Acta Physica Polonica B Proceedings Supplement **18**, 3-A1 (2025)

SELECTED ASPECTS OF PLANETARY PHYSICS*

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Received 7 April 2025, accepted 7 April 2025,
published online 29 April 2025

We give an overview of Polish activities in planetary physics, based on contributions presented at the National Mars Science Seminars and the Planetary Science Conference held at the Jagiellonian University in Kraków since 2019. During the five editions of the conference, about 50 presentations were discussed showing how robust and important the role of the Polish scientific community in planetary science is.

DOI:10.5506/APhysPolBSupp.18.3-A1

1. Introduction

At present, planetary science is one of the fastest developing and most interdisciplinary branches of science. This fast development is only possible due to modern planetary space missions. As planetary space missions have been acquiring large volumes of very specific data, new techniques and tools have been developed to process and analyze such datasets. Planetary physics not only helps us better understand the universe, but also prepare and test approaches for future space exploration. This overview focuses on the physics of the Moon, Mars, and Ceres. These three objects represent the most important types of bodies in the Solar System: a planet, a moon, and a dwarf planet. For these three objects, selected Polish achievements

* Presented at the Planetary Science Conference, Kraków, 11 October, 2024.

based on the past and ongoing planetary space mission data are presented. Also, concepts of planetary space missions to the Moon and Mars in which Polish scientists are participating are described.

2. Selected aspects of the Moon, Mars, and Ceres physics

2.1. Contributions to regolith studies

Regolith is an unconsolidated deposit, composed of dust, sand, gravel, and fragments of rocks, covering all planetary bodies that have a solid surface. Studies on regolith are essential for understanding the interactions between regolith and anthropogenic objects that are located in a lower atmosphere, on a surface, or under a surface. For example, areas covered by fine-grained deposits are difficult to cross by wheeled vehicles (see *e.g.*, [1]). Furthermore, regolith is one of the most important and easily accessible sources of mineral and water resources needed for further space exploration (see *e.g.*, [2, 3]).

To study regolith, it is convenient to use automatic or semi-automatic methods of image segmentation. For example, the semi-automatic PArticle Detection and Measurement algorithm [4] allowed for an investigation of all regolith images acquired by the Microscopic Imager [5] of the NASA Mars Exploration Rover Opportunity mission on Mars in the region of Meridiani Planum. The results showed that on the surface of Meridiani Planum fine sand grains (< 0.25 mm in diameter) are trapped under a gravel lag deposit (grains > 2 mm). Furthermore, on the plains of Meridiani Planum, no medium sand grains (0.25 to 0.50 mm) were found [6], although such sands are abundant inside large impact craters on Mars (see *e.g.*, [7, 8]). Therefore, there is a selective aeolian (wind) sorting of sand on Mars that leads to the deposition of medium sand grains, the most susceptible to wind transport, inside larger craters (≥ 100 m in diameter [6]). The coarse sands (0.5–2.0 mm) on the plains of Meridiani Planum originate mainly from iron-rich spherules, which are very common in this area. Spherules are round grains of several millimeters in diameter.

Martian spherules that were discovered on Meridiani Planum are concretions, but the conditions in which they were formed are still unknown [9]. Therefore, three types of terrestrial concretions were analyzed as analogs of Martian ones: *(i)* Utah concretions from the Dakota Formation (Cretaceous), *(ii)* Utah Navajo Formation concretions (Jurassic, [10]), and *(iii)* Romanian "Trovants" concretions (Miocene–Neogene). A common feature of Martian and terrestrial concretions is a similar ferric and sulphate mineralization. Therefore, we consider that Martian spherules and studied terrestrial concretions have probably formed in similar environments and that water was responsible for their formation [11, 12]. Copper was found in the

Navajo concretions, some Dacota concretions are mineralized with copper compounds [13], and ilmenite and rutile (sources of titanium) were found in Romanian concretions [14]; Martian spherules may thus accumulate important mineral resources and become a significant focus in future exploration of Mars.

