EVAPORATING EXOPLANETS FOR EVERYONE

AN OPEN-SOURCE FRAMEWORK TO PLAN AND INTERPRET OBSERVATIONS OF ATMOSPHERIC ESCAPE IN EXOPLANETS

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Cloud structure in the atmosphere of Venus. Credit: JAXA/ISAS/DARTS/Kevin M. Gill
Artist’s impression of iron rain in WASP-76b. Credit: ESO/M. Kornmesser (see Ehrenreich et al. 2020, Nature 580)
CAPRI, ITALY—It has been just 10 months since a pair of Swiss astronomers first identified a planet orbiting a sunlike star other than our own, but the tally of so-called “exoplanets” has now passed the total of nine familiar planets of our solar system. That mark came earlier this month at the Fifth International Conference on Bioastronomy on this island off the southern Italian coast, where astronomers reported several new sightings, including the first evidence of another multiple planet system around a sunlike star. And with the total steadily growing, researchers are beginning to identify tentative groupings of planet types, one of which, says Geoff Marcy of San Francisco State University, is “a class of planets that is completely unlike the planets in our solar system.”

Within the group of less massive companions in circular orbits, astronomers have been surprised to find a completely new class of planets, which they dubbed “hot Jupiters.” These giant planets are termed hot because their orbits are between 10 and 20 times closer to their parent stars than the Earth is to the sun, and their orbital periods—or “years”—are only a few days long. The original exoplanet, around 51 Pegasi, belongs to this class, and three more have since been discovered orbiting 55 Cancri, Tau Bootis, and Upsilon Andromedae, Marcy and Butler’s most recent find. “55 Cancri and Tau Bootis are close cousins of 51 Pegasi, while Upsilon Andromedae is a real twin,” says Marcy. Within a couple of months Mayor expects to announce four new members of this class, based on observations

Schilling (1996, Science 273)
CAPRI, ITALY—It has been just 10 months since a team of astronomers identified a planet orbiting a star only 11 light-years from our own. It has now become clear that such planets are only the tip of the iceberg. Within the group of less massive companion stars, there have been discoveries of planets that are closer to their stars than the terrestrial planets—so-called "hot Jupiters." The closest known planet orbiting 55 Cancri, for instance, is only about three Earth radii closer to the sun than the terrestrial planets. About the same size as Jupiter, it is thought to be a "hot Jupiter." But it is not clear whether or not these planets are real twin, says Marcy. Within a couple of months Mayor expects to announce four new members of this class, based on observations of other stars.
Hydrogen escapes thermally

Credit: D. Brain, M. Chaffin, H. Egan, R. Ramstad, B. Jakosky, S. Curry, J. Luhmann, C. Dong, R. Yelle
Simulations of an escaping atmosphere in the hot Jupiter WASP-107b
YOU WILL LOSE YOUR MAJESTIC FLUFF

HOT (SUB-)NEPTUNES, BEWARE

Direction of radius evolution

More irradiated  Less irradiated
HOT (SUB-)NEPTUNES, BEWARE
YOU WILL LOSE YOUR MAJESTIC FLUFF

- What are the timescales of mass loss and radius change?
- What is the efficiency of converting stellar irradiation into outflow?
- How much does the internal energy from planet’s core contribute to evaporation?
- And what about magnetic fields?!
Lyman-α transit spectroscopy of GJ 436 b

Ehrenreich et al. (2015, Nature 522)
Lyman-α transit spectroscopy of GJ 436 b

- Only the Hubble can observe
- Low-mass stars are faint in UV
- Interstellar medium attenuation

Ehrenreich et al. (2015, Nature 522)
Transmission spectrum of an evaporating warm Neptune

Pallé et al. (2020, A&A 638)
Metastable He spectroscopy has become very productive and popular!

OPEN-POLICY TOOLS
(OPEN-SOURCE, OPEN-DATA, ETC.)

batman: Bad-Ass Transit Model cAlculatioN
Welcome to the documentation for batman, a Python package for planet transit light curves. The package supports calculations of transit light curves for exoplanets.

And many others!
OPEN-POLICY TOOLS
FOR ATMOSPHERIC ESCAPE

p-winds

Python implementation of Parker wind models for planetary atmospheres. So many p’s! (Hence the name for the code.)

The main objective of this code is to produce simplified, 1-D models of the upper atmosphere of a planet, and perform radiative transfer to calculate observable spectral signatures.

Lampón et al. (2020, A&A 636)

Search for helium in the upper atmosphere of the hot Jupiter
WASP-127 b using Gemini/Phoenix

Leonardo A. dos Santos¹, David Ehrenreich⁴, Vincent Bourrier², Romain Allart¹, George King²,³, Monika Lendl¹, Christophe Lovis¹, Steve Margheim⁴, Jorge Meléndez², Julia V. Seidel¹, and Sérgio G. Sousa⁶

\[
\frac{\partial f_{\text{ion}}}{\partial r} = \frac{1 - f_{\text{ion}} \Phi e^{-\eta_0}}{v} - \frac{0.9 \rho f_{\text{ion}}^2}{1.3 m_n v} \alpha_{\text{rec}}
\]

\[
v \frac{\partial f_1}{\partial r} = (1 - f_1 - f_3) n_e \alpha_1 + f_3 A_{31} - f_1 \Phi_1 e^{-\gamma}
\]

\[
- f_1 n_e q_{13\alpha} + f_3 n_e q_{31\alpha} + f_3 n_e q_{31b} + f_3 n_{H^0} Q_{31},
\]

\[
v \frac{\partial f_3}{\partial r} = (1 - f_1 - f_3) n_e \alpha_3 - f_3 A_{31} - f_3 \Phi_3 e^{-\gamma_3} + f_1 n_e q_{13\alpha}
\]

\[
- f_3 n_e q_{31\alpha} - f_3 n_e q_{31b} - f_3 n_{H^0} Q_{31}.
\]


