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A Review of the Scientific Payloads of the MAVEN Mission and Their Observational Contributions

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Abstract: Launched in 2013, NASA's Mars Atmosphere and Volatile Evolution (MAVEN) mission is the first dedicated mission to study the upper atmosphere and climate evolution of Mars. It contains eight instruments which are organized into three payload packages: the Particles and Fields Package (PFP), the Remote Sensing Package (RSP), and the Neutral Gas and Ion Mass spectrometer (NGIMS). They measure solar wind interactions, ionospheric dynamics, and atmospheric composition which provide critical insights into processes driving atmospheric escape. MAVEN has revealed how solar forcing and seasonal variability contribute to long-term loss of volatile species. This paper aims to present a concise description of MAVEN's payloads and their role in advancing our understanding of the Martian atmosphere and its evolution.

1. Introduction

Mars remains the center of attraction for researchers and the public at large. The possibility of inhabiting the planet remains crucial for understanding the surface characteristics of Mars. It is evident that geological evidence suggests that "Mars had more favorable conditions for supporting life, with a thicker atmosphere and water flowing on its surface" *(Jakosky et al. (2018))* or (*Bougher et al. (2015)).* However, over billions of years, it is evident that the Martian atmosphere is significantly reduced, resulting in the current Martian climate, a cold, dry, CO_2-dominated planet with a very active atmospheric interaction with solar winds and radiation. This characteristic of the Martian climate is important not only for establishing the Martian climate history but also for understanding issues related to the colonization of other planets in the universe.

In order to answer these questions, NASA developed a mission called the Mars Atmosphere and Volatile Evolution (MAVEN). It was launched in November 2013. When it reached the orbit around Mars in September 2014, it became the first mission that is entirely devoted to studying the upper atmosphere, ionosphere of Mars, besides understanding the mechanism of atmospheric escape. It is to be noted that MAVEN is unique in the sense that it does not aim

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at studying the Martian surface or the lower atmosphere of the Mars like other previous missions. Instead, it is aimed at studying the interaction region among the solar winds that influence Martian atmospheres. It aims at identifying the amount of Martian atmospheric loss to space.

There are eight scientific instruments that are being flown with the MAVEN spacecraft, which fall into three complementary payload packages, each of which meets various mission objectives. These instruments for the Particles and Fields Package (PFP) are: SWIA, SWEA, SEP, STATIC, LPW, and MAG. These instruments taken collectively provide a description of the solar wind, ionized plasma of the ionosphere, and the electromagnetic environment of Mars that yields critical information about the effects of solar forcing on the planet's unmagnetized atmosphere. Next is the Remote Sensing Package (RSP), which contains the Imaging Ultraviolet Spectrograph (IUVS) that studies the global atomic makeup and topology of the thermosphere and exosphere by observing ultraviolet light emitted by selected species such as hydrogen, oxygen, and carbon that are directly related to atmospheric loss. These instruments are complemented by the Neutral Gas and Ion Mass Spectrometer (NGIMS), which is an in situ instrument that analyzes the atmospheric elements of hydrogen, oxygen ions, and other gas phases in altitudes of approximately 150-500 km to provide critical data for studying losses of volatiles.

In order to gain insight into Martian atmospheric contents and escape, one of the key instruments on board the MAVEN spacecraft is the Neutral Gas and Ion Mass Spectrometer (NGIMS). It is a quadrupole mass spectrometer that can directly analyze both neutral gases and ions for altitudes between 150-500 km, which is the region of maximal atmospheric loss. A key aspect of the NGIMS is that it allows for identifying and measuring major species such as CO_2, N2, oxygen, Ar, He, as well as isotopes of hydrogen and oxygen.

Perhaps one of the major areas where NGIMS has made a great contribution is with regard to isotope ratio measurements, like the excess presence of heavy isotope of carbon, nitrogen, and oxygen isotope relative to their lighter counterparts. These observations clearly establish that there is a considerable atmospheric loss that has taken place on a geological timescale on the Martian body, as the lighter isotopes migrate away into space. Moreover, analysis of the data provided by NGIMS suggests that there is considerable seasonal, daily, and solar cycle variability with regard to the density of major species.

