Characterizing the exoplanetary atmosphere by modeling its Hα and He 10830 Å transmission spectra

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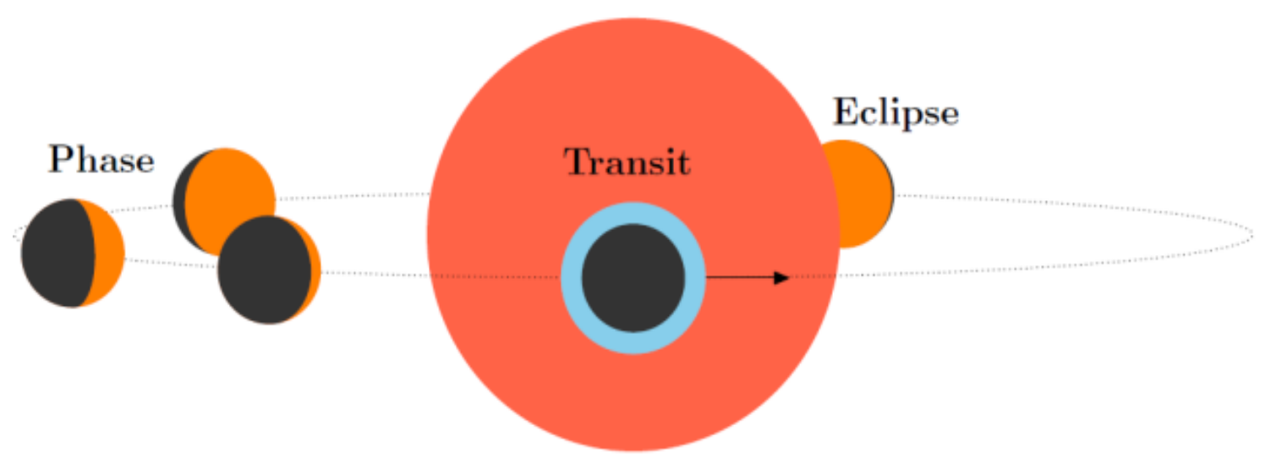
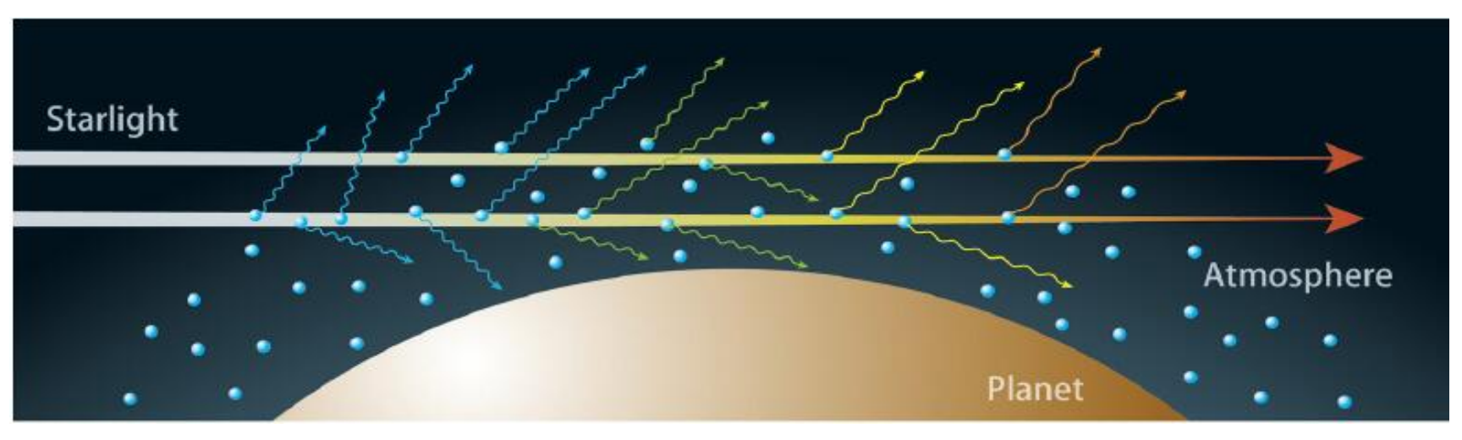
ABSTRACTS





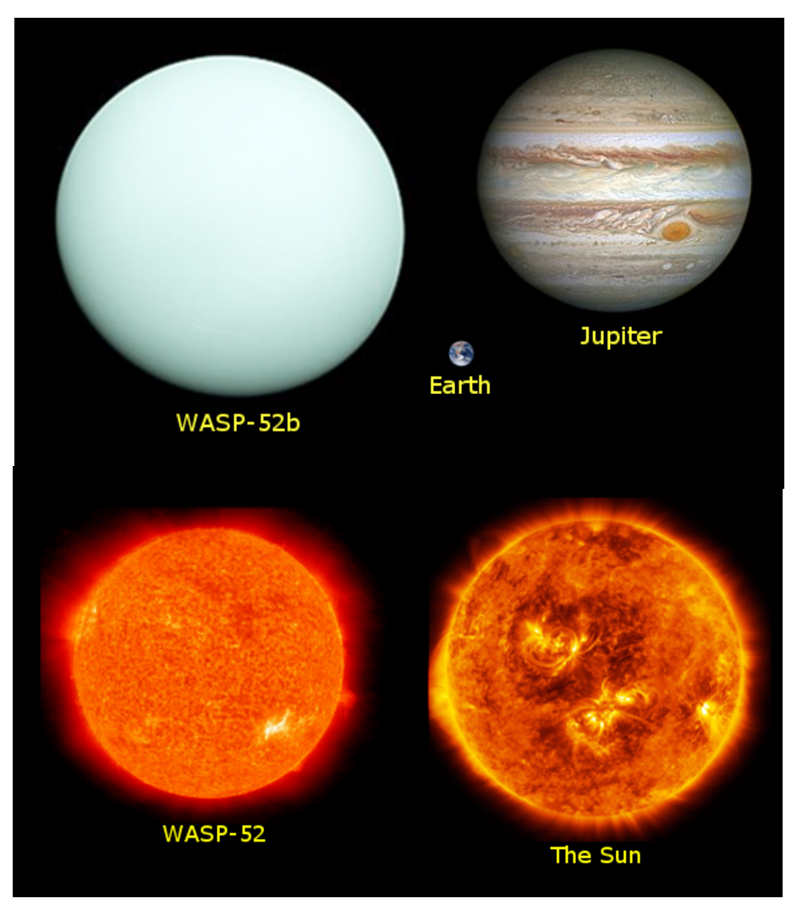
Escaping atmosphere has been detected by the excess absorption of Lyα, Hα and He triplet (λ10830) lines. Such processes may have important ramifications for the planetary composition, evolution, and even the population of planets as a whole. Simultaneously modeling the absorption of the Hα and He λ10830 lines can provide useful constraints about the exoplanetary atmosphere since the two absorption lines are basically thermospheric in origin.

