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Atomic oxygen ions as ionospheric biomarkers on exoplanets

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The ionized form of atomic oxygen (O^+) is the dominant ion species at the altitude of maximum electron density in only one of the many ionospheres in our Solar System — Earth's. This ionospheric composition would not be present if oxygenic photosynthesis was not an ongoing mechanism that continuously impacts the terrestrial atmosphere. We propose that dominance of ionospheric composition by O^+ ions at the altitude of maximum electron density can be used to identify a planet in orbit around a solar-type star where global-scale biological activity is present. There is no absolute numerical value required for this suggestion of an atmospheric plasma biomarker — only the dominating presence of O^+ ions at the altitude of peak electron density.

The search for biomarkers on a planet other than Earth — evidence that extraterrestrial life currently exists (or did so in the past) — has profound implications for both science and society. Approaches to the topic are done most credibly when the phrase "life as we know it" is used as the guiding principle since any other methodology is fundamentally speculative. Moreover, finding a biomarker on an exoplanet does not necessarily point to intelligent life. The additional characteristics needed for a reliable analogue to our terrestrial experience might involve, for example, a firm planetary surface, plenty of water upon it, a dense atmosphere containing oxygen, perhaps a global magnetic field, and finally a stable orbit around a solar-type star. Naturally, such life-as-we-know-it characteristics are just another way of pointing at Earth-like planets. Yet, to our knowledge, there are no postulated quantitative measures of terrestrial-like parameters that would specify biomarker success. The mass fraction of liquid water (0.02%)[1], the amount of oxygen at the surface (21%)[1] and the abundance of ozone in the stratosphere (12 parts per million, ppm)[2] are conditions on Earth obviously favourable for life, but are these specific values the ones needed to certify the presence of life elsewhere?

Just a few decades ago, when discoveries were first made of planets orbiting other stars, characterizing the constituents of an exoplanet's atmosphere was beyond observational capabilities. That situation quickly changed and today such studies are both detailed and diverse[3–5]. Strategies for progress range from proposed indices to indicate habitability[6], to lists of potential biosignature gases[7], to detection schemes for a life-supporting atmosphere on a very close target[8]. An engaging status report on overall context, with ambitious goals for biomarker detection, exemplifies the field's broad appeal[9].

Here we make a specific suggestion of a dimensionless parameter within a planet's upper atmosphere that can only occur if life flourishes on that planet. We use the plasma component of an atmosphere — its main layer of ions and electrons — to arrive at an ionospheric condition that is due uniquely to oxygenic photosynthesis on a planet orbiting a star like the Sun. We suggest that if the dominant ion at the altitude of peak electron density in an exoplanet's ionosphere is atomic oxygen in ionized form (O^+), that planet is one with thriving global biological activity.

Stars to target for ionospheric biomarkers

With so many stars in our Galaxy being M dwarfs (~70%), and many of them having planets[10], the current thrust has been to search for signs of life where there are the most targets. While this is a statistically sound approach, putting aside inconvenient adaptability issues should perhaps be more of a concern. The planets in habitable zones around M dwarfs are very close to their stars and thus are prone to experience gravitational locking. This results in the planet's dayside hemisphere continuously subjected to very strong ambient X-ray and extreme ultraviolet (EUV) radiation, episodic bursts of stellar activity (electromagnetic radiation and enhanced plasma winds) impacting the dayside, and strong atmospheric tides that are global. The long-term evolutionary consequences of such conditions are topics of active debate. Magnetic fields may prevent atmospheric stripping under intense EUV radiation. Yet, an Earth-analogue occupying the orbit of Proxima Centauri b would lose its entire atmosphere to ion escape through the magnetic poles in less than 400 Myr[11]. Among other issues are the complex roles of photodissociation of water vapour[12–14]. This leads to hydrogen escape and oxygen build-up in the absence of photosynthesis[15,16]. Even more uncertain than predictions of O_2 concentrations at the surface are estimates of the O densities at the upper atmospheric heights where an O^+ ionosphere can form.

