direct heating by the absorption of stellar XUV radiation, heating from exothermic chemical reactions, electron heating from elastic collisions with non-thermal electrons, heating by the absorption of stellar IR radiation, and Joule heating. The gas is cooled by IR emission from several molecules: these are CO_2, NO, O, H_2O, and H_3^+. Thermal conduction is calculated for the neutral, ion, and electron components separately, and the energy exchanges between these components are also calculated.

3. Discussion

Our model can be applied to a large range of systems. As an example, we show calculations for the upper atmosphere of the Earth at different ages between approximately 3 Gyr in the past to approximately 2.5 Gyr in the future. In all cases, the simulations differ from our model of the modern Earth only in the input solar XUV spectrum. At younger ages, the Sun was more active in X-rays and UV wavelengths than it currently is, and so the atmosphere was hotter and more extended. This likely has significant effects on atmospheric losses during these times. We plan to apply this code to better understand both the atmospheric evolutions of our own solar system planets and the formation of atmospheres on planets in a exoplanet systems.

Acknowledgements

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References

[1] Johnstone, C. P., M. Güdel, H. Lammer, and K. G. Kislyakova (2018), The Upper Atmospheres of Terrestrial Planets: Carbon Dioxide Cooling and the Earth's Thermospheric Evolution, submitted to Astronomy & Astrophysics.