In the work of Yan et al (2022), we simultaneously the Hα and He 10830 transmission spectrum of WASP-52b. We developed spherical Monte Carlo simulations of Ly-alpha resonance scattering inside the exoplanetary atmosphere for the first time. This work helps to constrain the stellar XUV flux and spectral energy distribution, H/He ratio (98/2) and mass loss rate of the exoplanetary atmosphere, and provides clues to the escaping atmosphere of hydrogen and helium.

In the work of Yan et al (2024), we self-consistently fitted the Hα and He10830 observations of HAT-P-32b simultaneously, by using hydrodynamic + NLTE + radiative transfer models. We constrained XUV level, H/He (~99.5/0.5), stellar Lyα flux, planetary mass loss rate. The high stellar Lyα flux indicates high stellar activity. We find that, despite the lower atmosphere may have a super-solar metallicity (more than 100-200 times), the metallicity in the upper atmosphere is possibly close to solar.

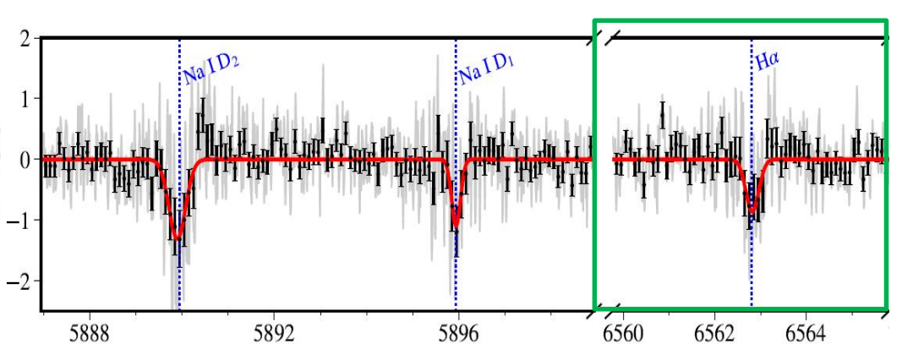
The high H/He indicate the helium abundance in the upper atmosphere is heavily reduced, which could be crucial to the study of planetary origin and evolution.

OBJECTIVES

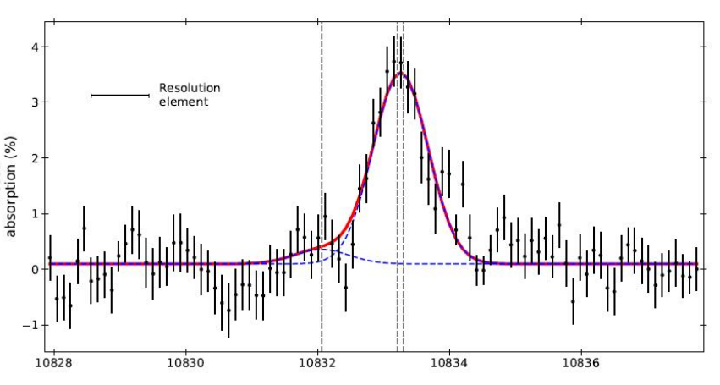


WASP-52b
Mp = 0.46MJ
Rp = 1.27RJ
Sep = 0.0272AU
Teq = 1304K

WASP-52
Spectral type： K2
Ms = 0.87Msun
Rs = 0.79 Rsun
Teff = 5014K
Age = 0.4 Gyr

