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Testing Models of Evaporating Extra-Solar Planets

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1. Introduction

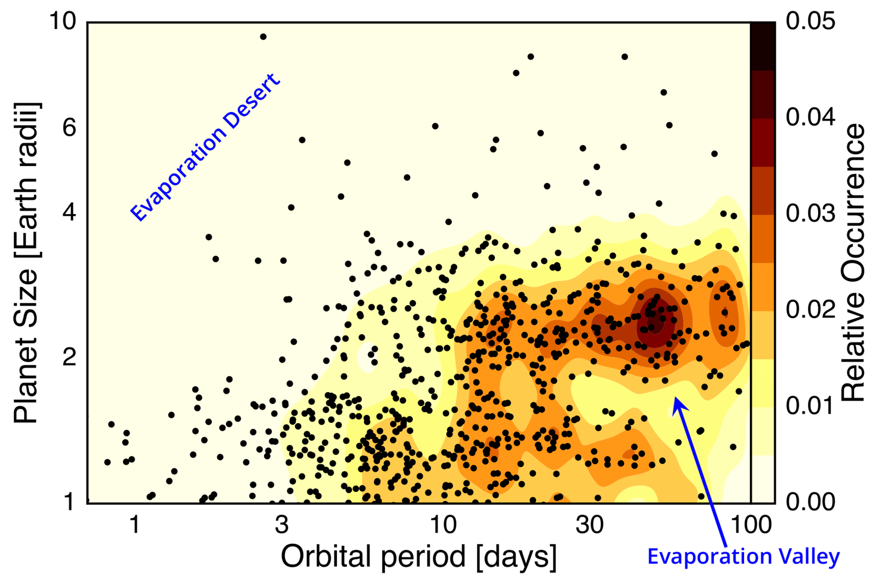

Fig. 1. Exoplanets detected in the California-Kepler survey. The evaporation valley and desert indicated are evidence of the importance of evaporation. *Reproduced from Fulton et al. 2017.*

Most exoplanets have periods shorter than 100 days. High irradiation by the close host star means volatile atmospheres that undergo evaporation.

Why is evaporation important?

- Evaporation models have been shown to predict features of observed radius - period distribution (Figure 1).
- Studying the evolution we can gain insight into the planetary structures at formation.

How to simulate an observation?

- Use the 10830 Å helium transition line (Figure 2) as probe, less prone to interstellar attenuation than the commonly used hydrogen Lyman-α.
- Calculate absorption curves with and without magnetic fields to determine the impact on expected line-shape.
- Magnetic field estimation can help with assessing planet properties.

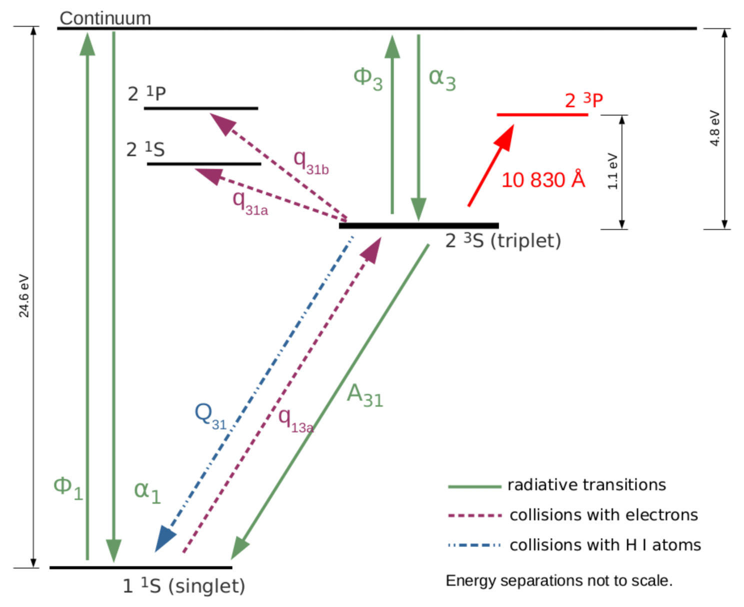

Fig. 2. Helium atomic processes. The transition in question is the 10830 Å absorption line indicated in red. *Reproduced from Oklopčić & Hirata 2018.*

2. Calculating He Fraction

To simulate a transit observation we calculate the amount of starlight absorbed by the atmospheric helium along the line of sight, for which we need the abundance of helium in the outflow.