The data that NGIMS is taking has proven to be crucial, especially during large dust storm events, where the global atmospheric circulation strongly alters the gas distribution. It is through NGIMS that the rapid variability that is observed in the atmospheric circulation is linked to atmospheric escape. Currently, information gathered by NGIMS, together with other instruments such as Imaging Ultraviolet Spectrograph (IUVS) and Particles and Fields Package (PFP) of MAVEN, is becoming beneficial in understanding the current atmospheric phenomena in line with global circulation phenomena such as solar forcing.

Taken together, these datasets provide a multi-scale understanding of the Martian upper atmosphere and its interaction with the Sun. We obtain in situ compositional information about the Martian atmosphere with NGIMS, global-scale information in ultraviolet radiation with IUVS, while PFP monitors the charged particles responsible for atmospheric loss. These instruments, functioning collectively, revealed the role of solar storms, seasonal variability, and solar cycle variability in causing the loss of volatiles from the Martian atmosphere.

During the past decade since its arrival in orbit around Mars, the spacecraft instruments have completely changed our understanding of the Martian environment from one that was static, frozen, and quiescent, to one that is still active with solar forcing. This mission not only provided direct evidence for the escape of hydrogen, oxygen, and other species into space, but it also established that these escape rates wax and wane with solar forcing, thereby contributing immensely to climate models of the Martian environment. Of course, the broader implications of atmospheric loss rates apply to terrestrial planets from Earth to new planets orbiting active stars.

This paper offers a detailed description of the Payloads on board the MAVEN spacecraft by discussing their significance, objectives, and contributions. We believe that by focusing on what each instrument does uniquely and the strength of what they can achieve together, it is possible to appreciate the importance of MAVEN in the study of planets by understanding atmospheric evolution.

2.1 Methodology describing the Neutral Gas and Ion Mass Spectrometer (NGIMS) Instrument

The Neutral Gas and Ion Mass Spectrometer (NGIMS) is one of the most direct "eyes and ears" that MAVEN has into the Martian upper atmosphere. Unlike remote instruments that observe from afar, NGIMS actually samples the air as MAVEN dips into low altitudes on

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each orbit. Positioned to work between ~150-500 km during periapsis passes above the surface, it flies through the thin Martian atmosphere, pulling in particles and measuring what they are made of.

At its heart, NGIMS is a quadrupole mass spectrometer. Incoming particles-whether neutral gases or charged ions-are sorted according to their mass-to-charge ratio. This enables the instrument to determine what type of gas is present-such as CO_2, N_2, atomic oxygen, or argon-and how much is present at any given altitude. Importantly, NGIMS is sensitive enough to pick out isotopes, the heavier and lighter versions of the same element, which tell scientists how much atmosphere has been lost over billions of years.

NGIMS alternates between the two main modes of operation: neutral and ion modes. NGIMS primarily samples in a way that is closely linked to the MAVEN elliptical orbit. As the spacecraft swoops down to its closest point-what's known as periapsis-NGIMS performs its most detailed sampling, building vertical "profiles" of atmospheric composition effectively. With time, as MAVEN orbits at varying local times and latitudes, even at different seasons, these snapshots meld into a broader picture of how the atmosphere changes daily, seasonally, and across solar cycles.

Once collected, the raw counts from NGIMS detectors are calibrated into number densities using pre-flight and in-flight reference data. Using the resultant number densities, scientists apply statistical analysis and curve-fitting techniques to reveal trends, such as seasonal peaks in CO_2 or the thinning of N_2 during winter. When NGIMS results are compared with data from other MAVEN payloads-like IUVS, which sees the atmosphere in ultraviolet light, or PFP, which tracks solar wind conditions-they tell a story of how Mars' atmosphere responds to both internal circulation and external drivers like solar storms.

