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The quest for He I 10830 triplet in exoplanets

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Introduction

Exoplanet atmospheres photoevaporate because of XUV stellar irradiation. Evaporation signs are detected mainly through the H Lyman-α line, or more recently in the He I 10830 line (actually a triplet). Despite of early efforts back in 2000 to find this line in transiting exoplanets, it was not until 2018 that the line was finally detected. The stellar high energy irradiation also plays a role in this line formation, but no direct observation of most of the XUV spectral range is possible in stars other than the Sun. We present an update of the X-exoplanets database, and improved scaling laws to calculate the XUV flux, that take into account the stellar activity level. Despite of the efforts to find a clear relation between the He I 10830 detections in exoplanet atmospheres, and the stellar XUV irradiation, this relation remained elusive so far. We report here a new parametrization that empirically demonstrates the relation between stellar XUV irradiation and the formation of He I 10830 in exoplanet atmospheres.

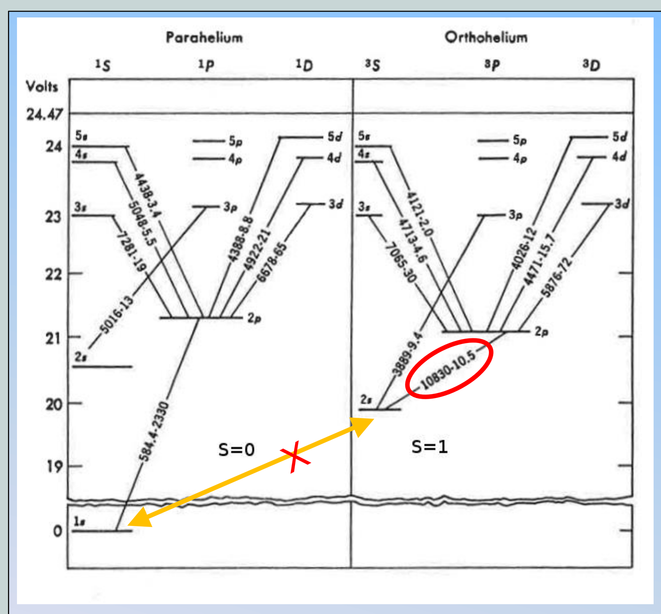


Figure 1. He I levels diagram, from Zirin (1988)

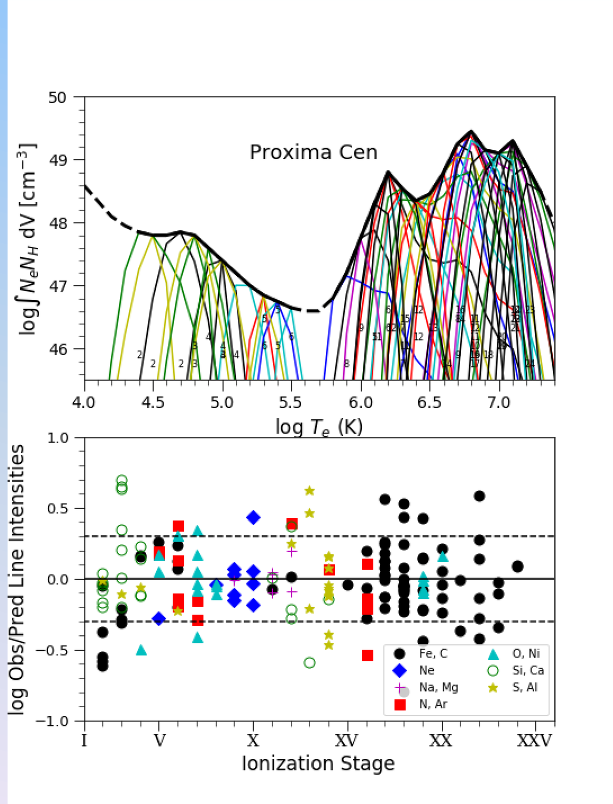


Figure 2. Coronal model (Emission Measure Distribution, EMD) of Proxima Cen. The upper panel shows the coronal model, with a solid black thick line (dashed if uncertain determination of EMD). Thin colored lines are indicative of the emissivity functions of the spectral lines, with the ions numbered below, weighted by the EMD. In the lower panel it is shown the observed-to-predicted line fluxes ratio for the measured spectral lines. Color code of the elements is the same in both panels.

