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Dave Brain, Ofer Cohen, Kevin France, Yoshifumi Futaana, Alex Gloer, Parker Hinton, Mats Holmstrom, François Leblanc, Yingjuan Ma, William Peterson, et al.

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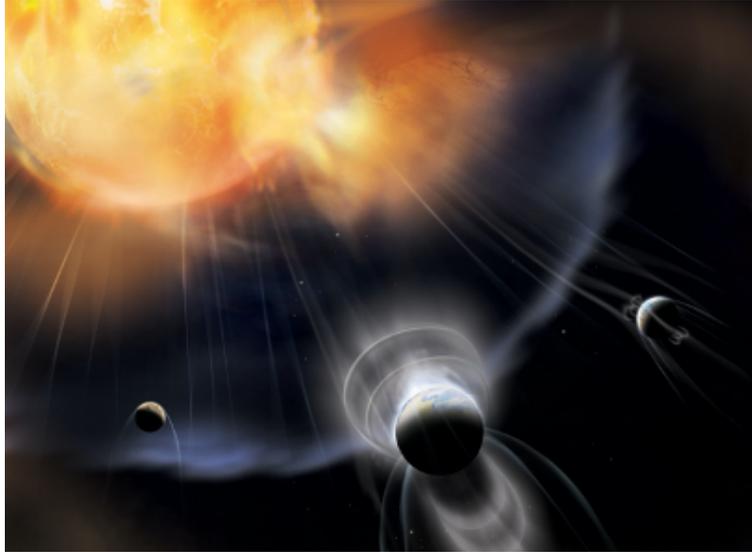
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The Influence of Planetary and Stellar Characteristics on Atmospheric Escape and Habitability



Dave Brain (University of Colorado)
Ofer Cohen (University of Massachusetts Lowell)
Kevin France (University of Colorado)
Yoshifumi Futaana (Swedish Institute of Space Physics)
Alex Gloer (NASA/GSFC)
Parker Hinton (University of Colorado)
Mats Holmstrom (Swedish Institute of Space Physics)
François Leblanc (LATMOS/CNRS, Sorbonne Université)
Yingjuan Ma (UCLA)
Bill Peterson (University of Colorado)
Shotaro Sakai (Tohoku University)
Ennio R. Sanchez (SRI International)
Neesha R. Schnepf (University of Colorado)
Robert J. Strangeway (University of California, Los Angeles)

Synopsis

Atmospheric escape occurs at planets everywhere, and influences the evolution of planetary atmospheres and surface habitability. We argue for developing a common understanding of atmospheric escape that accounts for different star and planet characteristics. This requires comprehensive measurements at multiple planets, new models that cover the entire parameter space, and interdisciplinary effort.

I. Motivation

'Atmospheric escape' is a catch-all term that refers to several distinct processes that provide sufficient energy to particles in planetary atmospheres that they escape to space. We know that planetary atmospheres lose particles to space over time, based both on direct observations and the telltale chemical signatures that escape processes create in atmospheres. This evidence indicates that escape can play an important role in the history of a planet's atmosphere and surface habitability by influencing the evolution of atmospheric abundance and composition.

Presently, scientists who study escape processes at Earth, solar system planets, and exoplanets employ varied strategies to estimate atmospheric escape rates, often focusing on a single planet, process, or set of physics in isolation. This fractured approach has prevented a comprehensive understanding of how atmospheric escape works at *any* planet, with the result that our understanding of escape at *all* planets is deficient. For example:

- It is unclear whether a planetary magnetic field inhibits atmospheric escape
- The community does not have consensus on what fraction of outflowing ions ultimately escape Earth's magnetosphere
- The role that atmospheric escape played in the divergent climate histories of Venus, Earth, and Mars is not well understood
- The interaction of Earth's atmosphere with the near-Earth space environment during periods of geomagnetic reversal is a poorly-explored topic
- We are not certain which of the thousands of detected exoplanets (orbiting a wide variety of stars) are likely to retain atmospheres

We argue that a major scientific goal for the next decade, then, should be to bring together observers, modelers, and theoreticians from the terrestrial, planetary, and exoplanetary communities in order to determine what properties of a planet and its host star lead to escape (or retention) of an atmosphere. Working together, these communities should develop common tools, approaches, and understanding that allow answers to the questions posed above. A key aspect of this work should be the evaluation of uncertainty in estimates of atmospheric escape. Though the topic is broadly interdisciplinary in its nature, the escape processes themselves are heliophysics processes that have been the subject of study for many decades. The heliophysics community should therefore take the lead in organizing the community around this exciting topic.

