Polarimetric Properties of Icy Moons of the Outer Planets

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The progress in the study of polarization phenomena exhibited by planetary moons is reviewed. Besides previously published data, we focus primarily on the new results of our recent polarimetric observations of the Galilean satellites of Jupiter, bright satellites of Saturn (Enceladus, Dione, Rhea, Iapetus), and the major moons of Uranus (Ariel, Umbriel, Titania, Oberon) at backscattering geometries, including phase angles approaching zero. In addition to a negative branch of polarization, which is typical of atmosphereless solar system bodies (ASSBs), some high-albedo objects, including E-type asteroids, reveal a backscattering polarization feature in the form of a spike-like negative polarization minimum. These optical phenomena serve as important tests of modern theoretical descriptions of light scattering by regolith surfaces. We found the polarimetric properties of different ASSBs near opposition are highly various. The possible reasons for such behavior are discussed.

1 Introduction

The surfaces of planetary satellites are covered with regolith particles which are likely to be aggregates. The properties of the regolith (the structure and packing density of the aggregates, the sizes of constituents, compositions, shapes, and orientation) can be inferred from measurements of the polarization characteristics, namely, the degree P and the plane of linear polarization θ. The degree of polarization P varies with the phase angle α (the angle between the Sun and the observer as viewed from the object), producing polarization phase curve.

Many atmosphereless solar system bodies (ASSBs) exhibit a brightening and negative values of the degree of linear polarization (NPB) near the opposition $\alpha \leq 20^{\circ}$. A class of high-albedo ASSBs (satellites of planets, E-type asteroids) reveals a unique combination of a nonlinear increase of brightness, so-called brightness opposition effect (BOE), and a sharp minimum of polarization (POE) centered at exactly the backscattering direction. There is also the so-called polarization longitude effect (PLE), i.e., a difference between the polarization

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curves for the leading and trailing hemispheres of satellites. Until the mid 1990s, the available polarimetric data, even for the bright Galilean moons of Jupiter, were rather limited and even mutually contradictory [1]. Polarization measurements of moons of the outer planets were scarce. Therefore, our goal was to fill in the missing data for the satellites of planets with different albedo which show the BOE. The objects of our program are the high-albedo Galilean moons of Jupiter (Io, Europa, Ganymede), Saturn's moons (Enceladus, Dione, Rhea, and Iapetus). We also include in our program the major moons of Uranus (Ariel, Umbriel, Titania, Oberon) as well as Jupiter's moon Callisto which are moderate-albedo objects, but demonstrate a sharp surge of brightness.

2 Observations

The polarimetric observations of the planetary satellites near opposition were carried out during different observing runs with different instruments in 1998–2015. The one-channel photopolarimeter of the 2.6 m Shain telescope and the UBVRI photopolarimeter of the 1.25 m telescope of the Crimean Astrophysical Observatory (CrAO) were used. A small part of observations was conducted at the 0.7 m telescope of the Chuguyev Observation Station of the Institute of Astronomy of Kharkiv National University (IAKhNU) and the 1 m telescope of the CrAO (Simeiz) using a one-channel photoelectric polarimeter of the IAKhNU. A description the polarimeters is given in [2]. The faint satellites of Uranus (Ariel, Umbriel, Titania, Oberon) were observed at the 6-m BTA telescope of the SAO with the multimode focal reducer SCORPIO-2 [3].

The degree of linear polarization P and the position angle of the polarization plane θ of the program objects were obtained with reduction programs specially designed for each polarimeter [2, 4]. From the observations of standard stars, we found the instrumental polarization fairly stable, always below 0.2% for all