**Fig. 4.** Transmission spectrum of WASP-127 b around the He triplet. Absorption is positive.
**p-winds**

AN OPEN-SOURCE CODE TO MODEL 1D EXOPLANET OUTFLOWS

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p-winds

FORWARD MODELLING: ABSORPTION IN FUNCTION OF TRANSIT PHASE

HD 209458 b, forward model

p-winds

RETRIEVALS: ATMOSPHERIC ESCAPE RATE AND OUTFLOW TEMPERATURE

HOT (SUB-)NEPTUNES, BEWARE
YOU WILL LOSE YOUR MAJESTIC FLUFF

• What are the timescales of mass loss and radius change?
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• And what about magnetic fields?!
p-winds

RETRIEVALS: ATMOSPHERIC ESCAPE RATE AND OUTFLOW TEMPERATURE

\[
\dot{m} = 0.14^{+0.08}_{-0.04} \, \text{M}_\oplus \, \text{Gyr}^{-1} \approx 0.5 \%^{+0.3\%}_{-0.1\%} \, \text{Gyr}^{-1}
\]

HAT-P-11 b is, likely, stable against evaporation

p-winds

WARNING: PRELIMINARY RESULTS!

CARMENES data is a kind courtesy of M. López-Puertas and M. Lampón
Keck/NIRSPEC result is under review (Kirk, Dos Santos et al. 2022)
p-winds

WARNING: PRELIMINARY RESULTS!

WASP-52 b, observed with Keck/NIRSPEC
Hot Jupiter

\[ \dot{m} = 0.63^{+0.26}_{-0.21} \, M_\oplus \, {\text{Gyr}}^{-1} \]

\( \text{or } \dot{m} \approx 1.2 \times 10^{11} \, \text{g s}^{-1} \)

Kirk, Dos Santos et al. (2022, AAS Journals under review)
**WARNING:** PRELIMINARY RESULTS!

HD 209458 b, observed with CARMENES

Hot Jupiter

\[ \dot{m} = 0.08^{+0.12}_{-0.06} \, M_\oplus \, \text{Gyr}^{-1} \]

or \( \dot{m} \approx 1.5 \times 10^{10} \, \text{g s}^{-1} \)

Data is courtesy of the M. López-Puertas and M. Lampón.
**p-winds**

**WARNING: PRELIMINARY RESULTS!**

GJ 3470 b, observed with CARMENES
Warm Neptune

\[ \dot{m} = 0.30^{+0.08}_{-0.06} \, \text{M}_\oplus \, \text{Gyr}^{-1} \]

or \[ \dot{m} \approx 5.7 \times 10^{10} \, \text{g s}^{-1} \]

or \[ \dot{m} \approx 2 \, \% \, \text{Gyr}^{-1} \]

Data is courtesy of the M. López-Puertas and M. Lampón
SAMPLE-LEVEL TRENDS

- $F_{\text{XUV}}$ vs. He absorption

Dos Santos et al. (2019, A&A 640)
SAMPLE-LEVEL TRENDS

- $F_{\text{XUV}}$ vs. He absorption

p-winds

WARNING: PRELIMINARY RESULTS!

Sample-level trends:
- $F_{\text{XUV}}$ vs. He absorption
- $F_{\text{XUV}}/\rho$ vs. mass loss rate

Energy-limited mass loss formulation:

$$m \propto \frac{F_{\text{XUV}}}{\rho_{\text{bulk}}}$$

pesky heating efficiency factor
p-winds

MORE RESULTS AND PROJECTS ARE IN THE PIPELINE!
MORE OPEN-SOURCE CODES
FOR ATMOSPHERIC ESCAPE STUDIES

PLATYPOS - PLAnetarY PhOtoevaporation Simulator

Tool to estimate the atmospheric mass loss of planets induced by stellar X-ray and extreme UV irradiation.

The ATES code

The ATES code has been created to perform hydrodynamical simulations of the atmospheric mass loss from irradiated exoplanets. For a detailed description of the code, we refer to [1] In the following we describe the code organization and how to run.

Requirements

The code can be compiled with both gfortran (tested successfully in version 9.3.0) and ifort (tested on the 2021.2.0 20210228 version). For the compiler choice, see below. A basic installation of python3 is required. The following libraries are used: numpy, tkinter, os, shutil, matplotlib, sys, time.

Installation

The code doesn't require any special installation, and can be directly downloaded from the Github page or, in alternative, the repository can be cloned via

git clone https://github.com/AndreaCaldirola/ATES-Code

Ketzer & Poppenhaeger (2022, proceedings of the XMM-Newton Workshop 2021)
Caldirola et al. (2021, A&A 655)
TAKE-HOME POINTS

• Hot Jupiters and (sub-)Neptunes are a laboratory to study atmospheric escape in exoplanets

• The whole community benefits from open-policy initiatives

• We need to analyze the sample of evaporating exoplanets with a common framework

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