**Possible formation mechanism of lunar hematite.** Yue Fu[1] , Huizi Wang[1] , Jiang Zhang[1] , Jian Chen[1] , Quanqi Shi[1] , Chao Yue[2] , Honglei Lin[3] , Ruilong Guo[1] , Anmin Tian[1] , Chao Xiao[1] , Wensai Shang[1] ; [1]Chinese Ministry of Education Key Laboratory of Particle Physics and Particle Irradiation, Shandong Provincial Key Laboratory of Optical Astronomy and Solar-Terrestrial Environment, Institute of Space Sciences, School of Space Science and Physics, Shandong University; 180 Wenhua Xilu, Weihai, Shandong, China(zhang_jiang@sdu.edu.cn; whz@mail.sdu.edu.cn); [2]Institute of Space Physics and Applied Technology, Peking University; No.5, Yiheyuan Road, Haidian District, Beijing, China; [3]Institute of Geology and Geophysics, Chinese Academy of Sciences; 19 Beitucheng West Road, Chaoyang District, Beijing, China

**Introduction:** As a magnetic field-weak and airless body, the Moon is directly irradiated by solar wind, Earth wind, and (micro)meteoroids. Understanding the formation processes of hematite on the Moon not only deepens our understanding of the interaction between solar/Earth wind and lunar surface but also might be useful in constraining when the geomagnetic field arose and has important scientific value for studying the evolution of the Earth-Moon system [1].

During about three-quarters of the lunar orbit, the Moon is immersed in the solar wind, which contains predominant protons, 1%–5% alpha particles, and other heavy ions (oxygen abundance < 0.1%)[2], depending on solar wind speed, heliographic latitude, and solar cycle[3]. During the remaining 3–5 days of each lunar lunation, the Moon is in the Earth’s magnetosphere. When the Moon is in the magnetosphere, some terrestrial ions may be transported from Earth's ionosphere and upper atmosphere to the Moon, which is called “Earth wind” [1].

Recent studies have shown that, compared to the solar wind, the flux of oxygen particles is much higher in the Earth wind [4], which may promote oxidization/oxyhydration processes. Li et al. (2020)[5] found the spectral absorption feature of hematite is around 850 nm, which is less affected by pyroxene or other common minerals. Through the study of the high-latitude datasets obtained by the Chandrayaan-1 Moon Mineralogy Mapper ($M^3$), the authors indicated that the absorption feature at 850 nm may indicate the existence of hematite, and the integrated band depth (IBD) between 750 nm and 1200 nm can characterize the relative concentration of hematite[5]. The oxygen from the Earth's ionosphere and upper atmosphere is possibly considered to be the oxidant in the hematite formation process, and the raw materials are ferrous iron or metallic iron on the lunar surface[5]. The hematite can be produced by a hydrothermal reaction on the Earth, in which $H_2O$ plays a significant role[6]. Honniball et al.(2022)[7] mapped the molecular water at high southern latitudes on the Moon and discovered a high-latitude water-bearing mineral host that may be a precursor to recently detected high-latitude hematite. Previous studies have shown that the IBDs of hematite have very weak latitudinal dependence[5]. Li et al. (2020) [5] proposed both aqueous and anhydrous mechanisms of hematite formation and pointed out that water can promote the reaction of the oxidation and oxyhydration processes but didn’t give specific evidence about it. In this study, we intend to further analyze the possible formation mechanisms of hematite.

**Methods:** We analyzed the data atlatitudes above 70° within a lunation from May 24, 2009 to June 21, 2009, during which the $M^3$ has wider coverage. We analyzed the data in a lunar cycle, as the IBD data can be affected by the observation conditions such as local time. The polar regions were divided into a grid of 5°(longitude)* 15°(latitude) and the mean value in each subregion is used to characterize the physical and chemical properties of the subregion.

For the content of hematite, we used the method of Li et al. (2020) [5], proposing that the lower spectral reflectance at 850 nm corresponds to higher abundances of hematite and using the ISSD (the integral of squared second derivatives) method to remove the $M^3$ spectra with the high noise level. Since the absorption feature of pyroxene occurs near 950 nm, the widespread presence of pyroxene on the Moon may affect the IBD calculation of hematite. To reduce the influence of pyroxene on the results, we used the spectra between 750 nm and 1000 nm to calculate the IBD parameter as the relative content of hematite. It should be noted that since the hematite on the Moon is rare, its abundance on the Moon is not yet clear, and the corresponding relationship between the IBD and its absolute abundance requires further instrumental calibrations or research on returned samples. The IBD of hematite represents only the relative content of hematite, which is referred to as the content of hematite in this work.

**Results and Discussion:** Here we present the hematite, water, ferrous iron, and nanophase metallic iron abundances (Figure 1) obtained from Chandrayaan-1 and Lunar Prospector datasets to discuss the possible formation processes of hematite involving the role of water. Figure 1 shows the mean content of different compounds in the high latitudes of the Moon with a grid of 5 °(longitude)* 15°(latitude). As shown in Figures 1a and 1b, we find that hematite content has a strong latitude dependence. The content of hematite increases with increasing latitude. The $OH/H_2O$ concentration also increases with the increase of latitude (Figures 1c and 1d), which is consistent with the previous study[8]. Then we calculate the variation of ferrous iron abundance at the high latitudes of the lunar surface (Figures 1e and 1f), but did not find a latitude-dependence. We also use the data of nanophase metallic iron amount calculated by Lemelin et al. (2022) [9]and analyze the amount of nanophase iron in the high latitudes of the lunar surface (Figure 1g and 1h). The amount of nanophase iron decreases with increased latitude. Previous studies have shown that magnetospheric ions or protons are almost isotropic[10]. So we suggested that the oxygen particles implanted into the lunar surface may be independent of the lunar latitude. Therefore, we suggest that the latitude dependence of hematite may be caused by the latitude dependence of water.

