# Developing an Exoplanet Atmospheric Retrieval Algorithm.


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## Abstract


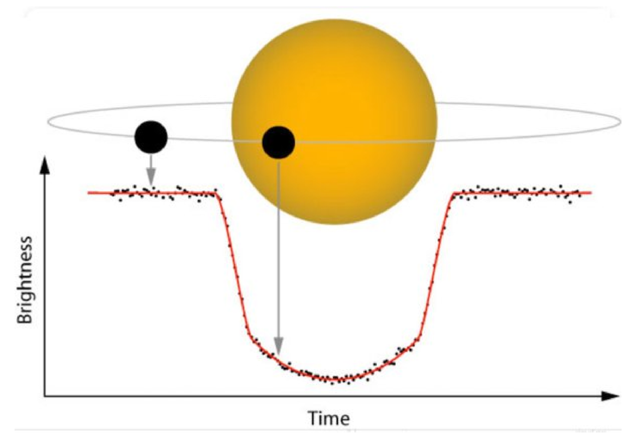


Figure 1. A transiting planet showing the corresponding dip in incoming flux.

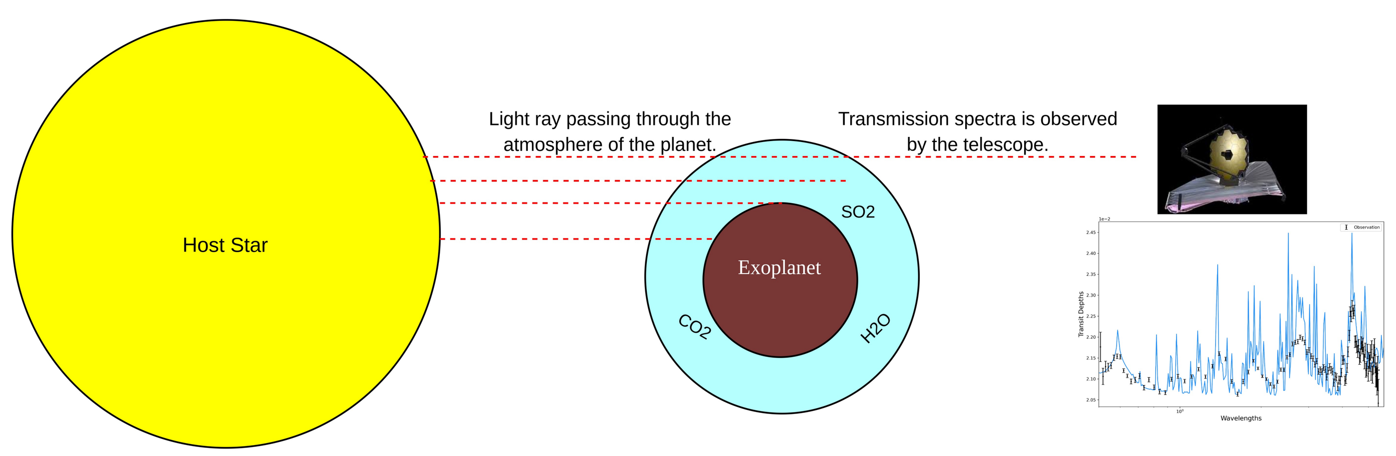


Figure 2. Some of the star light passing through the exoplanet's atmosphere is absorbed by atoms and molecules of various chemical species or scattered by other sources. This is seen as increased transit depths in the observed spectrum.

With the confirmation of more than 5,650 exoplanets and with the increasing quality of data characterising exoplanet atmospheres, from telescopes like JWST and future upcoming missions like ARIEL and Habitable World's Observatory. There is a need of robust, simple and fast tools to do preliminary characterisation of these data. Here, I present an exoplanet atmospheric retrieval algorithm in development which will be able to robustly characterize the present and future exoplanet observations for the preliminary detection of physical and chemical parameters of exoplanet atmospheres.


