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Constantly forming sporadic E-like layers and rifts in the Martian ionosphere and their implications for Earth

Glyn A. Collinson[1,2,3]*, James McFadden[2], Joseph Grebowsky[1], David Mitchell[2], Rob Lillis[2], Paul Withers[4], Marissa F. Vogt[4], Mehdi Benna[1], Jared Espley[1] and Bruce Jakosky[5]

Understanding and predicting processes that perturb planetary ionospheres is of paramount importance for long-distance radio communication. Perhaps the oldest known ionospheric disturbances are 'sporadic E layers'[1]: unpredictable and short-lived concentrations of plasma[2], which can bounce radio signals over the horizon for thousands of kilometres[3]. Consequentially, local radio broadcasts can become jammed by more distant transmissions, and thus sporadic E layers are a potentially serious complication for commercial radio, aviation, shipping or the military. According to the current theory of their formation, we should also expect an equal proportion of localized ionospheric density depletions to develop. However, no such 'sporadic E rifts' have been detected in over 85 years of ionospheric research. In addition, despite being common at Earth, no sporadic E layers have yet been reported at other planets. Here we report the detection of sporadic E-like phenomena in the ionosphere of Mars by NASA's Mars Atmosphere and Volatile Evolution (MAVEN) spacecraft, providing a physical explanation for previous unexplained observations at Mars[4–7]. We observe enhanced-density layers that can be explained through the presence of a sporadic E-like mechanism, and we establish the existence of sporadic E rifts in nature. We find that, unlike the case at Earth, Martian sporadic E features are trapped in a near-perpetual state of dynamic formation and may form at predictable locations. Also unlike the case at Earth, Martian sporadic E features are readily accessible to satellites, and indeed MAVEN has already encountered more of the phenomena at Mars than have ever been explored in situ at Earth with sub-orbital rockets.

Figure 1 shows a sketch illustrating how it is thought that sporadic E layers form at Earth[8–10]. In simple terms, the process is analogous to how a mountain range can be pushed up when two tectonic plates converge on a fault line. Physically, the process involves the generation and convergence of electromagnetic forces in the 'dynamo region'[2] of Earth's atmosphere (90–130-km altitude). Here the primary medium is a partially ionized gas: mostly neutral atoms with a small admixture of ions and electrons. Ions are constantly colliding with neutral atoms, and are blown by high-altitude winds ($\mathbf{V}_{\mathrm{wind}}$) across Earth's magnetic field lines (**B**). While the ions are primarily blown along with the neutral wind, the sideways tug of the electromagnetic force also causes all ions to drift in a direction perpendicular to the magnetic field. At Earth, sporadic E layers form where there is a sudden change in direction (a shear) in the neutral wind. If electromagnetic forces converge (Fig. 1, left), then the ions are swept together and concentrated into a narrow sporadic E layer of enhanced plasma density. Rifts, while never observed, should be a logical consequence of this sporadic E formation mechanism, whereby random wind shears should just as easily set up a system of diverging ion drifts, analogous to how rift valleys form when two tectonic plates diverge from a fault line.

NASA's MAVEN orbiter (2014–present) was launched to find out how the Martian atmosphere evolved and escaped over geological time. While the study of sporadic E features was not an original goal of the mission, the instruments she carries are ideal to explore such ionospheric phenomena in situ (see MAVEN instrumentation for an overview of the MAVEN scientific payload used in this study). We performed a preliminary (non-statistical) survey of MAVEN data from the dayside ionosphere of Mars, yielding 34 sporadic E-like candidates from 25 orbits (see Supplementary Information for tables and plots of all events). Figure 2 shows in situ data from two orbits of MAVEN, representing our current best examples. Contrary to expectations from Earth, in addition to the expected sporadic E-like layers (for example Figure 2a–d), MAVEN also encountered numerous ionospheric density voids consistent with sporadic E-like rifts (for example Figure 2e–h). At each event, the abrupt change in ionospheric plasma density was recorded by three MAVEN instruments (the Suprathermal and Thermal Ion Composition (STATIC) instrument[11], the Neutral Gas and Ion Mass Spectrometer (NGIMS)[12] and the Langmuir Probe and Waves (LPW) instrument[13]).

These events are consistent with sporadic E layers at Earth in terms of change in density and physical size: the mean change in electron density ($\Delta N_e/N_e$) of the 34 events was ±72% (±51%), with a maximum of 296% and a minimum of 17%, consistent with in situ observations of sporadic E layers at Earth by suborbital sounding rockets[14–16]. Encounters by MAVEN with layers and rifts were very brief, lasting only a few seconds at most, implying a physical thickness of a few kilometres, also consistent with sporadic E layers at Earth[16] (see section 'Comparison of density versus altitude plots of sporadic E-like features at Mars and Earth' in Methods and Extended Data Fig. 1 for a direct comparison).