In other words, NGIMS is much more than a mass spectrometer-it's a record of long-term atmospheric evolution and an in situ monitor of the Martian upper atmosphere. With the ability to measure both present-day composition and the fingerprints of long-term escape, it is central to the MAVEN mission of uncovering how Mars changed from a wetter, thicker-atmosphere world to the dry planet we see today.

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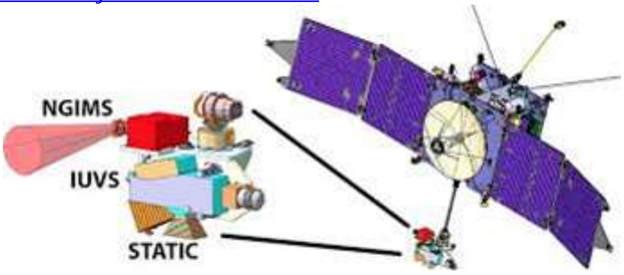

Figure 1: A schematic view of MAVEN satellite and some of its payloads. (NASA MAVEN instrument overviews; articulated payload platform descriptions.)

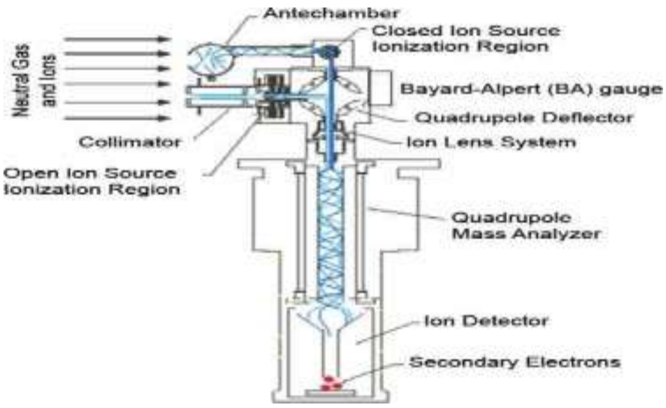

Figure 2: This figure shows the different components of Neutral Gas and Ion Mass Spectrometer (NGIMS) (Mahaffy et al. (2015), *The Neutral Gas and Ion Mass Spectrometer on MAVEN*, Space Science Reviews)

2.2 Description of Particles and Fields Package (PFP)

The Particles and Fields Package is the biggest set of instruments on board the MAVEN spacecraft. It is intended to investigate the presence of charged particles, plasma, and magnetic fields on Mars, allowing for a detailed understanding of the interaction between the solar wind and the upper atmosphere of the Martian planet.

The core of this instrument is the Solar Wind Ion Analyzer, or SWIA, which is designed to determine the density, velocity, and temperature of ions that make up the solar wind. Such observations enable the determination of the solar wind pressure, which is of particular importance given that Mars does not have an intrinsic magnetic field that could protect it from solar wind impacts.

Mars' upper atmosphere is vulnerable to solar-wind impacts with no magnetic shield in place. A related instrument is the Solar Wind Electron Analyzer (SWEA), which is concerned with electrons that are crucial to magnetic heating, ionization, and current systems. Results from SWEA data showed the role of incident electrons in causing aurorae and changing the ionosphere's chemistry.

At the same time, the Solar Energetic Particle (SEP) instrument monitors bursts of high-energy particles that occur during solar flares and coronal mass ejections. These high-energy particles could penetrate deeply into the Martian atmosphere, leading to an increase in ionization and heating of the Martian atmosphere, which subsequently accelerates gas escape. During solar storms, SEP data has played an important role in revealing the rapid increase in gas escape rates.

A direct measurement of the supra-thermal and thermal ions that escape into space, such as O^+, $O2^+$, or CO_2^+, is given by the SupraThermal and Thermal Ion Composition (STATIC) instrument. By understanding their composition, density, and velocity, the data brought by STATIC closes the information gap between NGIMS' observations of neutral gas composition in the Martian thermosphere to the plasma region explored by the other instruments of PFP. It was found that ion escape is one of the major atmospheric loss rates.

