GJ 436b and the stellar wind interaction: Simulations constraints using spectral

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The GJ 436 planetary system is an extraordinary system. The Neptune-size planet that orbits the M3 dwarf revealed in the Lyα line an extended neutral hydrogen atmosphere. This material fills a comet-like tail that obscures the stellar disc for more than 10 hours after the planetary transit. Here, we carry out a series of 3D radiation hydrodynamic simulations to model the interaction of the stellar wind with the escaping planetary atmosphere. With these models, we seek to reproduce the ~56% absorption found in Lyα transits, simultaneously with the lack of absorption in Hα transit.

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3D MODELLING

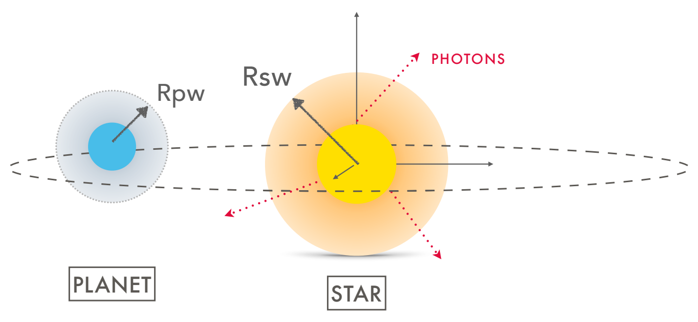


Figure 1: Simulation setup and boundary conditions. Photons are launched from the stellar radius but stellar and planetary wind are launched after their sonic point.

In a cartesian grid, we launch a partially neutral planetary wind using the values from the 1D atmospheric escape model of Allan & Vidotto 2019 and a fully ionised stellar wind using a Parker wind solution.
We also launch EUV-photons from the stellar radius.

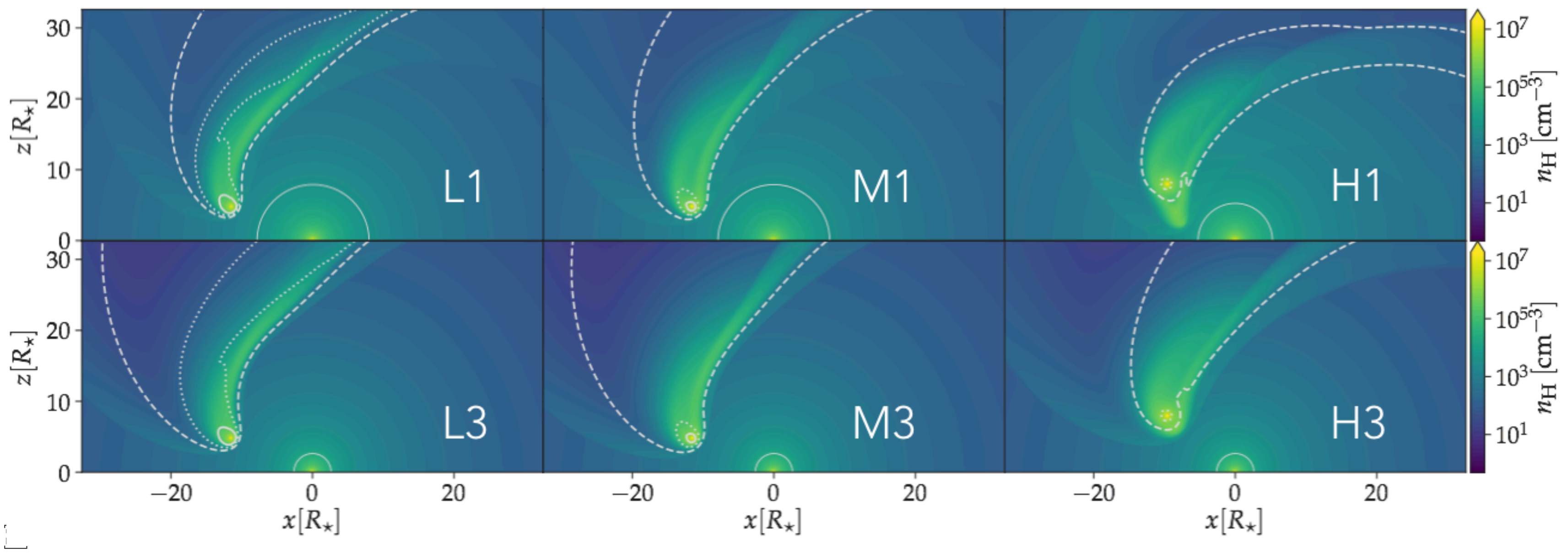
Our models take into account the gravity of the star and the planet and the stellar radiation pressure.
The rate of change of neutral hydrogen is governed by photoionisation, collisional ionisation and recombination.