Sporadic E-like layers and rifts were encountered all over Mars, though primarily in the southern hemisphere (Fig. 3), where the crust is magnetized with remnant magnetic fields[17] of the long-lost Martian magnetic dipole. This is logical, since at Earth the electric fields that underpin the formation of sporadic E layers require

[1]NASA Goddard Space Flight Center, Greenbelt, MD, USA. [2]Space Sciences Laboratory, University of California, Berkeley, CA, USA. [3]Institute for Astrophysics and Computational Sciences, The Catholic University of America, Washington, DC, USA. [4]Center for Space Physics, Boston University, Boston, MA, USA. [5]Laboratory for Atmospheric and Space Physics, Boulder, CO, USA. *e-mail: glyn.a.collinson@nasa.gov

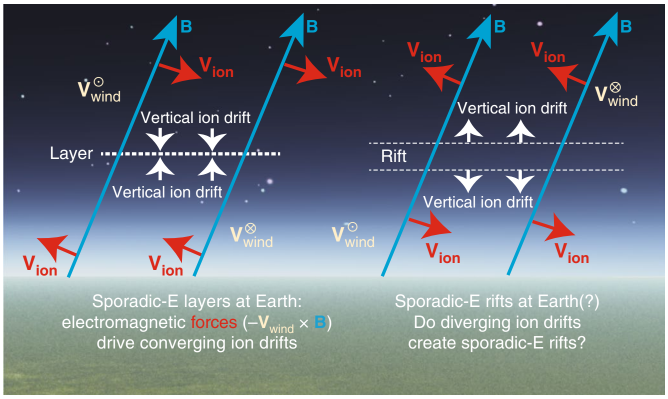

Fig. 1 | Formation of sporadic E layers at Earth. Ionospheric ions are blown across Earth's magnetic field lines by winds in the upper atmosphere, generating electromagnetic forces ($-\mathbf{V}\times\mathbf{B}$), which cause ions to drift perpendicular to the magnetic field. For over 50 years, it has been presumed that sporadic E layers form at Earth where there is a shear in the wind (and thus the electromagnetic force), resulting in a convergence of ion drifts. However, if this theory is correct, since wind shears are random, one should expect just as many sporadic rifts, whereby ion drifts diverge. Why have no rifts been detected?

both a neutral wind and a magnetic field to blow against[10]. All layers and rifts were encountered below 223 km, within the dynamo region of the Martian ionosphere (~120 km–~250 km), comparable to the region in which sporadic E layers form at Earth (as described above). While our survey was limited to the daytime, there is no physical reason why they should not form at all solar zenith angles.

Each event was centred on a strong shear in ion velocity (**V**, Fig. 2a,e) and a sharp change in ambient magnetic field direction (**B**, Fig. 2b,f). Each event also coincided with a highly localized perturbation in the magnetic field, which (according to Ampere's law) suggests that each event is concomitant with a localized electrical current in the Martian ionosphere. These combined observations strongly imply that these layers and rifts are forming at a nexus of electromagnetic forces ($-\mathbf{V}\times\mathbf{B}$). Without an in situ measurement of d.c. electric fields, neutral winds or three-dimensional (3D) ion flows, our conclusions must be tempered by caution. However, the most plausible physical explanation for these observations is a sporadic E-like mechanism, whereby a shear in electromagnetic forces results in converging and diverging ion drifts. Where electromagnetic forces and ion drifts converge, the result is an enhanced ionospheric layer (Fig. 2a–d). Where they diverge, they result in a depleted rift (Fig. 2e–h). For a comprehensive overview of in situ MAVEN observations during each event (including observations of superthermal electrons by the MAVEN Solar Wind Electron Analyzer (SWEA) instrument[18]), see Extended discussion of in situ MAVEN data and Extended Data Fig. 2.

These results provide a physical explanation for recent reports of MAVEN encounters with anomalous ionospheric density layers in the upper atmosphere of Mars[5,6], which hypothesized that they might be the result of an Earth-like sporadic E mechanism forming due to wind shear (for example Fig. 1). These results also provide a physical explanation for unexplained plasma density features observed in radio occultation experiments by Mariner 9 and Mars Global Surveyor[4,7]. These remote-sensing experiments measured anomalous enhancements and depletions in plasma density, with comparable density changes, altitudes and vertical extents to the MAVEN in situ encounters with sporadic E features (for more details see Extended Data Fig. 2 and section 'Comparison of density versus altitude plots of sporadic E-like features at Mars and Earth' in Methods). Furthermore, radio occultation observations of these unexplained anomalies occurred preferentially in regions of strong magnetic field, as with the sporadic E features discovered in this study. We therefore conclude that the Mariner/MGS anomalies can finally be explained as remote sensing of sporadic E-like features.

In addition to the Mariner/MGS anomalies, other so-called 'sporadic third layers' or 'low-altitude transient layers' have also been observed at lower altitudes (65–110 km) by radio occultation experiments from Mars Express[19] and MAVEN[20]. However, these are almost certainly an unrelated phenomenon. (1) The low-altitude transient layers are very different in appearance, being a gentle 'hump' in ionospheric density that is tens of kilometres across, as opposed to a sporadic E-like layer, which exhibits a thin, sharp spike in density only a few kilometres across. (2) Despite a confusingly similar name, these apparent structures cannot form through a sporadic E-like mechanism, since they are below the dynamo region of the ionosphere. Indeed, one current theory is that these transient layers may not actually exist at such low altitudes, and are simply the result of a mirage-like observational effect[20].

Martian sporadic E features exhibit three important differences from those at Earth. First, whereas sporadic E layers at Earth are formed at a shear in the neutral-driven ion winds, at Mars they commonly appear at a magnetic shear (Fig. 2a,b,e,f). Note that the same fundamental physical mechanism underpins sporadic E-feature formation at both planets: a convergence (or divergence) of ion drifts driven by the electromagnetic force ($-\mathbf{V}\times\mathbf{B}$). In theory, such a convergence could result from a shear in either **V** or **B**. However, at Earth the magnetic field is a fixed and orderly dipole, and thus sporadic E layers only have wind shears to form around (Fig. 1). However, the magnetic field in the Martian ionosphere is highly complex, abruptly changing direction from one location to another (see Fig. 3). Therefore, the ionosphere of Mars contains both shears in **V** and **B** (refs. [21,22]), either of which may result in the formation of a layer (or rift) through a sporadic E-like mechanism of convergent (or divergent) electromagnetic forces. Since the permanent Martian magnetic crustal anomalies produce permanent magnetic shears, this implies that Martian sporadic E features may occur at permanent and predictable locations (that is at the boundary between two crustal field anomalies).