We also considered whether the spectral characteristics of the Mars regolith may hinder remote detection of methane. A series of numerical simulations were carried out in the spectral range of the strong methane absorption band with different surface mineralogical compositions [15]. In the studies, a dolomite was considered as the surface mineral, as such a component makes methane detection more difficult. It was shown that the shape of the reflectance spectrum of the surface can significantly alter the absorption band of trace gases (*e.g.*, methane) in the atmosphere, especially if the reflectance features overlap with the central part of the band of the studied gas. The nature of the signal also depends on changes in the thermodynamic parameters of the atmosphere through which the signal passes. The effect of the variability of these factors and of the dust with various mineralogy present in the atmosphere should be further analyzed [15].

2.2. Studies on aeolian processes on Mars

Aeolian (wind) processes play a dominant role on present-day Mars. These processes form aeolian landforms and are responsible for dust storms. One of the most common aeolian landforms are ripples, which are ridges formed by the accumulation of sand or gravel grains by wind. The results of the investigations by the rovers in various regions of Mars indicated that at least two types of ripples are formed due to interactions between the surface and atmosphere of Mars: fine-grained ripples and coarse-grained ripples. The fine-grained ripples are covered by grains up to < 0.5 mm in diameter, and the coarse-grained ripples are armored by grains > 0.5 mm in diameter [16]. As the coarse-grained ripples on Earth are very rare (see *e.g.*, [17]), those observed on Mars are of particular interest. These ripples in large numbers are present on Meridiani Planum. Extensive investigation of these ripples revealed that they are covered by grains of about 1.3 mm in diameter. The height of these ripples varies from centimeters to tens of centimeters [16]. The orientation of the crests of larger ripples indicates the direction of paleowinds that blew 10 to 100 ka ago [18], but the crestline azimuths of the centimeter-sized ripples show modern wind directions [16].

In the locations investigated *in situ* by the rovers and landers on Mars: Gusev Crater, Gale Crater, Jezero Crater, and Elysium Planitia, no seasonality of aeolian landforms was observed, indicating that even if the wind changes direction during a Mars year, its intensity and/or frequency is not sufficient to change the orientation of aeolian landforms, such as wind streaks, or fine-grained ripples (*e.g.*, [19–22]). However, seasonality of aeolian landforms was observed on Meridiani Planum. The change from SE-oriented wind streaks to NW-oriented wind streaks occurred in the summer of every Martian year during the studied 10 Mars-year period. These findings showed that the wind on Mars can be of enough intensity to erode and form aeolian landforms on short seasonal timescales [23].

2.3. New approaches to study surface landforms on the Moon and Mars

The newest orbital observations of planetary surfaces, such as by the NASA Lunar Reconnaissance Orbiter Camera, the High Resolution Imaging Science Experiment (HiRISE) onboard the NASA Mars Reconnaissance Orbiter, or the Colour and Stereo Surface Imaging System onboard the ESA ExoMars Trace Gas Orbiter, have allowed Polish scientists to map and study volcanotectonic features and related fluvial and hydrothermal activity (*e.g.*, [24–26]). Studying planetary landforms via orbital imagery requires interpretation using more accessible Earth analogs of these landforms. Experimental, analytical, and computational modeling enhance the understanding of the processes that deform the surface. For example, inversion modeling of experimental surface displacements from terrestrial analogs of magma intrusions has shown that existing analytical solutions inaccurately estimate intrusion geometry, orientation, and depth due to oversimplified brittle rock mechanics [27]. Numerical simulations in the discrete element method explicitly model strain and fracturing, and revealed that displacement, strain, and dynamic fracturing during shallow magma intrusion depend on the strength of the planetary crust [28], but also different gravity on different planetary bodies [29]. Three-dimensional simulations verified by scaled laboratory experiments will further allow for a direct comparison with surface deformation and fracturing at magma-induced features [30, 31].