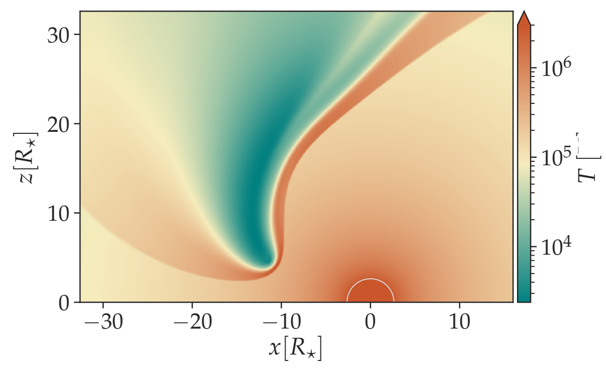
Table 1: Initial parameters for our models. We vary the coronal temperature and the stellar L_{EUV}

Parameter	L1	L3	M1	M3	H1	H3
Stellar wind						
r_{sw} [$R_\star$]	7.9	2.6	7.9	2.6	5.3	2.6
$T_\star$[10^6 K]	1	3	1	3	1	3
$\dot{M}_\star$ [$\dot{M}_\odot$]	0.1	0.1	0.1	0.1	0.1	0.1
v_{sw} [km/s]	181	313	181	313	130	313
L_{EUV} [10^{27} erg/s]	0.8	0.8	1.6	1.6	4	4
S_0[10^{36} s^{-1}]	5.0	5.0	9.6	9.6	24.3	24.3
Planetary wind						
r_{pw} [R_p]	5	5	5	5	5	5
T_{pw} [K]	3212	3212	4008	4008	5086	5086
$\dot{M}_p$[10^9 g/s]	5.5	5.5	9.8	9.8	20	20
v_{pw} [km/s]	9.7	9.7	12.0	12.0	16.7	16.7
$f_{ion,pw}$	0.43	0.43	0.52	0.52	0.68	0.68

RESULTS

Figure 2: Total hydrogen density distribution in the orbital plane for t= 97200 s except for models H1 and H3 were t= 86400 s. The white half-circle shows the launching radius of the stellar wind (Rsw). The contours levels shown the ionisation fraction of 0.6, 0.8 and 0.99 from inside to outside. Bottom: Temperature distribution for model L3.





The planetary wind meets the stellar wind producing a shock and a cometary tail. The amount of neutral material in the tail is governed by the strength of the stellar wind and the stellar L_{EUV} (the contours of dashed lines around the planet).
The direction of the tail depends on the strength of stellar wind. A stronger stellar wind pushes the tail in the radial direction.

The shock position depends on the total pressure balance of both winds. For a strong planetary wind and a weaker stellar wind (model H1), the shock can be found closer to the star leading to an eventual falling of planetary material to the star if the balance is never reached.

SPECTROSCOPIC ANALISIS

We calculate the line profile as a function of time from mid-transit for every model. Assuming a Voigt profile, we compute the absorption produced by the planetary neutral material in Lyα and Hα and compared them with observations.
To compute the n=2 level population we applied the subroutine *populate()* from the ChiantiPy package.