This hypothesis is supported by past 3D multifluid modelling of the Martian dynamo region, which predicts that the complex magnetic topology surrounding the crustal remnants results in a similarly complex tangled web of converging and diverging electrical fields[22]. As at Earth, converging electrical fields in the dynamo region will result in converging ion drifts, and the formation of a concentrated ion layer, consistent with our MAVEN observations. It is important to note, however, that while the two formation scenarios (wind shear versus magnetic shear) share a common formation mechanism, the detailed physics in each scenario may be quite different. Thus, these new observations at Mars strongly motivate future theory and modelling studies to better understand how layers and rifts can form around magnetic shears.

Furthermore, while such magnetic-shear-initiated sporadic E features do not currently occur at Earth, this may not always be the case. Models have suggested that during a geomagnetic reversal Earth's magnetic topology will become highly complex, introducing numerous magnetic shears into the ionosphere[23]. Thus, future exploration of sporadic E features at Mars may provide direct observational insights into what may occur in our own ionosphere during such a climactic upheaval in Earth's dipole field.

Second, while sporadic E layers at Earth are primarily composed of long-lived metallic Ions (Fe^+, Mg^+)[15,16,24,25] (deposited by meteors), at Mars we find layers composed of molecular ions (O_2^+, NO^+ and even CO_2^+, Fig. 2c), which are highly chemically reactive. If the forces concentrating (or depleting) the ionosphere were to relax, a layer or rift composed primarily of molecular ions would react away within minutes. Fig. 4 shows a simple chemical model of the

