PATCHY PROTON AURORA AT MARS: FIRST IMAGES, MULTIPLE MORPHOLOGIES, AND THREE NEWLY OBSERVED FORMATION MECHANISMS

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We present the first definitive observations of patchy proton aurora at Mars, indicating spatially variable precipitation of the solar wind across the full dayside of the planet under some rare (likely radial) upstream solar wind conditions. We also present more confined patchy aurora seen at other times when the upstream solar wind conditions are typical, which require formation mechanisms that exploit plasma turbulence related to specific interactions of the planetary induced and crustal field magnetosphere with the shocked solar wind. These results establish new forms of proton aurora variability, encompassing those previously proposed and extending our knowledge of possible formation conditions. Some of the aurora we observe open the possibility of tracking some upstream solar wind properties via auroral emission alone, and others suggest that at times the solar wind directly interacts with the entire planetary ionosphere, with unknown impacts on atmospheric heating and loss.

Introduction

Proton aurora at Mars were discovered due to anomalously bright Lyman alpha 121.6 nm emission in far-ultraviolet limb scan observations of the thermosphere by the MAVEN Imaging Ultraviolet Spectrograph (IUVS) [Deighan+2018]. These aurora have a CO_2 scale height, consistent with their generation by incident H Energetic Neutral Atoms (ENAs), which charge exchange upstream of the bow shock in the extended H corona of the planet, bypass the magnetic barrier that deflects the charged solar wind, and collide with the bulk thermosphere, producing detectable penetrating protons [Halekas+2015] and H emissions as a byproduct of collisional excitation and ionization of the incident ENA. A subsequent study by Hughes+2019 showed that proton aurora occurs nearly constantly on the dayside during Southern Summer, but that it is much less frequent in other seasons, with dayside occurrence rates of ~15%. Crismani+2019 speculated that some intermittent proton aurora visible during some but not all of a selected MAVEN periapsis occurred as a result of radial interplanetary magnetic field (IMF) conditions, which can destabilize the ordinary quasi-steady-state interaction of the induced magnetosphere with the solar wind. However, these observations were ambiguous between variations in time and space and could not be attributed to a unique location along the instrument line of sight, making causal interpretation of the auroral variation difficult.

Observations

The Emirates Ultraviolet Spectrograph (EMUS) [Holsclaw+2021] on the Emirates Mars Mission (EMM) [Amiri+2021] routinely observes the Martian disk in the far and extreme ultraviolet. As part of its science mission, the instrument makes images of the planet in H Lyman alpha at 121.6 nm and H Lyman beta at 102.6 nm, both of which are sensitive to H ENA / proton auroral emission. The high sensitivity of the spectrometer, required to enable detection of the distant oxygen corona, makes the instrument an extremely effective detector of auroral activity on the planet.

On multiple occasions over the course of Mars Northern Summer (Ls ~90-180), EMUS has observed patchy structure with spatial scales of less than 300 km in dayside emissions at both 102.6 and 121.6 nm, with no corresponding variation in longer wavelength emissions at 130.4 nm and 135.6 nm, which are sensitive to neutral O and ionospheric variability on the planet. The occurrence of small-scale emission variation in wavelengths emitted by the H atom, on spatial scales much smaller than could be produced by neutral atmosphere variability in H density or temperature, makes production of this patchy emission by incident protons or H ENAs a near certainty. We observe fine-scale spatial variation during a single 6 second integration along the EMUS slit, unambiguously establishing that at least some intermittent proton aurora previously observed by IUVS are likely due to spatial variation. The traditional mechanism for proton aurora formation due to spatially uniform H+ charge exchange upstream of the bow shock under normal solar wind conditions is incapable of producing this small-scale variability, requiring novel formation mechanisms.

Interpretation

We observe multiple qualitatively different morphologies of proton aurora in EMUS disk images and compare these with contemporaneous but not co-located measurements by MAVEN IUVS and particles and fields instruments. We conclude that multiple mechanisms are required to explain the patchy proton aurora we observe, including previously suggested radial IMF conditions, as well as newly observed (1) sheath turbulence resulting in charge exchange and ENA deposition in the region of the quasi-parallel interaction, (2) sheath proton deposition in the vicinity of the solar wind motional electric field +E pole, and (3) local acceleration of solar wind / planetary plasma into crustal magnetic field cusps during particular orientations of the upstream IMF clock angle. Future study detailing the precise nature of each mechanism, and particularly the effects of near radial IMF allowing solar wind proton deposition and ion acceleration across the entire dayside of the planet, will be essential to understanding the how these unusual proton aurora formation conditions affect the present-day state of the planet and determine their consequences for Mars atmospheric evolution.

References:

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