

1 The ionosphere is the ionized part of the Earth's atmosphere, stretching from about 60 km above the surface to more than 1000 km; it is shown here in purple, not to scale. (NASA's Goddard Space Flight Center/Duberstein)

The ionospheres of planets and exoplanets

Michael Mendillo examines how planetary ionospheres vary, and wonders whether they can provide biomarkers for exoplanet exploration.

If life as we know it is found on another planet in our galaxy, it would confirm that our understanding of solar–terrestrial processes is universal rather than a local phenomenon. The disciplines of geophysics, space physics, planetary science and astronomy – the core sciences of the RAS community – have much to contribute to that agenda, separately and, especially, in combination. As an example of the constructive links that this community can offer, this article deals with the unlikely pairing of ionospheric physics and astrobiology.

The Earth's ionosphere (figure 1) is our closest cosmic plasma, and the inevitable product of a planet with an atmosphere orbiting a star. All of the prominent gases found in the upper atmospheres of terrestrial and giant planets (CO_2 , N_2 , O_2 , O , H , H_2 , H_2O , CH_4 , NH_3) have ionization thresholds in the range ~ 10 – 16 eV; photons with wavelengths below ~ 120.0 nm thus have sufficient energy to ionize them. Our Sun's irradiance (photon flux versus wavelength) in the extreme ultraviolet (EUV) and soft

X-rays (collectively called XUV) exerts direct control on photochemical processes in the terrestrial ionosphere. These take place over a range of timescales, from minutes (solar flares), to diurnal (Earth's rotation), months (rotating solar active regions) and decades (solar cycle effects). The Sun's XUV photons penetrate to different heights and, because the cross-sections for ionization depend on wavelength, different ionospheric “layers” are produced as a function of altitude.

Within the Earth's dense neutral atmosphere below ~ 180 km, ions and electrons form and recombine chemically so quickly that plasma is produced and lost in place. This is called the photochemical equilibrium (PCE) domain and the resultant electron density emerges simply from the balance of solar production and chemical loss. At higher altitudes where the neutral gas is more tenuous, ions and electrons respond to gravity, winds and electric fields more rapidly than the pace of atmospheric chemistry; thus ionospheric structure depends on photochemical processes coupled with plasma dynamics.

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“This article deals with the unlikely pairing of ionospheric physics and astrobiology”

2 (a) Schematic summary of electron densities in ionospheric layers at Earth produced by the Sun's X-rays (E-layer) and EUV photons (F1-layer) under conditions of photochemical equilibrium involving molecular ions and electrons. The higher-altitude layer of maximum electron density (F2-layer) results from photochemistry and plasma dynamics of atomic ions and electrons. (From Bauer & Lammer 2004.) (b) The commonality of E- and F1-type ionospheric layers throughout the solar system, with individual labels assigned to each planet.

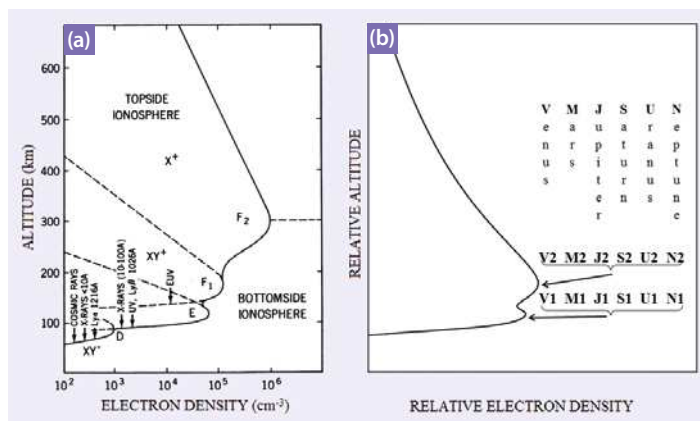
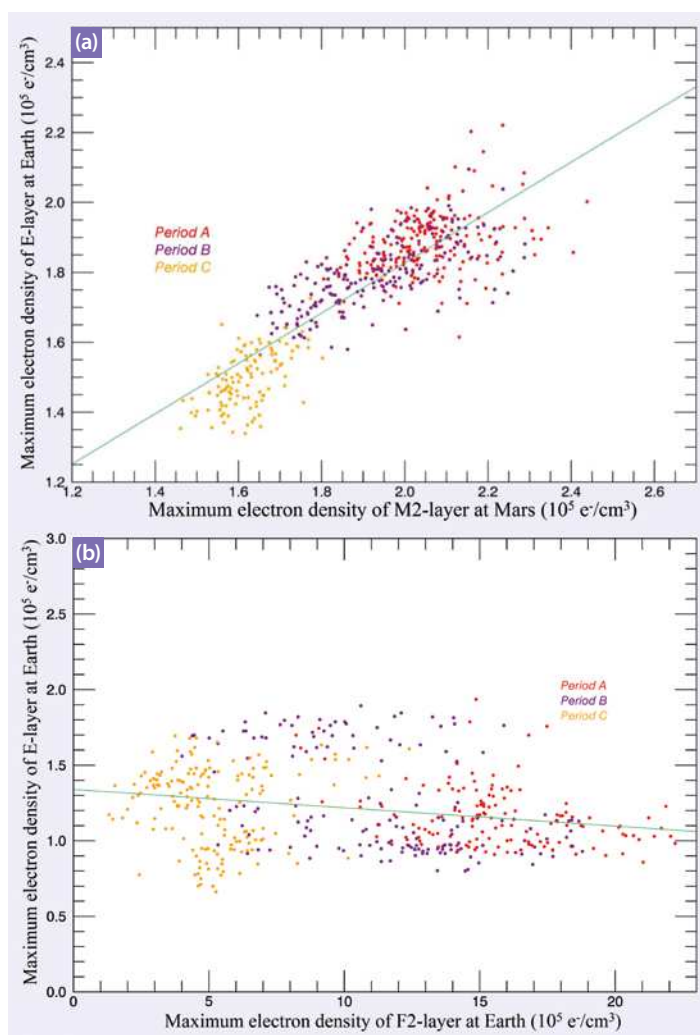