The effusive activity of lava flows can be unraveled through detailed mapping, stratigraphic reconstruction and impact crater retention age (see *e.g.*, [32]). Yet, this can be non-trivial given the high number and complex overlap of flows. Automatic Reconstruction Of Morphometry And Stratigraphy (AROMAS) is a Python-based workflow using open-source libraries to analyze complex lava fields on planetary bodies. AROMAS processes mapped lava flow contacts and local stratigraphy and automatically classifies individual units through topological sorting. For each flow, AROMAS also automatically computes the average width, the apparent length, and the estimated total length from the vent. The method was tested on pristine-looking flows located SE of Arsia Mons [33].

As aeolian ripples are common landforms on Mars, some automatic techniques are necessary to investigate their parameters and distribution. The methodology proposed by Choromański *et al.* [34] for the supervised classification of terrain on Mars takes advantage of integrating multiple data sources: the NAVCAM rover data from the Opportunity mission [35] and the imagery data from HiRISE [36]. The solution was evaluated using deep learning techniques (*e.g.*, convolutional neural networks). Very good semantic segmentation was achieved with an overall test dataset accuracy of more than 94% using only the orbital data, nearly 95% when the information from the digital terrain model was added, and close to 96% using all available data [34].

2.4. Explaining the origin of the Borealis basin on Mars

Mars had an active magnetic dynamo between 4.5 and at least 3.7 Ga [37]. Banded magnetic anomalies observed in the Mars crust testify to this activity. Their formation mechanisms are elusive, either rooted in magma generation in response to processes in the Martian mantle and solidification (*e.g.*, [38]), or due to a giant impact of magnitude similar to the event that generated the Moon 4.5 Ga (*e.g.*, [39, 40]). We have been testing the hypothesis of a giant impact, in which the crustal magnetic anomalies would be related to crystallization of magnetic minerals in dykes cooling below the Curie temperature, and/or serpentinization and crystallization of magnetic minerals by hydrothermalism in post-impact fractures [41–43]. Statistical analysis of magnetic anomaly orientations with respect to evenly spaced fictitious impact centers, located every node of a $5^\circ \times 5^\circ$ grid throughout the planet, shows that more than 50% of the observed banded anomalies are tangential $+/-10^\circ$ about an ellipse that would be centered in the region where the hypothetical Borealis basin would be located [44–46]. This basin, the existence of which is inferred from topography and gravity, was proposed to be the cause of the hemispheric topographic dichotomy boundary of Mars [39, 47]. Our results made it possible to confirm the likelihood of existence of this basin, as well as refine its location, impact obliquity [39, 48], and orientation.

Evidence of generation of crustal magnetic anomalies in response to a giant impact basin is in line with vertical megashears exposed in the basement of the most deeply eroded troughs of Valles Marineris [49]. The shears, identified from the HiRISE data [36], are parallel to the banded magnetic anomalies, and are located at the margin of the Borealis basin as defined from our analyses reported above. The shears may have been generated as basin ring normal faults, then reactivated with a transcurrent kinematics during tectonic extension of the Valles Marineris graben system. This new kinematics would have resulted from a stress regime controlled by the growing Tharsis bulge, as well as the crustal step imposed by the dichotomy boundary [49, 50].

2.5. Explaining the formation of faculae on Ceres

The images sent by the NASA Dawn mission to Ceres show several hundred bright spots on its surface, called faculae. There are several types of faculae on Ceres, but here we will focus only on two types: floor faculae, and ejecta faculae [51]. Floor faculae are generally attributed to brine upwelling [52] that frequently occurred during the early existence of Ceres. However, many floor faculae are quite young structures. For example, the facula on the floor of Occator crater (which was formed 53 Ma ago) is only 18 Ma old [53]. It was also proposed that the formation of the floor faculae is due to the heat released during the formation of the crater. The heat melted the ice. The water from the resulting brine evaporated. However, within a few million years, the heat was lost. Therefore, Czechowski [54] suggested a new hypothesis that indicates the role of gas in the regolith. Water will freeze after the temperature drops, but CO_2 can remain in a gaseous state. Its flow can be responsible for the formation of faculae through an interaction with the regolith, which consists of different grains. The most popular hypothesis that explains the formation of faculae of the second type is a series of impacts that threw bright material from the interior to the surface. However, this hypothesis needs many parameters to be met; therefore, Czechowski [54, 55] presented another hypothesis about formation of this type of faculae. His conclusion, based on numerical modeling, states that this type of faculae results from a strong separation of grains during the formation of impact craters.