II. Current State of the Field

In broad terms, any particle near the top of an atmosphere (where collisions are rare) can escape a planet's gravity if it is given enough energy and is directed "upward" [see reviews of atmospheric escape processes in, e.g., *Moore and Horwitz, 2007; Brain et al., 2016*].

Energy can be imparted by several different processes, depicted in [Figure 1](#). For neutral particles, escape energy can come from heating by solar photons (*thermal escape*), from chemical reactions (*photochemical escape*), or from collisions (*sputtering*). Since ions are charged particles, they have access to additional important sources of energy through interactions with electric fields. If enough energy is deposited in an upper atmosphere (typically through solar photons) then atmospheric particles can escape as a fluid (*hydrodynamic escape*).

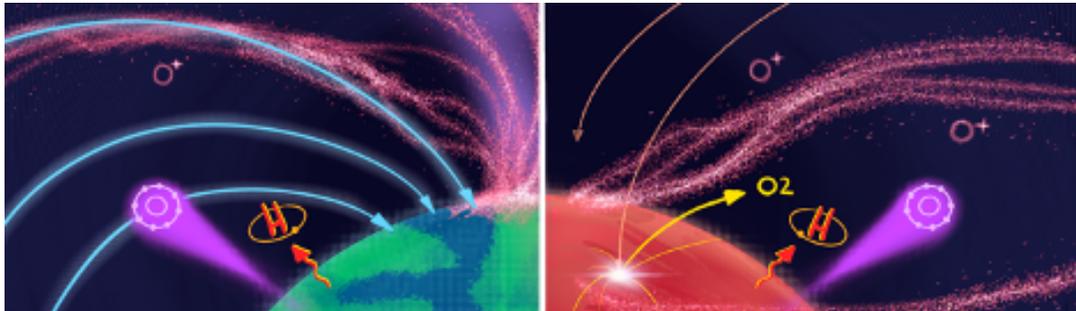


Figure 1: Cartoon of atmospheric escape processes acting at generic magnetized (left) and unmagnetized (right) planets. Ion loss (red O^+), thermal escape (red H), photochemical escape (magenta O), and sputtering (yellow O_2) are depicted. Hydrodynamic escape is not depicted. Credit: Cameron Pazol (University of Colorado undergraduate), 2021.

Each escape process can be relevant for a planet's atmosphere in different ways - the processes can have differing results for different atmospheric species and at different times in a planet's history. For example, thermal escape is important only for hydrogen at Venus, Earth, and Mars. Photochemical escape results in the direct escape of oxygen, but only at Mars due to its low escape velocity relative to Earth or Venus. Sputtering is not an escape process today for any species at Venus, Earth, or Mars, but appears to have been important in the past at Mars for heavy noble gases such as Argon. Ion escape results in the loss of species such as O^+ , O_2^+ , CO_2^+ , N_2^+ , and H^+ (all climatically important) at Venus, Earth, and Mars. Hydrodynamic escape is thought to have been responsible for removal of the primordial H and He atmospheres of all terrestrial planets early in solar system history.

Observations relevant to atmospheric escape have been made since the earliest spacecraft missions in the 1960's. Neutral escape (hypothesized as early as 1846) was inferred from UV observations of the upper atmospheres of Mars and Venus [e.g. *Barth et al., 1967; McElroy and Hunten, 1969; Barth et al., 1969, Anderson and Hord, 1971*]. Ion

escape/outflow was first measured at Earth [Shelley et al., 1972], followed by Venus, comets, Mars, Titan, and Pluto [e.g. Mihalov, 1980; Balsiger et al., 1986; Gloeckler et al., 1986; Lundin et al., 1989; Gurnett et al., 1982; McComas et al., 2016]. Figure 2 shows ion measurements from Earth, Venus, and Mars to scale.