Additionally, the Langmuir Probe and Waves (LPW) instrument offers a new perspective with its measurement of electron density, temperature, and plasma waves. It has brought about an understanding of the small-scale ionospheric structure of Mars, such as the role of plasma waves in particle acceleration and enhanced ion loss rates.

Lastly, the Magnetometer (MAG), despite its small presence, makes a major contribution. This instrument is involved in determining the vector magnetic fields that surround Mars. This information is crucial in understanding the extent to which the solar winds are responding to the scattered magnetic fields of the Martian crust. Such areas provide a mini-shield that influences atmospheric escape.

Overall, the group of instruments that make up the PFP offers a dynamic description of the Martian plasma environment. It helps to fill a gap that is created by NGIMS since it not only describes the type of gases that are observed, but also describes the process by which those gases are lost once they are ionized.

2.3 Briefs about Remote Sensing Package (RSP)

Though the Particles and Fields Package is concerned with local interactions of plasma, the Remote Sensing Package allows one to look at the issue from a global point of view. It is based on one very powerful instrument: the Imaging Ultraviolet Spectrograph (IUVS). While NGIMS or PFP instruments observe their direct surroundings, IUVS observes the Martian planet from orbit, registering ultraviolet radiation that testifies about the Martian upper atmosphere.

IUVS is responsible for identifying the extended coronae of hydrogen and oxygen that surround Mars. Both of these coronae are the atmospheric extensions that are direct indicators of water loss since both oxygen and hydrogen ions are formed from the destruction of water molecules. Variation in the coronae with seasonal and solar cycle changes helps IUVS understand the loss of water into space.

This instrument has also picked up observations of diffuse aurorae that extend into the Martian atmosphere (McClintock *et al. (2015))* or (*Schneider et al. (2015))*. These diffuse aurorae, caused by the collision of solar energetic particles with the atmospheric gases, provide additional proof of the interconnection between solar events and atmospheric phenomena.

2.4 Combined Insights

Taken together, the three instruments on board MAVEN provide a complete picture of the atmospheric history of Mars through their data. While NGIMS describes what gases are present and their concentration distribution with altitude, season, and solar activity, PFP describes the plasma magnetic processes that drive these gases out of the Martian induced magnetosphere. IUVS then describes what is occurring on a global scale with respect to the atmospheric escape.

By integrating these various perspectives, the MAVEN mission is able to determine the amount of atmospheric loss that the Martian planet went through. All these discoveries have given humanity a new understanding of its present atmospheric state, from being potentially habitable to what it is today: a cold, barren planet.

3. Results

The significant findings of several investigators in regard to study of the Martian upper atmosphere and ionosphere have been presented in this section. The long-term escape of water-derived species from the Martian thermosphere is complex and time-varying, resulting from the interplay between solar radiation, atmospheric composition, and dynamic transport (Jakosky et al., 2018; Chaffin et al., 2021). Observations from MAVEN's NGIMS instrument have provided critical in situ data that validate and improve theoretical models, in particular regarding the role played by water vapor in supplying hydrogen and oxygen to the upper atmosphere (Fedorova et al., 2020; Aoki et al., 2019). There is clear consensus regarding the seasonal modulation of escape, in particular enhancement of hydrogen and oxygen loss around perihelion and during global dust storms (Chaffin et al., 2018; Heavens et al., 2018; Vandaele et al., 2019). These findings reinforce the importance of water vapor transport from the lower atmosphere, a process now known to be more variable and vertically extensive than once believed (Clancy et al., 2017; Gonzalez-Galindo et al., 2024). However, models are still inconsistent in key aspects of their predictions, including the altitude of peak water vapor photolysis, magnitude of the dust-induced thermospheric expansion, and lag in the response of the escape rate to solar events (Erwin et al., 2021; Stone et al., 2018). Yet another area of active research involves the relative coupling between thermal and non-thermal escape processes. While photochemical models explain much of the neutral hydrogen and oxygen escape, ion escape dynamics, in particular under the influence of the solar wind and crustal magnetic fields, are insufficiently characterized (Lillis et al., 2015; Dong et al., 2015; Gunell et al., 2024). NGIMS and other MAVEN instruments have observed ion outflows implying a more significant role for electrodynamic and kinetic processes not currently incorporated into most large-scale atmospheric models (McClintock et al., 2015; Halekas et al., 2017).