Figure 2a offers a pictorial summary of the Earth's ionosphere. The main PCE regions are named the E-layer and F1-layer. Above the F1-layer, solar EUV photons dissociate O_2 to yield O as the dominant neutral gas. At these altitudes, EUV photons also ionize atomic oxygen, subsequent ion–electron recombination chemistry is slow, and thus plasma diffusion can compete effectively with chemistry. These multiple processes result in the maximum electron density occurring at much higher altitudes in the terrestrial ionosphere (called the F2-region).

The complexities of the F2-layer arise from its creation by varying solar XUV fluxes, multiple forms of ion–neutral-electron chemistry, dynamics of winds and electric fields and solar wind impact of a global magnetic field. The result is a highly variable complex system subject to episodic disturbances launched from the Sun, as well as by the intrusion of upward coupling from weather in the troposphere and stratosphere.

Is the scenario of an upper atmosphere as a complex system at Earth representative of ionospheres throughout our solar system? And, if so, are solar system ionospheres then representative of those to be expected at exoplanets? Figure 2b extends terrestrial ionospheric concepts to other planets. The messages that emerge range from the bureaucratic (terminology) to the profound (origin of life). The solar irradiance effects of X-rays and EUV are, in fact, consistent throughout the solar system. Ionospheric peak densities appear at two altitudes – planetary versions of Earth's E- and F1-layers. At Earth, the F1-layer is fully within the PCE domain, and its topside component becomes negligible in comparison to the F2-layer above, which dominates. At all other planets, plasma dynamics eventually control the topside ionosphere as well, and thus its identity as a PCE F1-layer loses meaning. For that reason, a new set of generic terms was introduced (Rishbeth & Mendillo 2004) using a planet's initial letter and numbering the layers from lower (1) to upper (2).

