MOON'S POLAR ICE AND HEMATITE: A CONSEQUENCE OF ANCIENT LUNAR DYNAMO. C. Dong[1], J. L. Green[2], L. Wang[1], D. S. Draper[2], M. Lingam[3,4], N. Liu[5], and S. A. Boardsen[6,7], [1]Princeton University (dcfy@princeton.edu), [2]NASA Headquarters, [3]Florida Institute of Technology, [4]Harvard University, [5]Washington University in St. Louis, [6]NASA Goddard Space Flight Center, [7]University of Maryland, Baltimore

Introduction: Water has been unambiguously detected on the Moon through both remote sensing and sample analysis [1,2]. Limited evidence, which mainly consists of D/H data for lunar samples, exists in the literature for tracing the origin of lunar water, based on which several sources have been proposed, including interior water [3], hydrated impactors [4], and solar wind implantation [5]. Remote sensing data have revealed a large gradient for water distribution on the Moon, with the majority of water concentrated in the polar regions as polar ice caps [2].

The origin of the polar ice caps remains controversial: although hydrated impactors and water migration have been proposed as potential mechanisms, their efficiencies and the resultant distribution of water remain unknown. It is therefore unclear if these processes can truly account for the observed water abundance patterns in the polar regions. Aside from water, the ferric mineral hematite has been exclusively concentrated near the polar regions [6]. The significance of hematite stems from the fact that it might provide insight into both oxidation processes on the lunar surface (which is highly reducing) and the evolution of Earth's atmosphere because it is suspected that the latter supplied the oxidants necessary to form the hematite [6]. In this study, we propose a novel mechanism for the formation of polar ice and hematite by considering and modeling self-consistent magnetic field interactions between the Moon and Earth immersed in the solar wind based on sophisticated three-dimensional (3-D) magnetohydrodynamic (MHD) simulations.

Although currently lacking an active dynamo, the Moon used to possess a dynamo magnetic field lasting from at least 4.2 until <2.5 billion years ago (Ga), as per magnetic measurements of Apollo samples and lunar meteorites [7,8]. During much of this period, the lunar dynamo was operational with surface field intensities of several tens of microtesla, which is comparable to Earth's present-day value (~31 µT at the equator). Under the influence of the solar wind, the lunar global magnetic field and its interaction with Earth's magnetic field at ancient times could have played a critical role in driving water and hematite formation on the Moon. The chief reason is that protons, one of the two ingredients for forming water, can be transported from solar wind to the lunar surface. The incident solar-wind protons are likely to combine with oxygen in lunar crusts, and/or escaping oxygen ions from Earth's upper atmosphere, to form water at high efficiencies. Given the oxygen isotopic similarities between the Moon and Earth, the occurrence of latter (delivery of oxygen ions from Earth to the Moon) is strongly favored and may have functioned as an oxidant to facilitate the synthesis of hematite. In this scenario, the magnetic field configuration of the Earth-Moon system determines the deposition and distribution of the implanted ions, and thus the synthesis of water and hematite on the Moon.

Method: Here we employ the state-of-the-art BATS-R-US multifluid MHD model that has been applied to study a number of planetary objects, e.g., Earth, Venus, Mars, and exoplanets [9,10,11]. We simulated the interaction between a large coronal mass ejection (also known as solar storm) and the entire magnetized Earth-Moon system at ~4 Ga, aimed at determining the associated H^+ and O^+ fluxes incident on the lunar surface. The large coronal mass ejection was approximated by an extreme "Carrington-type" space weather event [11]. The timeline of ~4 Ga was chosen because the polar ice caps have been inferred to be ancient (≥3 Ga) according to Chandrayaan-1 observations and the ages of polar craters [2]. Furthermore, during this epoch the young Sun was magnetically very active – large solar storms are expected to have erupted on a daily basis.

