Exploring the Martian Atmosphere's “dynamo region” to better understand phenomena that impact radio communication at Earth

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Abstract:

Understanding and predicting processes which perturb planetary ionospheres is of paramount importance for long-distance radio communication. Perhaps the oldest-known ionospheric disturbances are “Sporadic-E” layers; unpredictable and short-lived concentrations of plasma, which can bounce radio signals over the horizon for thousands of kilometers. Consequentially, local radio broadcasts can become jammed by more distant transmissions, and thus Sporadic-E is a potentially serious complication for commercial radio, aviation, shipping, or the military. However, we do not fully understand them because at Earth

they form at altitudes too low for satellites to orbit. NASA's Mars Atmosphere and Volatile Evolution (MAVEN) mission accidentally discovered not only does Mars have Sporadic-E, but they are long-lived and form at predictable locations. Thus, Mars offers what Earth cannot, a natural laboratory where we may reliably explore these layers with satellites. MAVEN has already encountered more of the phenomena at Mars than have ever been explored in-situ at Earth with sub-orbital rockets. However, while MAVEN can detect them, it was not designed to probe understand the underlying physics behind their formation. **We advocate that a key strategic knowledge gap at Mars should to “understand electrodynamic phenomena, including Sporadic-E layers and rifts, in the dynamo region of the Martian atmosphere”.** We advocate for a future mission to the “Dynamo Region” of the Martian atmosphere (120km-250km altitude), capable of full quantitative analysis of electrodynamic processes such as Sporadic-E. Such an orbital mission would become rapidly economical compared to exploration at Earth, where a new rocket must be built for each new event. This mission would provide new physical insights, discoveries, and better models of universal processes commonly occurring at Earth that directly impact our day-to-day lives.

Figure 1: Mars is a unique natural laboratory for the study of civilization-impacting phenomena that cannot be explored at Earth

What are Sporadic-E Layers and why are they important?

Long-range radio communications are strongly affected by density fluctuations in Earth's ionosphere. Perhaps the most famous disruptive ionospheric phenomenon are "Sporadic-E layers" (1); unpredictable and short-lived (hence "Sporadic") density plasma enhancements occurring in the E-layer of Earth's ionosphere (2) (hence "E"). Sporadic-E layers are highly reflective to Very High Frequency (VHF) radio waves, and can be used to bounce radio signals over the horizon for thousands of kilometres (3). This long-distance "*sporadic-E [radio] propagation*" (4) make these invisible concentrations of plasma near the edge of space detectable to anyone with an FM radio set; whenever a radio station is jammed or replaced by another far more distant transmission, then Sporadic-E is a likely culprit. To commercial radio, aviation, shipping, or the military, it is an unpredictable and potentially serious complication. Sporadic-E can also blind defence RADAR systems that detect incoming aircraft, ships, and missiles.

Figure 2: Sporadic-E forms from the convergence or divergence of electric fields in the "dynamo" region of the atmosphere

What is the "dynamo region"? How do Sporadic-E layers and rifts form?

While the broad brushstrokes of their formation is known (5) (6) (7) (Figure 2), the detailed physics behind the phenomena is not well understood, due to a paucity of in-situ observations. In simple terms, the process is analogous to how a mountain range can be pushed up when two tectonic plates converge upon a fault-line. Physically, the process involves the generation and convergence of electromagnetic forces in the "dynamo region" (2) of Earth's atmosphere (90 – 130km 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 ($\mathbf{V}_{\text{wind}}$) across magnetic field lines ($\mathbf{B}$). 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 (Figure 2 left panel), then the ions are swept together and concentrated into a narrow "Sporadic-E" layer of enhanced plasma density. "Sporadic-E Rifts", while never

observed at Earth, are 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.

Figure 3: Comparing Sporadic E layers and rifts at Mars (8), and Earth (9) (10)

Why study Sporadic-E at Mars?