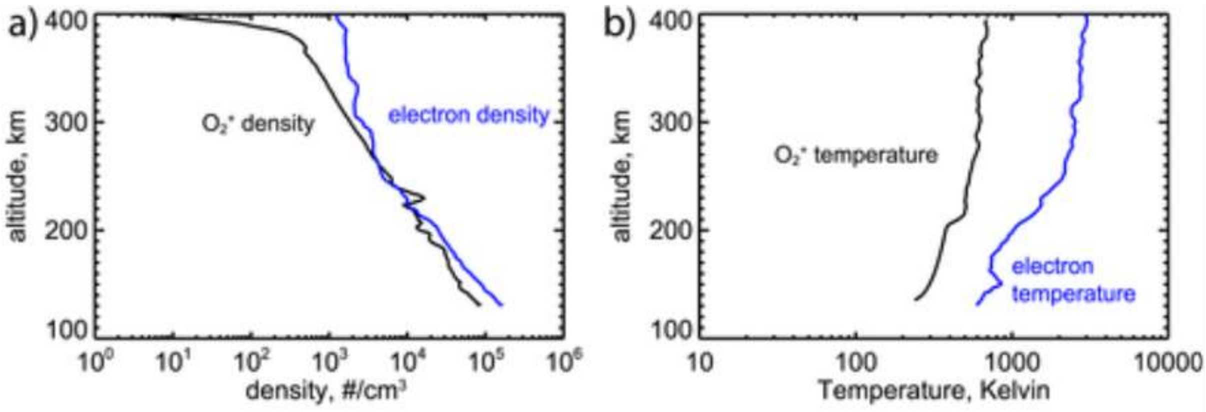

Figure 3(a): Altitude profiles of O_2^+ ion density (black) and electron density (blue) in the Martian ionosphere measured by MAVEN showing variation of plasma densities between ~100 and 400 km. *Adapted from Lillis et al. (2017), JGR: Space Physics.*

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Figure 3(b): Altitude profiles of O_2^+ ion temperature (black) and electron temperature (blue) in the Martian ionosphere from MAVEN observations, illustrating the thermal structure of ions and electrons with height. *Adapted from Lillis et al. (2017), JGR: Space Physics.*

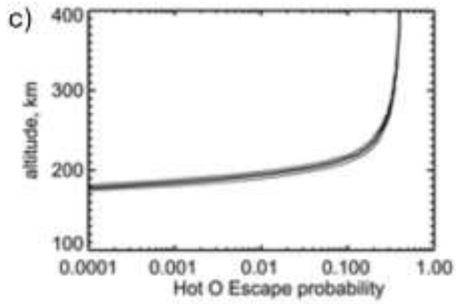

Figure 3(c): Variation of the hot oxygen (O) escape probability with altitude in the Martian upper atmosphere deduced from MAVEN observations and reflecting a steep rise in the probability of escape with increasing altitude. *Adapted from Lillis et al. (2017), JGR: Space Physics.*

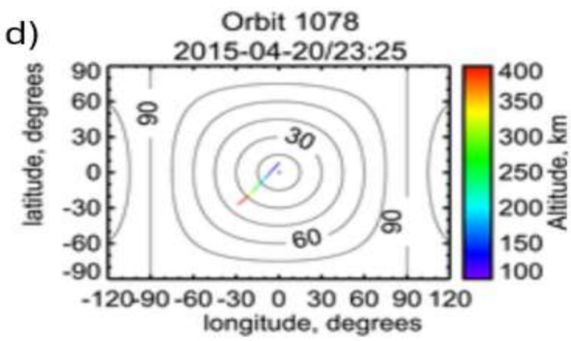

Figure 3(d): MAVEN orbit geometry in Mars–Solar–Orbital (MSO) coordinates for Orbit 1078 (2015-04-20, 23:25 UT), showing spacecraft latitude and longitude coverage; the color-coded track indicates altitude along the orbit, with gray contours representing constant solar zenith angle. *Adapted from Lillis et al. (2017), JGR: Space Physics.*