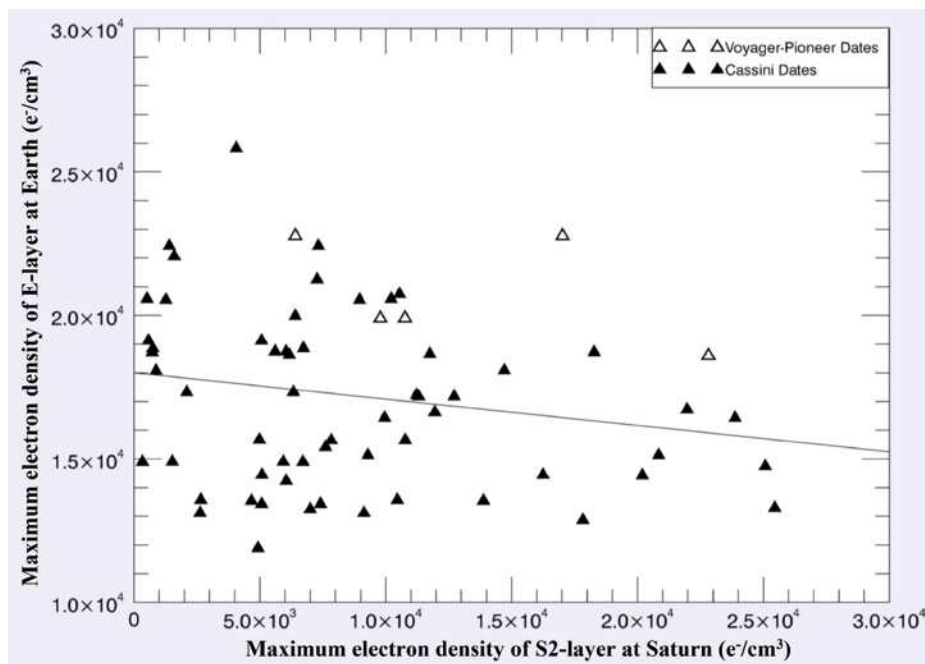
3 (a) High correlation (0.85) of average midday values of maximum electron density for PCE conditions of the E-layer at Earth (N_mE) and M2-layer at Mars (N_mM2). Different colours are used to display three solar cycle conditions defined by the solar flux index F10.7 over the years 2000–05: (A) 170 units, (B) 130 units, and (C) 100 units. (b) Lack of correlation (–0.23) between the PCE E-layer and the PCE+dynamics F2-layer at Earth as observed for midday values by the ionosonde at Chilton (UK). Colour coding is same as in top panel. (After Mendillo *et al.* 2016)



A more important message from this comparison is that there is no F2-layer at any other planet. All the others have their peak electron density in a dense regime of molecular ions; only Earth has its maximum electron density in a layer of atomic ions at a much higher altitude. The clue to resolving this situation lies in the type of atomic ion present at Earth: O^+ . The only planet in our solar system to have atomic oxygen ions at its altitude of maximum electron density is the only planet known to have life. Is that a coincidence or a fundamental message? How robust is this concept – can a basic characteristic of an ionosphere serve as a biomarker for exoplanets?

Coherences and divergences

In order to test the universality and coherence of ionospheric layers produced by solar X-rays and EUV, the planets Mars and Saturn are the best options because they have the most data available for comparative studies with Earth. Correlations of another planet's ionosphere with Earth's is easiest to do when the planet is in opposition, i.e. when Earth lies on a straight line between the planet and the Sun. In this circumstance, the same XUV irradiance impacts both planets. Yet, that stringent geometrical–orbital situation limits comparative studies to a very small dataset of planetary ionospheres. A solution is to take



4 Comparison of peak electron densities of the E-layer at Earth with the S2-layer at Saturn for “same-day” solar flux conditions, yielding a correlation coefficient of -0.19 . (After Mendillo *et al.* 2018a)

advantage of the fact that an enormous number of ionospheric observations are made on Earth every day. Thus, on a given day when a planetary observation was made, the side of the Sun facing that planet would be directed towards Earth within ± 14 days (depending on the differences in orbital longitude of the two planets). Whatever that “rotated Sun date” turns out to be, plenty of ionospheric observations were made on Earth to deduce the “same solar irradiance day” and make comparisons between the ionospheres. This assumes, of course, no dramatic changes occurred on the Sun over the days in question – not a concern for average responses within large datasets. The benefit of this approach is that every ionospheric dataset at a planet has a corresponding set of terrestrial measurements, and thus down-samples to opposition-only days can be avoided.

Examples of this methodology using datasets from Mars and Earth spanning a solar cycle are shown in figure 3a. The peak electron densities of the terrestrial E-layer come from midday averages of ionosonde stations in both hemispheres at Earth. The peak electron densities of the M2-layer at Mars come from electron density profiles $N_e(h)$ obtained by radio occultation experiments by the Mars Global Surveyor radio science experiment (Hinson *et al.* 1999). The high correlation coefficient (0.85) indicates that the ionospheres of Mars and Earth fluctuate in accordance with solar irradiance. The remaining variabilities come from solar irradiance and/or solar wind effects not captured by the rotated-Sun methodology, as well as from changes in planetary

neutral atmospheres driven by waves and tides. Nevertheless, the message is clear: the PCE-layers at Earth and Mars are highly correlated on a day-to-day basis throughout a solar cycle. All such correlations disappear when the Earth’s maximum electron density ($N_m F_2$) is compared with either the E- or F1-layers at Earth or with the M1- or M2-layers at Mars. Figure 3b demonstrates that point using same-day E and F2-layer observations from the ionosonde in Chilton (UK).