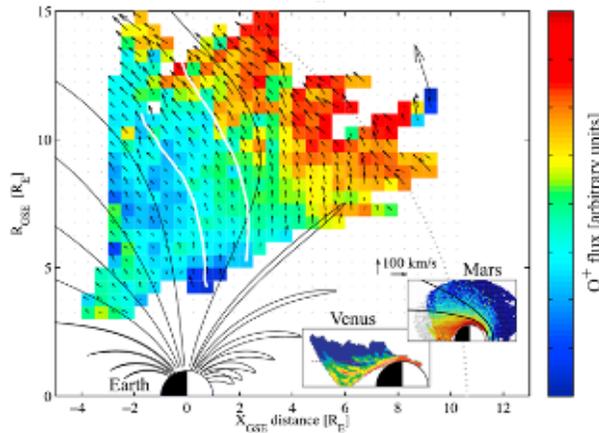


Figure 2: Oxygen ion escape fluxes from the Earth [Nilsson et al., 2011] in a cylindrical coordinate system. Analogous maps of escaping O^+ flux from Venus [Fedorov et al., 2008] and Mars [Ramstad et al., 2017] are inlaid with the same scale. Escape flux estimates vary by study, but all lie within about an order of magnitude of each other, sparking debate about the importance of a magnetic field. Figure courtesy R. Ramstad.

In parallel with observations, models of different escape processes have progressed over the past five decades. The sophistication of models has increased with time, spurred by increases in computational resources and by new observations that reveal important physics that influences escape rates. The community now has a variety of models for the atmospheric reservoirs for escape (thermosphere, ionosphere, exosphere) as well as the escape processes themselves (thermal, photochemical, ion, sputtering, and hydrodynamic escape). These models have become sufficiently sophisticated that there are now typically planet-specific versions of models. For example, one can find separate 3D thermosphere models for Earth, Venus, Mars, Jupiter, Titan, and exoplanets - and in most cases there are multiple examples of each. This situation has both advantages and disadvantages. Competing models can be compared with each other, providing increased confidence in a result when models agree, and a jumping-off point for further investigation when they disagree. It is difficult, however, to develop a unified understanding of atmospheric escape processes that bridges different planets.

In recent decades there has been increased attention on the influence of stellar characteristics (e.g. solar EUV flux, solar wind, flares and CMEs) on atmospheric escape rates. However, the “one planet at a time” nature of both spacecraft observations and existing models has made synthesis of the lessons learned at each planet difficult, and has made studies of the influence of planetary characteristics on atmospheric escape virtually impossible. Understanding of the influence of *both* stellar and planetary properties on atmospheric escape is required to answer the big picture questions posed in Section I, and is essential for understanding which exoplanets are most likely to retain habitable atmospheres.

A particularly intriguing planetary characteristic that may influence escape is the presence of a global dipole magnetic field. *McElroy* [1968] first proposed that planetary magnetic fields inhibit atmospheric escape, and evidence from atmospheric isotopes [e.g. *Donahue et al.*, 1982; *Owen et al.*, 1988] and some spacecraft observations of escape [*Wei et al.*, 2012; *Jakosky et al.*, 2018] have lent support for this idea, which became prevailing wisdom for several decades. The idea that planetary scale magnetic fields lead to reduced escape rates has been questioned over the past decade or more. One of the first to propose that magnetic fields do not protect atmospheres was *Strangeway et al.* [2010], who noted that the reported ion escape rates at Venus, Earth, and Mars agree to within about an order of magnitude (Figure 3). It may be that an intrinsic magnetic field encounters more power from the solar wind than an unmagnetized planet due to the large size of the magnetosphere relative to the planet, and that solar wind energy is transferred along magnetospheric field lines to the top of an atmosphere in the cusp regions, possibly resulting in *more* ion escape than results in the absence of a global field.