## Underlying Equations

The below transit depth equation [2] is obtained after solving the equation of radiative transfer in the case of a transiting exoplanet:

$$\left(\frac{R_{p,\lambda}}{R_*}\right)^2 = \frac{R_p^2 + 2\sum_{i=1}^{N_b}(1-e^{-\tau(\lambda,i)})b_i\Delta b_i}{{R_*}^2}$$

where, $\tau = \int_{r_{min}}^{r_{max}} \kappa_\lambda(r)ds$, is the optical depth which is the integral of absorption coefficient $\kappa_\lambda$ along a distance s within the medium, $R_p$ is the planetary radius, $R_*$ is the host star radius and b is the impact parameter of a light ray from the centre of the planet. The absorption coefficient also known as extinction coeffecient encodes information about the absorption of photons by the medium.

The extinction coeffecient is calculated as:

$$\kappa_\lambda(P,T) = n(P,T)\sigma(\lambda,P,T),$$

where n is the number density and $\sigma$ is the absorption cross-sections. These can come from various sources such as from gaseous atoms/molecules, rayleigh scattering, collision-induced-absorption and also from clouds, hazes or aerosols

## Flowchart of the Retrieval Algorithm.

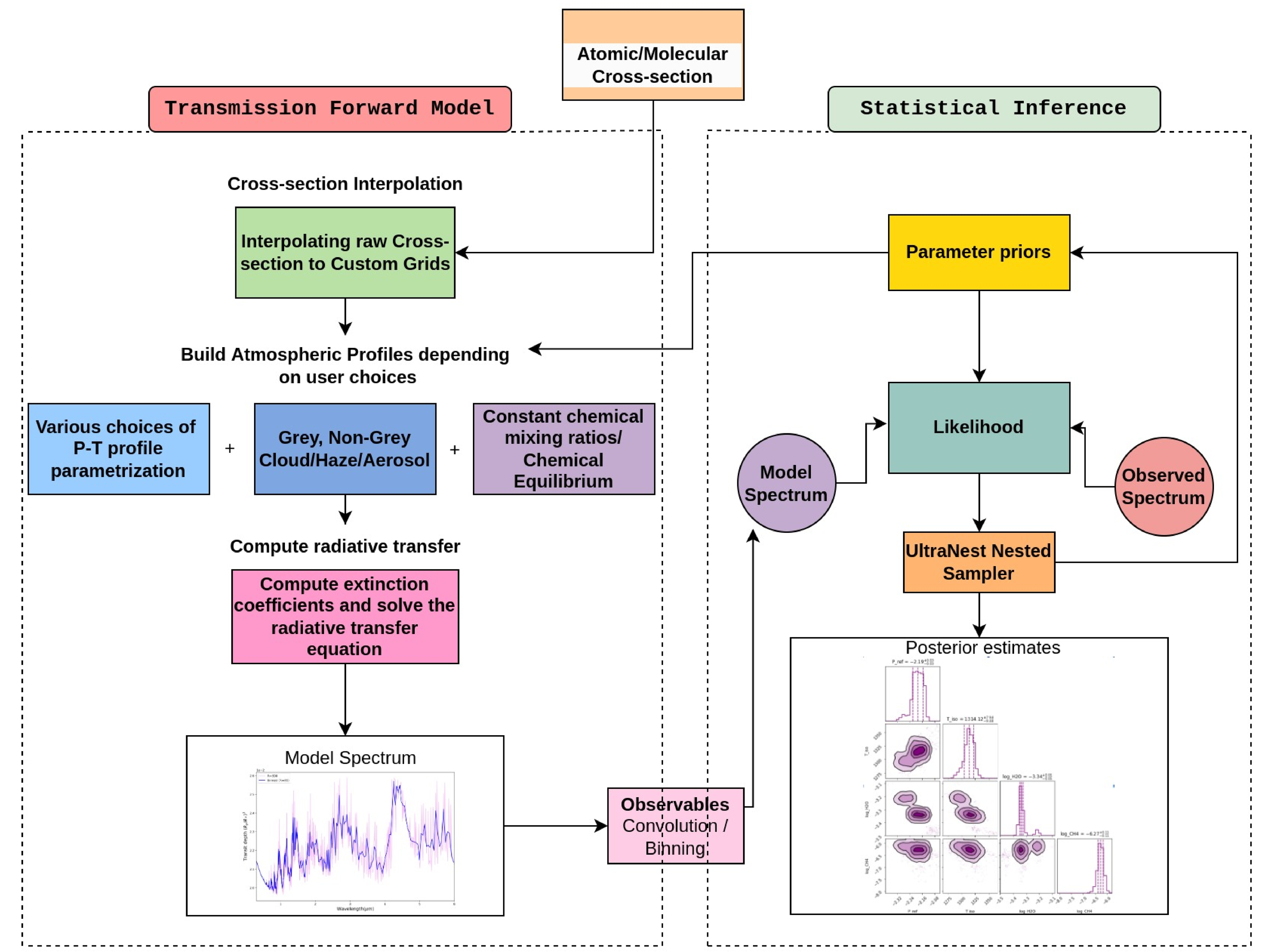


Figure 3. Flowchart of the Retrieval Algorithm showing the working of the Forward Model and the Statistical Inference Algorithm.

## Working of the Retrieval Algorithm.

An Exoplanet Retrieval Algorithm has two main components - one is the forward model and the other is the statistical inference algorithm.

- **Forward Model:** It is the main part of the retrieval algorithm that simulates a model spectrum. It can either be a transmission, emission or reflection model. It assumes many atmospheric characteristics by parameterised functions such as the pressure-temperature profile, cloud/aerosol/haze and the chemical mixing ratios. For a combination of these parameters, it then solves the equation of radiative transfer as stated previously, to provide us the model spectrum.
