Atmospheric Escape From TOI-700 d: Venus versus Earth Analogs. C. Dong[1], M. Jin[2], M. Lingam[3], [1]Princeton University (dcfy@princeton.edu), [2]Lockheed Martin Solar and Astrophysics Lab, [3]FIT/Harvard-Cfa

Introduction: The recent discovery of an Earth-sized planet (TOI-700 d) in the habitable zone of an early-type M-dwarf by the Transiting Exoplanet Survey Satellite constitutes an important advance. Here we assess the feasibility of this planet to retain an atmosphere – one of the chief ingredients for surface habitability – over long timescales by employing state-of-the-art magnetohydrodynamic models to simulate the stellar wind and the associated rates of atmospheric escape. We take two major factors into consideration, namely, the planetary atmospheric composition and magnetic field. In all cases, we determine that the atmospheric ion escape rates are potentially a few orders of magnitude higher than the inner solar system planets, but TOI-700 d is nevertheless capable of retaining a 1 bar atmosphere over gigayear timescales for certain regions of the parameter space. The simulations show that the unmagnetized TOI-700 d with a 1 bar Earth-like atmosphere could be stripped away rather quickly (<1 gigayear), while the unmagnetized TOI-700 d with a 1 bar CO2-dominated atmosphere could persist for many billions of years; we find that the magnetized Earth-like case falls in between these two scenarios.

Results: The steady-state stellar wind solution is shown in Figure 1. The stellar wind speeds at the orbits of TOI-700 planets are comparable to the solar wind speed at 1 AU (~200 – 600 km s−1). However, because of the much closer distances to the star, the stellar wind density and dynamic pressure are higher, as seen from panels (b) and (c) of Figure 1. The critical surface, defined as the region where stellar wind speed is equal to the fast magnetosonic speed, is also computed and shown in Figure 1. As with our solar system, all the planets in the TOI-700 system are outside this critical surface, i.e., the stellar wind environment of the planets is always "superfast."

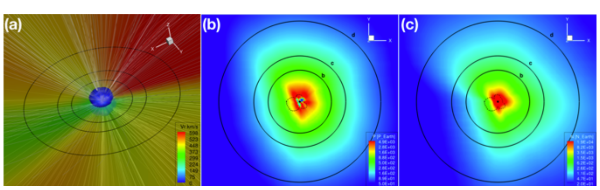

Figure 1. Steady-state stellar wind characteristics of TOI-700. (a) The 3D stellar wind configuration comprising select magnetic field lines. Contours in the background illustrate stellar wind speed at the equatorial plane (z = 0). The blue isosurface signifies the critical surface beyond which the stellar wind becomes super-magnetosonic (or "superfast"). Black solid lines indicate the orbits of three planets, namely, TOI-700 b, TOI-700 c, and TOI-700 d. (b) Stellar wind dynamic pressure in the equatorial plane normalized by the solar wind dynamic pressure at 1 AU. (c) Stellar wind density in the equatorial plane normalized by the solar wind density at 1 AU. In panels (b) and (c), the dashed line represents the critical surface location.

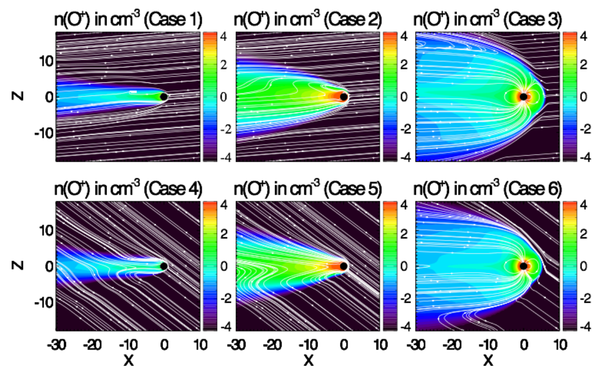

Figure 2: The logarithmic scale contour plots of the O^+ ion density (units of cm^{-3}) with magnetic field lines (in white) in the meridional plane based on the stellar wind conditions at P_{min} (first row) and P_{max} (second row), which respectively correspond to the minimum and maximum total stellar wind pressure (P_{tot}) over one orbital period of TOI-700 d. The first column shows the unmagnetized Venus-like cases, whereas the second and third columns depict the unmagnetized and magnetized Earth-like cases.

The salient results concerning atmospheric escape are depicted in Figure 2, which shows the calculated oxygen ion density with the associated magnetic field lines in the meridional plane for all six cases. This figure yields some general conclusions. Table 1 summarizes the six cases along with the associated atmospheric ion escape rates.

Case #	P_{sw}	n_{sw} (cm^{-3})	v_{sw} ($km\ s^{-1}$)	IMF (nT)	Planetary Type	Magnetic Field	O^+ Loss Rate (s^{-1})	Total Loss Rate (s^{-1})
Case 1					Venus-like	Off	1.93×10^{26}	2.10×10^{26}
Case 2	P_{min}	96.8	(-650.4, 47.4, -7.4)	(-46.7, 2.9, -3.7)	Earth-like	Off	1.18×10^{28}	1.18×10^{28}
Case 3					Earth-like	On	1.39×10^{27}	1.39×10^{27}
Case 4					Venus-like	Off	2.04×10^{26}	2.41×10^{26}
Case 5	P_{max}	451.6	(-471.2, 47.4, 4.3)	(9.2, 2.7, -7.0)	Earth-like	Off	1.61×10^{28}	1.61×10^{28}
Case 6					Earth-like	On	2.12×10^{27}	2.12×10^{27}

Table 1: Stellar wind input parameters and the associated atmospheric ion escape rates at TOI-700 d for P_{min} and P_{max}.

We select two locations in the orbit, namely, P_{min} and P_{max}, because they ought to yield the minimum and maximum ion escape rates, thus providing the range of values associated with this system. To begin with, as seen from Table 1, we note that O^+ constitutes the dominant ion species undergoing escape for all configurations considered here. The atmospheric oxygen escape rates vary from $O(10^{26})$ s^{-1} to $O(10^{28})$ s^{-1}, indicating that they are higher by a few orders of magnitude than the typical escape rates of $O(10^{25})$ s^{-1} for the terrestrial planets in our Solar system.

Let us first compare the unmagnetized cases, namely, the first and second columns in Figure 2. We find that the Earth-like case exhibits a stronger and broader flux of escaping O^+ compared to the Venus-like case; this result is also consistent with the atmospheric ion escape rates shown in Table 1. The reason chiefly stems from the fact that the upper atmosphere of a Venus analog is cooler than its Earth-like counterpart due to the efficient CO_2 cooling caused by 15 μm emission. In consequence, the exobase of a Venus-like planet is situated lower than that of an Earth-analog, thereby making the former more tightly confined. In other words, the extent of the atmospheric reservoir that is susceptible to erosion by stellar wind is smaller for the Venus analog as compared to an Earth-like atmosphere.

Now, let us hold the atmospheric composition fixed and vary the magnetic field, i.e., we compare the second column (unmagnetized Earth-analog) with the third column (magnetized Earth-analog) in Figure 2. Despite the fact that the magnetized cases exhibit a larger interaction cross-section with the stellar wind, the planetary magnetic field exerts a net shielding effect for the configurations studied herein for TOI-700 d. The presence of the global magnetic field reduces the atmospheric loss rate by roughly one order of magnitude relative to the unmagnetized case (see Table 1). Hence, of the three different scenarios considered in this work, unmagnetized Earth-like worlds are characterized by the highest atmospheric ion escape rates.

References:

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