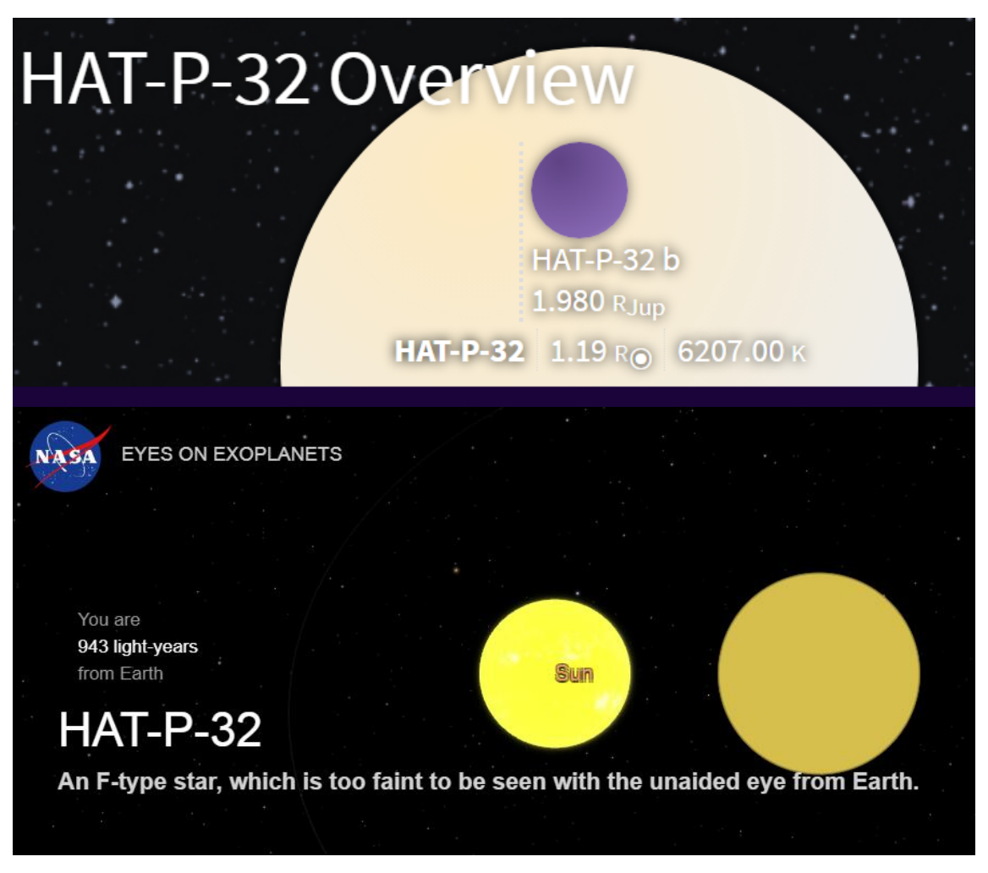


Hα: Spectroscopy
line center absorption
0.86%+-0.13%
Chen et al (2020)



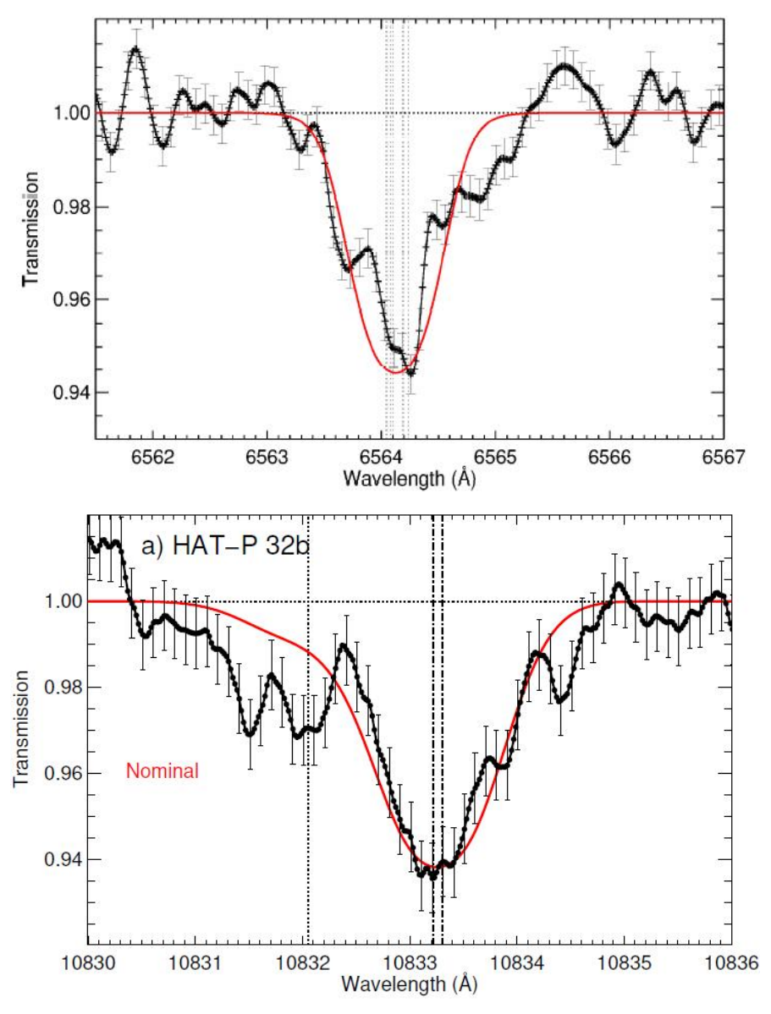
He10830 :
(1) Photometry
estimated absorption 1.31%+-0.94,
but no spectral shape
Vissapragada et al (2021)

(2) Spectroscopy
absorption 3.44%+-0.31%,
with line profile
Kirk et al (2022)



HAT-P-32b
Mp = 0.585MJ
Rp = 1.789RJ
Sep = 0.0343AU
Teq = 1836K

HAT-P-32
Spectral type： F
Ms = 1.16Msun
Rs = 1.219 Rsun
Teff = 6207K
Age = 3.8 Gyr



Hα and He 10830
were simultaneously
detected with
CARMENES by
Czesla+(2022)

Before our work, no self-consistent models have explained both the Hα and He 10830 signals simultaneously. Spectroscopy by HST and Spitzer suggested a super (100-200 times) solar metallicity in the lower atmosphere of HAT-P-32b! Is this also the case in the upper atmosphere? Aim to model the Hα and He 10830 lines, study the atmospheric outflow and the metallicity.

METHODS

We use the XUV driven hydrodynamic simulation to obtain the atmospheric structures, solve the rate equations of non-local thermal equilibrium related to hydrogen and helium to calculate the detailed level population, and then conduct the radiative transfer simulation to model the transmission spectrum of Hα and He 10830. Spherical Monte Carlo simulations of Lyα resonance scattering were developed for the first time to calculate the Lyα mean intensity distribution inside the planetary atmosphere, necessary in estimating the hydrogen level population.

$$\frac{\partial n_j}{\partial t} + \nabla \cdot (n_j \mathbf{u}) = S_j \qquad (1)$$

$$\frac{\partial (n\mathbf{u})}{\partial t} + \nabla \cdot (n\mathbf{u}\mathbf{u}) + \nabla p = n\mathbf{a}_{\rm ext} \qquad (2)$$