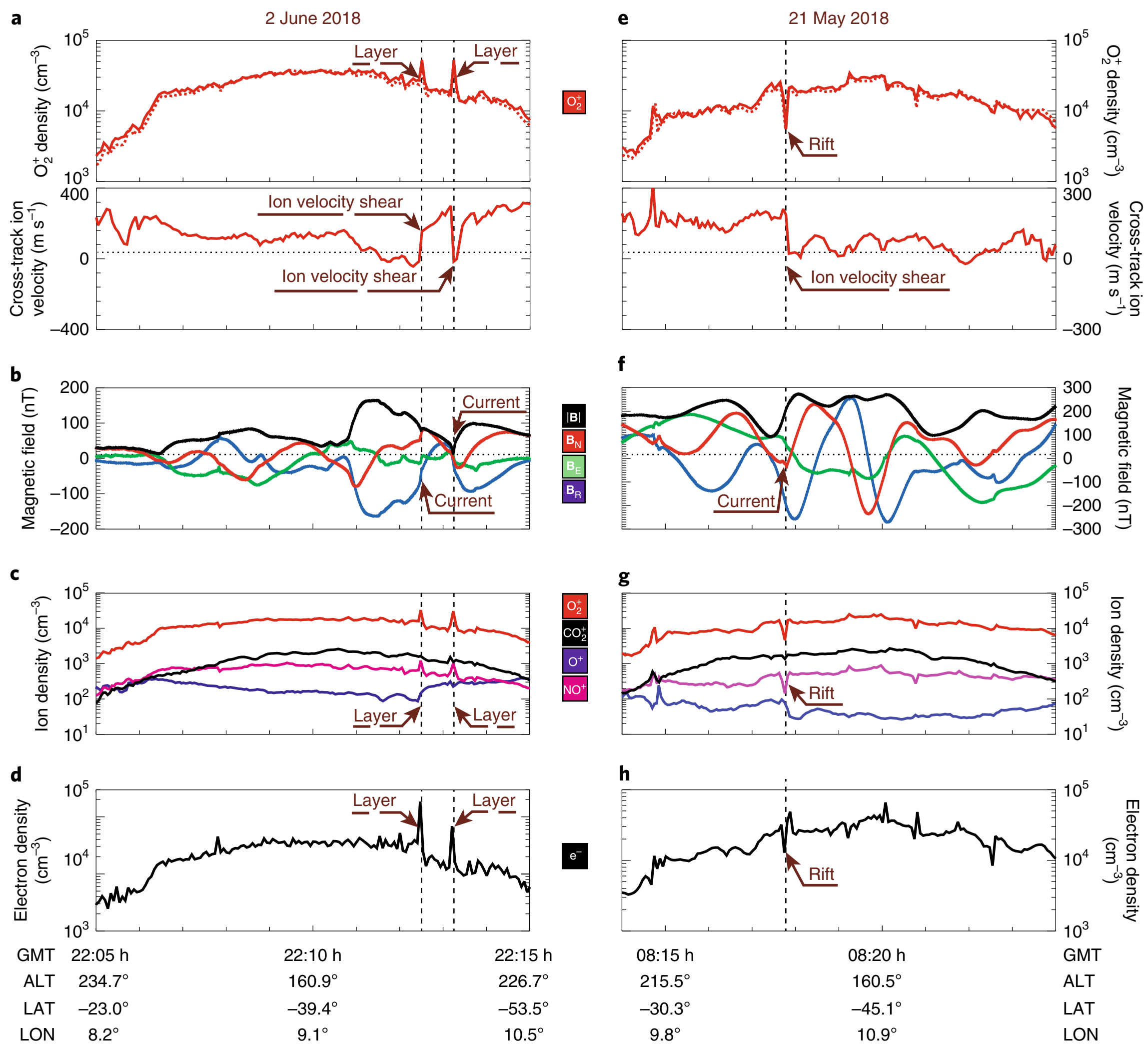

Fig. 2 | In situ MAVEN observations at a sporadic E-like layer and rift at Mars. a,e, Perturbations in the density and velocity of molecular oxygen ions (O_2^+) by STATIC[11]. **b,f**, Magnetic observations (nT) by the MAVEN magnetometer[29], showing total field strength (|**B**|) and components radial to the surface (B_R), northerly (B_N) and easterly (B_E). **c,g**, Densities of O_2^+, CO_2^+, O^+ and NO^+ measured by NGIMS[12]. **d,h**, Total density of ionospheric electrons measured by LPW[13]. The *x* axis shows local time in Greenwich Mean Time (GMT), altitude of MAVEN (ALT) in kilometres, and latitude (LAT) and longitude (LON).

four main ion species, from which we estimate that these structures should naturally decay away within ~200 to ~1,000 s (for more details, see the section 'Estimates of timescales of Martian sporadic E features from chemical composition' in Methods). Thus, either MAVEN, by incredible good fortune, just happens to have encountered every rift and layer within ~200 s of formation, or these are stable structures that are constantly being replenished and renewed. Since Ockham's razor would strongly suggest the later, we conclude that these Martian sporadic E features are in a perpetual state of dynamic formation, with layers constantly replenished with 'fresh' molecular ions from the surrounding ionosphere, and rifts constantly being excavated. Therefore, we find that at Mars, unlike Earth, it is possible to observe sporadic E features actively sweeping particles together (or apart). Since the underlying physics is the same at both planets, data from Mars can thus be used to build and test predictive models of the formation of sporadic E features, enabling future advancements in our understanding of a phenomenon that is highly disruptive to radio communications at Earth.

We note that Martian layers appear to be long lived and predictable, and to form through a slightly different mechanism than at Earth. Thus, one might reasonably argue that 'sporadic E' is the wrong term to use for these Martian layers. However, the layers at Mars and Earth are, nonetheless, both manifestations of the same physical phenomenon (sweeping together of ions along a shear in electromagnetic forces in the dynamo region of an atmosphere). Thus, we choose to retain the long-standing nomenclature of 'sporadic E-like' for consistency with the over 85 years of research into this phenomenon, since, while their existence at Mars is noteworthy, what makes them compelling is what they may teach us about electrodynamic phenomena at Earth.

Third, we find that sporadic E-like rifts are common at Mars. This raises the interesting question of why they have never been observed at Earth. One possibility is that such sharp rifts simply do not occur at Earth, as has been suggested by some theoretical studies[26]. However, their observation at Mars unambiguously demonstrates that such sharp ionospheric rifts can exist in nature. Thus, another possibility is that rifts are simply very challenging to detect at Earth. When they form, photoionization rapidly re-establishes an ambient concentration of the primary ionospheric species (NO^+, O_2^+, N_2^+), and the only evidence left behind would be a localized depletion in metallic ions (already a very minor constituent of the ionosphere). Such a structure would be very challenging to detect. It would be all but invisible to radar since the overall plasma densities would not be substantially affected. Furthermore, if rifts do exist at Earth, they form at altitudes

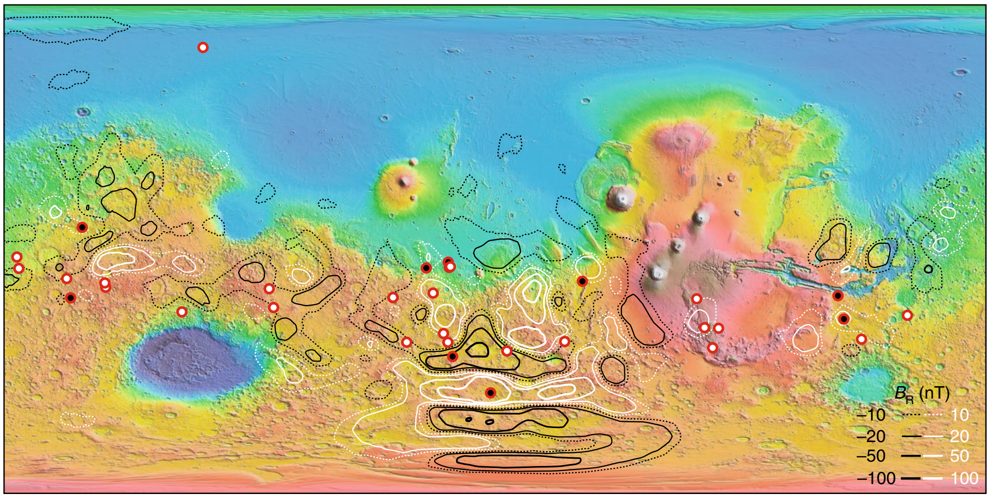

Fig. 3 | Map of sporadic E-like events at Mars encountered by MAVEN. Sporadic E-like layers (white dots) and rifts (black dots) have been encountered all over Mars, often near magnetic crustal remnants, but also at twists in the magnetic fields induced by the solar wind. Contour lines denote the radial component of crustal magnetic field strength (B_R) as measured by Mars Global Surveyor (ref. [17]) at 400 km, with outward-pointing fields in white, and downward fields in black.

