Photoevaporation from Water Dominated Exoplanet Atmospheres

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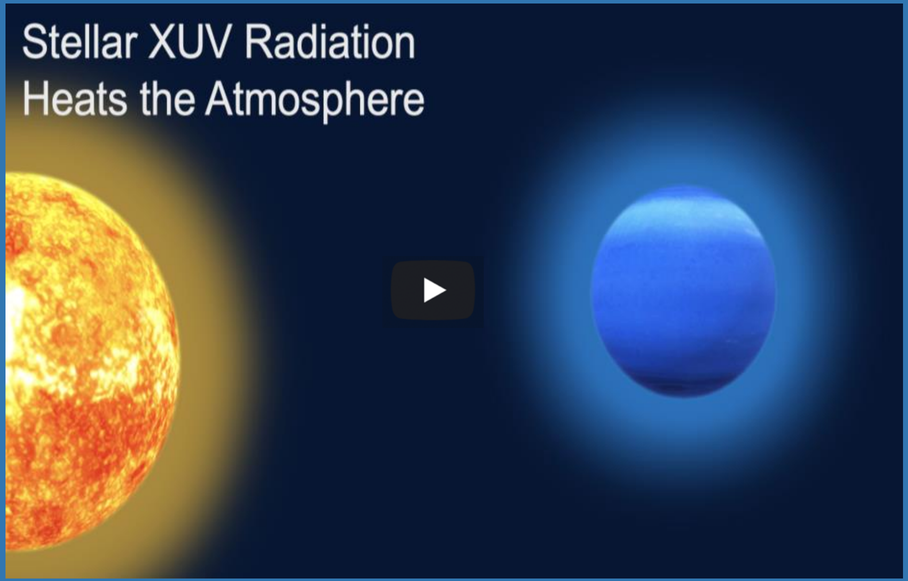
We present preliminary results of hydrodynamic simulations of photoevaporation from water-rich atmospheres using FARGO3D.

Abstract

What is photoevaporation?



Why is photoevaporation important?

Photoevaporation is an atmospheric escape mechanism that can be driven by stellar X-ray to UV radiation, which heats the atmosphere. This results in a net upwards thermal pressure, driving an outflow. This mechanism can, therefore, cause significant atmospheric escape.

Photoevaporation can significantly ablate the atmosphere or even strip it entirely, potentially rendering a planet uninhabitable.

The atmospheres of close-in, low-mass exoplanets are especially vulnerable to photoevaporation.

What research has been done previously?

Existing hydrodynamical studies of photoevaporation have mainly considered H/He dominated exoplanet atmospheres.

These studies have shown the importance of photoevaporation on low-mass close-in planets.

What's new about this research?

Only a limited number of studies have considered photoevaporation from atmospheres dominated by heavier elements, such as water. These models need to be developed to properly consider all the relevant physics.

Physics of Photoevaporation from Water-Rich Atmospheres

How does photoevaporation of heavier elements occur?

H/He atmospheres are extremely vulnerable to photoevaporation, as the particles are very light. As H escapes, it can ‘drag’ heavier elements, such as oxygen, along with it.

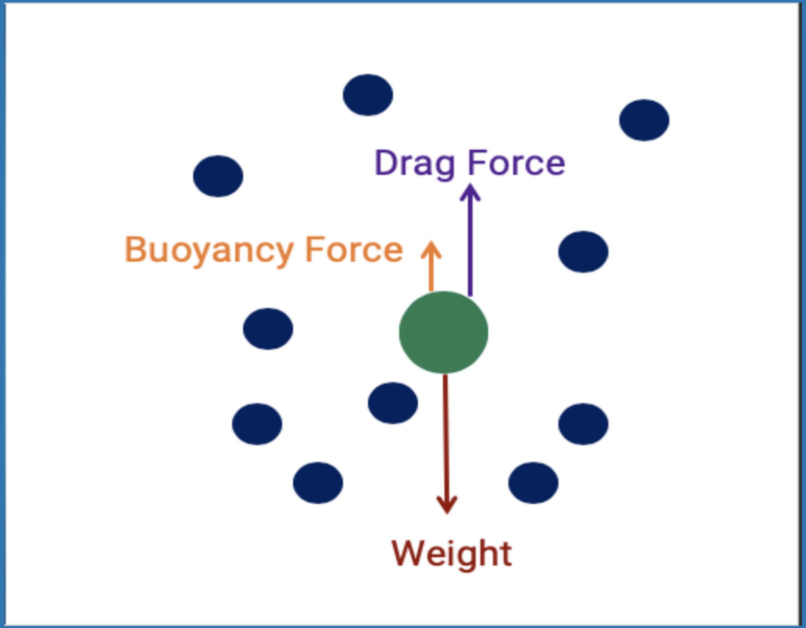


Figure 1: Force diagram showing the forces exerted on an oxygen atom (blue) due to its weight and the buoyancy and drag forces due to the escaping hydrogen (green). This force balance provides the basis of determining the crossover mass.

When can oxygen escape via photoevaporation?

