SPACE WEATHER AT MARS: 4.5 YEARS OF MAVEN OBSERVATIONS. C. O. Lee[1], J.G Luhmann[1], B.M. Jakosky[2], D.A. Brain[2], J. S. Halekas[3], R.J. Lillis[1], S.M. Curry[1], E.M.B. Thiemann[2], J. Gruesbeck[4], [1]UC Berkeley Space Sciences Laboratory (clee@ssl.berkeley.edu), [2]Laboratory for Atmospheric and Space Physics, University of Colorado Boulder, [3]Department of Physics and Astronomy, University of Iowa, [4]NASA Goddard Space Flight Center,.

Introduction: The Mars Atmosphere and Volatile EvolutioN (MAVEN) spacecraft has been continuously observing the variability of solar soft X-rays and EUV irradiance, monitoring the upstream solar wind and interplanetary magnetic field conditions and measuring the fluxes of solar energetic ions and electrons since its arrival to Mars in September 2014. Relevant observations from the instrument suite include solar flare activity based on solar irradiance measurements by the solar Extreme Ultraviolet Monitor (EUVM), the fluxes of solar energetic particles accelerated by shocks at the Sun and in the heliosphere from the Solar Energetic Particle (SEP) instrument, the solar wind plasma parameters by the Solar Wind Ion Analyzer (SWIA) and the vector measurements of the interplanetary magnetic field (IMF) by the Magnetometer (MAG).

Such a comprehensive set of observations at Mars gives us the opportunity to better characterize the local EUV and solar wind conditions during active space weather periods and to analyze the response of the Martian system to the upstream disturbances. Some of the Mars-impacting space weather events observed by MAVEN include the heating of the neutral atmosphere triggered by large flares [1][2], the perturbation of the Martian system and ion escape enhancements due to the passage and interaction of an interplanetary coronal mass ejection (ICME) [3; 4], and the triggering of diffuse auroral emission in the lower Martian atmosphere due to the precipitation of electrons during a SEP event [5][6].

Thus far, the strongest space weather event observed by MAVEN occurred in September 2017, when a series of solar flares and CMEs erupted from the Sun. This series of solar activity impacted the local space environment at Mars, including the upper atmospheric heating by emissions from the X-class solar flare, high fluxes of solar energetic particles (SEPs) impacting the atmosphere and reaching the surface, bright emissions of a diffuse (global) aurora, and observation of a Forbush-like decrease in the radiation environment due to the encounter of Mars with the ICME [4; and references therein].

Overview of the upstream space weather observations: Figure 1 shows the upstream solar wind conditions observed by MAVEN to date (November 2014 to the end of March 2019). This period corresponds to the end of the maximum phase through the (ongoing) minimum phase of Solar Cycle 24 (hereafter, SC 24), as indicated by the monthly sunspot numbers versus time shown in Figure 1a. Figures 1b-1d show the orbit-

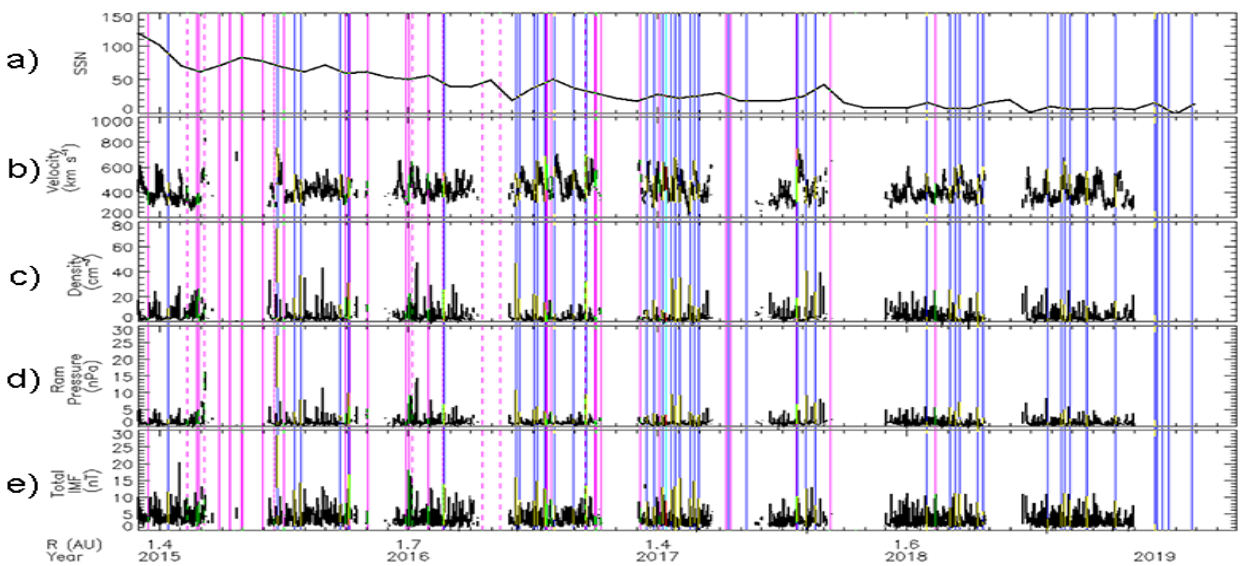

Figure 1. (a) NOAA monthly mean sunspot numbers (SSN) from November 2014 to the end of March 2019, corresponding to the end of Solar Cycle 24 maximum phase to the ongoing minimum phase. (b to e) 4.5 years of MAVEN observations of the solar wind speed, density, dynamic pressure and IMF magnitude. The solid magenta (blue) vertical lines mark the CMEs (CIRs) that impacted Mars.

averaged MAVEN/SWIA upstream solar wind speed, density, and dynamic pressure measurements together with the total IMF magnitude measured by MAVEN/MAG. The vertical lines shown in this figure give an indication to the types of space weather activity that dominates the solar cycle phases and experienced by Mars, such as impacts by ICMEs (magenta) during the SC 24 maximum phase and corotating solar wind streams (blue) during the SC 24 declining-to-minimum phase. In general the modestly active SC 24 maximum produced generally weaker solar events and heliospheric conditions, in comparison to the activity of SC 23 (e.g., the 2003 the Halloween Storm).

