




# POSEIDON: A Multidimensional Atmospheric Retrieval Code for Exoplanet Spectra

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## Summary

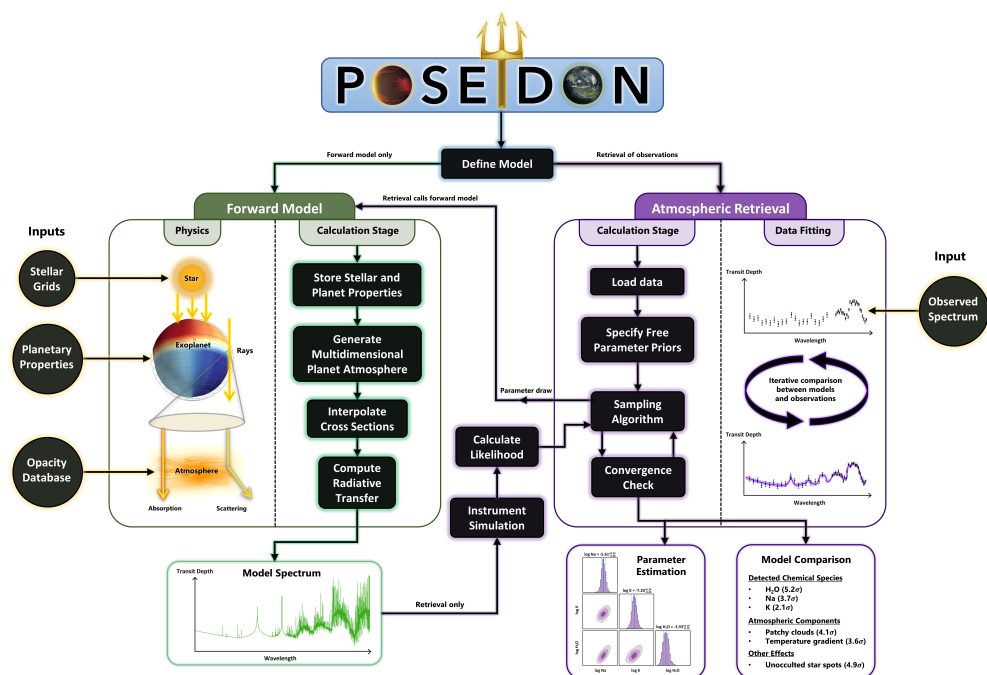
Exoplanet atmospheres are a dynamic and fast-changing field at the frontier of modern astronomy. Telescope observations can reveal the chemical composition, temperature, cloud properties, and (potentially) the habitability of these remote worlds. Astronomers can measure these atmospheric properties by observing how the fraction of starlight blocked by a planet passing in front of its host star changes with wavelength — a technique called transmission spectroscopy. Since the wavelengths where different atoms and molecules absorb are already known (from laboratory measurements or quantum mechanics), astronomers can compare models of exoplanet spectra to observations to infer the chemical composition of exoplanets.

POSEIDON is a Python package for the modelling and analysis of exoplanet spectra. POSEIDON has two main functions: (i) computation of model spectra for 1D, 2D, or 3D exoplanet atmospheres; and (ii) a Bayesian fitting routine ('atmospheric retrieval') that can infer the range of atmospheric properties consistent with an observed exoplanet spectrum.

## Exoplanet Modelling and Atmospheric Retrieval with POSEIDON

The first major use case for POSEIDON is 'forward modelling' — illustrated on the left of [Figure 1](#). A user can generate a model planet spectrum, for a given star-planet system, by providing a specific set of atmospheric properties (e.g. the chemical composition and temperature). The forward model mode allows users to explore how atmospheric properties alter an exoplanet spectrum and to produce predicted model spectra for observing proposals. The required input files (pre-computed stellar grids and an opacity database) are available to download from an online repository (linked in the documentation).