Given that M-dwarf planet atmospheres are still largely unconstrained by observations, initial ionospheric simulations dealt with the hydrogen atmospheres of Jupiter-like gas giant planets[17], and thus for planets not considered habitable. More relevant to possible life-hosting sites in orbits around M dwarfs are the sets of calculations using a twin Earth (same mass and atmosphere) close to M dwarfs[18], including the case of Proxima Centauri[11,19]. For such Earth-equivalent atomic oxygen concentrations in the upper atmosphere of an M-dwarf planet, its ionized form (O^+) would escape on rapid timescales (10s to 100s of Myr)[18] — increasing to ~400 Myr if the planet had a magnetic field[11]. The resulting oxygen-poor planet would need an ongoing global source of oxygen from either abiotic processes (for example, continuous volcanoes or cometary impacts), or from oxygenic photosynthesis. On more massive terrestrial-size planets[14], or those that formed with substantially more water (~10 Earth oceans), the O^+ loss timescale could be dramatically longer[16]. With proper tuning, either of these cases provides a long-lived abiotic

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source of oxygen that could mimic oxygenic photosynthesis. This reminds us that habitable zones are not all equal.

Here we remove the consequences of harsh stellar irradiance values from an M dwarf, and speculation about M-dwarf planets with extraordinarily dense primordial atmospheres or very plentiful oceans, by dealing with solar-type stars with Venus/Earth/Mars-type planets. Thus, while most M dwarfs are thought to host multiple terrestrial-sized planets[10], that does not necessarily make them as fruitful a hunting ground for biomarkers as looking for Earth-size rocky planets orbiting Sun-like stars. This does not imply that star–planet science in M-dwarf systems is less interesting. Yet, given that solar (G-type) stars comprise ~7% of the Galaxy, we simply offer arguments for giving more attention to the fewer targets (10% of the number of M dwarfs) associated with the case we know so well. Speculation might suggest that life could exist on a planet orbiting either an M dwarf or a G-type star without an O^+ dominant ionosphere, and thus our ionospheric argument holds only for a subset of all possibilities — but one of incontrovertible success here on Earth.

Ionospheres of the inner Solar System

Ample evidence exists in our Solar System for planets that have oxygen in both neutral and ionized states (O, O_2, O_3, O_2^+, O^+ and O^-)[20,21]. Yet, only Earth has an ionosphere completely dominated (>90%) by atomic ions (O^+) at its height of maximum electron density. All of the other ionospheres in the Solar System have molecular ions where their peak electron densities occur. In this section, we briefly review the formation processes of an ionosphere and focus our discussion on Venus and Mars as the prototypes of small rocky planets with atmospheres unaffected by photosynthesis in order to show explicit contrasts with Earth. In the following sections we briefly touch on outer Solar System bodies, and then address the enormous challenges of detection and the always present issues of false positive results.

A planet's ionosphere is that small fraction of its atmosphere that experiences a transformation of electrically neutral gases into a plasma of free electrons and ions by the absorption of energetic photons from the star it orbits. The EUV and X-ray radiation (collectively called XUV) from our Sun produce ionospheres on the three inner planets with permanent atmospheres (Venus, Earth and Mars)[20,22]. Figure 1 shows examples of the neutral and ionized atmospheres for all three planets.

While Venus has mass, radius, surface temperature and CO_2 concentration values that far exceed those of Mars, the ionospheres of Venus and Mars are remarkably similar in their photochemistry. Thus, for either Venus or Mars, their ionospheres illustrate the situation for a planet where photosynthesis has not made a dramatic alteration of its atmosphere. The core process is two-fold. First, the dominant gas is ionized:

$$CO_2 + XUV \rightarrow CO_2^+ + e^- \quad (1)$$

and then a rapid chemical transformation occurs due to the highly reactive properties of the trace amounts of atomic oxygen present:

$$CO_2^+ + O \rightarrow O_2^+ + CO \quad (2)$$

Thus, the dominant ion initially produced (CO_2^+) is not the dominant ion observed (O_2^+). The fact that Venus and Mars have ionospheres dominated by molecular oxygen ions is a side-product (albeit a very interesting one) of rather ordinary atmospheric chemistry under conditions of photochemical equilibrium. For example, the trace amounts of atomic oxygen that drive equation (2) are just one form of oxygen present in the Martian atmosphere (O, O_2 and O_3)[23,24]. They arise from the photodissociation of the small amounts of water vapour and the abundant carbon dioxide in the Martian atmosphere, together with associated oxygen chemistry.

The crucial point is that without oxygenic photosynthesis adding extraordinary amounts of oxygen to their atmospheres, the ionospheres observed at Venus or Mars are consistent with well-understood chemistry involving major and minor gases associated with the planet's formation and non-biological evolution. At their heights (h_{max}) of maximum electron density, the peak daytime value of ~5×10^5 e^- per cm^3 (Venus) and ~1×10^5 e^- per cm^3 (Mars) are matched by an equal number of O_2^+ ions. At altitudes above h_{max}, the small amounts of atomic oxygen present can also be ionized, and thus O^+ exists in their topside ionosphere, but at levels well below the O_2^+ abundances at h_{max} (Fig. 1). Recent MAVEN observations show that O exceeds CO_2 at heights above ~230 km and that O^+ reaches its maximum values near 250 km. However, the electron densities associated with the O^+ ions are so low (<1,000 e^- per cm^3) that CO_2 and O_2^+ remain the dominant neutral and the dominant ion, respectively, at all altitudes[23].

