ARES VI: Are 1D retrieval models accurate enough to characterize exo-atmospheres with transmission spectroscopy in the era of JWST and Ariel?

Résumé

The observed exoplanets transit spectra are usually retrieved using one-dimensional models to determine atmospheric composition. However, planetary atmospheres are three-dimensional. With the new state-of-the-art James Webb Space Telescope (JWST) and future space telescopes such as Ariel (Atmospheric Remote-sensing Infrared Exoplanet Large-survey), we will be able to obtain increasingly accurate transit spectra. The 3D effects on the spectra will be visible, and we can expect biases in the 1D extractions. In order to elucidate these biases, we have built theoretical observations of transit spectra, from 3D atmospheric modeling through transit modeling to instrument modeling. For that purpose, we used a Global Climate Model (GCM) to simulate the atmosphere, a 3D-radiative transfer model to calculate theoretical transmission spectra, and adapted instrument software from JWST and Ariel to reproduce telescope noise. Next, we used a 1D-radiative transfer inversion model to retrieve the known input atmosphere and disentangle any biases that might be observed. The study has been done from warm planets to ultra-hot planets to assess biases as a function of average planet temperature. Three-dimensional effects are observed to be strongly non-linear from the coldest to the hottest planets. These effects also depend on the planet's metallicity and gravity. If we consider the chemistry at equilibrium, we can observe very strong variations in one feature of a molecule, or very small variations over the whole spectra. We conclude that we cannot rely on the uncertainty of retrievals at all pressures, and that we must be cautious about the results of retrievals at the top of the atmosphere. However, at the probe's pressure limit, in the middle atmosphere, the results are still quite close to the truth. We also need to be careful about the chemical models used for planetary atmosphere. If the chemistry of one molecule is not correctly described, this will bias all the others, as well as the retrieved temperature. Finally, although fitting a wider wavelength range and higher resolution has been shown to increase retrievals accuracy, we show that this could depend on the wavelength range chosen, due to the accuracy of the retrieval model on modeling the features of these different parts of the spectra. In any case, 1D retrievals are still correct for the detection of molecules, even in the event of an erroneous abundance retrieval.

Mots-Clés: exoplanets, atmospheres, radiative transfer, chemistry, methods: numerical, techniques: transmission spectroscopy, meteorology