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Nonhydrostatic Density Profiles of Sodium & Potassium at Close-in Gas Giant Exoplanets

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Abstract

Hydrostatic equlibrium is an excellent approximation for collisional atmospheres and can even mimic the behavior of collisionless mediums due to Boltzmann's law. We focus on high-resolution observations of sodium (Na I) and potassium (K I) at close-in gas giant exoplanets as their formidable cross sections are able to probe very tenuous layers. Na & K when observed in transmission spectra are therefore not necessarily in hydrostatic equilibrium as opposed to molecules probing denser atmospheric layers.

While transmission spectroscopy can remarkably probe the average density of the absorbing layer in principle, the spatial distribution remains unknown. Consequently, the boundary between collisional and collisionless mediums (the exobase) cannot be inferred at present. This brings into question the origin and nature of a Na & K source.

As close-in gas giant exoplanets are known to be highly irradiated and embedded in a plasma environment at $\sim$ 10 R_* from the host star, we investigate scenarios where the canonical hydrostatic density distribution breaks down and cannot be used for the computation of model transit spectra.

1. Model

Transmission spectra models depend on a set of profiles, namely the temperature profile $T(r)$, the volume mixing ratios of absorbers $\chi_i(r)$, and the number density $n(r)$. While T and χ_i can be computed (i.e. assuming radiative and chemical equilibrium) or approximated as parametric profiles, the number density profile has thus far been assumed to be hydrostatic.

Given that close-in exoplanets are expected to undergo rapid atmospheric escape and that Jupiter's atmosphere in Na was recently shown to be purely exogenic [2], it is not obvious why hot Jupiter atmospheres should fulfill the condition of local hydrostatic equilibrium. To examine non-hydrostatic atmospheres, we describe three density profiles: (1) hydrostatic, (2) hydrodynamic, and (3) exogenic. Employing these profiles we are then able to simulate the expected transmission spectra for Na & K, where we assume constant volume mixing ratios χ_i for simplicity.

1.1 Hydrostatic Profile

An atmosphere described by a canonical number density distribution can be written following Boltzmann's law:

$$n(r) = n_0 \cdot \exp\Big[- \int_{R_0}^{r} \frac{1}{H(r')}\,\mathrm{d}r' \Big], \qquad (1)$$

where $H(r)$ is the pressure scale height, R_0 the reference radius of the planet and n_0 the number density at this reference radius.

1.2 Hydrodynamic Profile

An escaping atmosphere characteristic of a wind distribution. Assuming a constant outflow speed from the reference radius leads to

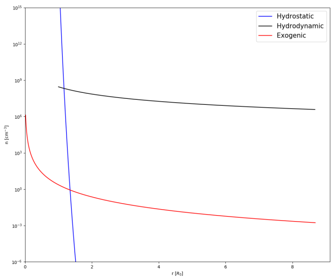
$$n(r) = n_0 \Big(\frac{R_0}{r} \Big)^2. \qquad (2)$$

1.3 Exogenic Profile

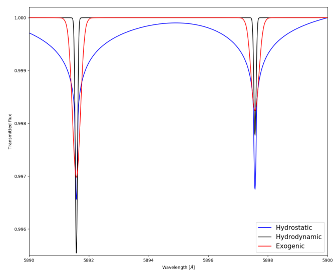
We model an ionization-limited exogenic cloud of sodium ($\chi_{\mathrm{Na}}(r) = 1$) based on the precise power law $\alpha = 3.34$ observed at Io:

$$n(r) = n_0 \Big(\frac{R_{Io}}{r} \Big)^{\alpha}. \qquad (3)$$

where n_0, the source density, is set following the tidal heating and photoionization described in [2].



(a) Number density profiles



(b) Transit spectrum

Figure 1: Test planet with parameters of HD 209458b.

2 Sodium at WASP-49b

[3] obtained a high-resolution spectrum of the hot Jupiter WASP-49b, observing significant absorption in the sodium doublet. While the line cores and the line wings of the spectrum can be fit individually with hydrostatic, isothermal models, it is difficult to reproduce the entire spectrum with a hydrostatic model. We use parameters for an isothermal model from [3] (hydrostatic a) and a model with approximately two isothermal layers obtained by [1] (hydrostatic b) using radiative transfer modeling of the atmosphere of WASP-49b. Lastly, we fit the spectrum with an exogenic source.

Table 1: Statistical parameters for the WASP-49b models.

Model	Reduced χ^2	D.o.f.	BIC
Hydrostatic a	2.688	48	136.8
Hydrostatic b	1.856	46	101.0
Exogenic	1.378	48	73.96

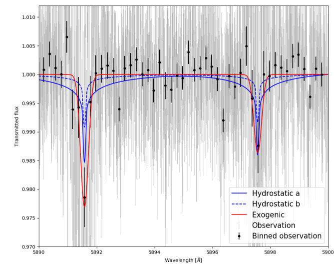


Figure 2: High-resolution spectrum of WASP-49b.

3. Summary and Conclusions

Figure 1 shows the main difference between hydrostatic and non-hydrostatic atmospheres in terms of transmission: Since hydrostatic number density profiles drop very fast in altitude, absorption occurs in optically thick layers. This leads to significant absorption in the line wings and a D2/D1 line ratio close to one.

The non-hydrostatic profiles, however, absorb significantly in an extended optically thin layer, leading to similar absorption in the line cores, but negligible absorption in the line wings. Furthermore, the D2/D1 line ratio is closer to two.

Both of these effects are observed in the high-resolution spectrum of WASP-49b, therefore the exogenic source provides the best fit to the data set out of our three models (see table 1).

As we enter an era of ultra-high resolution spectroscopy, precise measurements of the line wings and line core will be made. Therefore it will be important to carefully consider the physical processes thought to occur at close-in gas giant exoplanets as to better illuminate their environments.

References

[1] Cubillos, P. E. and others: Aerosol constraints on the atmosphere of the hot Saturn-mass planet WASP-49b, ApJ, Vol. 849, 2017.

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