On Earth, XUV radiation affects oxygen in multiple ways[20]. The molecular version is ionized by X-rays at altitudes near 110 km to form the so-called E layer of the ionosphere with maximum daytime electron densities of ~10^5 e^- per cm^3. The solar irradiance (photon flux versus wavelength) also dissociates O_2 to yield an abundance of atomic oxygen (O). For altitudes above approximately 200 km, atomic oxygen becomes the dominant gas and solar EUV creates the ionospheric F layer (O^+ and e^-) that has its maximum daytime electron density of ~10^6 e^- per cm^3 near 300 km. The fact that the terrestrial ionosphere has both prominent layers of molecular ions (E layer at ~110 km) and atomic ions (F layer at ~300 km), while Venus and Mars have only molecular ion layers, has profound implications for observations. Plasmas consisting of molecular ions and electrons dissociatively recombine quickly ($O_2^+ + e^- \rightarrow O + O$) to form neutral gases, and thus plasma densities in the ionospheres at Venus and Mars are significantly smaller on the nightside than on the dayside. Atomic ion–electron plasmas, on the other hand, have very slow radiative recombination rates ($O^+ + e^- \rightarrow O$), and thus the terrestrial F layer is production-dominated during the day and loss-inhibited at night. It is readily observable over an entire day (0–24 h local time).

The abundance of atmospheric oxygen at the Earth's surface has not always been at its current level of about 20–25% of the total gas population. Oxygen was initially a trace gas (<1 ppm) from shortly after the Earth's formation to 2.35–2.30 billion years ago[25,26]. Oxygenic photosynthesis then increased the oxygen abundance to more prominent levels (1–10% of present atmospheric levels), but ones not capable of sustaining advanced life forms[25,26]. It was only in the last 500 million years that surges in oxygenic photosynthesis were capable of elevating the abundance to current levels[25,26]. The terrestrial ionosphere had to change in response to each of those phases of atmospheric modification. For the past 500 million years, however, with no dramatic changes in Earth's oxygen abundances (nor in solar output), the current situation of an O^+ dominated ionosphere can be safely assumed to have been a constant feature. This suggests that our plasma criteria for life on an exoplanet not only avoids the problems of absolute values or abundance percentages for O^+ that might change with time, but also that the O^+ biosignature has temporal stability well over the timespan of human life on Earth.

A planet without life can, of course, have an ionosphere — but not one dominated by O^+ at its altitude of maximum electron density. That stresses the key role of oxygenic photosynthesis and the degree to which it can force a planet's atmosphere to be so chemically out of balance. If photosynthesis stopped completely on Earth, the oxygen in our atmosphere would decay by the many processes now active, with O_2 and O probably ending up as minor species in about 5,000 years[27] — probably to the levels now found on Venus