Results and Discussion: The results concerning atmospheric escape from Earth are depicted in Figure 1, which shows the calculated oxygen ion density with the associated magnetic field lines in the meridional plane for the case when the Moon is in Earth's magnetotail. Compared with normal solar wind conditions, the oxygen ion escape rate is enhanced by three orders of magnitude ($\sim10^{28}$ s^{-1}) due to the strong solar storm pressure and extreme ultraviolet radiation at ~4 Ga.

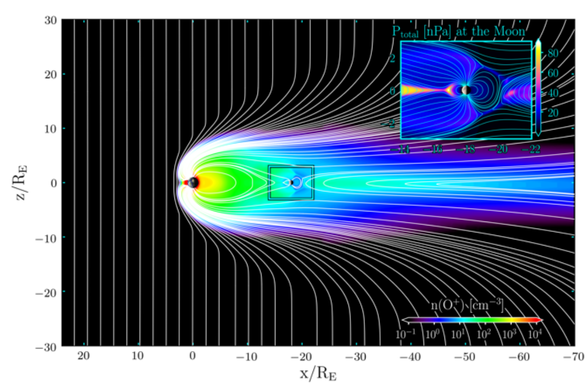

Figure 1: Logarithmic scale contour plots of the O^+ ion density (units of cm^{-3}) with magnetic field lines (in white) in the meridional plane. Zoomed-in subdomain shows the total pressure (units of nanopascal or nPa) around the Moon when it is in the magnetotail of Earth.

Figure 2 depicts the magnetized Earth-Moon system during the solar storm at ~4 Ga. The top and bottom panels illustrate the scenarios when the Moon is situated in front of and behind Earth, respectively. A comparison between the two cases illustrates that the magnetized Moon effectively protects Earth from the impact of the solar storm as indicated by the total pressure ahead of Earth. When the Moon is located in the magnetotail of Earth, the magnetic fields of Earth and Moon are connected, enabling ionized O^+ ions to be transported from Earth's upper atmosphere to the lunar surface.

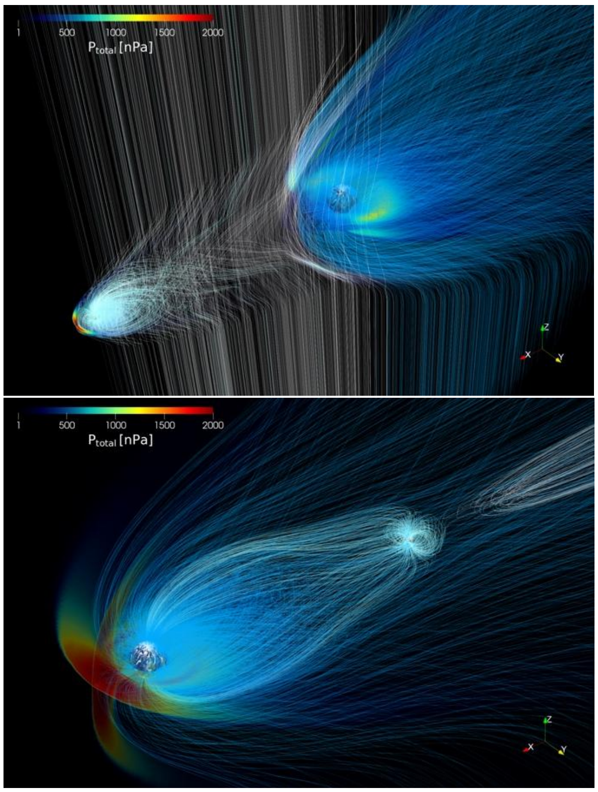

Figure 2: Three-dimensional magnetized Earth-Moon system during an extreme "Carrington-type" space weather event (or solar storm) at ~4 Ga. The top and bottom panels show the cases when the Moon is situated in front of and behind Earth, respectively.

Figure 3 depicts the proton (top panel) and oxygen (bottom panel) ion fluxes (units of $m^{-2}\ s^{-1}$) on the lunar surface when the Moon is in the magnetotail of Earth. These proton and oxygen ions are mainly concentrated toward the lunar polar surface due to the fact that charged particles generally move along the magnetic field lines. Polar water or ice can form as a result of the implanted H^+ and O^+. Meanwhile, oxygen delivered from Earth's upper atmosphere could be the major oxidant that stimulates lunar hematite formation.