An extreme space weather event at Mars: On 10 Sept 2017 during the declining-to-minimum phase of SC 24, active region 12673 (AR2673) produced some strong solar activity, including an X8.2 class flare and a fast (~3,300 km/s) and wide CME. Although AR2673 was not centrally facing Mars (~67°E from the Sun-Mars line), the solar events greatly impacted the local space environment at Mars. The space weather effects at Mars were simultaneously observed by instruments across several Mars missions, MAVEN, Mars Science Laboratory (MSL), Mars Express (MEX), Mars Odyssey (MO), and also Trace Gas Orbiter (TGO). Numerical results for the event period from the Wang-Sheeley-Arge (WSA)-Enlil coupled solar corona-solar wind model (hereafter, WSA-Enlil) were used to illustrate the global context of the solar and heliospheric sources of

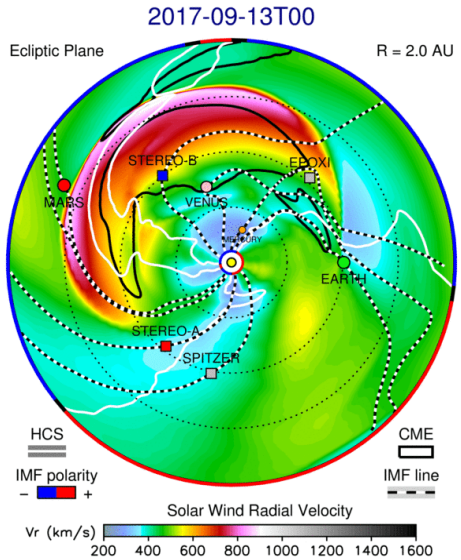

Figure 2. WSA-Enlil simulation snapshot showing the arrival at Mars of a merged structure of three CMEs (black contour lines) that erupted in succession from one active region at the Sun on 9-10 September 2017. The colors shown are the modeled solar wind speeds in the ecliptic plane. Figure adapted from [4].

the space weather conditions observed at Mars during this event period. Figure 2 shows a WSA-Enlil simulation snapshot of the solar wind speeds in the ecliptic plane. The black contour lines illustrate the modeled ICME structure that impacted Mars on 13 Sept 2017.

Figure 3 shows the upstream observations by MAVEN during this event period. The top panel shows the MAVEN/EUVM observations of the solar irradiance, where the detected peak irradiance is associated with the X8.2 solar flare event. The following three panels show the high energy SEP protons (15 to 220 MeV) and lower energy SEP protons (20 keV to 6 MeV) and electrons (20 keV to 200 keV) detected by MAVEN/SEP. The fifth panel shows the upstream solar wind dynamic pressure measured by MAVEN/SWIA (red dots) overplotted with the modeled values (black line). The bottom panel shows the magnetic field topology (closed, open, draped) derived from the photoelectron measurements by MAVEN/SWEA.

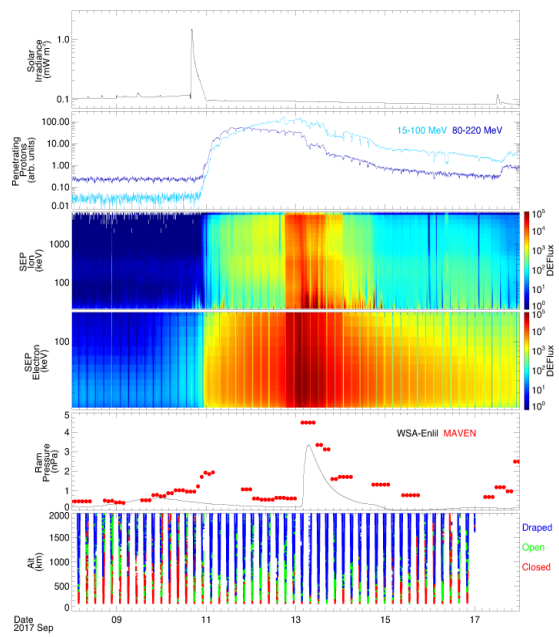

Figure 3. MAVEN observations of the space weather activity that erupted from the Sun on 9-10 Sept 2017. Figure adapted from [4].

References: [1] Thiemann et al.. (2015) *JGR,* doi:10.1002/2015GL066334. [2] Thiemann et al.. (2018) *GRL,* doi:10.1002/2015GL066334". [3] Jakosky et al. (2015), *Science*, doi:10.1126/science.aad0210. [4] Lee et al. (2018), *GRL*, doi:10.1029/2018GL079162. [5] Schneider et al. (2015), *Science*, doi: 10.1126/science.aad0313. [6] Schneider et al. (2018), *GRL*, doi: 10.1029/2018GL077772.