Does the same trend hold for planets in the outer solar system? Saturn is the planet with the most radio occultation profiles and, yet, the number published is distressingly small (five profiles from the Pioneer and Voyager missions and 59 from the Cassini mission). Moreover, the primary and secondary peak electron densities can often be difficult to identify because the $N_e(h)$ profiles are highly structured. Nevertheless, an identical analysis of rotated-Sun dates for Saturn with terrestrial ionosonde data yields a surprising result: the photochemical layers at Earth and Saturn cannot be correlated in any combination (Mendillo *et al.* 2018a). Figure 4 shows results comparing the best diagnosed layers (terrestrial E-layer versus Saturn’s S2-layer). The message from figure 4 is that while the Sun’s XUV obviously ionizes the dominant gases in Saturn’s upper atmosphere (H and H_2), the resulting plasma merely sets the background for more dominating plasma effects (either chemical and/or dynamical). The initial candidates for modifications from external sources are the influxes of water molecules and water-group ions from Saturn’s “ring

rain” (O’Donoghue *et al.* 2017) and the geysers on Enceladus. These exogenic agents are further enhanced by more complicated dust grains and molecules discovered as the Cassini satellite executed a series of flybys between Saturn’s rings and atmosphere before ultimately plunging to its demise in Saturn’s dense lower atmosphere (Hsu *et al.* 2018, Mitchell *et al.* 2018, Waite *et al.* 2018).

A unique ionosphere

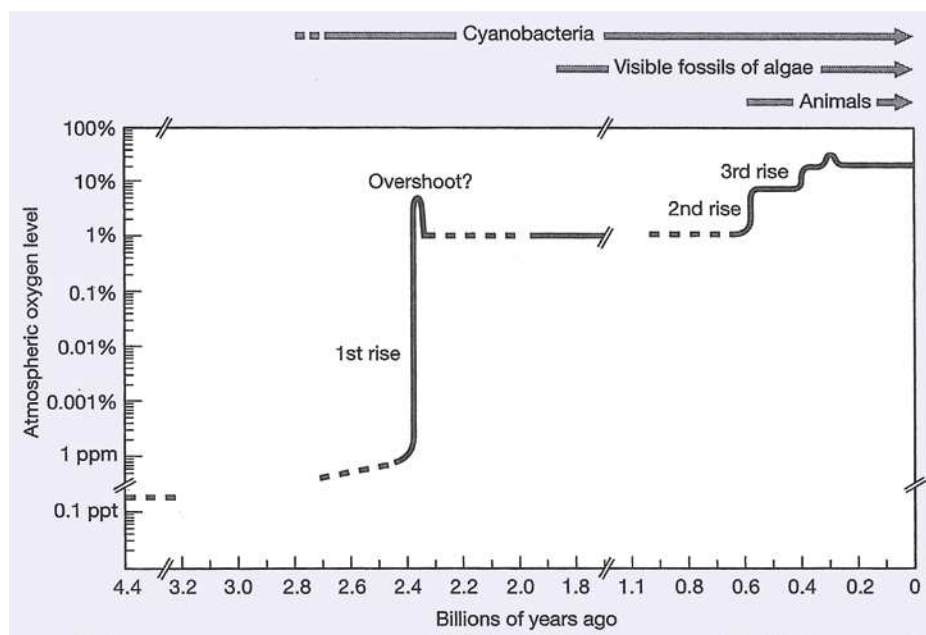
The commonality of ionospheric layers produced by PCE can also be described using ion compositions (figure 2). The E- and F1-layers at Earth, and all of their counterparts throughout the solar system, have electron densities matched by equal numbers of molecular ions. Earth is the only planet with a higher altitude layer (F2) that is the planet’s true layer of maximum electron density. The ion composition of this layer alone is not dominated by molecular ions, but rather by atomic oxygen ions (O^+). The reason for this is well known: photosynthesis. Biological activity accounts for the high abundance of oxygen on Earth and hence for its atomic ions in our ionosphere. Earth is the only planet with an oxygen-generating mechanism that has transformed its atmosphere from the surface to its exobase (height of escape). Moreover, the atmosphere is not in internal equilibrium. If oxygenic photosynthesis stopped, oxygen would cease to be a significant component of our atmosphere in about 5000 years (Walker 1980). The impact of photosynthesis upon ionospheric physics is that no planet in the solar system has a maximum electron density matched by O^+ ions. An ionospheric peak of O^+ thus becomes a biomarker – the first biomarker defined by a plasma. Moreover, it does not require a quantitative specification, but a relative one: if at the altitude (h_{max}) of maximum electron density (N_{max}) in a planet’s ionosphere, the matching number of ions are O^+ , then that planet has flourishing global life.