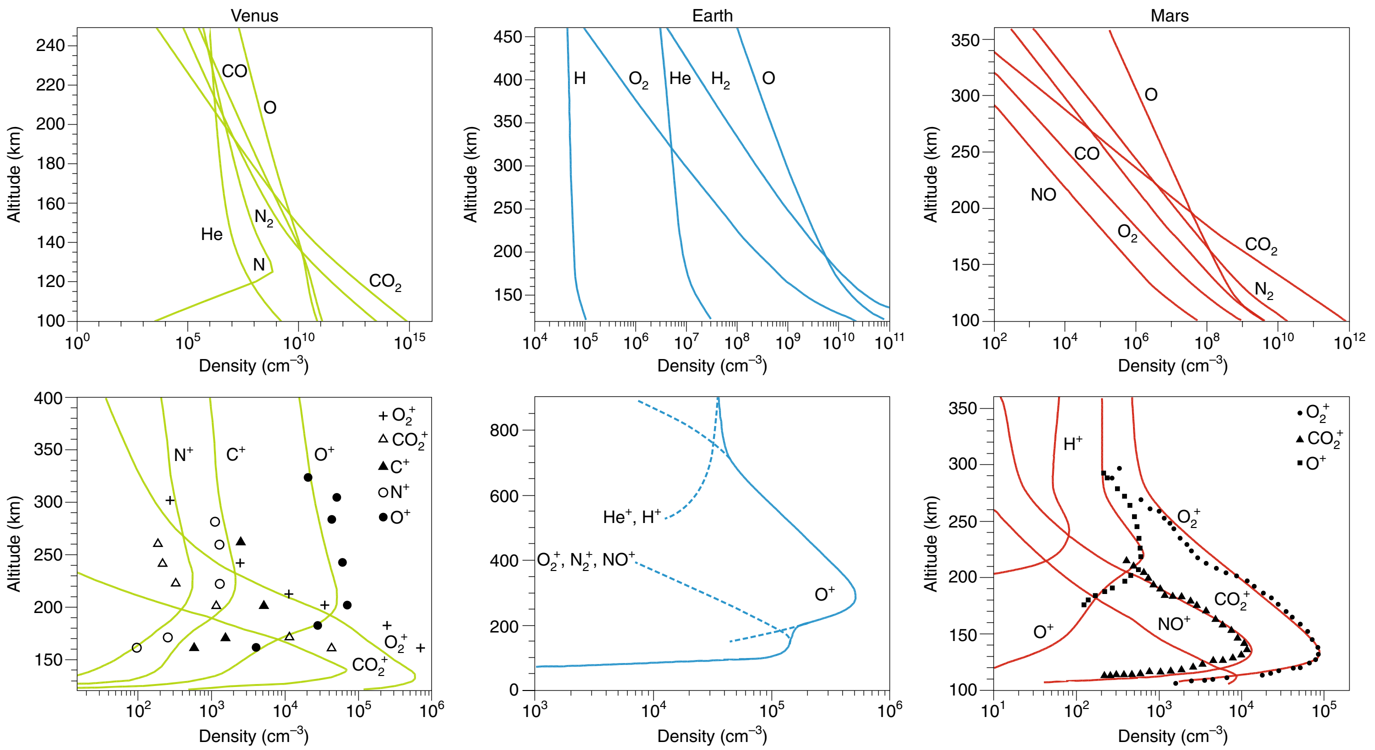

Fig. 1 | Vertical profiles of the abundances of the main gases and ions in the atmospheres of Venus, Earth and Mars. Top panels: the altitude ranges of the prominent neutral gases in the upper atmospheres of Venus, Earth and Mars that lead to their ionospheres. Bottom panels: solar extreme ultraviolet and soft X-rays penetrate to different altitudes to form the ionized layers shown. At Venus (left), ion compositions (portrayed by various symbols) were measured by the Pioneer Venus Orbiter and are compared with model results (solid lines). For Mars (right), the Viking descent probe observations provided the ion composition (various symbols) shown in comparison to model predictions (solid lines). Note that while atomic oxygen is the major gas at high altitudes at all three planets, Earth's abundance (middle) exceeds those at Venus and Mars, and thus O^+ never becomes the dominant ion in the ionospheres at Venus and Mars. Credit: adapted from ref.[20], Cambridge Univ. Press (Earth); ref. [49], Wiley (Mars); ref. [50], Wiley (Venus, bottom); ref. [51], Wiley (Venus, top).

and Mars — with Earth once again having its early atmosphere of N_2 and CO_2.

Ionospheres of the outer Solar System

No planet in the outer Solar System has an appreciable amount of oxygen in its upper atmosphere, and thus oxygen ions in any form (O_2^+ or O^+) are not significant components of their ionospheres. Their primordial atmospheric compositions of hydrogen (H and H_2) and helium have been maintained, and the plasma populations at their ionospheric peaks consist of H^+, H_2^+, H_3^+ and electrons[20,28]. We conclude that no signature of a gas giant's ionosphere can be used as an indicator of life.

More interesting speculation about life in giant planet systems deals with their satellites. These outer Solar System bodies have some of the most intriguing ionospheres, but none is similar to our terrestrial F layer. Saturn's moon Titan has a neutral atmosphere dominated by N_2 and many hydrocarbons, and its ionosphere can have a peak electron density of ~10^4 e^- per cm^3, matched by the sum of many molecular ions[29]. Moons of the other giant planets can have atomic ions at their altitudes of peak electron density, for example, Na^+ at Jupiter's moon Io[30], and N^+ at Neptune's moon Triton[31], but O^+ is not the dominant ion at the peak of the ionosphere on any lunar body. Finally, the icy moons of giant planets, comets, ice-covered asteroids, and Kuiper belt objects can have atmospheres dominated by water, but these are surface boundary exospheres — meaning gases are continuously produced by surface-sputtering agents followed by fast escape due to low gravity. For such ice-dominated bodies, photoionization produces very tenuous ionospheres that are dominated by water-family ions (H_2O^+, H_3O^+, OH^+ O^+, O_2^+), with peak densities essentially at their surfaces[20]. Earth remains as the only body in the Solar System with a robust layer of O^+ ions in its upper atmosphere.