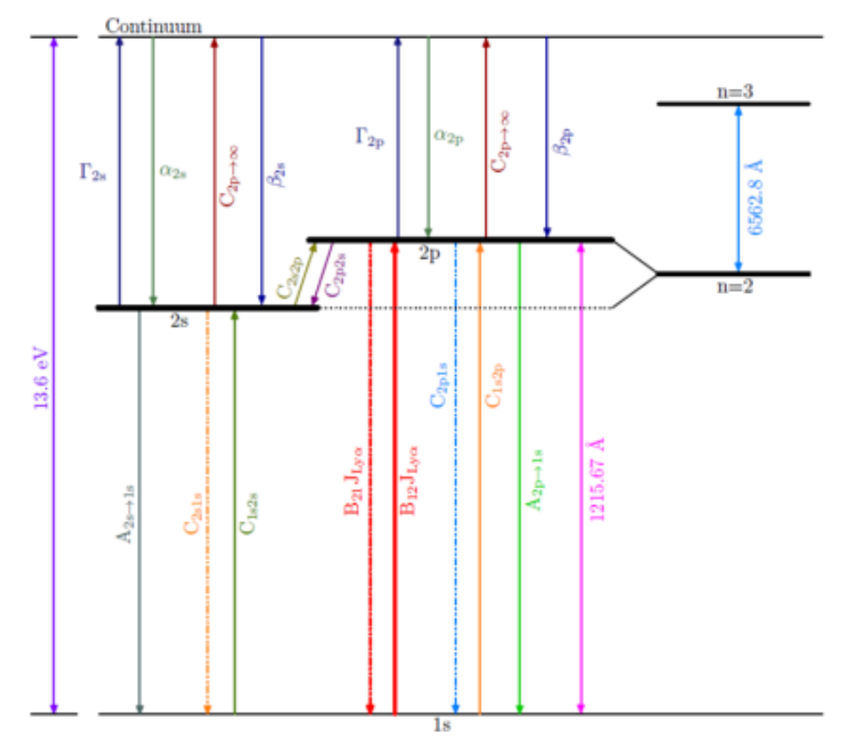
$$\frac{\partial \left[n\left(e+\frac{u^2}{2}\right)\right]}{\partial t} + \nabla \cdot \left[n\mathbf{u}\left(e+\frac{u^2}{2}\right)\right] + \nabla(p\mathbf{u}) = n\mathbf{a}_{\rm ext}\cdot\mathbf{u} + Q, \qquad (3)$$

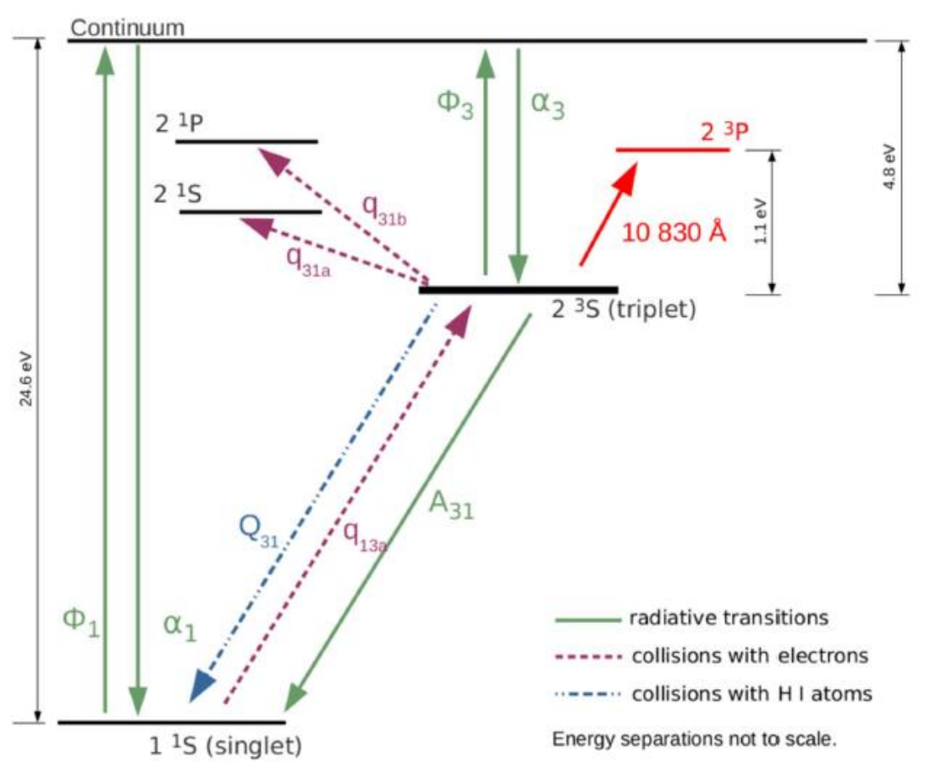
- *n, T, v,* **Mdot …**

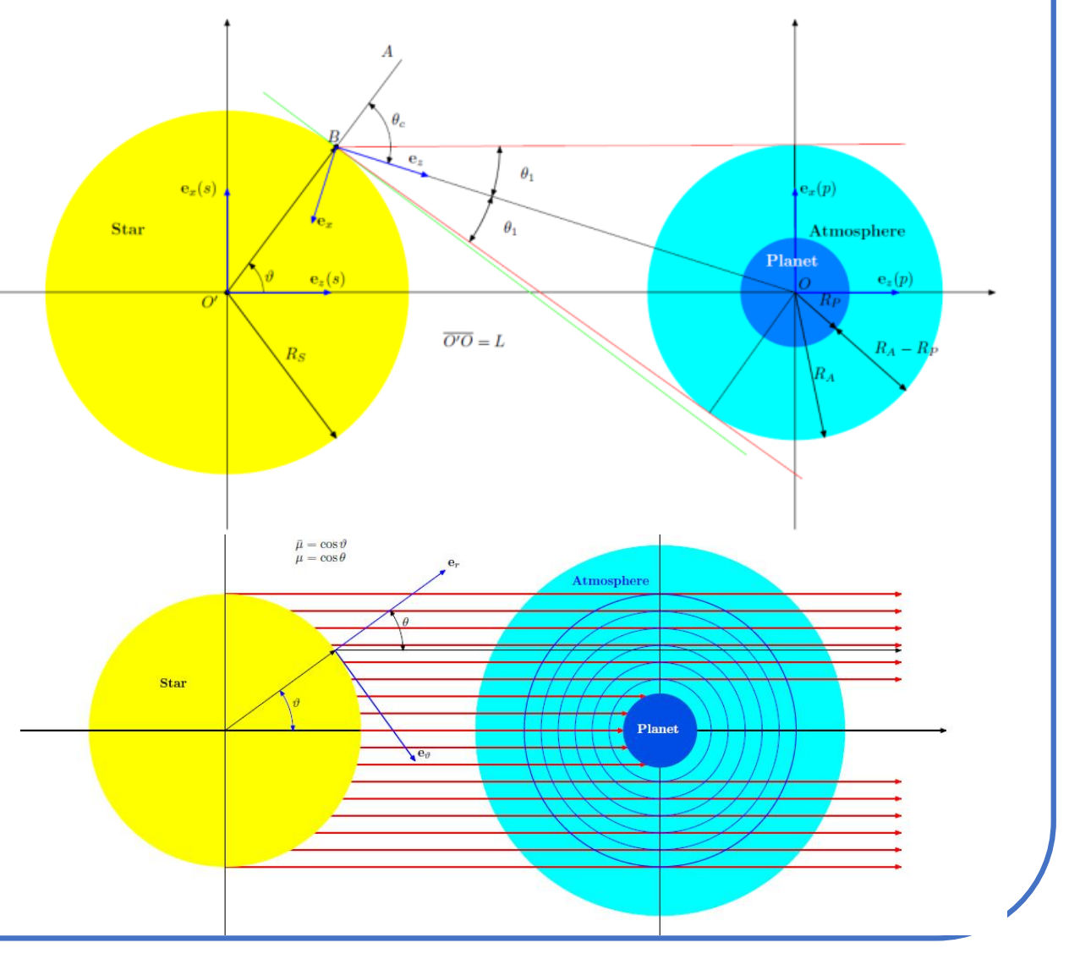
(H, H+, He, He+…)