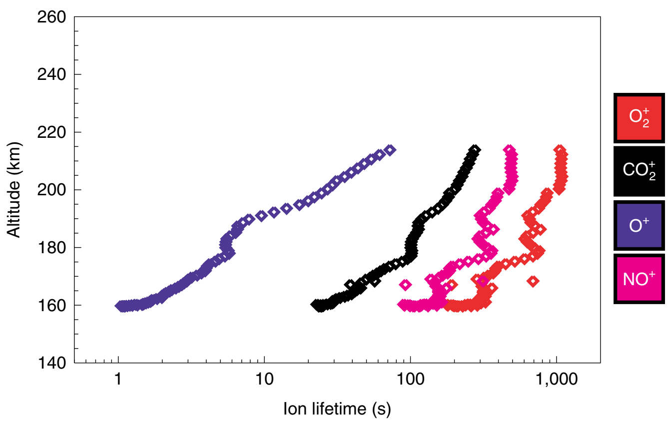

Fig. 4 | Ion lifetime at Mars. A highly simplified model of the lifetimes of ions in the ionosphere of at Mars, suggesting that any layers or rifts in O_2^+ or NO^+ would be extremely short lived, and thus must be constantly being replenished. Therefore, these structures must be in a constant state of active formation.

(90–130 km) that can only be explored for minutes at a time by sub-orbital rockets[15,24,27] and are inaccessible to satellites.

However, unlike the case at Earth, the Martian dynamo region (120–250 km) is readily accessible to satellites, and overlaps with the regions of highest plasma densities. Thus, Mars is a unique natural laboratory to study fundamental global electrodynamic processes that are inaccessible at Earth[28]. Considerable progress can be made through further exploration with MAVEN, which has made thousands of traversals into the Martian dynamo region, many times more than have ever been performed at Earth. These observations also provide strong motivation for a future mission to the dynamo region of Mars, capable of full quantitative analysis of electrodynamic processes through measurement of 3D electric and magnetic fields; neutral winds and composition; and ion drifts, composition and distribution functions. Until then, MAVEN has revealed that the underexplored Martian ionosphere is a new frontier, offering the promise of new insights, discoveries and better models of universal processes commonly occurring at Earth that directly impact our day-to-day lives.

Methods

MAVEN instrumentation. We use data from five MAVEN instruments described below, processed data from which are publicly available from NASA's Planetary Data System.

STATIC[11] measures ion composition and distribution functions of ions near Mars. While designed primarily to study the ionosphere, its broad energy range (0.1 eV–30 keV) and dynamic range enable it to also measure solar wind plasmas. STATIC has a time resolution of 4 s, a 360° × 90° field of view and the ability to resolve H^+, He^{2+}, He^+, O^+, O_2^+ and CO_2^+. In the ionosphere, bulk velocities of the plasmas are extremely small, and measurement of a 3D ion flow vector is not possible. However, STATIC has sufficient elevation resolution to enable calculation of a one-dimensional 'cross-track' ion velocity (in the frame of reference of the spacecraft) by measuring the angular defection of the incoming ions away from the spacecraft ram direction[28]. This is the cross-track velocity product presented in Fig. 2a,d. Without a full 3D measurement of ion wind, we are unable to calculate the overall vector of the resulting Lorentz force ($-\mathbf{V} \times \mathbf{B}$). However, we may still see unambiguous evidence for a shear in electromagnetic forces from this cross-track velocity data product, and the magnetometer.

The MAVEN magnetometer[29] consists of two triaxial fluxgate sensors, and measures the magnetic field vector with a cadence of 32 Hz and resolution of 0.02 nT. Measurements are accurate to within ~0.1 nT.

NGIMS[12] measures the density and composition of neutral atoms and ions in the upper atmosphere of Mars. It utilizes a dual ion source and a quadrupole analyser. The standard deviation in individual ion measurements due to random uncertainties is dependent on the density level and is ~50% at 0.1 cm^{-3} and ~25% above 1 cm^{-3}.

The LPW[13] instrument consists of two cylindrical probes mounted on ~7-m booms, and can measure the electron density and temperature or the spectral power density of waves (d.c. 2 MHz) in the ionosphere of Mars. The values of electron density shown in Fig. 2 are accurate to within approximately 40%.

The MAVEN SWEA[18] instrument (data from which are presented in Extended discussion of in situ MAVEN data) is a symmetric hemispheric electrostatic analyser, which measures electrons in the energy range of 3–4,600 eV. The sensor is mounted on the end of a 1.5-m boom, and has an energy resolution of 17%, a field of view of nearly 80% of the sky, and 2 s measurement cadence.

Further analysis of MAVEN data. *Comparison of density versus altitude plots of sporadic E-like features at Mars and Earth.* Extended Data Fig. 1 compares our recent in situ observations using MAVEN (Extended Data Fig. 1a,b) with remote-sensing observations from Mars of previously unexplained ionospheric 'density anomalies' (Extended Data Fig. 1c,d), which we posit were early remote-sensing detections of sporadic E features at Mars, and in situ observations of a sporadic E layer at Earth (Extended Data Fig. 1e,f). All plots show ionospheric plasma density versus altitude.

In situ observations at Mars by MAVEN (this study): the orbit of MAVEN is highly elliptical (~150-km periapsis, ~6,200-km apoapsis), and thus when flying through the ionosphere its velocity vector has a substantial vertical component. MAVEN passed through the sporadic E feature very rapidly, with durations consistent with a narrow structure only a few kilometres thick (Extended Data Fig. 1a,b).