- **Statistical Inference Algorithm:** A bayesian statistical sampling algorithm such as Markov Chain Monte Carlo (MCMC) or Nested sampling maps the entire parameter space of the parameters considered by comparing the model with the observations. In our case, we use the nested sampling code "UltraNest", which calculates the likelihood of the model spectrums by comparing them to the observed data and eventually provides us the posterior estimates of the assumed parameters, enabling statistically robust constraints on exoplanet properties. Nested sampling algorithms also provide the evidence of a model which can be used to compare different models with each other to find the best one. Since these forward models don't assume any component of self-consistent physics and chemistry and are rather described by free-parameters, it enables the retrieval to evaluate millions of models in a convenient amount of time.

## Results

Here I show the results from a retrieval performed on the HST observations of the hot-jupiter exoplanet HD 209458 b and show that our results are comparable to the results retrieved from an already established retrieval algorithm "POSEIDON"[1][3].

| Parameters | *Poseidon (best-fit parameter values)* | *Our Code (best-fit parameter values)* |
|---|---|---|
| Log reference pressure (bar) | -0.71 | -0.77 +- 0.07 |
| Log H2O (VMR) | -4.73 | -4.72 +- 0.17 |
| Log Na | -6.78 | -6.42 +- 0.20 |
| Log K | -8.11 | -7.98 +- 0.29 |
| Log CH4 | -8.73 | -7.33 +- 0.83 |
| Log NH3 | -6.19 | -6.26 +- 0.26 |
| Log HCN | -6.06 | -6.60 +- 0.55 |
| Temperature(K) | 792.9 | 712 +- 57 |
| Log cloud deck pressure(bar) | -0.61 | -0.63 +-25 |

Figure 4. A comparison table showing the retrieved values of various parameters with POSEIDON and our code.

