## A Catalogue of Exoplanet Atmospheric Retrieval Codes

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#### ABSTRACT

Exoplanet atmospheric retrieval is a computational technique widely used to infer properties of planetary atmospheres from remote spectroscopic observations. Retrieval codes typically employ Bayesian sampling algorithms or machine learning approaches to explore the range of atmospheric properties (e.g., chemical composition, temperature structure, aerosols) compatible with an observed spectrum. However, despite the wide adoption of exoplanet retrieval techniques, there is currently no systematic summary of exoplanet retrieval codes in the literature. Here, we provide a catalogue of the atmospheric retrieval codes published to date, alongside links to their respective code repositories where available. Our catalogue will be continuously updated via a Zenodo archive.

Keywords: planets and satellites: atmospheres — techniques: spectroscopic — methods: data analysis

# 1. INTRODUCTION

Spectroscopic observations provide one of our only windows into exoplanet atmospheres. Refining our understanding of atmospheric physics and chemistry ultimately depends on decoding the spectral signatures imprinted in the light from these distant worlds. Given a set of spectral observations of an exoplanet, atmospheric retrieval codes (see Madhusudhan 2018; Barstow & Heng 2020, for recent reviews) invert the spectra to yield probability distributions and detection significances for the underlying atmospheric properties.

While many exoplanet retrieval codes have been developed in the last 15 years, there is no systematic resource summarising the codes reported in the literature. Our goal in this research note is to offer a catalogue summarising the exoplanet retrieval code landscape at the onset of the JWST era. This catalogue also includes links to publicly available retrieval codes, which can facilitate code intercomparisons (e.g., Barstow et al. 2022).

# 2. EXOPLANET RETRIEVAL CODE CATALOGUE

Table 1 contains our initial exoplanet retrieval code catalogue. At the time of writing (March 2023), we have identified 50 distinct retrieval codes in the exoplanet literature. Of these codes, 39 employ at least one Bayesian sampling technique, whilst 11 codes adopt machine learning algorithms. We sort the codes according to a rough chronology of their first atmospheric retrieval application (on either real or simulated observations) and provide references for the first application of each code to each class of exoplanet spectrum (transmission, emission, reflection, etc.). We apologise for any errors or omissions in the initial catalogue.

We will continuously update this resource by hosting a live version of the catalogue on a Zenodo repository. Given the fast-moving nature of the exoplanet field, we encourage authors to contact us with any updates or corrections to ensure this catalogue can remain a current and helpful resource for the exoplanet community.

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 ${\bf Table~1.~Catalogue~of~Exoplanet~Atmospheric~Retrieval~Codes}$ 

Code / Authors	Spectrum Type	Parameter Exploration	Code Link	References
Sampling Based				
Madhusudhan & Seager	Transmission Emission	Grid, MCMC	_	Madhusudhan & Seager (2009)
NEMESIS	Emission Transmission Reflection	OE, NS	Link	Lee et al. (2012) Barstow et al. (2013) Barstow et al. (2014)
SCARLET	Transmission Emission Reflection	MCMC, NS		Benneke & Seager (2012) Benneke et al. (2019) Wong et al. (2020)
MassSpec	Transmission	MCMC	_	de Wit & Seager (2013)
CHIMERA	Emission Transmission Reflection	OE, MCMC, NS, SC-Grid	Link	Line et al. (2013) Swain et al. (2014) Piskorz et al. (2018)
TauREx	Transmission Emission	MCMC, NS	Link	Waldmann et al. (2015b) Waldmann et al. (2015a)
Lupu et al.	Reflection	MCMC, NS	_	Lupu et al. (2016)
HELIOS-R	Emission	NS	Link	Lavie et al. (2017)
APOLLO	Transmission Emission	MCMC	Link	Howe et al. (2017) Howe et al. (2022)
POSEIDON	Transmission Emission	NS	Link	MacDonald & Madhusudhan (2017) Coulombe et al. (2023)
ATMO	Transmission Emission	MCMC, NS, SC-Grid	_	Wakeford et al. (2017) Evans et al. (2017)
Brewster	Emission	MCMC, NS	_	Burningham et al. (2017)
Pyrat Bay	Transmission Emission	MCMC	Link	Kilpatrick et al. (2018) Cubillos & Blecic (2021)
HyDRA	Emission	NS	_	Gandhi & Madhusudhan (2018)
PSG	Reflection Emission Transmission	OE, NS	Link	Villanueva et al. (2018)
AURA	Transmission	NS	_	Pinhas et al. (2018)
exoretrievals	Transmission	NS	_	Espinoza et al. (2019)
Brogi & Line	Emission	NS	Link	Brogi & Line (2019)
PLATON	Transmission Emission	NS	Link	Zhang et al. (2019) Zhang et al. (2020)
petitRADTRANS	Transmission Emission Reflection	MCMC, NS	Link	Mollière et al. (2019) Mollière et al. (2019) Alei et al. (2022)
MERC	Transmission	NS	_	Seidel et al. (2020)
species	Emission	MCMC, NS, SC-Grid	Link	Stolker et al. (2020)
Gibson et al.	Transmission	MCMC	_	Gibson et al. (2020)
$\mathrm{ExoReL}^{\mathcal{R}}$	Reflection	NS	_	Damiano & Hu (2020)
Alfnoor	Transmission	NS	_	Changeat et al. (2020)
PETRA	Transmission	MCMC, SC-Grid	_	Lothringer & Barman (2020)

