Joint observations by Tianwen-1 and MAVEN: Ushering in a new era of rapid dynamical coupling in the Martian space environment

Yuming Wang,[1,2,*] Shiyong Huang,[3,*] Rentong Lin,[1,2] and Zhigang Yuan[3]

[1]National Key Laboratory of Deep Space Exploration/School of Earth and Space Sciences, University of Science and Technology of China, Hefei 230026, China

[2]CAS Center for Excellence in Comparative Planetology/CAS Key Laboratory of Geospace Environment/Mengcheng National Geophysical Observatory, University of Science and Technology of China, Hefei 230026, China

[3]School of Earth and Space Science and Technology, Wuhan University, Wuhan 430072, China

*Correspondence: ymwang@ustc.edu.cn (Y.W.); shiyonghuang@whu.edu.cn (S.H.)

Received: January 30, 2026; Accepted: March 27, 2026; https://doi.org/10.1016/j.xinn.2026.101366

Citation: Wang Y., Huang S., Lin R., et al., (2026). Joint observations by Tianwen-1 and MAVEN: Ushering in a new era of rapid dynamical coupling in the Martian space environment. The Innovation **7(6)**, 101366.

Mars possesses a tenuous atmosphere but lacks a global intrinsic magnetic field. Solar extreme ultraviolet radiation partially ionizes the neutral particles in the atmosphere, giving rise to a structured ionosphere. The supersonic solar wind, carrying the interplanetary magnetic field (IMF), interacts directly with the ionosphere. This interaction not only generates the Martian induced magnetosphere but also modulates the long-term evolution of the Martian atmosphere. The variations in the magnitude and orientation of the IMF regulate a series of physical processes on Mars, including the dynamics of planetary pickup ions, the response of the induced magnetosphere, the variability of the induced magnetosphere boundary (IMB), magnetic reconnection at the IMB, the formation of localized mini-magnetospheres above crustal magnetic anomalies, etc. Collectively, these processes exert a profound influence on planetary ion escape fluxes, underscoring the pivotal role of the IMF in shaping the coupled dynamics of the Martian induced magnetosphere and upper atmosphere/ionosphere.

Previous numerical simulations have demonstrated that the magnetic field topology and oxygen ion plume within the Martian induced magnetosphere undergo rapid reconfiguration following IMF rotations, with response timescales as short as several minutes. Such rapid dynamical coupling necessitates multi-spacecraft observations to distinguish cause-and-effect relationships: one spacecraft is required in the upstream solar wind to monitor incident driver conditions, while the other spacecraft operates within the Martian space environment to capture the downstream planetary response.

Despite the deployment of multiple orbiters at Mars over the past decades, the lack of joint observations by magnetometer-equipped spacecraft with complementary orbital coverage has historically precluded simultaneous observations of upstream solar wind conditions and downstream signatures in the Martian space environment. Prior multi-spacecraft eras, such as Mars Global Surveyor with Mars Express in the 2000s and Mars Express with Mars Atmosphere and Volatile Evolution (MAVEN) after 2014, provided valuable contemporaneous measurements. However, these configurations were limited by either non-ideal orbital phasing, which rarely permitted true upstream-downstream alignment, or incomplete instrumentation, which precluded coordinated magnetic field and plasma measurements at both locations.

The arrival of China's first Mars exploration mission (Tianwen-1)[1] in 2021, operating in tandem with NASA's MAVEN mission (in orbit since 2014), has overcome these limitations for the first time. With Tianwen-1's elliptical orbit optimized for upstream solar wind monitoring and MAVEN's complementary orbit enabling comprehensive downstream coverage, and with both spacecraft equipped with magnetometers and ion analyzers, this configuration enables joint magnetic field and plasma observations of the upstream solar wind and downstream Martian space environment with unprecedented coordination. This breakthrough has ushered in a new era in the dynamical coupling of the Martian space environment (Figure 1).