3. Polish involvement in future planetary space missions to the Moon and Mars

3.1. Lunar missions and instruments

Galago is a hopping platform concept for low-gravity planetary bodies with a total mass less than 9 kg and 50 cm in diameter [56]. The Astronika company is responsible for the design and manufacturing of the platform, while Space Research Centre Polish Academy of Sciences (CBK PAN) provides the scientific input, from potential payload selection, through landing site selection, to exploration scenarios. Galago was initially planned for Mars, but the first realized model is dedicated to the Moon. Galago is capable of performing up to 1.25 km long traverses in 6 hours. The platform would increase the scientific return of future missions by studying lunar geological processes, regolith properties, and dust dynamics.

The Lunar Geology Orbiter (LUGO) is an orbiter mission concept [57, 58], which has been conceived through a collaboration of industrial and scientific partners from mainly Central and East European ESA member states. The mission aims at constraining the age and formation of lunar Irregular Mare Patches, and confirming the existence and location of hollow lava tubes in the shallowest tens of meters of the lunar crust that could be used as shelters for future astronauts.

3.2. Mars missions and instruments

The present ESA strategy for Mars exploration assumes a periodical series of orbital and lander missions throughout the next decade to prepare Europe for manned Mars exploration at the turn of this century [59]. CBK PAN participated in defining the strawman payload of Spotlight, a low-orbit spacecraft to be launched in 2032 or 2033 as part of the Lightship-1 mission [60], currently in the payload proposal submission stage.

Following up the Mars Exploration Program Analysis Group report from 2023, Warsaw University of Technology in cooperation with the NASA Ames Research Center is developing a methodology for acquiring geospatial data using a distributed solution based on a swarm of small rovers supported by drones. The main goal of the swarm is autonomous relief modeling and the creation of derived geomorphological maps, as well as the search for traces of water and life on Mars.

The Jagiellonian University with the AGH University of Krakow proposed a new approach to study the Mars environment based on propagation of electromagnetic waves of Extremely Low Frequency (ELF, 3Hz–3kHz; [61]). The ELF experiment is an autonomous platform with a total weight of 8 kg consisting of two magnetic antennas (70 cm long and 6 cm in diameter). The main objectives of the ELF experiment on Mars are to locate subsurface liquid water on the planet, to investigate changes in the ionosphere of Mars, and to determine the intensity of electrical activity of the lower atmosphere [62].

4. Perspectives

The participation in planetary space missions allows us to explore whole new worlds in a way that was several decades ago only possible for Earth. The next phase of space exploration will assume our constant presence on the Moon and beyond. This will be feasible only when we are able to obtain resources *in situ*. *In situ* resource utilization can be related to the atmosphere, surface, and subsurface of planetary objects. Therefore, further studies of the interactions between the near-surface environment of planetary bodies and human anthropogenic objects are necessary. The Polish contribution in planetary physics helps identify future mission targets, plan the next missions, and develop new tools and techniques for space exploration. Poland has great potential to be one of the most important players in planetary science and space exploration, with a key role for collaboration between Polish academia and space industry.

S. Poppe acknowledges funding from the National Science Centre (NCN), Poland to the DAGGER project (No. 2023/49/B/ST10/02360). The work of N. Zalewska was supported by statutory funding grant No. 852-3-17-12 FBW from CBK PAN. The Valles Marineris tectonic and magnetic anomaly works were funded by the EXOMHYDR project carried out within the TEAM program of the Foundation for Polish Science cofinanced by the European Union under the European Regional Development Fund, and the National Science Center (NCN), Poland Preludium Bis grant No. 2021/43/O/ST10/01726.

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