(Yang & Guo2018, Yan & Guo2021)

1D hydrodynamic +
NLTE +
Radiative transfer model

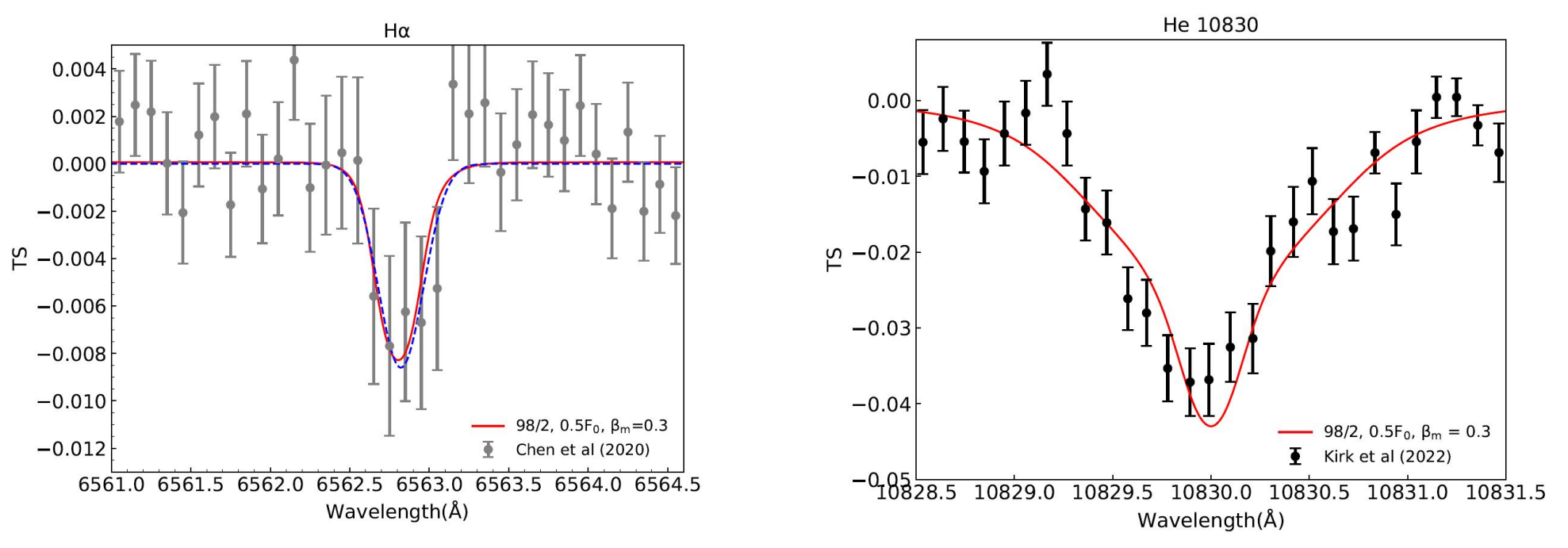






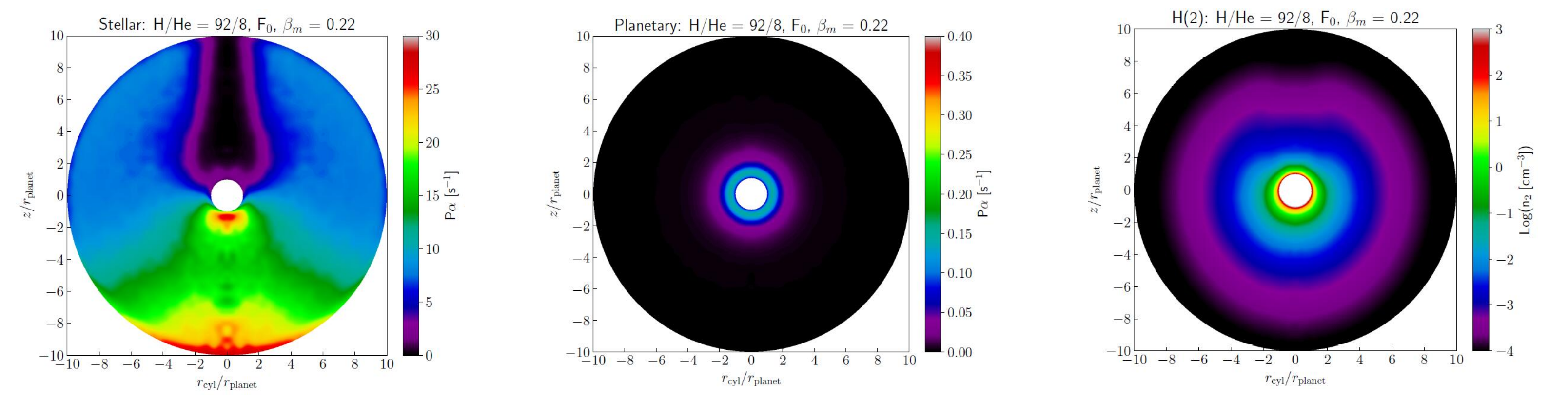
RESULTS

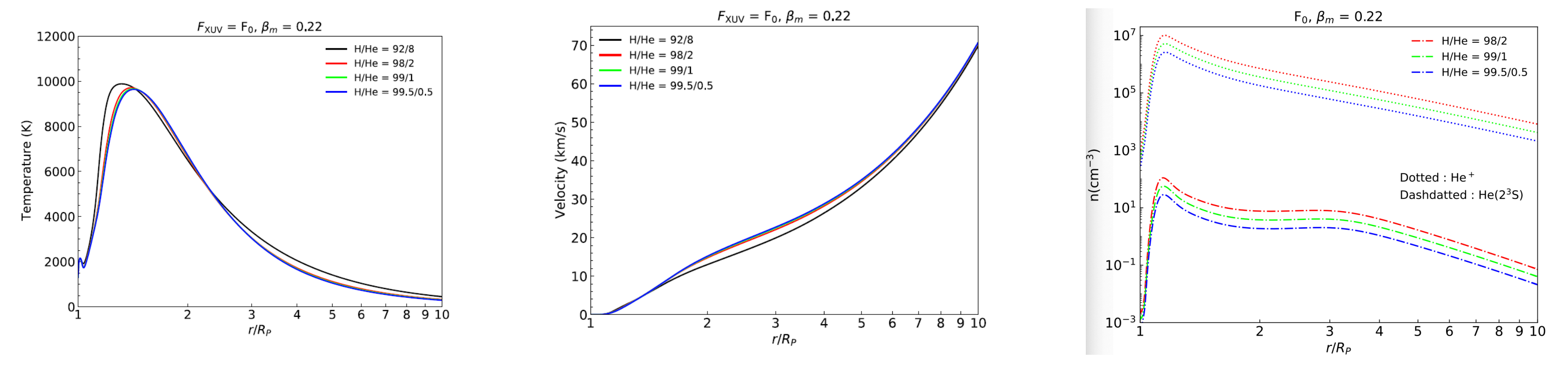