Beyond merely adding new data, these joint observations have revealed a fundamental characteristic of Mars-solar wind coupling that was previously obscured by single-spacecraft limitations: the Martian space environment responds to external drivers with remarkable speed and sensitivity. The four studies highlighted below demonstrate that dynamical reconfiguration occurs on timescales of minutes, far shorter than previously appreciated, challenging the paradigm of sluggish planetary response and opening new avenues for understanding planetary atmospheric evolution.

The Martian magnetotail, whose morphology and behavior are tightly coupled to upstream solar wind conditions, is highly dynamic, rendering it extremely sensitive to external perturbations. However, due to the limitations of previous single-spacecraft observations, the interaction between the solar wind and the Martian magnetotail remains an open question to date.

Tianwen-1 has a highly elliptical orbit with the pericenter about 3.5 Martian radii, enabling it to reach the Martian distant magnetotail region. With the Tianwen-1 positioned in the Martian distant magnetotail region and the MAVEN spacecraft monitoring the upstream solar wind, Guo et al.[2] reported the response of the Martian magnetotail to the solar wind disturbance. They observed that perturbations in solar wind (specifically, variations in dynamic pressure and IMF orientation) detected by MAVEN coincided with the flapping of the magnetotail recorded by Tianwen-1. Quantitative analysis demonstrates that a 20% increase (or decrease) in solar wind dynamic pressure and a 30° (or 50°) rotation of the IMF clock angle could cause the Martian magnetotail to swing rapidly. Furthermore, through cross-correlation analysis, the time lag between the onset of the flapping of the magnetotail current sheet and solar wind perturbations is approximately 2–3 min, indicating the rapid response of the Martian magnetotail to solar wind disturbance.

The Martian bow shock is a boundary where the supersonic, super-Alfvénic solar wind is decelerated to subsonic, sub-Alfvénic speeds and deflected upon encountering the planet. As the outermost interface for the interaction between solar wind and Mars, this boundary plays a fundamental role in regulating the transfer of energy and momentum into the Martian space environment. The dynamic variability of the bow shock acts as a diagnostic proxy: it not only responds to upstream solar wind perturbations but also reflects the intrinsic plasma and magnetic properties on Mars.

The positional and morphological variability of the Martian bow shock is governed by a suite of upstream parameters, including solar extreme ultraviole radiation, solar wind dynamic pressure, and the magnitude and orientation of the IMF. However, the underlying physical processes remain poorly understood under the specific scenario of weakly disturbed solar wind. To address this gap, using magnetic field and plasma data from Tianwen-1 and MAVEN missions, Cheng et al.[3] conducted an in-depth analysis of the oscillatory behavior of the Martian bow shock under weak solar wind perturbation conditions. The magnetometer and ion analyzer aboard Tianwen-1 have repeatedly detected abrupt changes in key physical parameters in the vicinity of the Martian bow shock. Through comparative analyses of transient structures near the bow shock and the ripple-like features of the shock front, oscillatory phenomena in the Martian bow shock are identified. During the same period, the MAVEN spacecraft was situated upstream of the Martian bow shock in the solar wind but detected weak solar wind perturbations. Furthermore, the simulation study demonstrates that the Martian bow shock exhibits low strength when the Mach number is low, rendering it susceptible to oscillations even under weak solar wind perturbations. In contrast, at higher Mach numbers, the bow shock can maintain stability despite stronger solar wind disturbances. These findings provide critical insights into the sensitivity of the Martian space environment to solar wind perturbations.