Conclusion: For the first time, we presented sophisticated multifluid MHD simulations including the entire magnetized Earth-Moon system for the H^+ and O^+ fluxes incident on the lunar surface during an extreme "Carrington-type" space weather event (or solar storm) at ~4 Ga. The much higher solar storm proton fluxes and amplified escape rates of oxygen ions from Earth's upper atmosphere translate to high incident fluxes of H^+ and O^+ at the lunar polar surfaces, thereby potentially driving the formation of the majority of water and hematite on the Moon, especially at the poles. We demonstrated that the existence of ancient polar ice caps and hematite is, in fact, a natural consequence of the enhanced solar activity and the intricate magnetic field configuration of the Earth-Moon system at this early epoch.

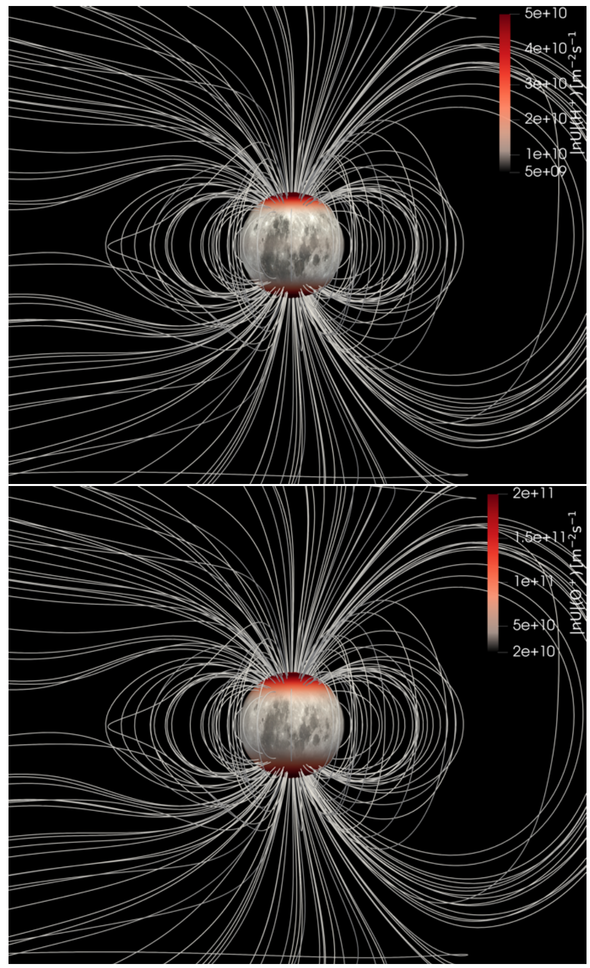

Figure 3: Proton (top panel) and oxygen (bottom panel) ion fluxes (units of $m^{-2}\ s^{-1}$) on the lunar surface when the Moon is in the magnetotail of Earth.

References: [1] Tartese A. M. et al. (2014) *Phil. Trans. R. Soc. A*, *372*, 20130254. [2] Li S. et al. (2018) *Sci. Adv.*, *115*, 8907–8912. [3] Hui H. et al. (2013) *Nat. Geosci., 6*, 177–180. [4] Daly R. T. & Schultz P. H. (2018) *Sci. Adv.*, *4*, eaar2632. [5] Liu Y. et al. (2012) *Nat. Geosci.*, *5*, 779–782. [6] Li S. et al. (2020) *Sci. Adv.*, *6*, eaba1940. [7] Mighani S. et al. (2020) *Sci. Adv.*, *6*, eaax0883. [8] Green J. et al. (2020) *Sci. Adv.*, *6*, eabc0865. [9] Dong C. et al. (2018) *PNAS*, *115*, 260–265. [10] Dong C. et al. (2018) *ApJL*, *859*, L14. [11] Dong C. et al. (2017) *ApJL*, *847*, L4.