The He line triplet needs from a population of the 2s level.
1s → 2s is radiatively forbidden. Thus there are two options:

- Collisional excitation (> 20,000 K needed). This is the case of hot massive stars, and winds in late type giants (e.g. Dupree, Sasselov & Lester 1992)
- P-R mechanism: Photoionization (λ < 504 Å, E> 24.6 eV) followed by recombination, and cascade to populate levels in the ortohelium. This mechanism is present in late dwarfs, although with contributions from collisional excitation in some cases (Sanz-Forcada & Dupree, 2008)

In a (rather cold) exoplanet atmosphere environment, the most logical explanation is the P-R mechanism. The ionizing radiation comes from the stellar corona. Seager & Sasselov (2000) proposed to observe this line in exoplanets. A relation between stellar XUV and the He I line is expected. But a clear relation remains elusive so far…

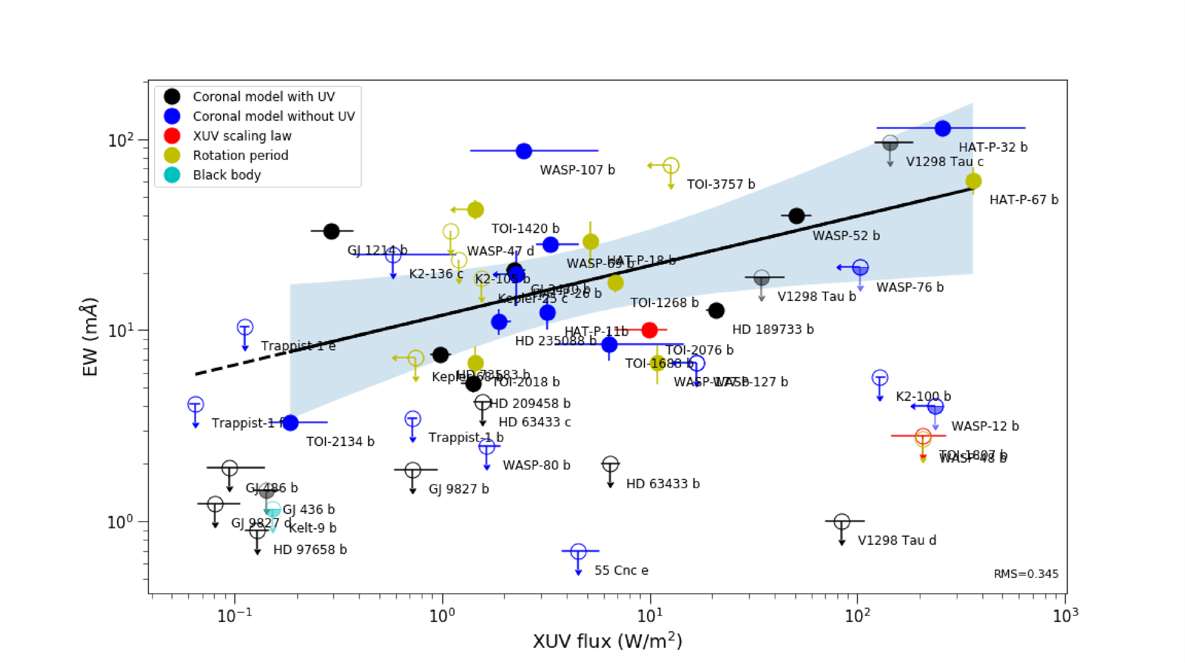
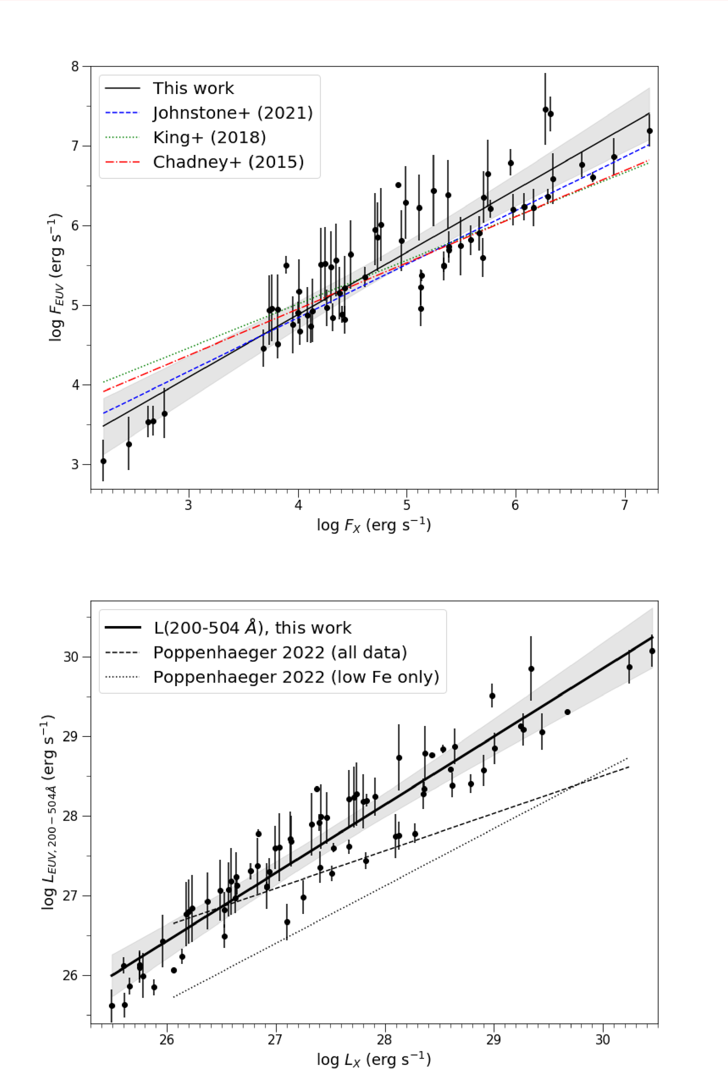


