Role of Planetary Obliquity in Regulating Atmospheric Losses: G-dwarf vs. M-dwarf Earth-like Exoplanets.

C. F. Dong, Z. G. Huang, M. Lingam, Princeton University (dcfy@princeton.edu), University of Michigan, Harvard-CfA, Florida Tech

Introduction: Over the past decade, much attention has been directed toward understanding what factors contribute to exoplanetary habitability [1]. In particular, it is widely accepted that orbital parameters play a major role in governing habitability [2]. One of the chief orbital parameters is the obliquity (axial tilt). The fact that Earth’s obliquity is subject to only mild fluctuations is believed to play a vital role in maintaining its stable climate.

Exoplanets around M-dwarfs are typically anticipated to have very low (or zero) obliquities due to rapid tidal energy dissipation. This effect may be particularly pronounced for the inner planets of multi-planet systems such as the Kepler-186 system. Nevertheless, there are mechanisms that permit the existence of high obliquity M-dwarf exoplanets. Perhaps the most famous among them are the “Cassini states” that involve the precession of the planet’s spin and orbital angular momenta at the same rate; the Moon has a non-zero obliquity of 6.7° due to this reason. Hence, it is feasible for certain M-dwarf exoplanets to have high obliquities [3,4].

Another factor that plays a vital role in regulating surficial habitability is the presence of an atmosphere. Moreover, an atmosphere also permits the detection of biosignature gases (e.g., molecular oxygen) via spectroscopy. Recent numerical and theoretical studies indicate that both magnetized and unmagnetized planets around M-dwarfs might be particularly susceptible to the depletion of ~ 1 bar planetary atmospheres over sub-Gyr timescales due to the high ultraviolet fluxes and intense stellar winds they experience [5-9].

In view of the preceding discussion, it is worthwhile asking the question: how does obliquity regulate atmospheric escape rates? It is, however, important to note that the rotational and magnetic axes of Earth are separated only by ~ 10°. Hence, it is plausible that these two axes are potentially aligned for Earth-like planets as well, viz., the angle between the two might be fairly small. In this study, we opt to perform a parametric analysis of how magnetic obliquity (i.e. the angle between the magnetic axis and orbital axis) affects the atmospheric ion loss from magnetized exoplanets.

Method: In our Solar system, the most sophisticated codes tend to use magnetohydrodynamic (MHD) models for modeling the interactions of the solar wind with both magnetized (such as Earth) and unmagnetized (such as Mars and Venus) planets. We use the BATS-R-US MHD model that has been well validated and applied to different solar system objects to study the atmospheric loss from exoplanets [5-9]. For the stellar wind parameters (such as the stellar wind velocity, density and magnetic field), we adopt the AWSoM model to simulate those parameters based on the observed magnetograms of M-dwarf stars [7].

Results: We focus on two distinct examples due to their astrobiological relevance [10]: an Earth-like planet around a solar-type star and an Earth-like planet around a late-type M-dwarf using TRAPPIST-1 as a proxy. There are several interesting features that stand out in both cases, viz., solar-type stars and late M-dwarfs.

First, the atmospheric ion escape rate is ~10^{-6} s^{-1} in the case of G-dwarf Earth-like planets, whereas the escape rate increases to ~10^{-2} s^{-1} for M-dwarf planets due to the extreme stellar wind conditions and high energy radiations in the close-in habitable zones (HZs) [9]. In other words, a ~ 1 bar atmosphere of an Earth-like planet would take O(10^{10}) yrs to be depleted for a G-type star and O(10^8) yrs for an M-dwarf based on normal stellar wind conditions.

Second, the variation in the atmospheric ion escape rates is virtually independent of the magnetic obliquity for an Earth-analog around a solar-type star. We find that the total variation is less than 10% (see Figure 1). In contrast, when we consider an Earth-like planet around a late Mdwarf, we determine that the variation is modest (but non-negligible); in quantitative terms, the maximum escape rate is more than twice (or 200%) the minimum value. The chief reason why the obliquity plays a weak role in determining the escape rate for solar-type stars stems from the temperate stellar wind and radiation in HZs.

As shown in Figures 2 and 3, the magnetosphere of the G-dwarf planet is larger than that of the M-dwarf planet; therefore, regardless of magnetic obliquity’s...
value, the ionosphere does not experience much difference. On the other hand, for an Earth-analog around TRAPPIST-1, the dual effect of the compressed magnetosphere and high energy radiation makes the ion sources (e.g., electron impact ionization and charge exchange) more sensitive to the magnetic configuration.

Figure 2. The logarithmic scale contour plots of the O⁺ ion with magnetic field lines (in white) in the meridional plane for a magnetized Earth-like planet orbiting around a solar-type star. Different plots correspond to different planetary magnetic obliquities [9].

Figure 3. A magnetized Earth-like planet (with different magnetic obliquities) orbiting around TRAPPIST-1 [9].

Third, we see that the maximal ion escape rate is attained at a magnetic obliquity of 90° whereas the minimum occurs at 0° or 180° (Figure 1). While the atmospheric escape rates at 0° and 180° are nearly the same, there is a clear distinction between 90° and 270°. The reason behind the latter behavior has to do with the relative orientation of the interplanetary magnetic field (IMF) and the planetary magnetic field. At the magnetic obliquity of 90°, the IMF can directly connect to the dayside planetary surface due to the field polarity, whereas the IMF can only connect to the nightside surface at the magnetic obliquity of 270°; see the third column of Figure 2. Therefore, stellar wind particles, especially electrons (with relatively low energy) can be transported along the field lines and ionize the atomic oxygen in the upper atmosphere via impacts as shown in Figure 4.

Conclusions: We found that the maximum escape rates arose at obliquities of 90° or 270° (depending on field polarities), whereas the minimum rates were attained at 0° or 180°. The reason is that the cusp (comprising open field lines) faces the stellar wind at obliquities of 90° or 270°, and allows the stellar wind particles to deposit their energy in the planetary upper atmosphere. For Earth-like planets around solar-type stars, it is found that the escape rate is virtually independent of the obliquity. On the other hand, for late M-dwarfs, we determined that the escape rate varies by more than a factor of ~ 2.

From our simulations, we found that the timescale required to deplete a ~ 1 bar Earth-like atmosphere is O(10^{10}) and O(10^{9}) yrs, for solar-type stars and late M-dwarfs, respectively. If we assume that the source of atmospheric oxygen is water from oceans, we find that the mass of Earth’s oceans (M_H2O) cannot be depleted over the main-sequence lifetime of a solar-type star. In contrast, for a late M-dwarf we determine that M_H2O could be depleted over a timescale of O(10^{10}) yrs, which is shorter than the star’s lifetime.

Figure 4. (a) Logarithmic scale contour plots of the O⁺ ion density with O⁺ ion velocity vectors (in black) and magnetic field lines (in white) in the meridional plane for the M-dwarf planet with obliquity of 90°. The black arrows depict both the direction and the magnitude of O⁺ ion velocities. (b)-(d): Logarithmic scale contour plots of the photoionization rate R_{O^+, ph}, electron impact ionization rate R_{O^+, imp} and charge exchange rate R_{O^+, CX} (with stellar wind protons) of O⁺ ions [9].