Biomarkers document the existence of life – something very different from specifying conditions thought to be conducive to the origin of life. And, to avoid excessive speculation about unknown types of life, the focus must be on life as we know it. This implies a planet located in a solar-type star’s habitable zone, with a solid surface, plenty of water, oxygen (O_2 and O_3) in its atmosphere, enough gravity to hold on to its atmosphere and a global magnetic field as a protective shield. Technological biomarkers are not considered here, e.g. the remote detection of a constellation of GPS-like navigational satellites in orbits around an exoplanet, or coded radio signals found via the search for extra-terrestrial intelligence (SETI).

Biomarkers and detections

What is a **biomarker**? The *Oxford English Dictionary* offers: “A substance used as an indicator of the presence of biological origin, of a specific organism, or a physiological condition or process.” Astrobiologists say: “An object, substance, and/or pattern whose origin specifically requires a biological agent” (Des Marais & Walter 1999).

A **false positive** is an abiotic observation that mimics biologically produced observables. A **false negative** is a biosignature that is not detectable.



5 History of oxygen in the Earth's atmosphere. (From Catling 2013)

The history of oxygen on Earth

While the earliest signs of life on Earth appeared within ~1 billion years of its formation, the first significant rise in oxygen occurred about 2.4 billion years ago (Ga), called the Great Oxidation Event (GOE). Figure 5 shows the current best estimates of the history of oxygen in the terrestrial atmosphere (Catling 2013). The major GOE source of O_2 is from photosynthesis by cyanobacteria. This led to a rise in O_2 from ~1 ppm to $\leq 2\%$ of the atmospheric content. Such levels of O_2 on another planet would be a false-negative biomarker (see box “Biomarkers and detections”): life exists, but its oxygen levels are undetectable from afar. Yet GOE abundance was sufficient to lead to ozone in the stratosphere (Catling 2013). During the long period of stability following the GOE, when O_2 stayed at ~2% of the atmosphere for nearly two billion years, the distribution of gases within the Earth's upper atmosphere has yet to be modelled. This means that ionospheric simulations (using models of the solar irradiance versus time) cannot yet predict the mix of ions and electrons present over that time span.

In more geologically recent times, the timescale for atmospheric evolution switches to millions of years ago (Ma), and there was a second rise in oxygen (to ~10%) at 580 Ma. This fostered the Cambrian explosion of varied and larger animals and probably led to an O^+ dominated ionosphere. At 400 Ma, the third rise in oxygen occurred, leading to the present O_2 level of 21% in our atmosphere – and to forms of life far more interesting than bacteria and arthropods.

Ionospheric biomarker case studies

Is the 21% oxygen content in our current atmosphere the value that defines oxygen as a biomarker? Will 10% do? If it would,

the ionospheric biomarker for an Earth-type planet orbiting a solar-type star would be “available” for detection for over 500 million years.

Mars has oxygen in many forms (O , O_2 , O_3), all at trace levels, and its presence is not due to photosynthesis. Venus also

has trace levels of oxygen – again, not from life on the planet, but from the same processes that occur at Mars: photodissociation of CO_2 and trace amounts of H_2O . These

atmospheric processes near the surface determine the characteristic signatures to be found at higher altitudes. Figure 6 offers a comparison of the upper atmospheres and ionospheres of Venus, Earth and Mars. These terrestrial-size planets demonstrate the only possible cases in our solar system where the proposed ionospheric biomarker could yield a false positive. As the lower panels show, O^+ ions on Venus and Mars experience local maxima in their topside ionospheres, but these are not for N_{max} at h_{max} . Moreover, these O^+ populations could not build up in time to exceed N_{max} because they occur at altitudes where vertical plasma diffusion and horizontal transport by solar wind “pick-up” processes lead to escape. Charge exchange with hydrogen (e.g. $O^+ + H \rightarrow H^+ + O$) also removes O^+ to form lower mass H^+ that readily escapes. The message from figure 6 is that Earth-sized planets close to our Sun's habitable zone (i.e. Venus and Mars) do not have ionospheric O^+ biosignatures because there is no oxygenic photosynthesis on those planets.