WASP-52b Upper: Transmission spectra of Hα and He 10830 of the best-fit.
Middle: Lyα scattering rate, H(2) populations. Lower: temperature, velocity, and density of Helium



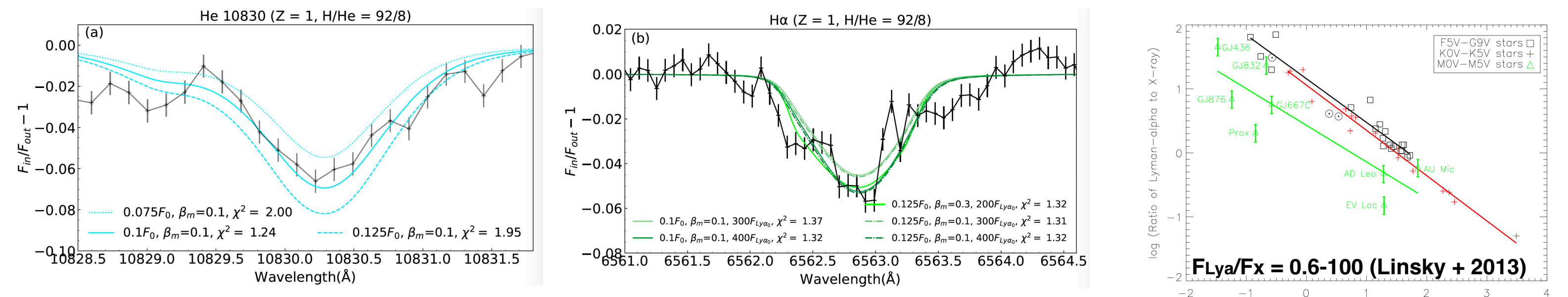
H/He = 98/2, Fxuv = 0.5F0, β = 0.3
Mdot = 2.8e11g/s