At Earth, the layers form at an altitude of about 60 miles (100km) where the air is too thin for an aircraft to fly, but too thick for any satellite to orbit. The only way to reach them is with a rocket, but these missions are short lived, lasting only tens of minutes before falling back to Earth. Thus, for every single Sporadic-E event we explore *in-situ* at Earth, we require a 2-3 year mission development, and over a million dollars of public investment. As a result, very few have been encountered and our understanding of the physics underlying their formation is poorly constrained. As a result, we cannot build predictive models for a phenomenon that can be highly disruptive to radio transmissions.

NASA's MAVEN orbiter (2014 – present) recently made four important discoveries (8); **(A)** Sporadic-E-like layers form also at Mars (Figure 3A), and are similar in general character as to those at Earth (Figure 3C); **(B)** The discovery of “Sporadic-E-like rifts” at Mars, a new natural phenomena not yet observed at Earth; **(C)** Martian Sporadic-E is common, long lasting, and occurs in predictable locations; **(D)** Martian sporadic-E layers and rifts are in a constant state of quasi-stable formation. Therefore, unlike at Earth, at Mars it is possible to catch and observe these phenomena undergoing active formation with satellites.

Thus, **Mars is a unique natural laboratory to study fundamental global electrodynamic processes that are inaccessible at Earth.** While differences exist between Martian and Terrestrial Sporadic-E, the underlying physics is the same at both planets. At Mars, can finally observe Sporadic-E undergoing formation, from which we may build and test predictive models of the formation of Sporadic-E at Earth, enabling significant future

advancements in our understanding of a phenomenon that is highly disruptive to radio communications.

However, while MAVEN can detect and map Martian Sporadic-E layers and rifts, it was not designed to study these phenomena, and lacks key instruments to explore and understand the fundamental underlying physics behind electrodynamic phenomena. Thus, a new mission would be required to explore the physics of the Martian dynamo region.

What new measurements are required?

The tools to understand and explore electrodynamic phenomena such as Sporadic-E already exist, and thus a mission to the Martian dynamo region could be achieved with existing technology. We now briefly outline a strawman payload for such a mission, describing the core measurements required.

- **3D Electric and Magnetic Fields** – While magnetometers have been flown to Mars, no mission has yet measured or mapped electric fields. Yet, from experience at Earth, simultaneous measurements of both are vital for understanding the physics underlying natural phenomena. In the case of Sporadic-E, understanding the direction and strength of electric field is key to understanding their formation (see Figure 2).
- **Neutral and Ion Winds** – In the Dynamo region (of both Earth and Mars), a core mechanism for generating electromagnetic forces are neutral winds that carry ions across field lines. On rare occasions, MAVEN was configured to measure neutral winds in the upper thermosphere of Mars (11). Additionally, one of its ion sensors was able to calculate a 1 dimensional component of cross-track ion velocity (8). Similar to NASA's *Dynamics Explorer* mission, a future mission to Mars should be equipped to consistently measure both neutral and ion winds in the upper thermosphere.
- **Neutral and ion density** – Finally, to detect the presence of Sporadic-E and other electrodynamic phenomena, the spacecraft should have the common ability to sense the density of the neutral and ionized gasses in the upper atmosphere of Mars.
- **Region of interest** – MAVEN has encountered Sporadic-E-like layers and rifts all over Mars (8), though primarily in the southern hemisphere where the crust is magnetized with remanent magnetic fields (12) of the long-lost Martian magnetic dipole (13). All layers and rifts were encountered below 223km, within the “*dynamo region*” of the Martian ionosphere ($\approx 120 \text{ km} \rightarrow \approx 250 \text{ km}$), comparable to the same region in which Sporadic-E form at Earth.

Summary

We advocate that a key strategic knowledge gap at Mars should to “*understand electrodynamic phenomena, including Sporadic-E layers and rifts, in the dynamo region of the Martian atmosphere*”. We advocate for a future mission to the “Dynamo Region” of the

Martian atmosphere (120km-250km altitude). A strawman payload would include 3D electric and magnetic fields, plus neutral and ion winds and densities. Such a mission could be achieved for low cost with existing technology. Given that every orbit of Mars would be comparable to a sounding rocket flight at Earth, it would not take many orbits before it became very economical to use the Martian dynamo region as a natural laboratory for probing fundamental and universal upper atmospheric processes.

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