How confident are we that no planet in the outer solar system has O^+ as its dominant ion? Pretty certain. The four gas giant planets are dismissed because their

atmospheres are predominately hydrogen and thus have H^+ , H_2^+ and H_3^+ in their ionospheres. The jovian planets have many remarkably interesting moons, but not one has an ionosphere dominated by oxygen ions at any altitude. Comets and icy moons have atmospheres derived from surface

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“An ionospheric biomarker occurs at the greatest distance from a planet's surface”

sputtering agents (photons, solar wind, or micrometeors), and their hydrated ions form surface-boundary ionospheres, meaning ones with maximum electron densities

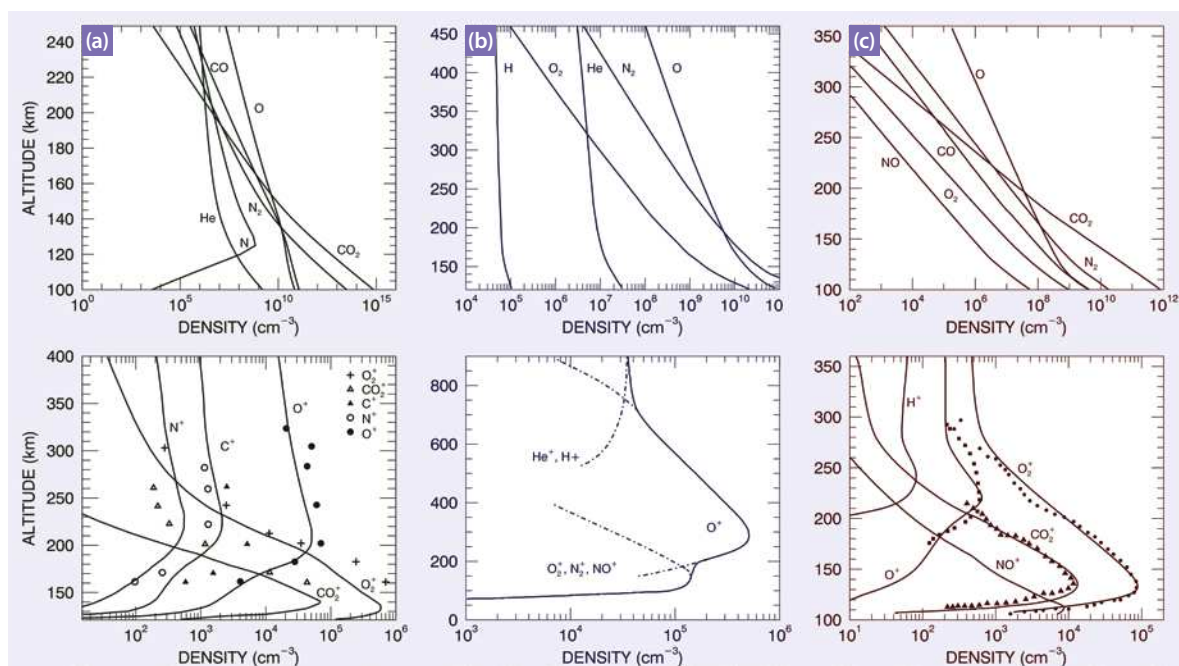
at their surfaces. These are transient atmospheres – continuously produced and continuously lost – and thus far from the stable conditions for the evolution of life.

Detecting an ionospheric biomarker

The possibilities for observing an O^+ dominated ionosphere on an exoplanet have been treated in some detail (Mendillo *et al.* 2018b). The challenge is substantial: no current remote-sensing instrument could do so. Of course, it would be far easier to detect O_2 as a biomarker but, as mentioned above, the quantitative level required remains uncertain. A significant benefit of an ionospheric biomarker is that it occurs at the greatest distance from a planet's surface. Surface biomarkers such as glints from oceans and spectral signature of vegetation, including seasonal changes, can be obscured by clouds, which are no concern at ionospheric heights.

Remote sensing in the UV is a fundamental diagnostic for O and O^+ at Earth. However, interstellar hydrogen absorbs photons below 91.2 nm, ruling out possible detections of O^+ using 61.7 nm and 83.4 nm emissions from exoplanet ionospheres. Transiting planets offer the possibility of atmospheric signatures from the dawn and

6 The neutral upper atmospheres (top) and ionospheres (bottom) of (a) Venus, (b) Earth and (c) Mars. Note that only Earth has a layer of O^+ ions linked to the maximum electron density. (After Mendillo *et al.* 2018b)



dusk limbs. Transmission spectroscopy is challenging for neutral gases, and even more so for the less dense plasma populations in an upper atmosphere. Atmospheric eclipse spectroscopy is even more difficult because of the bright stellar signal.

