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Observability of hydrogen-rich exospheres in Earth-like exoplanets

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Abstract

The existence of an extended neutral hydrogen exosphere around small planets can be used as evidence of the presence of water in their lower atmosphere. Our objective in this study is to assess the detectability of the neutral hydrogen exosphere of an Earth-like planet transiting a nearby M dwarf using Lyman-α transmission spectroscopy. Using an empirical model of the Earth's exosphere, we compute the excess absorption of in the stellar Lyman-α line while in transit, and use realistic estimates of the uncertainties involved in observations to determine the observability of the signal. The excess absorption in Lyman-α is observable using LUVOIR/LUMOS in M dwarfs up to a distance of $\sim$15 pc. The analysis of noise-injected data suggests that it would be possible to detect the exosphere of an Earth-like planet transiting TRAPPIST-1 within 20 transits

1. Introduction

Detecting an extended hydrogen exosphere around a rocky exoplanet would be compelling evidence for the presence of water in the lower atmosphere of the planet, since the atomic H is a product of photodissociation of water; thus evaporating exoplanetary oceans could fuel H-rich exospheres [1, 2, 3]. This could be a new path to characterize habitability-zone (HZ) exoplanets and trace their water content. This is especially relevant for planets around M dwarfs, which are targets of intense searches for rocky planets because their HZ is closer to the star and transiting planets produce large signals.

Currently, the only telescope that has access to the Lyα line is the Hubble Space Telescope (HST), and the instrument usually employed for these observations is the Space Telescope Imaging Spectrograph (STIS). In the future, projects such as the Large Ultraviolet/Optical/Infrared Surveyor (LUVOIR) [4] and the Habitable Planet Explorer (HabEx) [5] will build upon on the FUV (far-ultraviolet) capabilities of HST in several aspects.

2. Model

The Earth's exosphere was observed using the Lyman Alpha Imaging Camera (LAICA) on board the Proximate Object Close Flyby with Optical Navigation (PROCYON) on 9 January 2015, when the spacecraft was at a distance of 0.1 au from the Earth. This observation revealed that the geocorona spans more than 38 $R_\oplus$, and [6] produced an empirical model of the geocorona using a modified Chamberlain model [7]. We used this model to compute the column densities of the exosphere of an Earth-like planet as viewed while in-transit. In addition, we produced a grid of models of transiting events with stars of radii varying between 0.1 $R_\odot$ and 0.6 $R_\odot$ and distances from 2 to 20 pc.

3. Lyman-α signature

For a small ($R = 0.1$ $R_\odot$) and nearby ($d = 2$ pc) M dwarf, the expected excess transit depth between Doppler velocities is approximately 400 ppm for *HST*/STIS, and such a precision is beyond the capabilities of the instrument. Our estimates show that the space telescope LUVOIR will be able to characterize exospheres in Earth-like planets using the LUMOS spectrograph. The number of transits necessary to obtain a reliable detection varies strongly depending on the target, but we can set a flexible limit at distances up to 15 pc for 30 transits. The astrophysical background contamination will not be a limitation for nearby targets, neither will the Earth's own exosphere.

We analyzed two test cases with noise-injected, simulated data: case 1 had $R = 0.20$ $R_\odot$ and $d = 5$ pc; for case 2, we used a system similar to TRAPPIST-1, in which $R = 0.12$ $R_\odot$ and $d = 10$ pc. In both cases, even though they did not involve the most favorable conditions, we obtained reliable detections within 10 (20) transits with LUVOIR-A (-B) (see Figs. 1 and 2). Although an Earth-like exosphere is not observable in Lyα spectroscopy with *HST*/STIS, we were able to obtain a reliable detection using noise-injected data in the case of an exosphere 500 times more dense in 50 transits with this instrument, for a target at a distance of 5 pc (see Fig. 3).

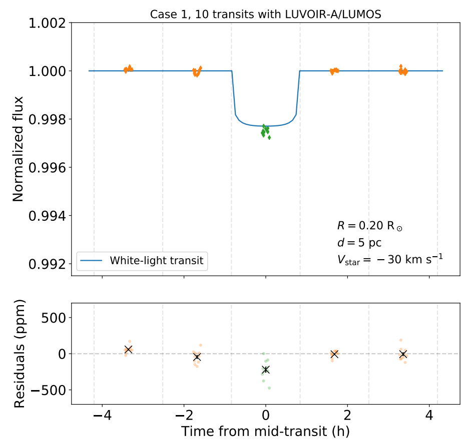

Figure 1: Simulated LUVOIR-A/LUMOS Lyα light curve of an Earth-like planet transiting an M dwarf with $R = 0.20$ $R_{\odot}$ and $d = 5$ pc.

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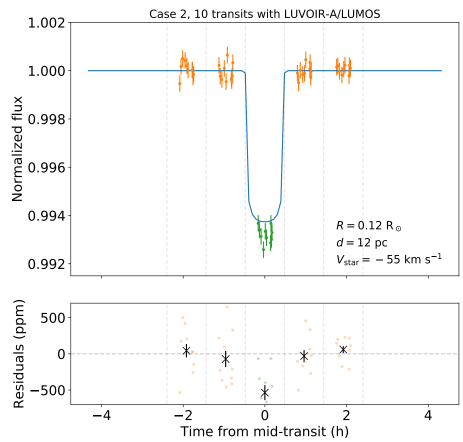

Figure 2: Same as Fig. 1, but for a star similar to TRAPPIST-1.

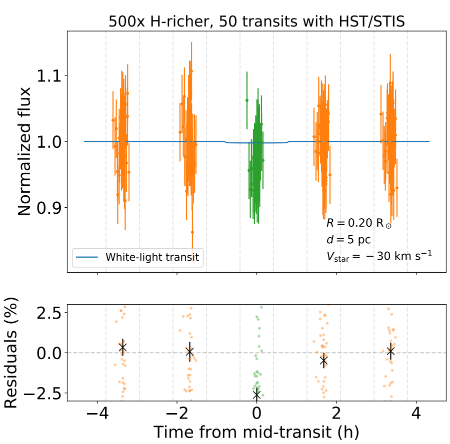

Figure 3: Simulated *HST*/STIS Lyα light curve of a H-rich rocky planet transiting an M dwarf with $R = 0.20$ $R_{\odot}$ and $d = 5$ pc.