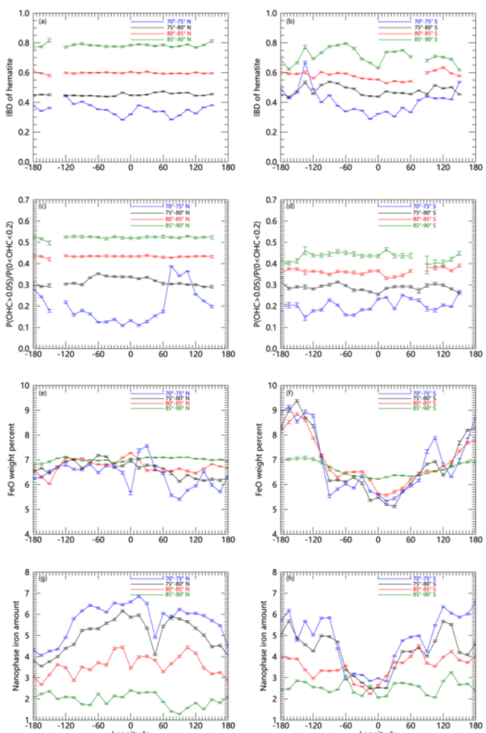


Figure 1. Content of different materials in the high latitudes of the Moon with a grid of 5 °(longitude)* 15°(latitude) and the mean value is used in each region. (a-b) The IBD of hematite. (c-d) The probability of 2.8 μm absorption depth between 0.05 and 0.2 represents the $OH/H_2O$ abundance level. (e-f) FeO weight percent (g-h) Nanophase iron amount.

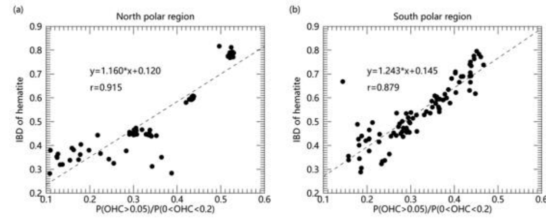


Figure 2. Comparison of hematite with water concentrations in the polar regions. ((a) northern polar region (b) southern polar region). The equations in the figure show the result of linear regression fit and R in the figure represents the linear correlation coefficient between two variables.

In order to reveal the role of water in the hematite formation, we also carry out the correlation analysis of hematite and water in the polar regions (Figure 2). The results show that there is an obvious positive correlation between the content of hematite and water concentration. It indicates that water may play an essential role in the formation process of hematite.

**Acknowledgments:** We thank all the members of the Chandrayaan-1 $M^3$ and Lunar Prospector instrument teams. The $M^3$ data were downloaded from the Planetary Data System (http://pds-imaging.jpl.nasa.gov/data/m3/).

**References:**

[1] Ozima, M.; Seki, K.; Terada, N.; Miura, Y.N.; Podosek, F.A.; Shinagawa, H. (2005) Nature, 436, 655–659 [2]Hundhausen, A.J. (1970) Reviews of Geophysics, 8, 729–811. [3]Kasper, J.C.; Stevens, M.L.; Lazarus, A.J.; Steinberg, J.T.; Ogilvie, K.W. (2007) ASTROPHYSICAL JOURNAL, 901–910. [4] Terada, K.; Yokota, S.; Saito, Y.; Kitamura, N.; Asamura, K.; Nishino, M.N. (2017) Nat Astron, 1. [5] Li, S.; Lucey, P.G.; Fraeman, A.A.; Poppe, A.R.; Sun, V.Z.; Hurley, D.M.; Schultz, P.H. (2020) Sci. Adv, 6. [6] Sun, W.; Huang, R. fang; Li, H.; Hu, Y. bin; Zhang, C. chan; Sun, S. jun; Zhang, L. peng; Ding, X.; Li, C. ying; Zartman, R.E.; et al. (2015) Ore Geol Rev, 65, 97–131. [7]Honniball, C.I.; Lucey, P.G.; Arredondo, A.; Reach, W.T.; Malaret, E.R. (2022) Geophys Res Lett, 49. [8] Jones, B.M.; Aleksandrov, A.; Hibbitts, K.; Dyar, M.D.; Orlando, T.M. (2018) Geophys Res Lett, 45, 10,959-967 [9] Lemelin, M.; Lucey, P.G.; Camon, A. (2022) Planet Sci J, 3, 63.[10] Harada, Y.; Futaana, Y.; Barabash, S.; Wieser, M.; Wurz, P.; Bhardwaj, A.; Asamura, K.; Saito, Y.; Yokota, S.; Tsunakawa, H.; et al. (2014) J Geophys Res Space Phys, 119, 3573–3584.