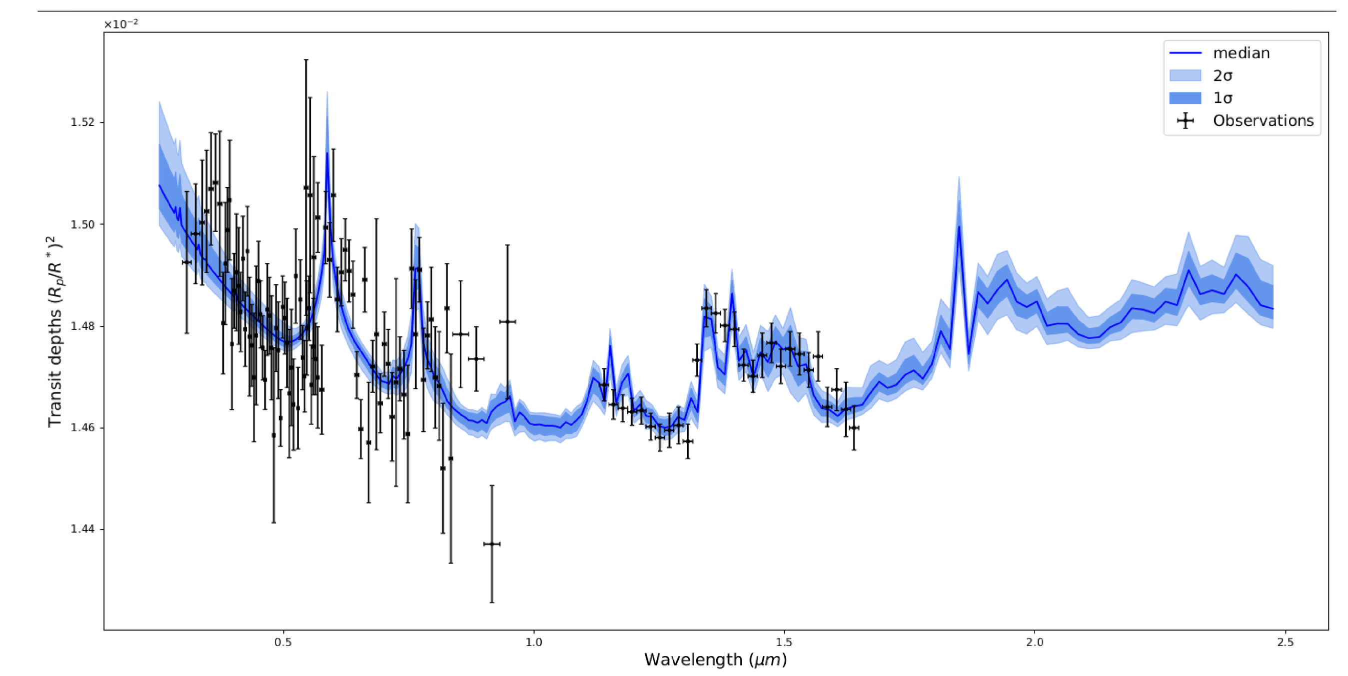


Figure 5. Best-fit transmission spectrum from our retrieval code to the HST data of HD-209458 b. Figure shows the 1 and 2 sigma regions in blue shades and the observations in black.

A retrieval with basic model assumptions was performed to constrain the volume mixing ratios of $H_2O$, $CH_4$, $NH_3$, HCN, Na and K with both POSEIDON and our code. Retrieved mixing ratios in the logarithmic scale are comparable to each other in case of all the atoms and molecules. A simple isothermal temperature profile was assumed which is also comparable to the POSEIDON retieved values. The retrieval also hints to the presence of clouds for the best-fit spectrum to the observations.

Of course to find the most constrained parameters one must assume more model parameters like presence of hazes and non-isothermal temperature profiles[3].

## References


[1] Ryan J. MacDonald.
Poseidon: A multidimensional atmospheric retrieval code for exoplanet spectra.
*JOSS*, 2023.

[2] Tyler D. Robinson.
A theory of exoplanet transits with light scattering.
*The Astrophysical Journal*, 2017.

[3] Nikku Madhusudhan Ryan J. MacDonald.
Hd 209458b in new light: Evidence of nitrogen chemistry, patchy clouds and sub-solar water.
*MNRAS*, 2017.