False positives

Can a dominant layer of O^+ occur on a terrestrial-size planet without life? As mentioned above (and shown in Fig. 1), that experiment has already been done at Venus and Mars. In both cases, the ionospheres exhibit a transition from O_2^+ ions to O^+ ions at heights that are well above their altitudes of peak electron density. Could these high-altitude O^+ ions accumulate until their density exceeds that of the O_2^+ ions at lower altitudes? Two processes prevent a high-altitude plasma layer of O^+ and e^- from being the maximum ionospheric layer: (1) the atmospheres of Venus and Mars have trace amounts of hydrogen that destroys O^+ ions by reactions that form H^+. These light ions, as well as a family of hydrogenated-ions[32], readily diffuse upward to escape. Thus chemistry and transport prevent a high-altitude O^+ layer exceeding the dominant O_2^+ layer below. (2) Ionospheric escape at Venus and Mars is enhanced by solar wind capture due to the absence of a global magnetic field. If either planet had a global magnetic field (**B**), could it prevent escape to the point of allowing a large O^+ layer to form? On Earth, charge-exchange chemistry in the topside ionosphere also converts some of the O^+ to H^+ (Fig. 1). Both types of ions diffuse upward along the Earth's dipole magnetic field lines to form a giant doughnut-shaped 'plasmasphere' typically extending to four Earth radii[(20)]. The morphology of this extension of the Earth's ionosphere is one of exponentially decreasing electron densities along closed **B**-lines out to the geomagnetic equator. There are no additional plasma layers in this vast region above the ionosphere. The presence of a strong **B**-field does not prevent hydrogen chemistry nor does it lead to the build-up of a high-altitude O^+ layer, and thus our proposed criterion holds for an exoplanet with or without a magnetic field.

Can a planet have a robust oxygen atmosphere that formed without the specific type of oxygenic photosynthesis that has so transformed Earth's environment? Continuously active volcanoes rich in O_2 and oxygen-bearing gases are a possible steady source function for oxygen on any rocky planet, but one inconsistent with our avoidance of unfounded speculation. Could water sources of oxygen be possible? That topic was explored for planets in orbit around M-dwarf stars as part of our introduction, together with associated questions about the longevity of O_2 as a residual of escaping water. For G-type stars, the presence of water on a terrestrial-size planet is probably a common occurrence sometime in that planet's history. Locally, that appears to be true for at least three of our four terrestrial-size planets (that is, Venus, Earth and Mars). The photodissociation of water vapour on Earth is not sufficient to account for its oxygen content[21]. Thus an exoplanet with surface water in orbit around a solar-type star, but without oxygenic photosynthesis, will not have a robust and long-lived oxygen component in its atmosphere, and thus no dominant O^+ peak in its ionosphere.

Searching for large amounts of O_2 or O_3 is easier than for small amounts of O^+. The quantitative levels of O_2 and O_3 needed for biomarker success have indeed been the subjects of substantial investigation[33–35]. Yet the use of O_2 and O_3 has also been met with skepticism[36,37], bringing into question the use of these molecules as requirements for life. Finally, in atomic form, O reaches dominance at high altitudes on three inner planets (Venus, Earth and Mars), so that criteria fails as either a dimensionless or quantitative biomarker, leaving our proposed O^+ signature as the key ionospheric feature that distinguishes Earth from Venus and Mars.

Detection of O^+ ionospheres

At present, there have been no detections of plasma signatures from an exoplanet's ionosphere. At Earth, where ionospheric physics has flourished for nearly a century, there are many methods of determining the O^+ distribution within the upper atmosphere. We put aside in situ measurements in favour of the remote-sensing methods more appropriate for exoplanets. Radio backscatter techniques have clear O^+ signatures[20], but radar studies of an exoplanet are beyond any known current capability. If radio occultation studies of an exoplanet become possible[38,39], neutral gas densities at low altitudes and plasma densities at high altitudes can be observed. If achieved, the plasma-scale height of the planet's topside ionosphere can reveal if the dominant ion present is O^+ (with some assumptions about temperatures).