One feature of diurnal ionospheric morphology that might be an advantage is that an O^+ dominated ionosphere is far more robust at dusk versus dawn as a result of the slow rates of recombination chemistry in the ionosphere. The only image of the Earth's ionosphere taken by an instrument on another celestial body demonstrates this effect. Figure 7 shows a 10-minute exposure of Earth in the wavelength band 125.0–160.0 nm taken from the surface of the Moon during the Apollo 16 mission. The dayside hemisphere (left) is dominated by “dayglow” from atomic oxygen (O). Two emission features can be seen in the post-sunset sector: aurora from high latitudes (lower right) and “nightglow” bands (mid-image). These tropical arc features at $\pm 15^\circ$ about the geomagnetic equator arise from the persistence of ionospheric O^+ after sunset.

All habitable zones are not equal

Can “life as we know it” occur on an Earth-sized planet in orbit about a star very different from the Sun? If so, would the proposed ionospheric biomarker be useful, or could multiple false positive or false negative situations arise? Questions about non-solar-type stars are truly appropriate because there are so many stars not like the Sun. The rule of Nature that there are always more small things than large things certainly holds for the stellar population. Stars much larger than the Sun live short lives; they are usually excluded as targets for exoplanet

biosignatures because, for the only case we know, life on Earth took a very long time to develop from primitive to advanced forms. Stars smaller than the Sun have enormous life spans and, moreover, they are everywhere! M dwarfs (also called red dwarfs) account for perhaps 75% of stars in the Milky Way. They are small and dim – not one can be seen by the naked eye. Their red colour comes from their low surface temperatures (~ 3500 K), and that results in their habitable zones being very close to the star, typically much closer than Mercury's 0.4 au from the Sun.

M dwarf stars are ideal places to look for planets in habitable zones. An Earth-size planet in a rapid orbit around a small star results in frequent transit events, dimming the star light, that are relatively easy to detect. But there are concerns about the likelihood of planets so close to their star being capable of hosting life. Proximity to a star results in gravitational locking (in which the orbital period matches the rotation period) and thus one half of the planet receives stellar photons continuously while the other side never does. When coupled to strong atmospheric tides, such modes of energy input do not bode well for global photosynthesis. Moreover, M dwarfs have strong ambient UV emissions and are among the most active stars in the galaxy, with frequent outbursts of X-rays and stellar wind eruptions. The TRAPPIST-1 system, for example, with seven terrestrial planets orbiting an M8-type dwarf, has three planets in the habitable zone. Vida *et al.* (2017) reported that over an 80-day period of monitoring the star (with a rotation period of ~ 3.3 days), active regions produced 42 flares. The largest one was comparable

to the famous Carrington Event of 1859, which subjected the Earth to the largest recorded geomagnetic storm. The terrestrial space-weather community would glow with delight to study such a system, but it does not appear to be hospitable!

Overall, the broad study of star–planet interactions has much to learn from planetary systems subjected to active M dwarf stars (Airapetian *et al.* 2017). The field of comparative ionospheres has, to date, dealt only with four terrestrial and four gas giant planets affected by disturbances from a single star – our Sun. The diversity of stars and their planetary systems will surely expand the field of star–planet space physics in dramatic ways.

M dwarf planets with ionospheres?

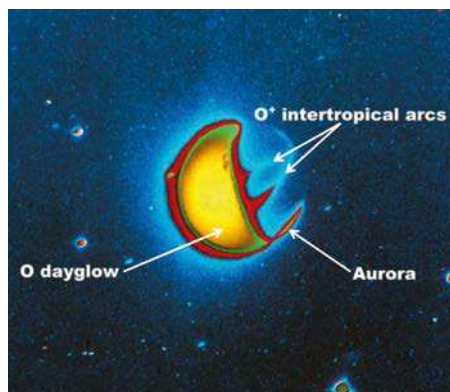
While M dwarfs are the hot topics of our galactic family, their energetics cast doubt on the chances of planets in their habitable zones having global life. Yet astrobiologists and other exoplanet experts have found ways for M dwarf planets to have atmospheres rich in oxygen – without photosynthesis. Using ionospheric O^+ dominance as a biomarker would thus lead to false positive signals. The abiotic source proposed for O_2 is the photodissociation of water vapour from vast oceans (Tian 2015, Lugar & Barnes 2015). In this scenario, hydrogen would escape, but oxygen would be retained by the planet's gravity – although the resulting ionospheric O^+ would escape in 10–100 Myr. Escape times are much longer if hindered by a strong planetary magnetic field. Yet, simulations using an Earth-analogue planet at the Proxima Centauri-b location had all plasma escaping via the magnetic poles in less than 400 Myr (Garcia-Sage *et al.* 2017). Attempting to extend that time can result