 ${\bf Table} \,\, {\bf 1} \,\, {\it continued}$ 

Table 1 (continued)

Code / Authors	Spectrum Type	Parameter Exploration	Code	References
			Link	
METIS	Transmission	MCMC	_	Lacy & Burrows (2020)
Carrión-González et al.	Reflection	MCMC	_	Carrión-González et al. (2020)
ARCiS	Transmission Emission	NS	_	Min et al. (2020) Chubb & Min (2022)
PICASO	Reflection Emission Transmission	NS, SC-Grid	Link	Mukherjee et al. (2021) Miles et al. (2022) Batalha et al. (2023)
Cerberus	Transmission	MCMC	_	Swain et al. (2021)
Aurora	Transmission	NS	_	Welbanks & Madhusudhan (2021)
BART	Transmission Emission	MCMC	Link	Harrington et al. (2022)
ExoJAX	Emission	MCMC	Link	Kawahara et al. (2022)
ThERESA	Eclipse Mapping	MCMC	Link	Challener & Rauscher (2022)
p-winds	Transmission	MCMC	Link	Dos Santos et al. (2022)
smarter	Transmission	NS	_	Lustig-Yaeger et al. (2022)
tierra	Transmission	MCMC	Link	Niraula et al. (2022)
rfast	Reflection Emission Transmission	MCMC	Link	Robinson & Salvador (2023)
Machine Learning				
HELA	Transmission	RF	Link	Márquez-Neila et al. (2018)
ExoGAN	Transmission	NN	Link	Zingales & Waldmann (2018)
INARA	Reflection Emission	NN	Link	Soboczenski et al. (2018)
plan-net	Transmission	NN	Link	Cobb et al. (2019)
Fisher et al.	Transmission	RF	_	Fisher et al. (2020)
Johnsen & Marley	Reflection	MLP	Link	Johnsen et al. (2020)
Nixon & Madhusudhan	Transmission	RF	_	Nixon & Madhusudhan (2020)
MARGE+HOMER	Emission	NN+MCMC	Link	Himes et al. (2022)
exoCNN	Transmission	NN	Link	Ardevol Martinez et al. (2022)
VI-retrieval	Transmission	NN+VI	_	Yip et al. (2022)
Vasist et al.	Emission	NN+VI	_	Vasist et al. (2023)

Note—Retrieval codes are ordered according to their first published exoplanet retrieval application (on either real or simulated spectroscopic data) for each category of exoplanet spectra. For years when multiple codes were published, the order is determined by the date of first arXiv submission. 'Emission' refers to secondary eclipse emission spectra, phase-resolved emission spectra, or direct thermal emission from a self-luminous object (i.e. directly imaged exoplanets or brown dwarfs). Parameter exploration acronyms are as follows: Optimal Estimation (OE); Markov Chain Monte Carlo (MCMC); Nested Sampling (NS); Self-Consistent Grid (SC-Grid); Random Forest (RF); Neural Network (NN); Multilayer Perceptron (MLP); and Variational Inference (VI). Publicly available retrieval codes, at the time of this publication, have links to the code repository.

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