WATER IN LUNAR HOLES? Junichi Haruyama[1], Tomokatsu Morota[1], Motomaro Shirao[2], Harald Hiesinger[3], Carolyn H. van der Bogert[3], Carle M. Pieters[4], Paul G. Lucey[5], Makiko Ohtake[1], Masaki Nishino[1], Tsuneo Matsunaga[6], Yasuhiro Yokota[6], Hideaki Miyamoto[7], and Akira Iwasaki[7], [1]ISAS, JAXA, Japan, [2]Taito-ku, Tokyo 111-0035, Japan, [3]Westfälische Wilhelms-Universität, Germany, [4]Brown University, USA, [5]University of Hawaii, USA, [6]NIES, Japan, [7]The University of Tokyo, Japan. (e-mail:Haruyama.junichi_at_jaxa.jp)

Introduction: Recently, three spacecraft (Chandrayaan, Cassini, and Deep Impact) detected adsorbed hydroxyl and/or water (up to several hundred ppm) over almost the entire lunar surface based on near-infrared spectroscopic observations [1-3]. The hydroxyl and/or water probably originated from solar wind proton implantation [4-6]. Water molecules formed at lower latitudes may migrate to higher latitudes and be trapped in cold areas [4-7]. Therefore, permanently shadowed areas (PSAs) of the lunar polar regions have been regarded as possible reservoirs of water on the Moon. Ground-based observations [8-10] and optical investigation by the Terrain Camera (TC) [11] on the Japanese lunar orbiter SELENE (nicknamed Kaguya, launched in 2007) indicated very low to no possibility of water ice at the floor surface of the south-pole Shackleton crater, whereas the Clementine bastatic radar experiment suggested the presence of water ice in such craters [12]. Recently, the near-infrared spectroscopy instrument on board the LCROSS spacecraft successfully detected a water plume after the Centaur impact on a target in a PSA of the Cabeus crater [13]. Thus water could be buried in the polar regions, although it is not visible at the surface. If solar wind proton implantation is a realistic phenomenon on the Moon, the deep lunar holes discovered by the TC could also be good reservoirs of water on the Moon.

Deep Holes on the Moon: The first deep hole discovered in the 10 m resolution TC data is located at (303.3°E, 14.2°N), in the Marius Hills of the Oceanus Procellarum [14]. Two additional large, deep holes (~100 m of diameter and ~50 – 100 m of depth) were discovered by a global survey of a TC dataset with solar elevation angles exceeding 40 degrees in which deep holes are recognized as completely dark spots [15]. The newly discovered holes are located at Mare Tranquillitatis (33.2 °E, 8.3 °N) and at Mare Ingenii (166.0 °E, 35.6 °S)(Fig. 1). These are possible skylights of lava tubes [14, 15]. Subsequently, the Narrow Angle Camera on the Lunar Reconnaissance Orbiter that was launched in 2008 successfully imaged the holes with 0.5 - 1m resolution (Fig. 2). LRO found additional smaller pits of a few tens of meters in diameter (see LROC Home Page). There may be numerous other shallower and smaller pits. However, the TC data with solar elevation angles exceeding 40 degrees covered more than 95% of the lunar mare regions. Therefore, large hole structures of several tens of meters in diameter or larger are probably rare.

Water on the floors of lunar holes?: As Haruyama et al. [15] suggested, if the holes opened simultaneously with or just after the formation of surrounding surfaces (the ages of MHH, MTH, and MIH are 3.5Gyr [14], 3.7Gyr [16], and 3.2Gyr [17], respectively), and the solar proton flux was similar to the current flux of 4×10^8 /cm^2/sec [6], the maximum integrated amount of protons inside MHH, MIH, and MIH and their connected lava tubes would be 5.2×10^2, 1.6×10^3, and 1.1×10^3 tons, which would correspond to water of 4.7×10^3, 1.4×10^3, and 9.8×10^3 tons. (These values have been re-estimated from [15].) While these abundances are not entirely protected from loss, the holes are possibly better reservoirs of H^+ and/or H_2O molecules than the lunar surface for several reasons. First, angles through which trapped molecules on the bottoms of the holes can escape to space are smaller than the 2π at the surface. Second, there are some areas within theholes that are reached by solar wind protons but not UV radiation. Third, small dust particles ejected from the inner walls of holes by micrometeorite impacts have continuously fallen to the bottoms of the holes and prevented H^+ and/or H_2O molecules from being destroyed by UV and escaping to space. Fourth, more mild temperatures of shadowed floors of the holes would retain more H^+ and/or H_2O molecules than at the surface. Fifth, H^+ and/or H_2O molecules may have diffused into possible connecting lava tubes and deposited there.