We first solve for the outflow streamlines:

Hydrodynamic case:

- anisotropic heating
- pressure gradient generated
- strong day-to-night-side flow
- expect blue-shifted line

MHD case:

- flow follows magnetic field lines
- no net flow along closed lines
- no night-side flow
- expect red-shifted line

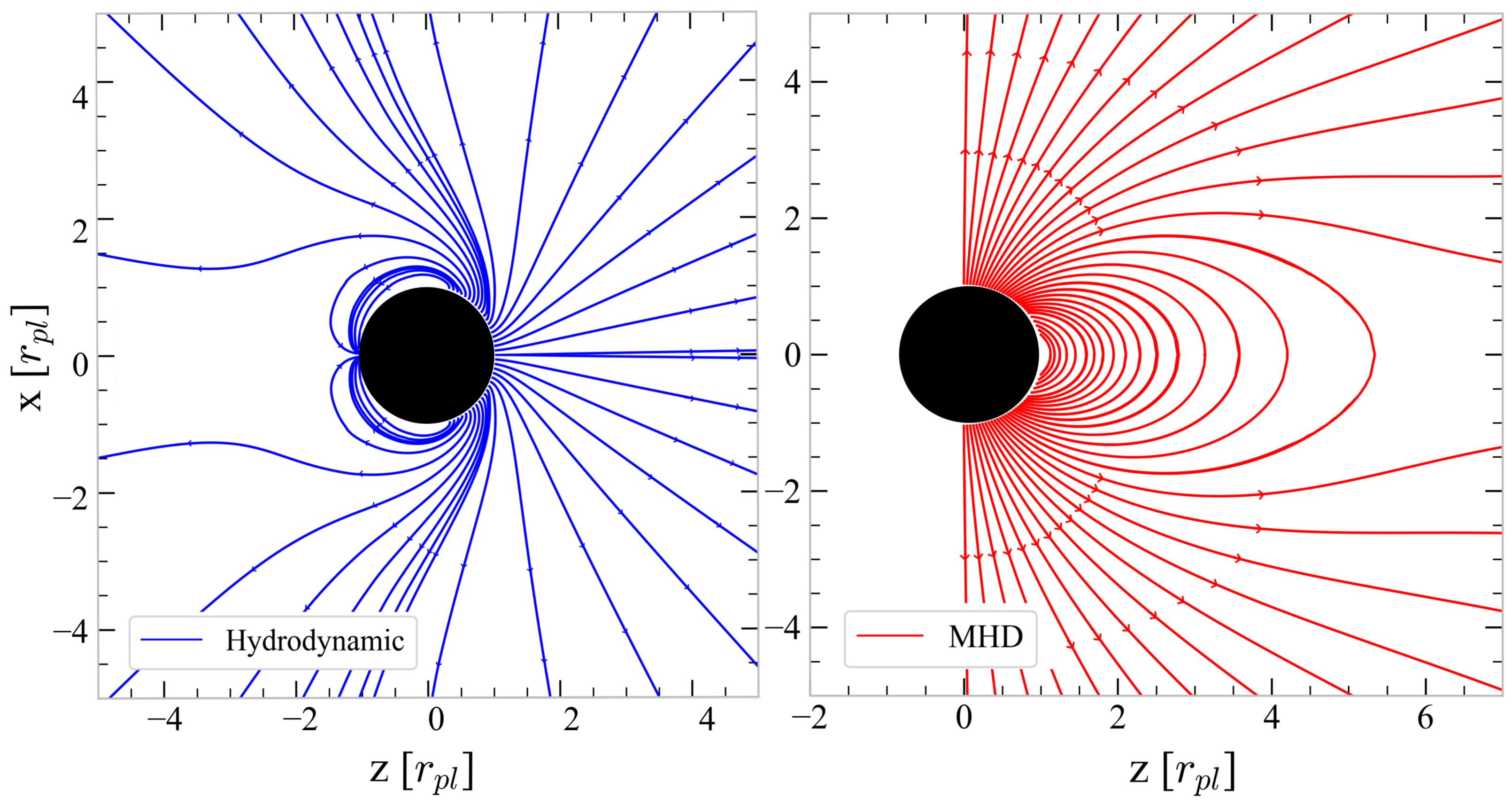

Fig. 3. Atmospheric streamlines of hydrodynamic and MHD simulations with the star along the positive z axis. Outflow of exoplanets with significant magnetic fields (~ 3G) follow magnetic field lines, hence the MHD case illustrates magnetic field lines.

We then calculate the abundance of helium in the metastable 2^3S state, which generates the 10830 Å transition line, by solving the population and depopulation equations along the streamlines:

Hydrodynamic case:

- fraction peaks at ~2 r_{pl}
- stays consistently high

MHD case:

- fraction peaks earlier
- falls off faster

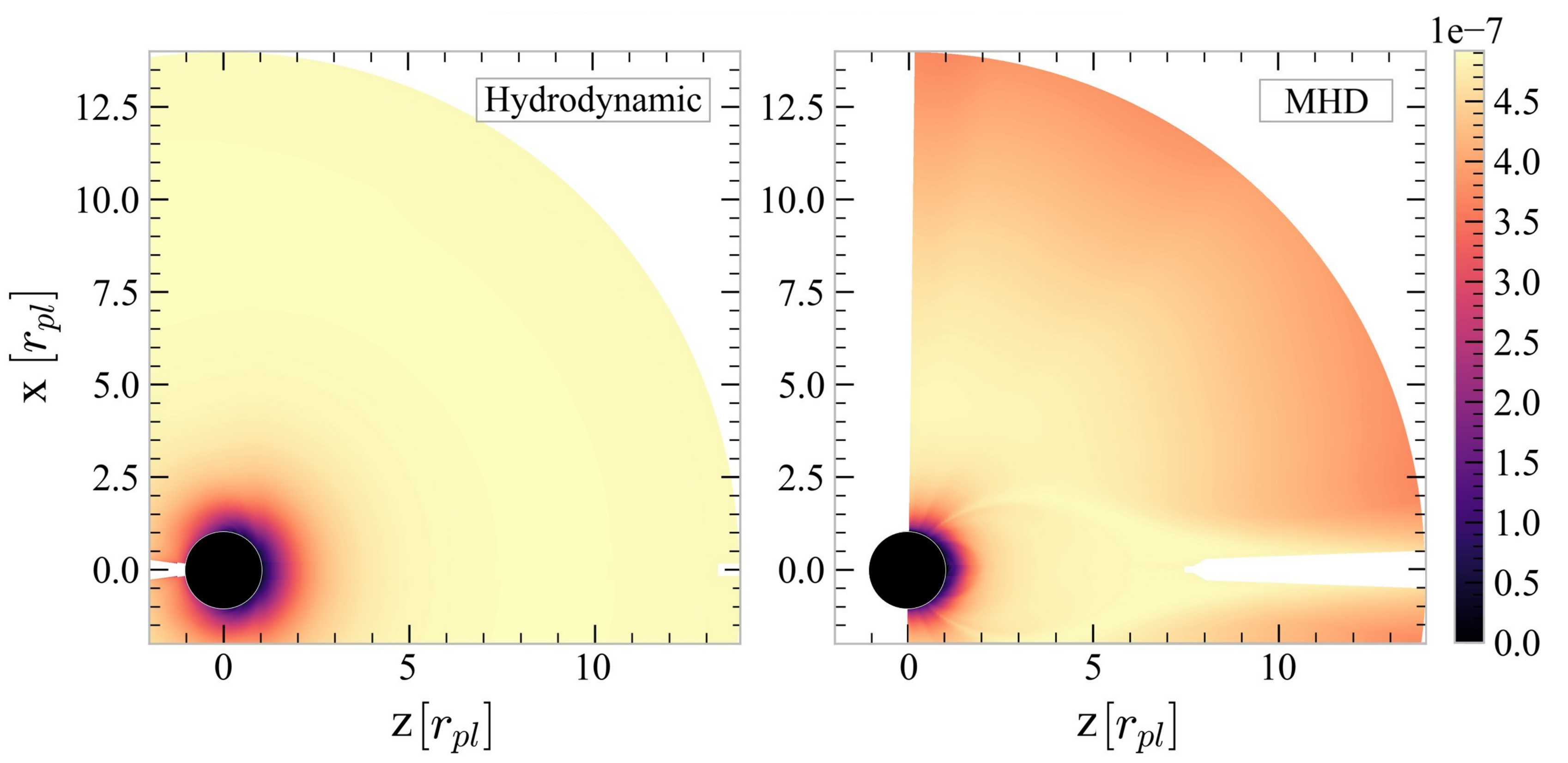

Fig. 4. Fraction of helium in the 2^3S state for hydrodynamic and MHD simulations.

3. Calculating Absorption

Finally, we calculate the expected absorption line:

- Set up a grid on the side of the planet.
- Sum the optical depth τ(λ) of helium in the 2^3S state along the lines of sight.
- Exponentiate the optical depth to find the absorbed intensity.
- Sum the absorbed intensities at different impact parameters weighted by the effective ring-like area covered.
- Normalise to the total stellar flux.

