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A high-performance atmospheric radiation package: With applications to the radiative energy budgets of giant planets

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ABSTRACT

A High-performance Atmospheric Radiation Package (HARP) is developed for studying multiple-scattering planetary atmospheres. HARP is an open-source program written in C++ that utilizes high-level data structure and parallel-computing algorithms. It is generic in three aspects. First, the construction of the model atmospheric profile is generic. The program can either take in an atmospheric profile or construct an adiabatic thermal and compositional profile, taking into account the clouds and latent heat release due to condensation. Second, the calculation of opacity is generic, based on line-by-line molecular transitions and tabulated continuum data, along with a table of correlated-*k* opacity provided as an option to speed up the calculation of energy fluxes. Third, the selection of the solver for the radiative transfer equation is generic. The solver is not hardwired in the program. Instead, based on the purpose, a variety of radiative transfer solvers can be chosen to couple with the atmosphere model and the opacity model.

We use the program to investigate the radiative heating and cooling rates of all four giant planets in the Solar System. Our Jupiter's result is consistent with previous publications. Saturn has nearly perfect balance between the heating rate and cooling rate. Uranus has the least radiative fluxes because of the lack of CH_4 and its photochemical products. Both Uranus and Neptune suffer from a severe energy deficit in their stratospheres. Possible ways to resolve this issue are discussed. Finally, we recalculate the radiative time constants of all four giant planet atmospheres and find that the traditional values from (Conrath BJ, Gierasch PJ, Leroy SS. Temperature and Circulation in the Stratosphere of the Outer Planets. Icar. 1990;83:255–81) are significantly overestimated.

1. Introduction

Many atmospheric radiative transfer programs have been developed for a specific purpose or for a specific planet. For example, the RFM (reference forward model) was developed to provide reference spectra for the infrared spectrometer on the Envisat satellite [1]; the SARTA (Stand-alone AIRS Radiative Transfer Algorithm) was designed to support the AIRS mission [2]; the NEMESIS (Nonlinear Optimal Estimator for MultivariatE Spectral analySIS) planetary atmospheric radiative transfer model [3] was built to interpret the observations of Saturn and Titan from CIRS (Composite Infrared Spectrometer) onboard Cassini. Later on, their functionalities have been extended beyond their original purposes but still limited to the study of a specific class of planets. Adapting this type of radiative transfer model to an entirely different planet is possible but laborious and error-prone due to various hard-wired functions/assumptions intrinsic to the original design.

In the era of high precision spectroscopy on exoplanets enabled by future telescopes such as JWST, there is a pressing need to develop a generic radiative transfer program that is capable of computing atmospheric radiances and energy fluxes for exoplanets with arbitrary atmospheric composition and the presence of exotic clouds (e.g. [4]). Such a radiation model should be validated against the knowledge of Earth and other planets in the solar system where the observational constraints are available. Moreover, most radiation models used in planetary and exoplanetary studies are based on the models developed in the 1990s (e.g. [5,6]). Although they are still working well, their software structures and efficiencies are behind the current industrial standard. Upon these considerations, it is the motivation behind the development of the new radiative transfer model.

Here we provide a new, open-source radiation model for Earth, planets and exoplanets that can calculate both line-by-line spectra and correlated-*k* energy fluxes in parallel. The line-by-line spectra calculation is validated against the existing model (SARTA) de-

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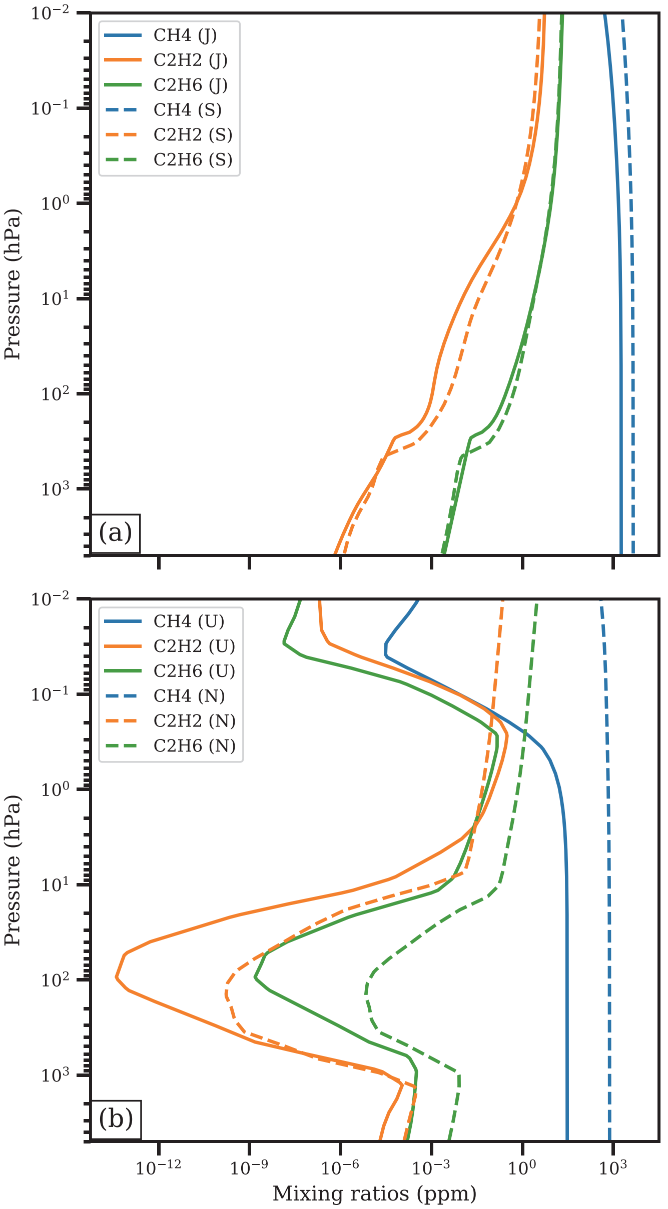