In the optical domain (ultraviolet, visible and infrared), O^+ ions can be detected directly via resonantly scattered starlight, by the photons emitted by the recombination of O^+ ions and electrons, and by absorption-line spectroscopy. While an exoplanet's atmosphere decreases exponentially with height, our proposed plasma biosignature would actually increase with altitude (as at Earth, where O^+ becomes an increasing percentage of the total atmosphere with altitude). The dominating density of O^+ at h_{max} criterion is thus the atmospheric biomarker most distant from an exoplanet's surface. This has a benefit over searches of an exoplanet's atmosphere close to the surface (or surface properties themselves, for example, glints from oceans[40]) since near-surface characteristics can be obscured by persistent haze or cloud cover — features not present at ionospheric heights.

To illustrate possibilities (and major difficulties) in detecting O^+ on distant worlds, we first consider the EUV wavelengths used to observe the coupled O/O^+ system at Earth[41]. The shortest wavelengths (61.7 nm and 83.4 nm) are not available for targets beyond the Solar System because the interstellar medium contains hydrogen that absorbs wavelengths below 91.2 nm. Thus, while 83.4 nm can be detected from our ionosphere out to heliopause distances[42,43], and 61.7 nm from Earth (and potentially other ionospheres within the Solar System; S. Chakrabarti, personal communication), they are not remote sensing options for O^+ at interstellar distances.

The ionospheric recombination reaction of relevance is

$$O^+ + e^- \rightarrow O^* \rightarrow O + \text{photon} \qquad (3)$$

The radiative yield includes emissions at 130.4 nm and 135.6 nm in the far-ultraviolet and at 777.4 nm and 844.6 nm in the visible. Major advances in terrestrial ionospheric physics have come from satellite observations of these wavelengths, and from ground-based instruments for the visible wavelengths.

Under daytime conditions, the resonant scattering of sunlight from neutral atomic oxygen overwhelms the $O^+ + e^-$ radiative recombination source at these wavelengths and thus the ionospheric component is beyond current methods of detection. Under nighttime conditions, however, O^+ recombination signatures at these lines are readily observed with surface brightness values of ~100 rayleighs[41] (terrestrial aurorae seen by the naked eye are about 5,000–10,000 rayleighs). At low levels of brightness, the detection of ionospheric EUV signals from planets around other stars remains a formidable challenge.

The visible light signature from equation (3) is strongest at 777.4 nm, and many studies of the Earth's ionosphere have been conducted using photometers and all-sky imagers at that wavelength[44,45]. These are, however, state-of-the-art detections of very faint surface brightness values — less than 100 rayleighs from even the most robust ionospheric peak densities of $\sim 10^6$ ions and electrons per cm^3. Thus, visible light detections of O^+ from an exoplanet are also beyond current methods, as are detections of visible aurorae[46].

Turning to infrared possibilities, the first Earth-based detection of neutral atomic oxygen (O) in the atmosphere of another planet was accomplished using 63-μm observations of the Martian thermosphere by the GREAT/SOFIA team[47]. Observations of oxygen ions (O^+) within the infrared band have not yet been attempted from an observatory (ground-based or airborne) below the dense O^+ layer of the terrestrial ionosphere; exoplanet detections will probably require space-based instruments.

Observations of the Earth's ionosphere as a remote sensing experiment for exoplanet atmospheres revealed a plasma signature of calcium ions[48]. Calcium ions are produced by meteor ablation with column abundances of $\sim 5–50 \times 10^9\ cm^{-2}$. The column abundance of terrestrial O^+ is much larger ($\sim 2–200 \times 10^{12}\ cm^{-2}$). Possible detections of O^+ using transmission spectroscopy during transit observations would have O^+ larger at the dusk terminator compared to dawn's because of the persistence of an atomic ion ionosphere after sunset. For resonant scattering (reflection) spectroscopy conducted when a planet passes behind a star, the exoplanet's largest dayside column contents of O^+ would be present prior to ingress and after egress. Yet, as discussed in the text, daytime emissions of neutral O far exceed emissions from O^+.

We hope this paper will instigate studies by the optical and radio remote sensing communities of the detectors needed and integration times required for observations of exoplanet O^+ ionospheres.

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Author contributions

M.M. wrote the draft manuscript, providing its focus on the unique properties of Earth's ionosphere and its observational methods; P.W. provided input on planetary atmospheres (Venus and Mars), and P.A.D. provided input on exoplanet atmospheres.

Competing interests

The authors declare no competing financial interests.

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