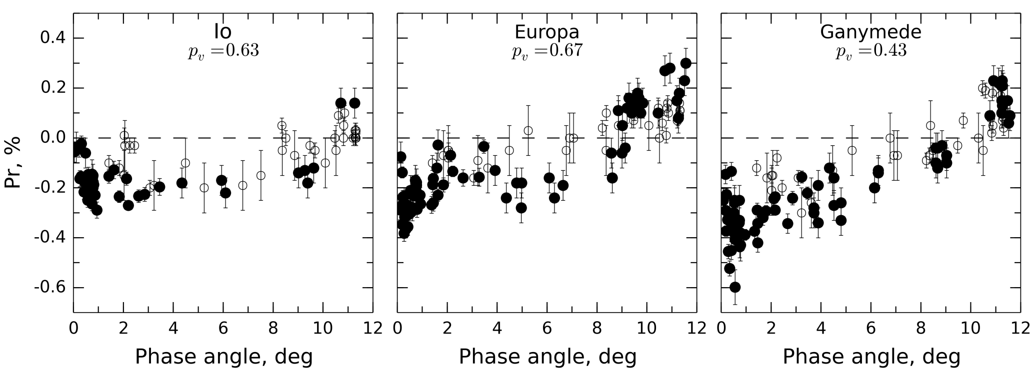

Figure 1: NPB for Io, Europa, and Ganymede with sharp minima of polarization centered at small phase angles. Dark symbols correspond to the present work, filters R and WR; open symbols to data from [5], filter V.

instruments. It was taken into account. A typical random error in the degree of linear polarization ranges from 0.02% to 0.1%, depending on the brightness of the satellite, the count accumulation time, and the observing conditions.

In planetary astrophysics, the polarization quantity of interest is $P_r = P \cos 2\theta_r$, where θ_r is the angle between the measured direction of the plane of linear polarization and the normal to the scattering plane. Thus, we present the results of our observations in the form of the phase–polarization curves (P_r versus α).

3 Results

3.1 The Galilean satellites: Io, Europa, Ganymede, and Gallisto

The polarization–phase curves for Io, Europa, and Ganymede are plotted in Fig.1.

We found that for all observations with $P \gg \sigma_P$, angle θ_r lies near 90°, and the values P_r are negative at all phase angles smaller than the inversion angle. As one can see in Fig. 1, the sharp asymmetric features with polarization minima about $-(0.3 \div 0.4)\%$ at phase angles $< 1°$ are observed. The shape of the negative polarization branches (NPB) of the satellites varies considerably from almost flat for Io up to strongly asymmetric curve for Ganymede.

Europa clearly demonstrates two minima at the NPB: $P_{min} \approx -0.4\%$ at $\alpha \approx 0.8°$ and $P_{min} \approx -0.2\%$ at $\alpha \approx 5.5°$. The same effect can be seen for Io and Ganymede, although less pronounced. The sharp secondary minimum of polarization centered at very small phase angle, called polarization opposition effect, was predicted by Mishchenko for high-albedo ASSBs [8].

A detailed study of the PLE for Callisto was carried out by Rosenbush [6]. The NPBs for the leading and trailing hemispheres of Callisto are the regular curves of polarization without any sharp asymmetric features like the POE (see Fig. 2).

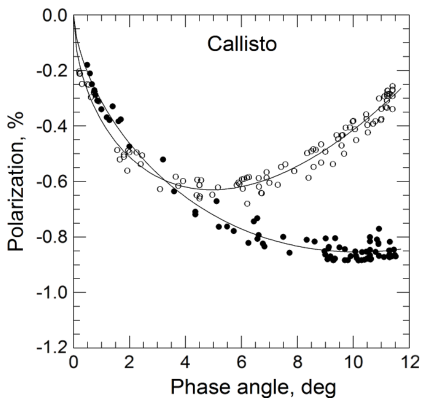

Figure 2: NPB for the leading (dark symbols) and trailing (open symbols) hemispheres of Callisto in the V filter after the correction for the orbital longitudinal variations [6]. Solid curves represent the best fit to the data by a trigonometric expression [7].

3.2 Saturn's moons: Enceladus, Dione, Rhea, and Iapetus

The NPBs for Enceladus, Dione, Rhea are plotted in Fig. 3. Enceladus is a unique object having the highest albedo ($p_v = 1.38$) of any object in the solar system. Moreover, Enceladus shows the ice fountains over the south polar region. Data for NPB of Enceladus are still rather limited because they are obtained for the first time. The asymmetric NPBs with polarization minima $P_{min} \approx -0.8\%$ at $\alpha_{min} \approx 1.8°$ are observed for Rhea and Dione. The NPB for Rhea is more sharp asymmetric than that for Diona.

