Location of water deposits in the polar regions of the Moon. Gunther Kletetschka [1, 2*], Jaroslav Klokočník [3], Nicholas Hasson [1, 4] Jan Kostelecký [5, 6], Aleš Bezděk [3, 7], and Kurosh Karimi[2], [1]Geophysical Institute, University of Alaska, Fairbanks, 903 N Koyukuk Drive, Fairbanks, AK, USA, gkletetschka@alaska.edu, [2]Institute of Hydrogeology, Engineering Geology and Applied Geophysics, Faculty of Science, Charles University, Albertov 6, 12000 Prague 2, Czech Republic, [3] Astronomical Institute, Czech Academy of Sciences, CZ 251 65 Ondřejov, Fričova 298, Czech Republic, [4] Water and Environmental Research Center, Institute of Northern Engineering, University of Alaska Fairbanks - Fairbanks, AK 99775 1764 Tanana Loop AK, USA, [5] Research Institute of Geodesy, Topography and Cartography, CZ 250 66 Zdiby 98, Czech Republic, [6] Faculty of Mining and Geology, VSB-TU Ostrava, CZ 708 33 Ostrava, Czech Republic, [7] Faculty of Civil Engineering, Czech Technical University in Prague, CZ 166 29 Praha 6, Czech Republic

Summary: The magnetic tail of the Earth that contains terrestrial ions of hydrogen and oxygen is periodically penetrated by the Moon's trajectory. This allows for ion transfer mechanism, a hypothesis that a part of the terrestrial atmosphere that was lost in the past is now preserved within the surface of lunar polar regolith. Using novel harmonic geopotential coefficients, we discovered gravity strike angle anomalies that point to frozen water locations in the polar regions of the Moon. Our analysis predicts that impact cratering processes were responsible for specific pore space network that were subsequently filled with the water filling volumes of permafrost in the lunar subsurface. In this work, we not only locate the regions of the water ice deposits but also predict the accumulation of up to ~3000 km3 of terrestrial water (Earth's atmospheric escape) now filling the pore spaced regolith, portion of which is distributed along impact zones of the polar regions of the moon. These unique locations serve as potential resource utilization sites for future landing exploration and habitats (e.g., NASA Artemis Plan objectives).
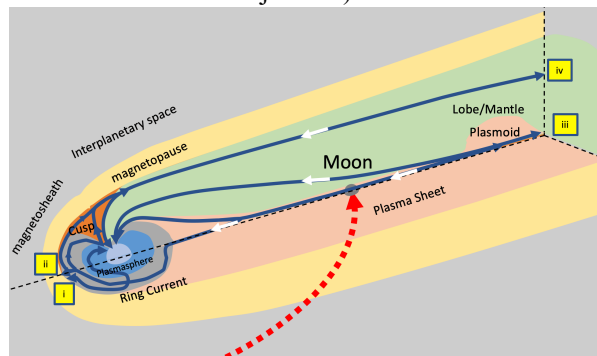

Fig. 1: A. Sketch showing three-dimensional cutaway of Earth's magnetosphere. The blue and white arrows are motion pathways of ions (for details see Seki et al, 20055) illustrating the mechanism for oxygen/hydrogen ions transfer to the Moon. Red dotted line with the arrow shows motion of the Moon into the magnetospheric tail. Escape locations into the interplanetary space is marked by locations i, ii, iii, iv.

Introduction: NASA's return to the lunar surface (i.e. Artemis Plan) requires mission planning for near

surface water ice resources [1]. The best knowledge, for these later known resource extraction sites, can be obtained from remote investigations. However, when applying remote sensing data (e.g. Gravity), the lunar hydrology and mechanisms of deposition is unlike contemporary earth analogues and recent advances allow new applications for assessing water ice resources. For example, the lunar surface regolith is coupled with ion-magnetohydrodynamical processes that may have contributed to the deposition of water ice formation on its surface and now deep permafrost. This is because the lunar environment is exposed for five days of each Earth orbit period to a magnetic field tail extending all the way from the Earth's geodynamo [2].