Determining the origin of water on the Moon is a siginicantly interesting objective. Comets, meteorites, and/or interstellar dust may have brought water to the Moon. In fact, materials of possibly cometary origin were reported in the plume from the LCROSS experiment [13, 18]. Solar wind protons do not contain deuterium, so the deuterium to hydrogen ratio of water trapped at the bottoms of the holes could be a clue to the origin of water on the Moon. Furthermore, it is important to study the rocks composing lava tubes that possibly connect to lunar holes when considering water on the Moon. Such rocks have not been subjected to solar wind implantation or meteorite impacts. Therefore, any water contained in the rocks probably originated from the lunar interior.

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. **References:** [1] Pieters, C.M. et al. (2009), *Science* 326, 568, [2] Sunshine, J.M. et al. (2009), *Science* 326, 564, [3] Clark, R.N. (2009), Science 326, 562, [4] Watson, K. et al. (1961) *JGR* 66, 3033, [5] Arnold, J. R. (1979), *JGR*. 84, 5659, [6]Starukhina L.V. and Y.G. Shkuratov (2000), *Icarus* 147, 585, [7] Butler B.J. (1997), *JGR* 102, E8, 19283, [8] Stacy N.J.S. et al. (1997), *Science* 276, 1527, [9] Campbell, B.A. et al. (2003), *Nature* 426, 137, [10] Campbell, D.B. et al. *Nature* 443, 835, [11] Haruyama, J., et al. (2008), *Earth Planets, Space* 60, 243, [12] Haruyama, J. et al. (2009), *Science* 322, 938, [13] Colaprete, A., et al., (2010), Science 330, 463, [14] Haruyama, J. et al. (2009), *GRL* 36, L21206, doi:10.1029/2009GL040635, [15] Haruyama, J. et al. (2010), LPSC #1285, [16] Haruyama, J. et al. (2008), Science 323, 905. [17] Hiesinger, H. et al. (2000), *JGR* 105, 29239, [18] Goldstone, G.R. et al. (2010), Science 330, 472.

LINK: LROC Home Page (for small pits) http://lroc.sese.asu.edu/news/index.php?/archives/253-How-Common-are-Mare-Pit-Craters.html