Without a second spacecraft, it is challenging to determine their orientation. Thus we cannot tell from these data if they are horizontal, as at Earth, or are inclined at some angle to the surface due to the orientation of the magnetic shear.

Remote sensing at Mars by Mars Global Surveyor: Extended Data Fig. 1c,d shows examples of the previously unexplained density anomalies reported using radio occultation measurements by Mariner 9 and Mars Global Surveyor[4]. These features in radio occultation experiments have comparable density changes, altitudes and vertical extents to the features present in the in situ observations reported herein. Furthermore, radio occultation observations of these features occur preferentially in regions of strong magnetic field. Thus, we conclude that the most plausible explanation for these phenomena is that they represent early remote sensing of sporadic E-like layers (for example Extended Data Fig. 1c) and rifts (Extended Data Fig. 1d).

In situ observations at Earth by suborbital spacecraft: finally, for comparison with terrestrial sporadic E layers, Extended Data Fig. 1e,f shows two examples of encounters with sporadic E layers in Earth's ionosphere. Extended Data Fig. 1f shows a sporadic E layer encountered by a Nike Apache Rocket, launched in April 1965 from the USNS *Croatan*[27]. It measured electron density every 55 m, resolving the shape and structure of the sporadic E layer to be a focused peak in density of the order of a kilometre across. The sporadic E layers were encountered on both the ascent and descent, at a horizontal separation of several hundred kilometres. Extended Data Fig. 1e shows ion-composition measurements from inside a sporadic E layer by NASA Sounding Rocket 21.115, launched over Puerto Rico[16]. The layer was composed primarily of long-lived metallic ions (Fe^+, Mg^+) of meteoric origin, and unlike the case in Martian sporadic E-like layers O_2^+ is only a minor constituent.

When the thickness and altitude profiles of these established terrestrial sporadic E layers are compared with those at Mars, it is seen that they are very similar in terms of thickness (a few kilometres) and overall shape.

Extended discussion of in situ MAVEN data. In this section, we continue the discussion of MAVEN in situ observations of our two prime events (Fig. 2, main body of the Letter).

STATIC. Extended data Fig. 2a,d shows additional data products from MAVEN STATIC[11]. For the sake of continuity, the top panel shows plasma densities as in Fig. 2 (main text). The second panels show time–energy spectrograms, where the y axis is the energy of ions (between 0.1 and 100 eV), and the colour denotes differential energy flux. At each of the sporadic E-like events, there is a clear break in the energy spectrum, which is associated with the abrupt change in ion velocity.

The third panel in Extended Data Fig. 2a,d shows a time–angle spectrogram (in raw counts), where the y axis shows the elevation look angle. Abrupt changes in the number of counts throughout both these plots correspond to instrument mode changes, or an automatic increase in particle attenuation by the sensor. However, at each of the three sporadic E-like events, an abrupt shift in the angular spectrum is seen, again corresponding to the abrupt change in ion velocity at each event.

The fourth and final panel in Extended Data Fig. 2a,d shows a time–mass spectrogram, where the y axis denotes particle mass in AMU. At the moment of each sporadic E-like event, an associated increase or decrease in counts may be observed. However, for a calibrated distribution of the relative masses of each species during each event, see Fig. 2c,f in the main text (as measured by NGIMS).

SWEA. Extended Data Fig. 2b,e shows measurements of superthermal electrons by MAVEN SWEA[18]. The top panel shows time–energy spectrograms, where the y axis is electron energy in electronvolts, and the colour denotes differential energy flux. This plot exhibits the canonical spectra of electrons originating primarily from the dayside Martian ionosphere. Below this are the density and temperature of superthermal electrons (3–4,500 eV), calculated using an integral moment. Neither event coincided with a substantial change in superthermal electron density. There is, however, evidence for a slight change in temperature across each event, although not substantially larger in amplitude than other variations observed on the same orbits.

Ratio of gyrofrequency to collision frequency. Extended Data Fig. 2c,f shows a data product derived from NGIMS[12], LPW[13] and the MAVEN magnetometer[29]. It denotes the ratio between the frequency of gyration around the local magnetic field line and the frequency of collisions with the neutral atmosphere. This ratio is calculated for two particles, the primary ionospheric species (O_2^+) in red, and an electron (e^-) in black. For a detailed description of the method for calculation of this ratio, see ref. [28]. These plots show that, at the altitudes where the sporadic E-like events were observed, the ions were colliding with the neutral atmosphere more frequently than they were able to gyrate around the field lines. Thus, they are collisionally bound to the neutral atmosphere and may be dragged across magnetic field lines by high-altitude winds. However, the electrons remain firmly bound to the magnetic field lines throughout. Thus, with the ions partially demagnetized, and the electrons frozen to the field, MAVEN observed these events within the dynamo region of the Martian ionosphere, precisely the region where sporadic E layers form at Earth.

Estimates of timescales of Martian sporadic E features from chemical composition. The compositional dependence of sporadic E-like features at Mars (Fig. 4) provides clues to their timescales of formation. In a simple model, the relative increase or decrease in density should be proportional to $[1-\exp(T_{\text{lifetime}}/T_{\text{formation}})]$, where T_{lifetime} is the lifetime of each ion species and $T_{\text{formation}}$ is a time constant for formation of these features. To take an example, for the rift at 168 km shown in Supplementary Fig. 1b), we calculate ion lifetimes due to the following reactions, representing the primary sinks for the species shown in Supplementary Fig. 1b.