Figure 3. He I 10830 equivalent width (EW) against XUV (5-504 A) coronal irradiation at the planet orbit. Positive detections are marked as solid circles; half-filled circles are upper limits measured by our team (CARMENES); and empty circles are upper limits reported by other authors. Color code depends on the method employed to calculate the XUV stellar emission. A direct relation EW vs XUV only has a poor correlation coefficient of r = 0.52



The X-exoplanets project (Sanz-Forcada+ 2011) observes planet-hosting stars in X-rays to carefully model its corona (Fig. 2), in order to predict the EUV spectral response. Figure 5 includes stars present in the original X-exoplanets sample, now reanalyzed together with new planet host stars. A new parametrization based on stellar activity level shows better results than our previous work and others in the literature.
Best fit to the current sample provides useful X-ray to EUV relations. If we define R_X=log (L_X/L_{bol}) +5.61

$$\frac{L_{EUV,H}}{L_{bol}} = (-0.062 \pm 0{,}021)R_X^2 + (0{,}764 \pm 0{,}037)R_X + (-4.798 \pm 0{,}052) \quad [100\text{-}920\ \text{Å}]$$

$$\frac{L_{EUV,He}}{L_{bol}} = (-0.023 \pm 0{,}016)R_X^2 + (0{,}825 \pm 0{,}029)R_X + (-5.273 \pm 0{,}040) \quad [100\text{-}504\ \text{Å}]$$

Figure 4. Comparison of other scaling laws with our data (EUV luminosity calculated using coronal models), from Sanz-Forcada et al., in prep. *Upper panel*: Surface EUV (100-920 Å) vs surface X-ray (5-100 Å) flux, defined as F=L/(4 π R_*^2). The deviation of other scaling laws from our data is more evident for high and low activity stars. *Lower panel*: Comparison between our data and directly measured EUV fluxes on EUVE spectra, but inadequately corrected from effects of interstellar medium absorption and geocoronal He II 304 Å emission. 1-σ error bands to our data are indicated in both panels.