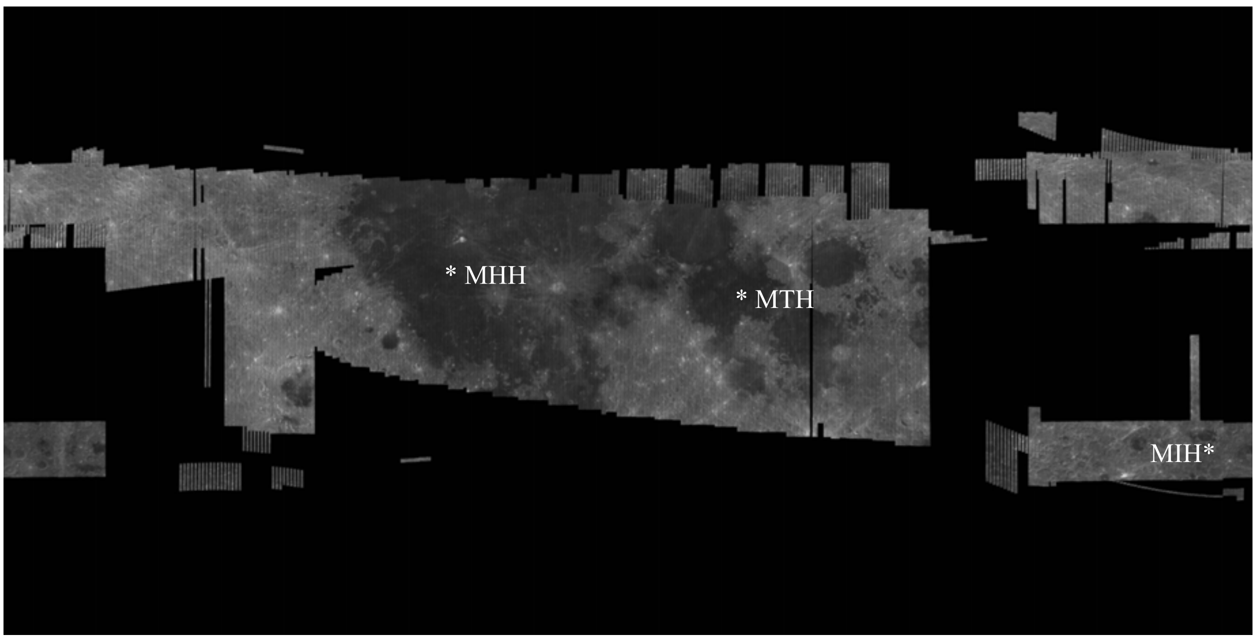

Figure 1. The locations of three lunar holes; Marius Hills Hole, Mare Tranquillitatis Hole and Mare Ingenii Hole are indicated by *MHH (303.3 °E, 14.2 °N), *MTH (33.2 °E, 8.3 °N), and *MIH(166.0 °E, 35.6 °S,). The back-ground is the SELENE Terrain Camera observation coverage at solar elevation angles > 40°. (from Haruyama et al. 2010[14])

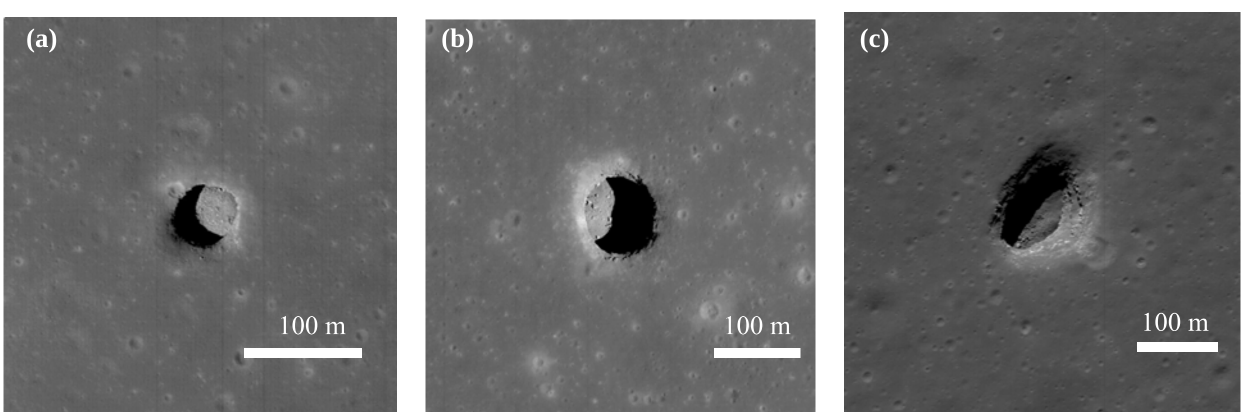

Figure 2. Images of lunar holes taken by LRO Narrow Angle Camera: a) MHH (image ID: M122584310L), b) MTH (image ID: M126710873R), c) MIH (image ID: M123485893R). Based on shadow measurements, the depths from inner edges of holes are estimated to be ~45m, ~105m, and ~ 45m for MHH, MTH, and MIH, respectively.