- Recombination with electrons.
- $CO_2^+ + O \rightarrow O_2^+ + CO$.
- $CO_2^+ + O \rightarrow O^+ + CO_2$.
- $O^+ + CO_2 \rightarrow O_2^+ + CO$.

Rate constants come from ref. [30], electron temperatures (necessary to calculate recombination rates) come from LPW and neutral densities come from NGIMS. Calculated ion lifetimes at 168 km for O^+, CO_2^+, NO^+ and O_2^+ are 2.9, 57, 313 and 690 s respectively. Given the expression above, a formation time of ~200 s would give relative decreases in O^+, CO_2^+, NO^+ and O_2^+ in ratios of 0.01, 0.25, 0.8 and 0.95 respectively (note that these are not the expected fractional decreases themselves, but the ratios of the fractional decreases). These ratios are not inconsistent with the sharp increases and decreases seen in Supplementary Fig. 1b. Understanding the chemistry of sporadic E-like layers and rifts at Mars will require realistic, detailed modelling in future.

Thus, the ion compositions of these sporadic E-like layers and rifts are consistent with a structure that has formed within the last ~200 s. Since all layers and rifts so far encountered have had, to the first order, a similar composition (that is, substantial enhancements/depletions in reactive primary species), two possibilities exist. Either MAVEN, by incredible good fortune, just happens to have encountered every rift and layer within ~200 s of formation, or these are stable structures that are constantly being replenished and renewed. Since Ockham's razor would strongly suggest the later, we conclude that these Martian sporadic E features are in a perpetual state of dynamic formation.

Data availability

MAVEN data are available from the Planetary Plasma Interactions Node of the NASA Planetary Data System (https://pds-ppi.igpp.ucla.edu/).

Code availability

Software to analyse data from the MAVEN Particles and Fields package is available through the MAVEN Science Data Center (https://lasp.colorado.edu/maven/sdc/public/), and through the University of California at Berkeley's Space Science Laboratory TPLOT package (http://sprg.ssl.berkeley.edu/data/maven/misc/socware/).

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Author contributions

G.A.C. analysed the data and wrote the paper. J.G. contributed the explanation for the fundamental physical mechanism at play. J.M., D.M., M.B., J.E. and B.J. conceived and designed the experiment. P.W. and M.F.V. compared our in situ results with remote previous sensing observations. R.L. analysed the data.

Competing interests

The authors declare no competing interests.

Additional information

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Correspondence and requests for materials should be addressed to G.A.C.