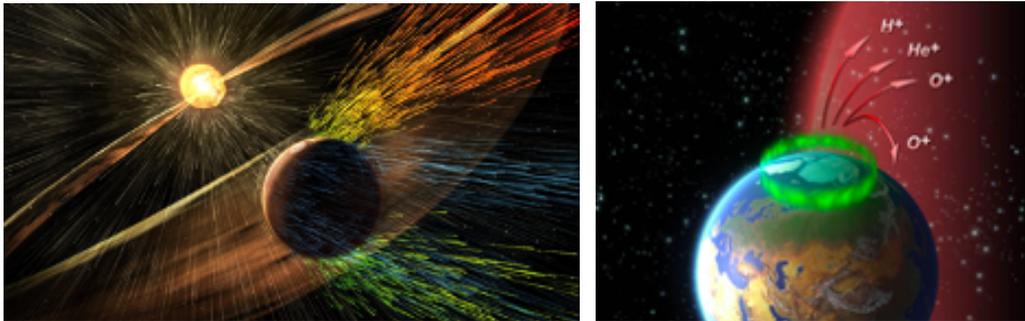


Figure 3: (left) Artist's sketch of atmospheric charged particles escaping from the Martian atmosphere in response to a Coronal Mass Ejection. MAVEN results confirm that atmospheric escape has played a major role in changing the Martian climate, possibly due to the lack of a global magnetic field at Mars. However, atmospheric ion escape occurs at Earth (right) and is correlated with the energy of the solar wind, despite – or perhaps enhanced by – the presence of Earth's global magnetic field. The escape is concentrated in the magnetic cusp regions. Image credits: NASA / MAVEN and ESA.

Initial modeling investigations suggest that neither argument is fully correct. Atmospheric ion escape is not purely correlated or anti-correlated with increasing planetary magnetic field strength. Instead, these global plasma models hint that atmospheric escape rates are maximized for intermediate magnetic field strengths [e.g. *Sakai et al.*, 2018; *Egan et al.*, 2019; *Sakata et al.*, 2020]. Too strong a magnetic field prevents outflowing planetary ions from escaping the system, while too weak a magnetic field results in planetary ions being accelerated by the solar wind back into the atmosphere. However, these models do not yet capture all of the relevant physics, and are often limited by computational resources to relatively weak planetary magnetic field strengths.

III. Needs

Our goal is to understand atmospheric escape as a suite of interconnected heliophysics processes that occur at all planets, and to understand how the different characteristics of stars and planets, in combination, influence whether escape is significant. In other words, we want to move the community from a “How does this apply to my planet of interest?” mindset to a more holistic approach where each planet is considered in its region of a larger parameter space. To accomplish this we have identified three main needs in the next decade. They are described here without regard to priority - an ideal outcome would be comparable progress in all three areas.

A. Development and validation / verification of models that bridge the gap between currently siloed communities

Physics-based models provide a powerful means of computing escape rates from planets. Unlike spacecraft data, models can tell us about the entire system at any given moment and for a variety of conditions, and can be used to probe the physics responsible for energizing and removing atmospheric particles. Models can vary a single parameter (e.g. the composition of the atmosphere, the luminosity of the star) to determine its influence on the system. Useful models include all physical processes which may influence the modeled escape rate. They are validated by observations where it is possible to do so, and verified against theory and/or other models where it is not possible to validate (i.e. outside the range of parameters for which observations are available). Model verification is especially important when considering exoplanets, where few direct observations of escape are available.

Over the past few decades the communities that study atmospheric escape from Earth and other planets have diverged in their modeling tools and approach, driven by key differences in the objects that they study.

One notable example is how ion escape is modeled at unmagnetized planets vs. at Earth. For unmagnetized planets, where the solar wind interacts directly with the upper atmosphere, an ionosphere needs to be included self-consistently in order to properly simulate the interaction process and reproduce observed features [e.g. *Ma et al.*, 2013]. For magnetized planets, modeling ion outflow is an extremely challenging task, and fully self-consistent models for Earth are currently not feasible. A major reason for this is the difficulty in simulating plasma motion in strong magnetic fields (Alfvén speed scales with magnetic field strength, requiring a small timestep that makes long-term calculation difficult) [*Toth et al.*, 2012]. As a result, most Earth magnetosphere models have a lower boundary that is well above the ionosphere, and separate models for the ionosphere and magnetosphere must be coupled to compute escape rates. *Glocer et al.*

[2018] only recently presented the first two-way coupled ionospheric outflow - magnetosphere model for Earth that includes kinetic ion effects.