Despite improvements in observational coverage, vertical transport mechanisms like eddy diffusion and wave propagation are still poorly constrained (Kuroda et al., 2022; Chaufray et al., 2023). These parameters are critical to determining how lower atmospheric moisture reaches the thermosphere and assessing the timing/intensity of photodissociation-driven escape. Finally, transient phenomena such as coronal mass ejections (CMEs), auroral precipitation, and regional dust events require real-time high-resolution models that most

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existing frameworks are ill-equipped to handle (Rahmati et al., 2016; Du et al., 2023). Answering these questions will require a combination of extended MAVEN data analysis, the development of real-time data-assimilative models, and new mission architectures capable of multi-point, vertical profiling (González-Galindo et al., 2024; Chaufray et al., 2023). Continued synergy between observational and theoretical work will be essential to resolve these uncertainties and refine our understanding of Mars's atmospheric evolution and its implications for past habitability (Bougher et al., 2015). The persistent escape of water-derived species-hydrogen, oxygen, and water vapor-from the Martian thermosphere remains a key driver of the planet's atmospheric loss and climate evolution. This review has synthesized recent findings from MAVEN's NGIMS instrument and complementary models to demonstrate how seasonal, solar, and dynamic atmospheric processes modulate escape fluxes in both neutral and ionized forms (González-Galindo et al., 2024; Cravens et al., 2017). The observed variability in escape, especially during perihelion and dust storm conditions, underlines the crucial role of vertical transport and photochemical interactions in connecting the lower and upper atmosphere (Fedorova et al., 2020; Kass et al., 2019; Chaffin et al., 2021). While significant progress has been made in validating theoretical models with in situ data, important uncertainties remain. These include the precise altitude of water vapor photolysis (Fedorova et al., 2020; Aoki et al., 2019), the role of crustal magnetic anomalies in ion escape (Lillis et al., 2015; Dong et al., 2015), and improved treatment of transient events and vertical mixing within atmospheric models (Erwin et al., 2021; Kuroda et al., 2022). Overcoming these challenges will require continuing to combine high-resolution observations with multi-fluid modeling and data-assimilation frameworks, (Bougher et al. 2015; Kuroda et al. 2022). Notably, determining the processes responsible for the atmospheric escape at Mars will elucidate not only the climatic history of the planet but also put it into perspective toward a better understanding of how other planets evolve and to what degree they might prove habitable, both in our solar system and beyond Jakosky et al. 2018.

4. Conclusion

The review summarizes, in detail, the NASA mission of MAVEN and highlights how its major payload suites-the Particles and Fields Package (PFP), the Remote Sensing Package (RSP), and the Neutral Gas and Ion Mass Spectrometer (NGIMS)- contribute to progressing the understanding of the Martian upper atmosphere and the long-term atmospheric escape. Combining in situ sampling, plasma diagnostics, and global ultraviolet imaging, the combined findings from published literature from MAVEN have shown that the dominant roles in shaping atmospheric escape involve solar forcing, seasonal dynamics, dust-driven circulation, and photochemical processes that control the escape of hydrogen, oxygen, and other volatile species. The NGIMS data, in particular, have transformed knowledge about the composition of thermosphere isotope ratios and variability during all events, including dust storms, while the PFP instruments characterize ion acceleration and solar wind interactions. IUVS covers the mapping of extended hydrogen and oxygen coronae that are linked with water loss. Key uncertainties persist: vertical transport, crustal magnetic field effects, and response of escape processes to transient solar events. The study concludes that continued synergy in observations, advanced multi-fluid and data-assimilative modeling, and future multi-point missions will be necessary to resolve remaining gaps in reconstructing full atmospheric evolution of Mars and its implications for planetary habitability.

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