



Simulations of Uranus Spectra at Visible and Near-Infrared Wavelengths Using ARS

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Introduction: As part of an ASI-funded project aimed at enhancing the readiness of the Italian scientific community for upcoming NASA-led missions to the icy giants, we are conducting a comprehensive validation of atmospheric visible and infrared radiative transfer tools. In this work, we present the initial results and the primary technical challenges addressed in the successful adaptation of the ARS (Атмосфера, Радиация, Спектр - Atmosphere, Radiation, Spectrum) code [1] to simulate spectra from the Uranus atmosphere in the visible and infrared wavelength ranges.

Physical context: Simulating the spectra of icy giants' atmospheres requires accounting for a unique set of conditions, primarily driven by the extremely low temperatures found at these distant locations from the Sun. Among the key challenges are: (1) the significant depletion of optically active volatile species, such as water and ammonia, in the upper troposphere, which is probed at visible and infrared wavelengths; (2) the condensation of methane, the most optically active species, within the same pressure ranges; and (3) the dominant role played by Rayleigh scattering and collision-induced absorption (CIA) of molecular hydrogen in shaping the spectrum. Regarding the third point, we note that both Rayleigh scattering and CIA are poorly constrained by experiments at the very low temperatures relevant to the Uranus atmosphere, and no existing models fully account for CH₄-induced H₂ CIA in the wavelength range of interest.

Methods: Our immediate goal has been to reproduce the Uranus spectra simulations presented in [2], which were derived using the state-of-the-art NEMESIS code [3], also developed by the same authors. These simulations were defined as best-fit models to experimental measurements obtained from the Hubble Space Telescope and ground-based observations at the IRTF. Given the detailed description of the input parameters provided in [2], adapting the ARS code has allowed us to focus on a few specific issues.

First, the ARS code, initially designed for line-by-line simulations and later adapted to include the correlated-k formalism, has now been further extended to work directly with gaseous cross-sections, as provided in databases such as EXOMOL [4]. However, we found that the theoretical data from these databases do not yet provide a satisfactory representation of methane absorption in the visible and near-infrared ranges. As a result, we resorted to experimental cross-sections presented in [5]. Second, we incorporated Rayleigh scattering by introducing a pseudo-aerosol into the simulation, with a density profile that matches the increase in volume cross-section with depth associated with the scattering phenomenon. We were somewhat surprised by the necessity to use discrete ordinate methods, such as DISORT [6], for modeling Rayleigh scattering, despite the relatively small number of terms in the corresponding Legendre decomposition of the phase

function.

Fig. 1: Comparison between composite experimental Uranus spectrum at subsolar point (Hubble, IRTF) and ARS simulation.

Fig. 2: Jacobians for gaseous methane volume mixing ratio (a). The vertical profile is sampled in 200 points, uniformly distributed in the log P space.

Results: Ultimately, we were able to achieve a satisfactory match between the experimental spectra and the ARS simulations (see Fig. 1) in the range [0.4-1.9] μm , thus advancing the project to the computation of Jacobians for gaseous mixing ratios and aerosol densities (fig. 2) and to the assessment of retrieval capabilities of conceptual VISNIR spectro-imagers (Fig. 3), according to the methods summarized in [7].

Fig. 3: Comparison of diagonal elements of a priori (\mathbf{S}_a) and a posteriori (\mathbf{S}) state vector covariances, for different parts of the state vector. a1, a2 and a3 are three distinct aerosol populations. A priori covariances are set to 1. Any decrease from the a priori value represents a net information gain provided by the data. S/N 100 was assumed for this simulation.

Future steps: Our work will now aim to (1) extend the simulation spectral range to 5 μm (2) incorporating H_3^+ auroral emissions and (3) comparing the results with JWST spectra, once they become available in the literature [8].

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