Kirk et al (2022): Mdot = 1.4e11g/s

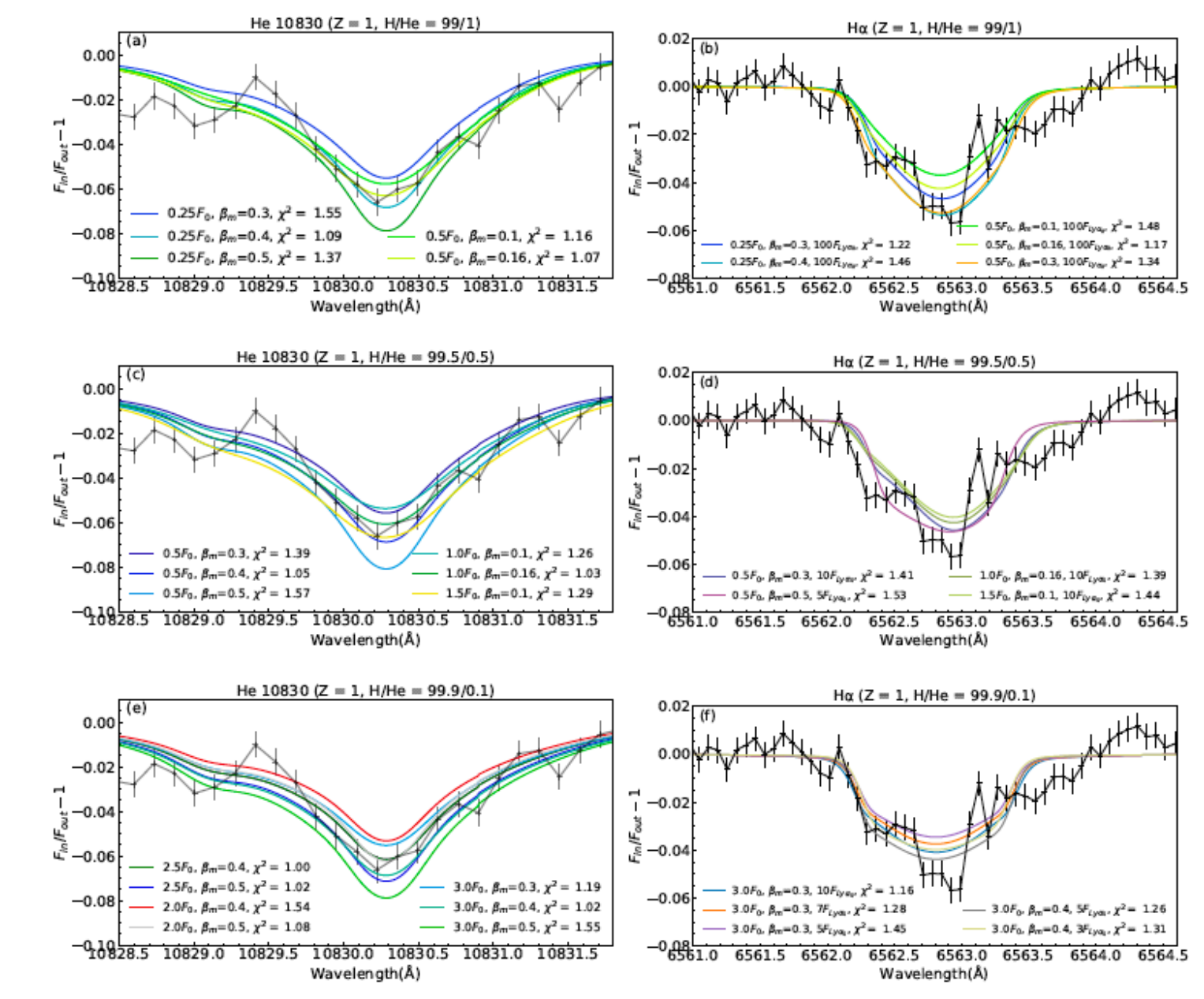


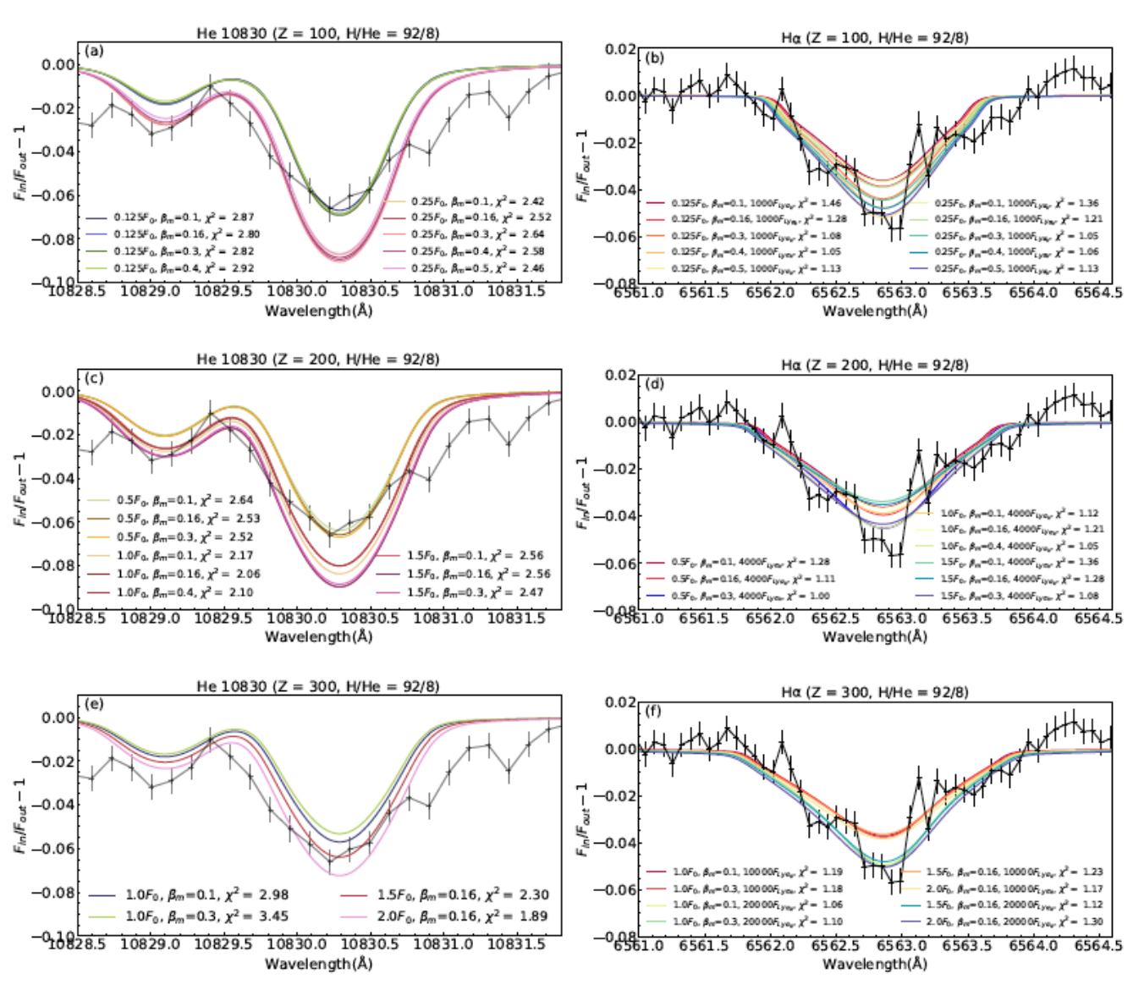


HAT-P-32b solar metallicity: Z=1, H/He = 92/8, 99/1, 99.5
super-solar Z= 100, 200, 300x, H/He = 92/8



Z=1, H/He = 92/8: Need low Fxuv and β to fit He 10830; need extremely high stellar Lyα to pump H. FLyα/Fx = 1700-2300. Rule out this scenario!