The Martian ionosphere contains a high density of low-energy thermal ions, which can be accelerated by dynamical processes when entering

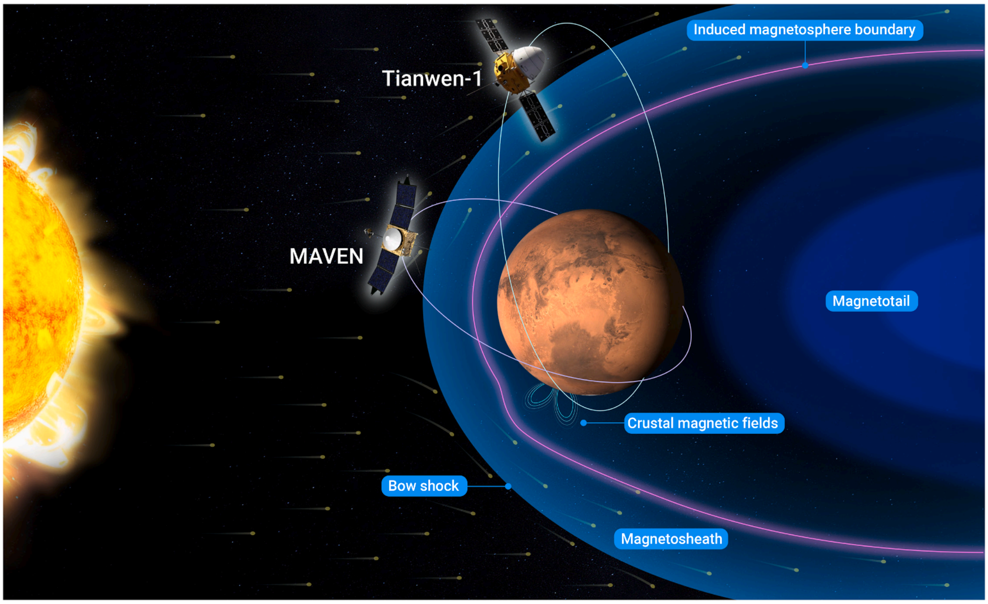

Figure 1. Illustration of joint observations by Tianwen-1 and MAVEN in the Martian space environment

the magnetosphere or magnetosheath. However, the mechanisms governing ion acceleration and escape from the ionosphere into the magnetosphere remain incompletely understood.

Utilizing high-cadence, simultaneous magnetic field and plasma measurements from Tianwen-1 and MAVEN missions, Lin et al.[4] presented novel observational evidence of magnetic reconnection in the dayside upper Martian ionosphere during IMF rotation. These joint observations provide unambiguous confirmation that protons and oxygen ions originating in the ionosphere are accelerated by the reconnection process triggered by IMF rotation. Notably, the estimated ion escape flux during this event exceeds average plume and tailward escape rates by an order of magnitude. These results suggest that magnetic reconnection may constitute a significant pathway for ion acceleration from the upper ionosphere during the short periods of IMF rotations, offering new insights into the evolution of the Martian atmosphere and a potential mechanism for early water loss on Mars.

The Martian ionosphere functions as a plasma barrier that impedes and deflects the solar wind and its embedded IMF. The field lines of the IMF drape around the interface separating the ionosphere from the shocked solar wind, forming draped magnetic field topologies. Induced electrical currents generated both at this boundary and within the ionospheric plasma produce an induced magnetic field. The superposition of these draped and induced fields constitutes the total magnetic field within the Martian induced magnetosphere. Actually, the structure and dynamics of the induced magnetosphere are highly sensitive to upstream solar wind conditions. Under radial IMF conditions, where the IMF aligns parallel to the solar wind flow, global hybrid simulations and observations from a single spacecraft suggest that the magnetic barrier between the ionosphere and the shocked solar wind dissipates entirely, resulting in the structural degeneration of the induced magnetosphere.