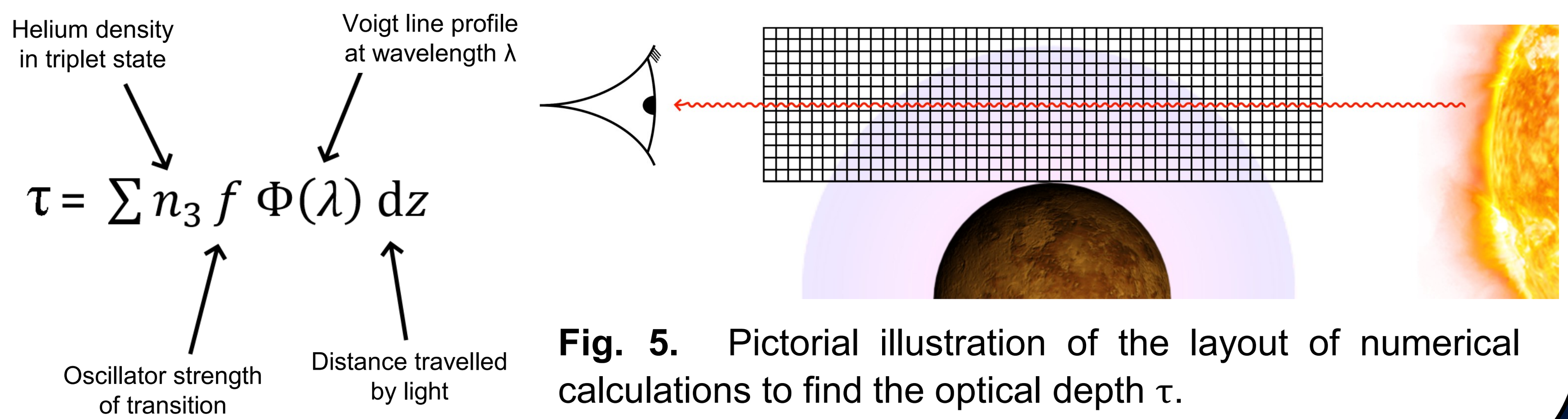

Fig. 5. Pictorial illustration of the layout of numerical calculations to find the optical depth τ.

4. Results & Future Work

Simulations show a significant absorption trace in both cases:

- **Hydrodynamic case**: line blue-shift is clearly detectable.
- **MHD case**: line is slightly red-shifted, practically indistinguishable from an unshifted line.

We conclude that the shift of the 10830 Å line can in principle be used to determine whether an exoplanet has a negligible magnetic field (blue-shift) or a significant magnetic field (no shift or red-shift).