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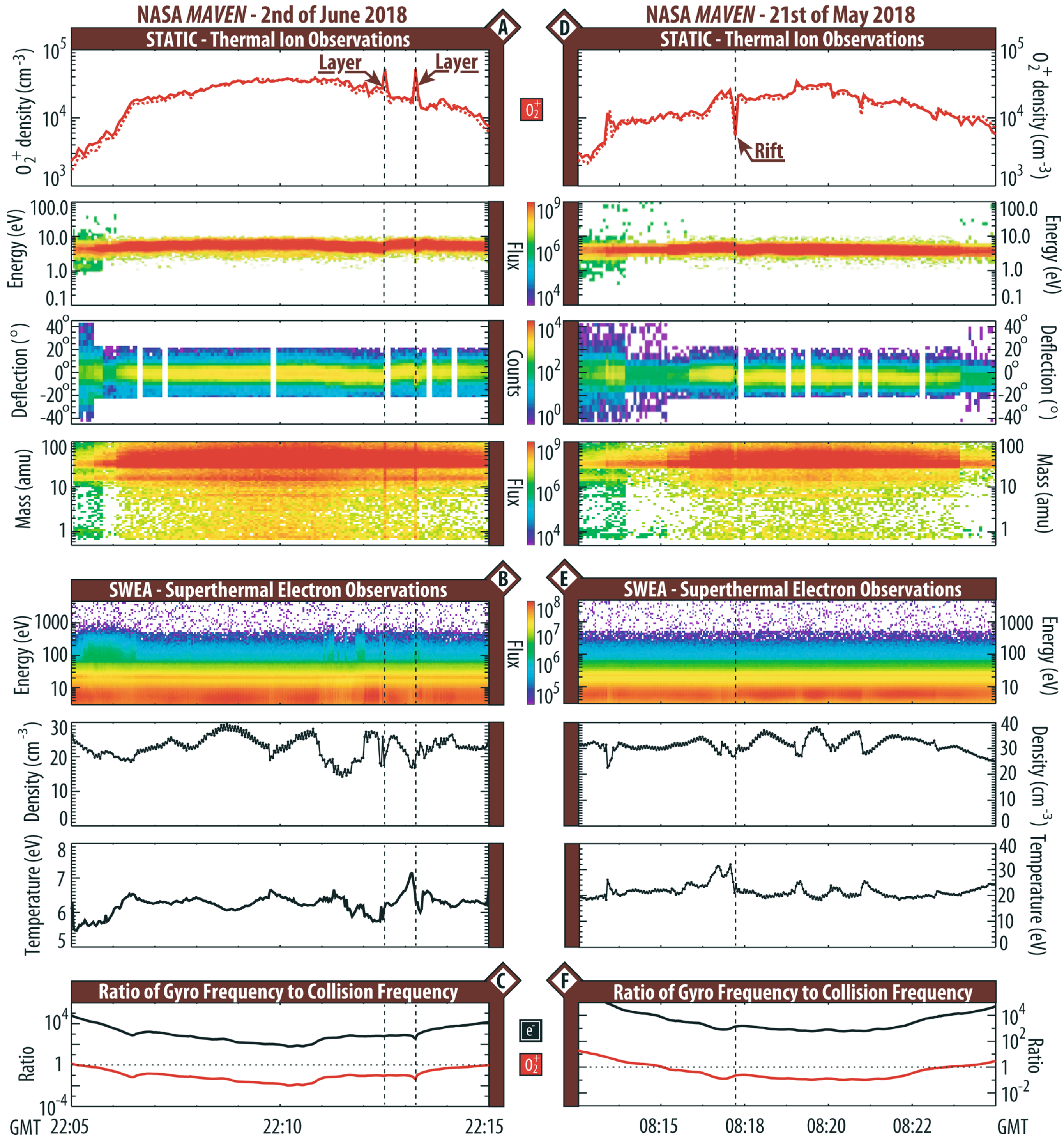
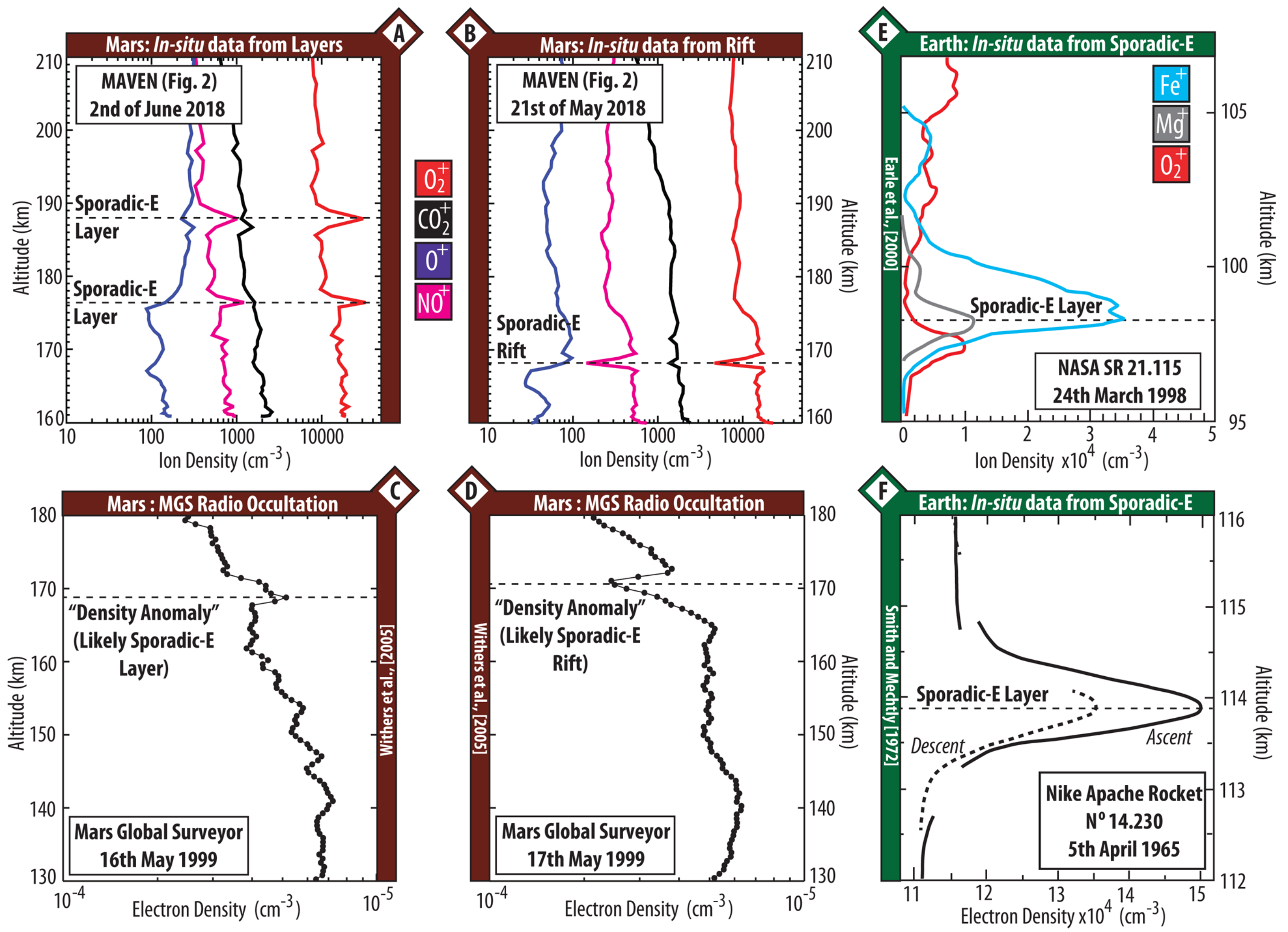


Extended Data Fig. 1 | Comparison of plasma density vs. altitude of Sporadic E at Mars and Earth. Comparison of observations of Sporadic-E-like features at Mars (red) and Earth (green). Each panel shows plasma density (cm-3) versus altitude (km). Top panels show observations of ion density (each species colour coded), Bottom panels show electron densities. Panels **a**,**b**.) MAVEN in situ observations (Fig. 2, main paper); Panels **c**,**d**.) remote-sensing observations by the Mars Global Surveyor (MGS); Panels **e**,**f**.) In situ observations of Sporadic E at Earth by suborbital rocketcraft. Consistent with previous remote-sensing results from Mars and at Earth, Martian Sporadic E appear to be narrow structures only a few kilometres across.



Extended Data Fig. 2 | Expanded MAVEN data plots. Expanded plot of additional supporting MAVEN data from our two prime events.