The second major use case for POSEIDON is atmospheric retrieval — illustrated on the right of [Figure 1](#). To initialise a retrieval, a user provides an observed exoplanet spectrum and the range of atmospheric properties to be explored (i.e. the prior ranges for a set of free parameters defining a model). A Bayesian statistical sampling algorithm — nominally [PyMultiNest](#) ([Buchner et al., 2014](#)) — then repeatedly calls the forward model, comparing the generated spectrum to the observations, until the parameter space is fully explored and a convergence criteria reached. The main outputs of an atmospheric retrieval are the posterior probability distributions of the model parameters and the model's Bayesian evidence. The Bayesian evidences from multiple retrievals, in turn, can be subsequently compared to compute a detection significance for each model component (e.g. the statistical confidence for a molecule being present in the planetary atmosphere).



**Figure 1:** Schematic architecture of the POSEIDON atmospheric retrieval code. Users can call POSEIDON in two main ways: (i) to generate a model exoplanet spectrum for a specified planet atmosphere (green arrows); or (ii) to fit an observed exoplanet spectrum by statistical sampling of a model's atmospheric properties (purple arrows). The diagram highlights code inputs (circles), algorithm steps (rectangles), and code outputs (bottom green or purple boxes).

POSEIDON was first described in the exoplanet literature by (MacDonald & Madhusudhan, 2017). Since then, the code has been used in 17 peer-reviewed publications (e.g., Alam et al., 2021; Kaltenegger et al., 2020; Sedaghati et al., 2017). Most recently, a detailed description of POSEIDON's new multidimensional forward model, TRIDENT, was provided by (MacDonald & Lewis, 2022).

## Statement of Need

Recent years have seen a substantial improvement in the number of high-quality exoplanet spectra. In particular, the newly operational JWST and a profusion of high-resolution ground-based spectrographs offer an abundance of exoplanet data. The accurate interpretation of such data requires a retrieval code that can rapidly explore complex parameter spaces describing a rich variety of atmospheric phenomena.

POSEIDON provides the capability to model and retrieve transmission spectra of planets with inhomogeneous temperatures, compositions, and cloud properties (i.e. 2D or 3D models). Several studies have highlighted that not including these multidimensional effects can bias retrieval inferences (e.g., Caldas et al., 2019; Line & Parmentier, 2016; MacDonald et al., 2020; Pluriel et al., 2022). However, existing open-source exoplanet retrieval codes assume 1D atmospheres for computational efficiency. POSEIDON, therefore, offers an open-source implementation of state-of-the-art multidimensional retrieval methods (see MacDonald & Lewis, 2022 and MacDonald & Lewis, in prep.) to aid the interpretation of high-quality exoplanet spectra.

In a 1D configuration, POSEIDON compares well with other retrieval codes. When applied to Hubble Space Telescope observations, POSEIDON produces consistent retrieval results with the ATMO and NEMESIS retrieval codes (Lewis et al., 2020; Rathcke et al., 2021). Recently,

(Barstow et al., 2022) presented a comparison of five exoplanet retrieval codes, including POSEIDON, which demonstrated good agreement on simulated Ariel (Tinetti et al., 2020) transmission spectra. POSEIDON also offers exceptional computational performance: a single 1D forward model over a wavelength range sufficient for JWST analyses takes 70 ms (see MacDonald & Lewis, 2022, Appendix D), while publication-quality 1D retrievals typically take an hour or less. POSEIDON also supports multi-core retrievals via PyMultiNest's MPI implementation, which achieves a roughly linear speed-up in the number of cores. Therefore, POSEIDON allows users to readily explore 1D retrievals on personal laptops while scaling up to multidimensional retrievals on modest clusters.

## Future Developments

POSEIDON v1.0 officially supports the modelling and retrieval of exoplanet transmission spectra in 1D, 2D, and 3D. The initial release also includes a beta version of thermal emission spectra modelling and retrieval (for cloud-free, 1D atmospheres, with no scattering), which will be developed further in future releases. Suggestions for additional features are more than welcome.

## Documentation

Documentation for POSEIDON, with step-by-step tutorials illustrating research applications, is available at <https://poseidon-retrievals.readthedocs.io/en/latest/>.

## Similar Tools

The following exoplanet retrieval codes are open source: PLATON (Zhang et al., 2019, 2020), petitRADTRANS (Mollière et al., 2019), CHIMERA (Line et al., 2013), TauRex (Al-Refaie et al., 2021; Waldmann et al., 2015), NEMESIS (Irwin et al., 2008) Pyrat Bay (Cubillos & Bleicic, 2021), and BART (Harrington et al., 2022)

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