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“The space-weather community would glow with delight to study such a system”

in the border between exploratory science (“what if...”) and excessive speculation becoming strained. Studies using vast oceans (equivalent to 10 times the oceans on Earth) on a terrestrial-size planet in the habitable zone of an M dwarf star might indeed produce sufficient O_2 (and thus a long-lived ionosphere with O^+ at its peak) to qualify as a false positive biomarker for life (Schaefer *et al.* 2016). Abiotic sources requiring 10 Earth oceans, or extraordinarily oxygen-rich volcanoes, or remarkably frequent comet impacts might well define what is meant by overly optimistic astrobiology. Is it not more likely that close-in planets orbiting highly active M dwarf stars will turn out to be highly sterilized rocks – extreme cases of Mercury? Nevertheless, as MESSENGER has shown, and BepiColombo will study more comprehensively, intimate star–planet science can be fascinating – even without life hiding in caves or ice in shadowed craters.

What's next?

Exoplanet scientists have not fully explored how current or future observational techniques might address plasma signatures from an exoplanet's atmosphere. To guide possible approaches to new types of observations, modelling studies are needed for both the terrestrial and exoplanetary atmospheres. Ionospheres are in the thermospheres of a planet's upper atmospheres – regions of a neutral atmosphere that are far less dense than the gas abundances observed at surface levels. This suggests two avenues of approach for atmospheric models: for exoplanets, models of the lower atmosphere need to be extended to the upper atmosphere to approach the whole atmosphere capability that exists in the terrestrial case; and for the Earth, the time-history of its upper atmosphere is needed over time frames extending to billions of years ago. These bring substantial challenges.



7 EUV remote-sensing image of the Earth's ionosphere (Carruthers *et al.* 1972), with colourized version from NASA: <https://images.nasa.gov/details-S72-40821.html>. See the cover of this issue for a larger version of the image.

Simulations of an ionosphere require knowledge of the altitude dependence of the constituents of a planet's upper atmosphere and the stellar irradiance at XUV wavelengths. These are not independent variables. An atmosphere evolves as its star and planet do, and thus self-consistent models are needed of star–planet systems.

For the present-day Earth, global circulation models (GCMs) address this with success. But how do we study earlier epochs? Projects such as the Sun-in-Time (Sonett *et al.* 1991, Güdel 2007) and the Solar-wind-in-Time (Fionnagáin & Vidotto 2018, Pognan *et al.* 2018), when coupled with the long-term history of the geomagnetic field, can yield the Thermosphere-Ionosphere-in Time. This will produce the time span over which the terrestrial ionosphere was dominated by O^+ ions at the altitude of peak electron density, and thus the time span for which the proposed ionospheric biomarker is reliable for Earth-like planets orbiting Sun-like stars.

For exoplanets, the same set of requirements is needed for each star–planet case

to be studied. The fact that XUV radiation is absorbed by hydrogen in the interstellar medium means this is not an easy observational issue. Scaling XUV irradiances from visible light or infrared observations will probably be needed. Examples of estimates of an exoplanet's stellar irradiance appear in Garcia-Sage *et al.* (2017).

These topics involve more disciplines than can conveniently be handled by hyphens – astro-biology, bio-physics, geo-chemistry etc. In the words of Otto Neurath of the Vienna Circle: “Our endeavour is to link and harmonize the achievements of individual researchers in their respective fields of science. From this approach there naturally follows an emphasis on collective efforts” (1929, in Sigmund 2017). The need for multidisciplinary research communities to contribute their expertise to the detection of life beyond Earth rests upon two well-known foundations: the most difficult science (and therefore the most satisfying basic research) occurs at the boundaries between disciplines; and there is no topic more engaging to socie-

ties across the globe than the potential for life off Earth.

The opportunities to get involved are plentiful, but a first step may not be obvious.

One starting point might be looking into the journal *Astrobiology*, which devoted its entire issue of June 2018 to six major review articles on biomarkers in an exoplanet's atmosphere (introduced and summarized by Kiang *et al.* 2018). Collectively, they serve as a state-of-the-art primer for new researchers, although you might need a mini-sabbatical to get through them all, not to mention the remarkably long lists of references! A draw for the communities of astrophysics, planetary science and space physics might be that the words atom, ion, electron, plasma or magnetic field are very rarely used, if ever, in astrobiology papers. It is time to change that. ●

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FURTHER READING

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