Fig. 1. Vertical profiles of hydrocarbons from 1-D photochemical models. a) Jupiter and Saturn's profiles are from Moses, Fouchet [35] and Moses, Bezard [36]. b) Uranus and Neptune's profiles are from Moses, Fouchet [35].

veloped for the Earth's satellite (AIRS) and the analytical solution published in Zhang, Nixon [7]. The correlated-*k* opacities are generated using the line-by-line opacities. Depending on the backend radiative transfer equation solver, multiple scattering due to clouds and polarization can be accounted for. This paper presents the clear sky results for giant planets. Validation of the line-by-line calculations against SARTA and cloud radiative effects will be discussed in a companion paper for the Earth.

The rest of this paper is organized as follows. In Section 2, we discuss the key components of the model, including the atmospheric model, the opacity model, and the backend radiative transfer equation solver. In Section 3, we apply the model to the giant planets in the solar system and calculate their heating/cooling rates and radiative time constants. The radiative forcing for ice giants are discussed in detail. Finally, in Section 4, we summarize our major findings.

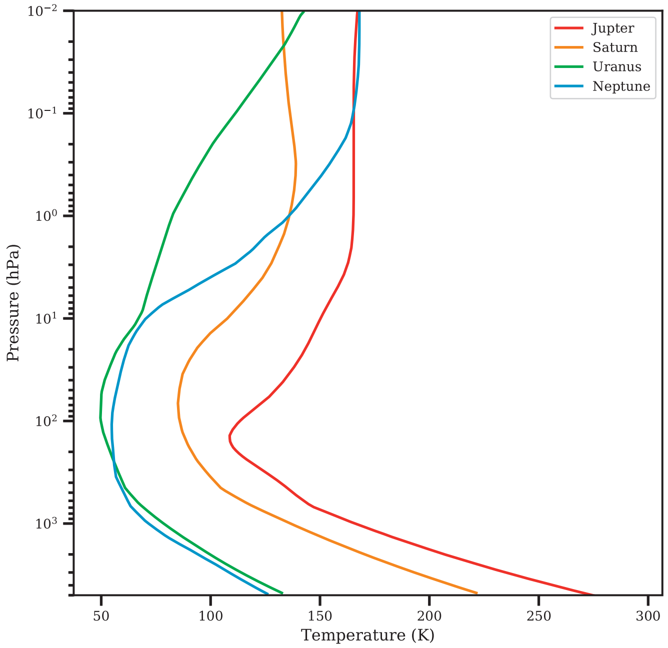

Fig. 2. Temperature profiles from the stratosphere to the upper troposphere used in the model. Similar to the hydrocarbon profiles, these temperature profiles are from Moses, Bezard [36] and Moses, Fouchet [11].

2. Overview of the implementation of HARP

HARP consists of three modular components: 1) An atmospheric model that either reads in or constructs a 1D atmosphere with thermal and compositional structure. The program is able to construct a (moist) adiabatic profile using the formulation of Li, Ingersoll [8], which allows the simultaneous condensation of multiple species and can handle any amount of condensable species, from zero to infinity. 2) An opacity model that calculates line-by-line optical properties (absorption coefficients, single scattering albedo, and coefficients in Legendre polynomial expansions of phase functions) for every layer of the atmosphere from a given atmospheric profile. The correlate-*k* method is also provided as an option to further boost the calculation of radiative heating/cooling fluxes. 3) A backend radiative transfer model that takes the optical properties of the atmosphere computed in the opacity model as input and solves the radiative transfer equation. All three models are able to run in a stand-alone fashion, but they can also be combined to perform an efficient radiative transfer calculation from first principles. The program is written in a modern computer language (C++) that utilizes high-level data structure and algorithms. The code style conforms to the C++ (11) standard, avoiding all language extensions. With efficiency being the priority, the opacity model and the radiative transfer model are executed in parallel for each atmospheric band, which significantly accelerates the speed of the program. On average, the program can compute one million eight-stream radiative transfer calculations in less than 10 m on 15 Intel Xeon E5-2695 CPUs. The scaling using multiple cores is almost linear, meaning that using 15 CPUs will speed up the processing time by 15 times. Details of the numerical method used in each component are presented in the Appendix A.

3. Heating rates and radiative time constants on giant planets

The radiative heating/cooling rates of Jupiter's stratosphere has been calculated and discussed by many authors (e.g. [7,9,10]).