Iapetus is a unique moon of Saturn with the greatest albedo asymmetry of any object in the Solar System. Its leading hemisphere has albedo $p_v = 0.02$–0.05, whereas the trailing hemisphere has $p_v = 0.6$. As a result, the large variations of polarization degree with longitude of Iapetus are revealed. In Fig. 4 we present the observations obtained for the bright trailing hemisphere (open symbols) as well as for the leading hemisphere (dark symbols). As one can see (Fig. 4, left panel), a strongly asymmetric phase curve of polarization for the bright trailing hemisphere with minimum $P_{min} \approx -0.7\%$ at $\alpha_{min} \approx 1.5°$ is revealed. The PLE for Iapetus is shown in Fig. 4 (right bottom panel). It is in a good agreement with the albedo distribution (Fig. 4, right upper panel) which is derived from a mosaic of Cassini images [9].

3.3 The major moons of Uranus: Ariel, Titania, Oberon, and Umbriel

Observations of the satellites were carried out at the 6 m BTA telescope [4] within the phase angle range of 0.06 – 2.37°. The NPB for Ariel, Titania, Oberon, and Umbriel in the V filter are presented in Fig. 5 (left panel). For Ariel, the maximum branch depth $P_{min} \approx -1.4\%$ is reached at the phase angle $\alpha_{min} \approx 1°$; for Titania $P_{min} \approx -1.2\%$, $\alpha_{min} \approx 1.4°$; for Oberon $P_{min} \approx -1.1\%$, $\alpha_{min} \approx 1.8°$.

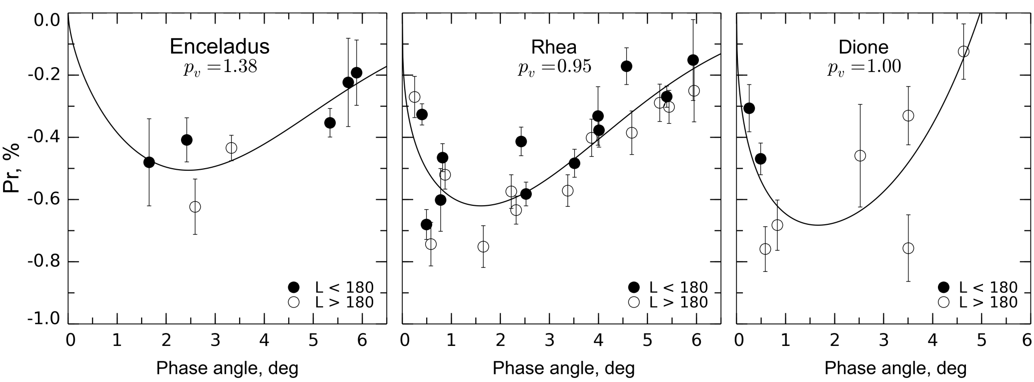

Figure 3: NPB for Enceladus, Rhea, and Dione. Dark and open circles show data for leading ($L < 180°$) and trailing ($L > 180°$) hemispheres, respectively. Solid curves represent the fit to the data by a trigonometric expression [7].