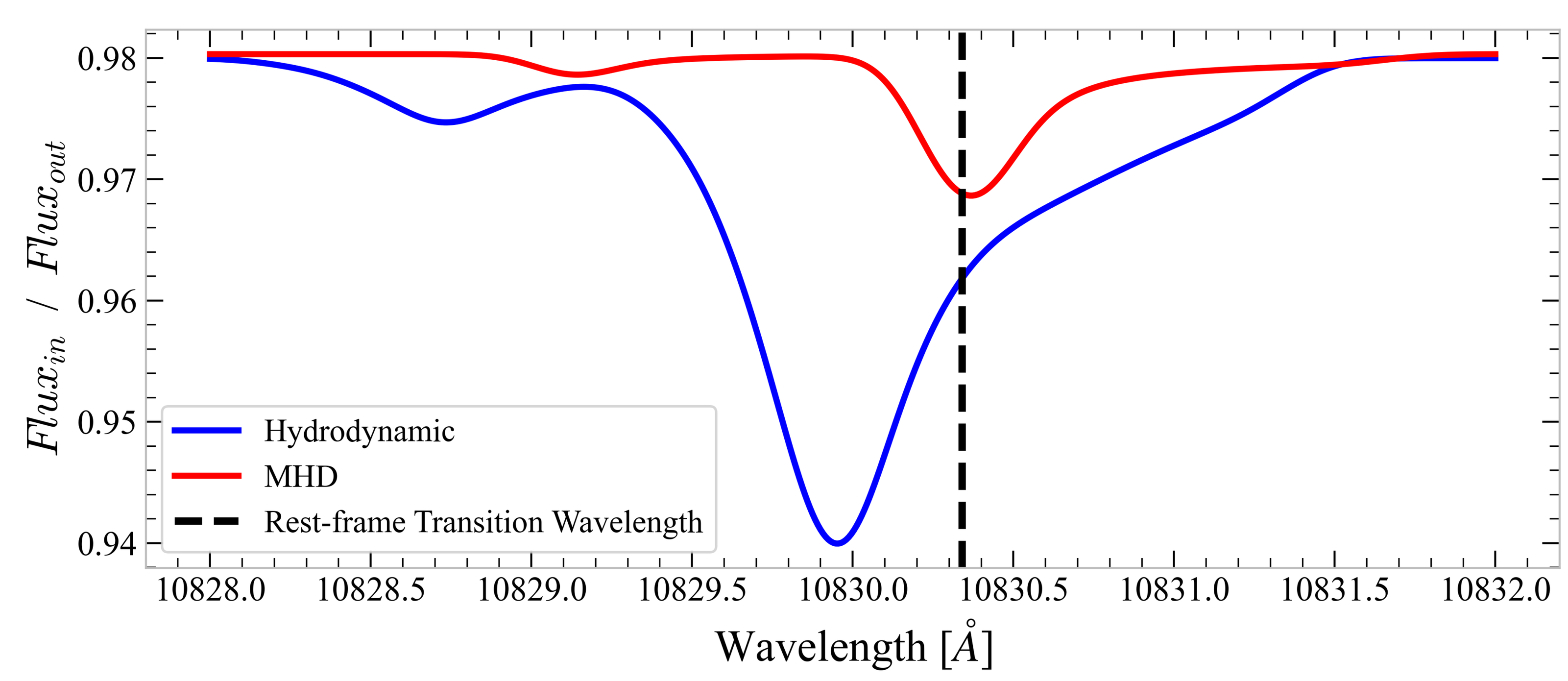

Fig. 6. Simulated absorption lines around 10830 Å for hydrodynamic and MHD cases

Further investigation can be done on what magnetic field strengths generate detectable red-shifts and on what stellar type has the optimal ionising flux to generate a blue-shift.

References

Fulton B.J. et al. (2017) The California-Kepler Survey. III. A gap in the radius distribution of small planets. *Astron. J.* 154:109

Oklopčić A., Hirata C.M. (2018) A new window into escaping exoplanet atmospheres: 10830 Å line of helium. *Astrophys. J. Lett.* 855:L11