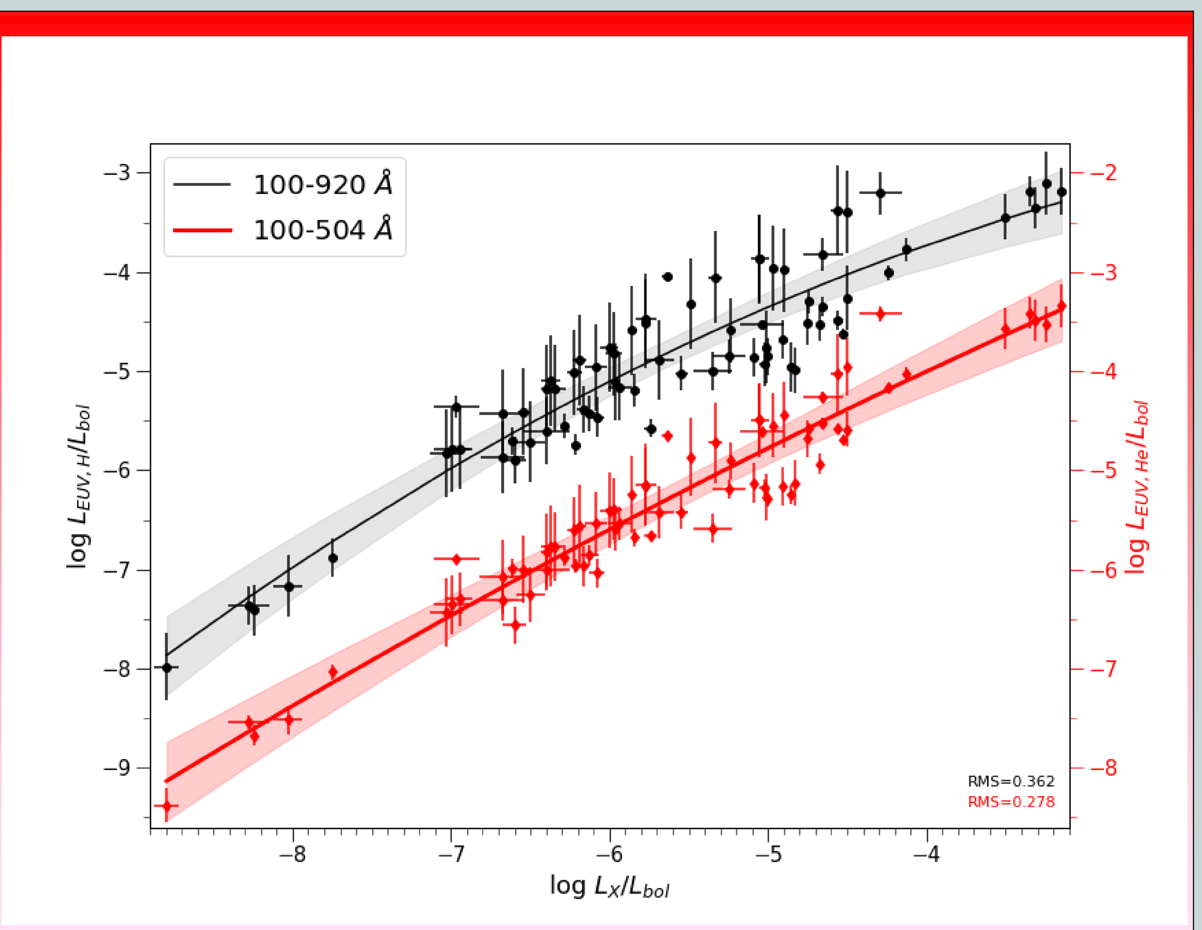


Figure 5. X-ray luminosity as measured in a sample of X-exoplanets, against modeled EUV luminosity, in two spectral ranges relevant for ionization processes in the planet atmosphere