Whether escaping hydrogen can drag oxygen along with it, depends on the mass of oxygen being less than the cross over mass (m_c; Hunten 1987). However, significantly, this equation assumes oxygen is a trace species. Furthermore, the cooling effect of oxygen has not yet been considered properly.

$$m_c = m_H + \frac{k_B T F_H}{g X_H b_{HO}}$$

$m_c \leq m_o$	$m_c > m_o$
Oxygen can't escape	Oxygen can escape

Figure 2: The crossover mass (m_c) can be thought of as a threshold mass when heavier species escape. Species less massive than the crossover mass are dragged along by the escaping hydrogen. In a hydrogen dominated atmosphere, the crossover mass depends on the outflow temperature (T), hydrogen flux (F_H), gravitational field strength (g), the molar mass fraction of hydrogen (X_H) and the experimentally measured binary diffusion parameter (b_{HO}).

Computational Test Cases

FARGO3D is a state of the art hydrodynamics code designed for protoplanetary discs.

Its highly accurate algorithms and capacity to simulate multiple fluids makes it ideal for developing simulations of multi-species atmospheres. However, as this has never been done before, it is vital we extensively test it.

Two test cases of FARGO3D being used to simulate an atmosphere, for the first time, are shown below.

Atmospheric Species Uncoupled

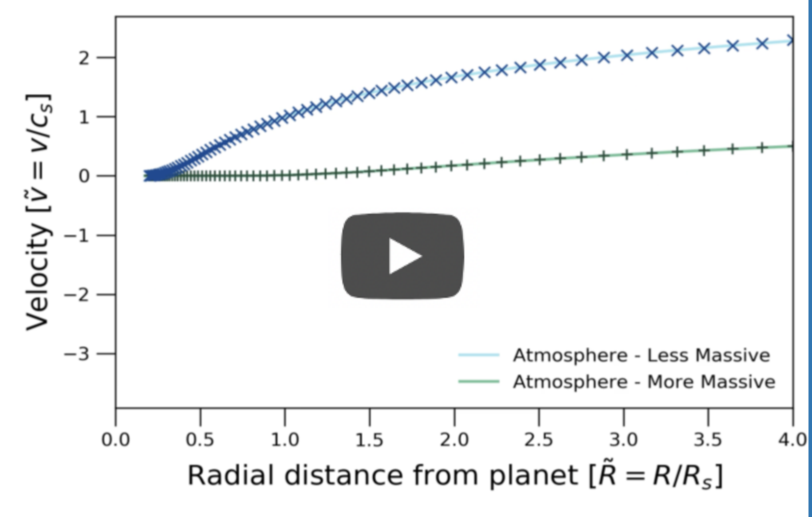


Figure 3: Blue denotes the lightest species and green denotes the more massive species. The analytic solutions are represented by lines and the 'x' and '+' represent the FARGO3D simulation data points. The simulation's inner boundary was set to 0.2 planetary radii. As the species are uncoupled, there are very few collisions between them and the two solutions evolve towards the isothermal analytic solution corresponding to each species' sound speed.

Atmospheric Species Coupled

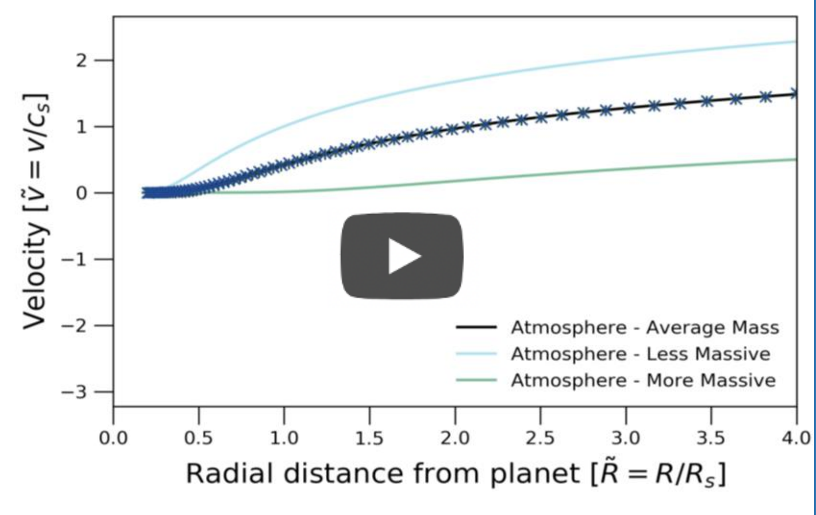


Figure 4: Blue denotes the lightest species and green denotes the more massive species. The analytic solutions are represented by lines and the 'x' and '+' represent the FARGO3D simulation data points. The simulation's inner boundary was set to 0.2 planetary radii. As the species are coupled, there are many collisions between them and the two solutions evolve towards approximately the same analytic solution corresponding to a nearly average sound speed.

Summary

- Photoevaporation can cause significant atmospheric loss from primordial H/He atmospheres
  - Especially for low-mass, close-in exoplanets

- Limited research into water-rich atmosphere &
  - Neglects oxygen cooling

- Currently developing a framework of models to understand photoevaporation from water-rich exoplanets

Future Work

- Incorporate Radiative Transfer & Heating and Cooling
- Framework of Planets & Stars
- **Model Lower Atmosphere**
- Model Interaction with Magma Oceans