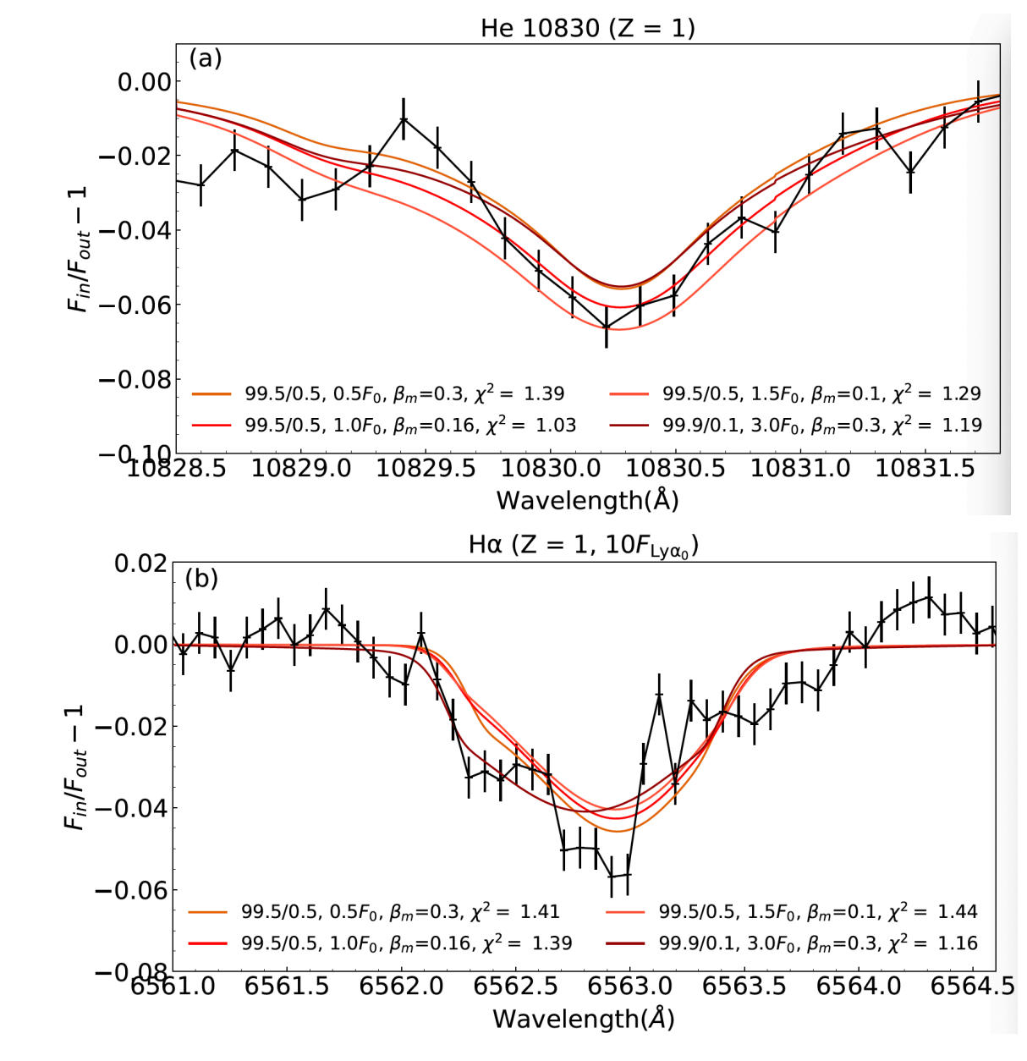




Z=1, H/He = 99/1: 0.25-0.5Fxuv₀, ~100 FLyα₀
FLyα/Fx = 115-230, still exceed the upper limit in Linsky + (2013).
Ruled out due to the extremely high stellar Lyα flux.
Z=1,H/He = 99.5/0.5: 0.5-1.5Fxuv₀, ~5-10 FLyα₀, FLyα/Fx = 4-12
Z=1, H/He = 99.9/0.1: 2.0-3.0Fxuv₀,~3-10 FLyα₀
Accepted, with reasonable β values.

Z = 100, H/He = 92/8: 0.125-0.25Fxuv₀, ~1000 FLyα₀
Z = 200, H/He = 92/8: 0.5-1.5Fxuv₀, 4000 FLyα₀
Z = 300, H/He = 92/8: 1.0-2.0Fxuv₀,~10000-20000 FLyα₀

Ruled out this scenario !



Best-fit models: Z = 1, FLya = 10FLyα0 (400000erg/cm^2/s)
1) H/He = 99.5/0.5, Fxuv =0.5F0, β = 0.3, Mdot = 1.5e13g/s
2) H/He = 99.5/0.5, Fxuv =1.0F0, β = 0.16, Mdot = 1.0e13g/s
3)H/He = 99.5/0.5, Fxuv = 1.5F0, β = 0.1, Mdot = 1.0e13g/s
4)H/He = 99.9/0.1, Fxuv = 3.0F0, β = 0.3, Mdot = 1.0e13g/s

Comparison with other work:
Czesla + 2022: Fxuv = 1.0F0, β = 0.16 ,
H/He = 99/1, Mdot = 1.6e13g/s
H/He = 90/10 3.6e12g/s
Lampon + 2023: Fxuv = F0, β = 0.16 ,
H/He = 99/1+0.5-1, Mdot = (1.3±0.7) e13g/s

CONCLUSIONS

- **Creativity**：For the first time, we self-consistently fitted the Hα and He10830 observations of WASP-52b and HAT-P-32b simultaneously, by using hydrodynamic + NLTE + radiative transfer models.
- **Results**：Constrained the metallicity, XUV level, H/He, stellar Lyα flux，planetary mass loss rate.
- **Significance**：Important because the Hα and He10830 are basically thermospheric in origin (referee's comments); provides new insights for the study of hydrogen-helium atmospheric escape in exoplanets.

REREFENCES

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