Ion transfer: While the loss of the ions from the atmospheres of terrestrial planets depends on processes at the atmosphere-surface interface, there is a significant loss mechanisms occurring in the upper atmosphere. This has to do with the presence of ionosphere enabling loss of ions due to space plasma acceleration mechanisms and can control the evolution of the atmosphere. Geomagnetic field creates an obstacle to the solar wind preventing a direct abrasion of terrestrial neutral ions (oxygens, hydrogens) via thermal and non-thermal activities. Four main pathways of terrestrial ions constitute of (i) magnetopause escape, (ii) magnetopause ring current dayside escape, (iii) antisunward flow escape, and (iv) lobe/mantle escape (Fig. 1). When ions are escaping via these pathways, they can be returned towards the earth and be added back to the atmosphere. This occurs when the collision-less path distance becomes small enough that plasma on this length scale dissipates and the geomagnetic field lines and plasma field lines become reconnected.

Gravity aspects: Underground density anomalies can be detected this way. The method was developed for the study of geological structures on the Earth (the impact craters, subglacial volcanoes, lakes, lake basins, paleolakes or oil&gas deposit sites around the world) and for the impact craters, maria and catenae on the Moon [3,4].

Gravity studies mostly apply the traditional gravity anomalies or second radial derivatives of the disturbing

gravitational potential. This work uses a wider set of functions of the disturbing gravitational potential, which we call "*gravity aspects*". These are derivation operators acting on the *gravity anomalies Δg*, the *Marussi tensor* (**Γ**); the second derivatives of the disturbing potential (T_{ij}), with the second radial component T_{zz} and the two of these three *gravity invariants* (I_j), given their *specific ratio* (*I*), the *strike angles* (θ), and the *virtual deformations* (*vd*). Our prior usage revealed their diverse sensitivity to the underground density contrasts, due to causative associations. Here, we compute these operators to a high degree and order with sufficient numerical stability. It appears that such application provides a clearer and more comprehensive data extraction from these satellite gravity measurements. Theory of this approach was outlined in the book of Klokočník et al [4], with further references and examples presented by our specific application that can use such method methods Moon exploration, provided in the Supplementary material.

Gravity data: The input data now uses harmonic geopotential coefficients of the spherical harmonic expansion to degree and order d/o of the perturbational gravitational potential (Stokes parameters). A set of these coefficients define a global static gravitational field. We use the best models available built from satellite records [5,6]. This defines the limits of d/o = 1200 and 1500 for the models GRGM1200A [5], and GL1500E [6] respectively, using the applied limit d/o = 600 (recommended by the authors of these models themselves). Application of these models allows for ~~the~~ theoretical ground resolutions of ~10 km. The precision is nearly 10 mGal. For this paper, we selected the GRGM1200A model (after performing tests concerning the degradation of gravity aspects for different harmonic degree and discovering the order and/or appearance of artifacts).

Results: We computed gravity aspects, namely the strike angles θ near the lunar poles - see Fig. 1 for the south pole region. We then used three color modes to express the degree of alignment of strike angles: green as misaligned, blue partially aligned, and red with high degree of alignment (Fig. 1).

Discussion and Conclusions: We applied gravity aspect analyses on the Moon. Calculation of theta angles (gravity strike angles) is sensitive to the anisotropy of the Moon's regolith. Our method detected specific regions near the north and south poles that point to the presence of significant volume of pore space. This pore space was likely formed by impact cratering processes over eons. Since the polar regions have been confirmed to accumulate water/ice deposits, it is then likely that these identified regions now hold significant amounts of water as ice, necessary for resource extraction in-situ and use during future planned missions (Artemis [1]).
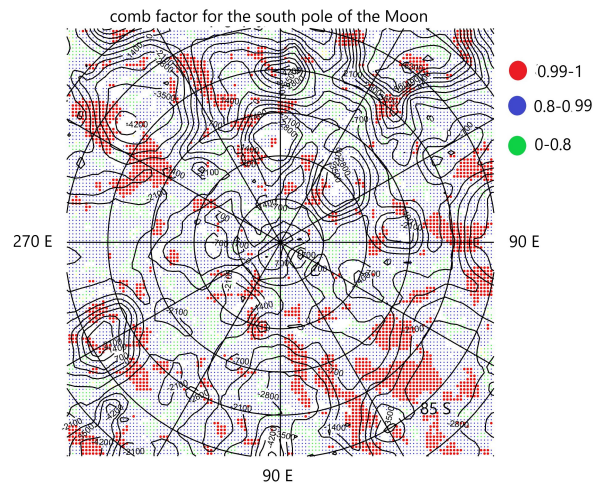

Fig. 1: Geophysics, and topography of the Moons south polar region. The plot characterizes the alignment of gravity strike angles (sensitive to significantly fractured regions), using a comb factor. When comb factor is near 1, the region contains significant pore space at depth that can be filled by volatile deposits.

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