However, previous studies based on single-orbiter observations suggested that the induced magnetic field could play a major role and serve as a magnetic barrier under radial IMF conditions. Since this interaction between Mars' ionosphere and solar wind is highly dynamic, joint observations of the upstream solar wind and the downstream Martian space environment are needed to figure out whether an induced magnetosphere can form under radial IMF conditions. Lin et al.[5] analyzed joint observations from Tianwen-1 and MAVEN, coupled with state-of-the-art 3D global hybrid numerical simulations, and demonstrated the unambiguous formation of the Martian induced magnetosphere under radial IMF conditions for the first time. This induced magnetosphere comprises the draped and the induced magnetic fields. Crucially, magnetic pressure buildup above the ionosphere surpasses incident solar wind pressure, establishing a stable magnetic barrier that prevents direct solar wind penetration. This finding supports that the induced magnetosphere still persists under radial IMF and indicates that ion escape rates during such intervals may be lower than previously predicted for a degenerated magnetosphere scenario.

Collectively, these four studies establish that the "new era" in Mars space physics is defined not merely by the technical achievement of multi-spacecraft operations but by a transformative shift in our conceptual framework. The Martian space environment is not a sluggish system responding to solar wind variations on hour-long timescales; rather, it is a tightly coupled, minute-scale responsive system where boundaries reconfigure, ions accelerate, and the entire induced magnetosphere reorganizes with remarkable speed. This paradigm has three profound implications. First, it demands revision of atmospheric escape models that assume quasi-steady conditions. Second, it establishes Mars as the premier laboratory for studying rapid, externally driven magnetospheric dynamics among unmagnetized bodies. Third, it validates the essential role of multi-point measurements in planetary space physics—insights simply inaccessible to single-spacecraft observations.

The joint observations by Tianwen-1 and MAVEN have inaugurated a new era in Mars space physics by establishing that the Martian space environment operates as a tightly coupled, rapidly responsive system. Building upon foundations laid by earlier multi-spacecraft configurations on Mars, this mission pairing has overcome the historical limitations of orbital phasing and instrumental coverage to reveal minute-scale reconfiguration timescales that challenge traditional models of planetary response. In the near future, this will be further advanced by NASA's ESCAPADE mission, launched on November 13, 2025. Its dual-spacecraft configuration is specifically designed for stereo magnetospheric imaging. ESCAPADE will provide continuous upstream monitoring coupled with true multi-point downstream measurements, enabling direct observations of boundary motion and wave propagation that even Tianwen-1/MAVEN cannot fully resolve. potentially enabling predictive models of planetary space weather. Furthermore, China's second Mars mission—Tianwen-3 for Mars sample return—is scheduled to launch in late 2028. Up to five spacecraft will orbit and monitor Mars, setting a new record, assuming that MAVEN and Tianwen-1 remain operational at that time. These advances inform not only the Mars space environment but also our understanding of Venus, comets, and unmagnetized exoplanets, which is essential for assessing habitability across terrestrial worlds throughout the solar system and beyond.

FUNDING AND ACKNOWLEDGMENTS

This work was supported by the National Natural Science Foundation of China (42188101, 42574215 and 42130204).

DECLARATION OF INTERESTS

The authors declare no competing interests.

REFERENCES

1. Wan, W.X., Wang, C., Li, C.L., and Wei, Y. (2020). China's first mission to Mars. *Nat. Astron.* **4**:721
2. Guo, Z.Z., Fu, H.S., Cao, J.B. et al. (2024). Rapid response of Martian magnetotail to solar wind disturbance: Tianwen-1 and MAVEN joint observations. *Geophys. Res. Lett.* **51**:e2024GL112399
3. Cheng, L., Wang, Y., Ma, Y. et al. (2025). Bow Shock Oscillations of Mars Under Weakly Disturbed Solar Wind Conditions. *Nat. Commun.* **16**:9649
4. Lin, R., Huang, S., Wang, Y. et al. (2025). Direct observations of acceleration of planetary ions from Mars' ionosphere through magnetic reconnection when IMF rotates. *Geophys. Res. Lett.* **52**:e2025GL118290
5. Lin, R., Huang, S., Zhou, J. et al. (2026). Mars' induced magnetosphere can form under radial interplanetary magnetic field. *Innovation*:101312. DOI:10.1016/j.xinn.2026.101312