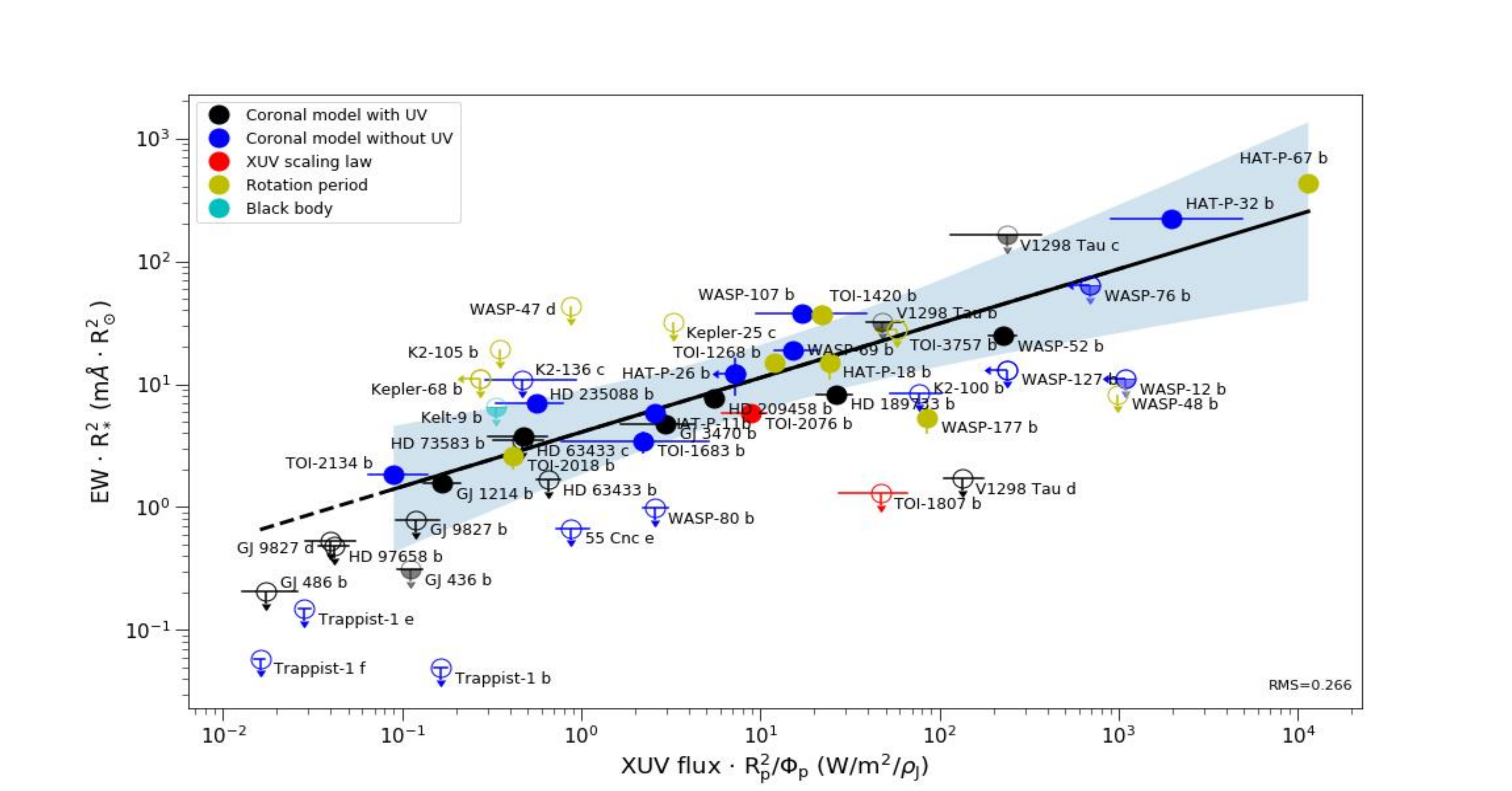


Figure 6. He I 10830 equivalent width (EW) against XUV (5-504 A) coronal irradiation at the planet orbit. They are weighted by stellar and planetary surface, and the gravitational potential of the planet, in Jovian units. Symbols as in Fig. 3. A good correlation coefficient of r=0.90 is achieved

CONCLUSIONS

- The careful calculation of XUV flux, and an adequate parametrization, show that the He I 10830 line in exoplanets atmospheres is triggered by stellar coronal irradiation
- A tight relation between X-ray and EUV luminosities allows for a quick calculation of the ionizing irradiation reaching a planet atmosphere. If no X-ray flux is available it is still possible to use a relation between rotation period and X-ray flux to have an estimate.
- A careful analysis of high-resolution X-ray and UV spectra provides the best coronal models (X-exoplanets). This allows us to calculate better scaling laws between X-rays and EUV to be applied in planet atmospheric modelling.