Lymanα transit

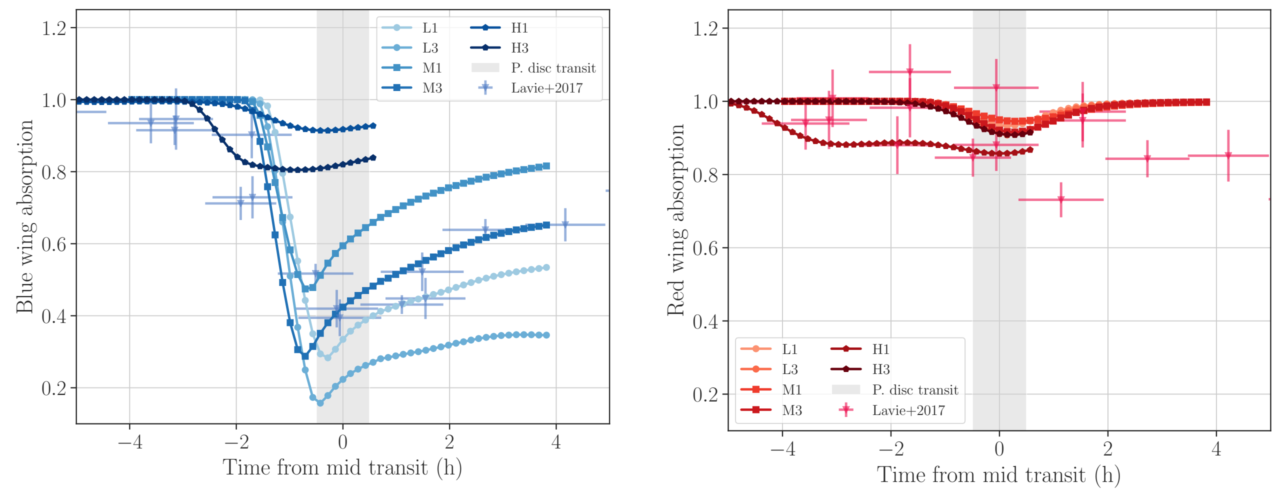


Figure 4: Blue ([-120,-40] km/s) and red ([30,110] km/s) wing Lyα absorption as a function of time for all the models together with the observations from Lavie et al. 2017. The grey band shows the duration of the optical transit.

Hα transit

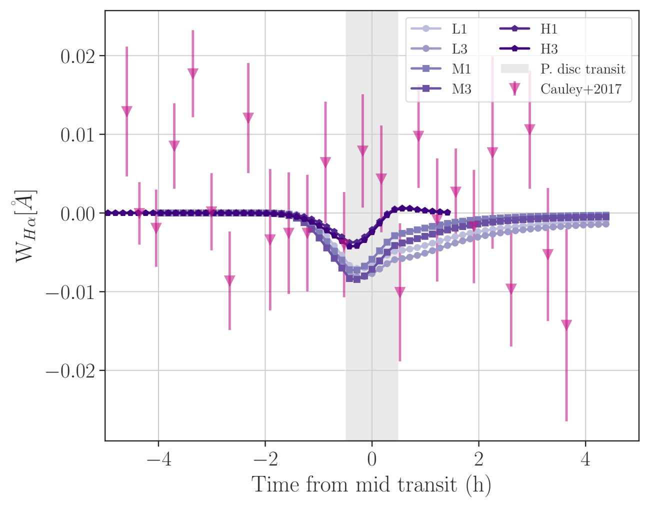


Figure 5: Equivalent width of Hα as a function of time from mid-transit for all our models. Pink triangles in show the observations from Cauley et al. 2017. The grey band represents the duration of the optical transit.

CONCLUSIONS

- ★Lyα absorption correlates more strongly with the stellar L_{EUV} in the blue-wing as we found a larger absorption depth for lower L_{EUV}. Blue-wing absorption is also dependent on the stellar wind strength, since the absorption depth is larger for a stronger wind (considering the same L_{EUV}).
- ★Models L1 and M3 can best reproduce the observed blue-wing absorption depth and duration in Lyα, but fail to reproduce the early-ingress or the absorption in the red-wing of the line.
- ★Early blue-wing absorption in Lyα can be reproduced with model H1 when material falls down towards the star, although this model has the smallest absorption depth.
- ★We found no detectable Hα absorption in agreement with observations despite the huge absorption found in Lyα.
- ★From model L1 and M3 we could assume that the stellar wind of GJ436 has a temperature between [3-4]x10^5 K and a velocity around [250-460] km/s at the planet orbit. Assuming a stellar mass-loss rate of 2x10^{-15} $M_\odot$/yr.
- ★The stellar EUV luminosity in these models is between [0.8-1.6]x10^{27} erg/s, given a planetary mass-loss rate between ~[6-10]x10^9 g/s.

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