Steady advances in computational resources over the past decade or so have made it possible for global models for unmagnetized planets to add planetary magnetic fields [e.g. *Sakai et al.* 2018, *Egan et al.* 2019, *Sakata et al.*, 2020], though the models are not validated in this regime and there may be missing or poorly-captured physics in the low-altitude cusp regions most important for ion acceleration and escape.

To evaluate atmospheric escape from any star-planet combination it is important to have tools that work across the full parameter space of planetary and stellar characteristics, rather than relying on a patchwork of models (that have different implementation and assumptions) to cover the parameter space. **This requires substantial funded joint model development efforts to promote discussion and collaboration between modelers.**

B. Directly comparable measurements of atmospheric energization and escape at a variety of solar system objects, along with simultaneous measurements of the solar inputs that drive escape

Measurement-based estimates of atmospheric escape have been made for many solar system objects (e.g. Venus, Earth, Mars, Titan, comets, Pluto). Several caveats make directly comparing published escape rates between planets problematic. First, published escape rates vary depending upon the instrument capabilities, spacecraft orbit, data selection, and data treatment. Second, there is also natural variability in escape rates with different drivers associated with the solar Extreme Ultraviolet (EUV) flux [e.g. *Kollmann et al.*, 2016; *Ramstad et al.*, 2015], and solar wind [e.g. *Slapak et al.*, 2017; *Ramstad et al.*, 2017; *Persson et al.*, 2020]. This suggests that the time period over which data were taken influences the escape rate. Third, the range of solar and solar wind drivers experienced by these objects is different, even over the same period, due to their different heliocentric distances and longitudes.

The most comprehensive set of measurements to date has been made by the MAVEN spacecraft at Mars [*Jakosky et al.*, 2015]. MAVEN has been measuring escape rates via the full suite of escape processes active at Mars, and simultaneously measuring the solar and solar wind energetic inputs that drive escape (EUV and X-ray photon fluxes, solar wind and solar energetic particle energy fluxes, interplanetary magnetic field and associated magnetic pressure). There is, at present, no analogous dataset for other solar system bodies of interest, including Venus, Earth (!), Titan, comets, Pluto, or giant

planets. We argue that comprehensive measurements relevant to atmospheric escape (reservoirs for escape, drivers of escape, and escape itself) should be made at other planetary bodies.

Comparing measured atmospheric escape rates from a variety of objects with a range of sizes (from comet to giant planet), external conditions, and magnetization states is the best (only?) way to validate models for escape. For this comparison to be meaningful we must understand (and if possible control or correct for) differences in measurement technique, instrument performance, solar inputs, and planetary characteristics. A particularly helpful situation would be simultaneous measurements of escape and its heliophysical drivers made at multiple solar system objects by similar instruments. It should be possible to make significant progress in this area using SmallSat Missions at different objects, and multipoint measurements (similar to the ESCAPE mission currently in development for Mars) at a single object.

C. An interdisciplinary approach led by Heliophysics that includes contributions from Planetary Science, Astrophysics, and Earth Science

The physics that drive atmospheric escape are heliophysics processes. Most are ultimately driven by energy from a star, and energize particles in the thermospheres, ionospheres, exospheres, and magnetospheres of planets. It is our view that the Heliophysics community should therefore lead the field on this topic by acknowledging its importance and taking steps to answer outstanding questions about atmospheric escape. However, valuable measurements, models, and insight come from other communities as well, including Planetary Science, Astrophysics, and Earth Science (for example, the influence of atmospheric escape on a planet's bulk atmospheric chemistry).

By promoting discussion and collaboration between the communities, we will be able to better answer big picture questions relevant in all communities. This requires more opportunity for NASA-funded cross-divisional research, and opportunity for Heliophysics investigations on NASA Planetary and Astrophysics missions. NASA's NExSS community and Interdisciplinary Consortia for Astrobiology Research provide two examples of cross-divisional collaboration - the first focused on exoplanets and the second focused on astrobiology. These kinds of efforts should be expanded to better include Heliophysics, or adapted for the specific needs of NASA's Heliophysics Division.

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