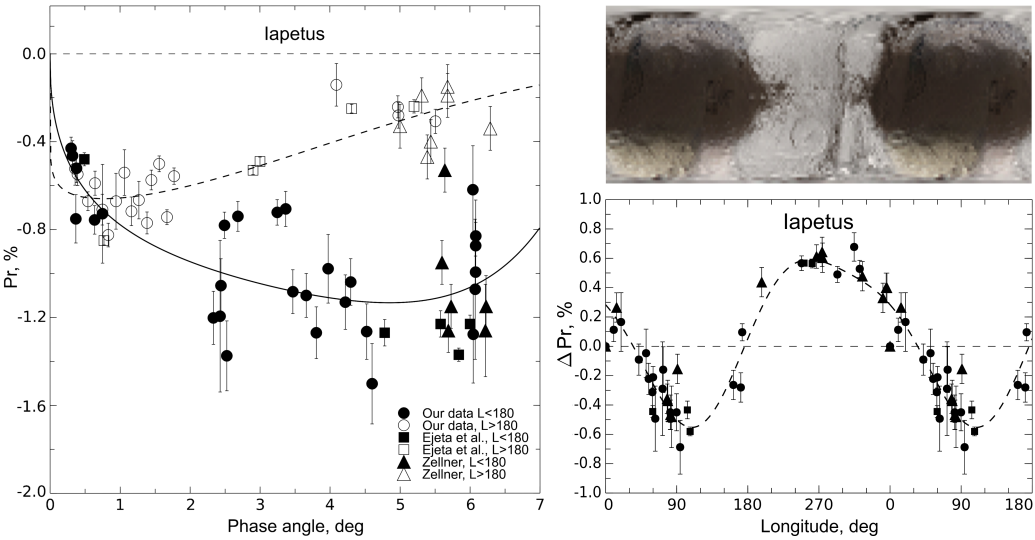

Figure 4: Phase-angle (left panel) and longitude (right bottom panel) dependencies of polarization for Iapetus. The albedo distribution map [9] is given in the right upper panel. Circles show our data, filters R and WR; squares data from [10, 11], filter R; triangles data by Zellner [12, 13], filter V.

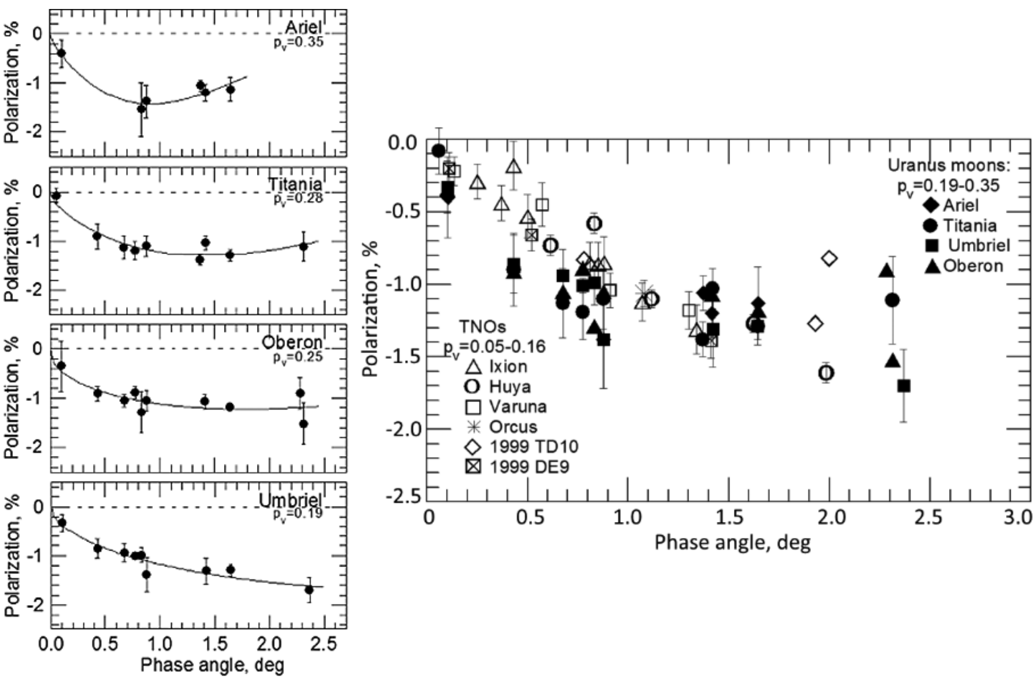

Figure 5: NPB for the Uranian satellites (left panel). Right panel shows a comparison of the phase-angle polarization dependencies of the Uranian moons (dark symbols) and TNOs (open symbols). Data for TNOs are taken from [14].

For Umbriel, the polarization minimum was not reached: for the last measurement point at $\alpha = 2.4°$, polarization amounts to -1.7%. The declining P_{min} and shifting α_{min} towards larger phase angles correlate with a decrease of the geometric albedo of the Uranian moons. There is no longitudinal dependence of polarization for the moons within the observational errors which indicates a similarity in the physical properties of the leading and trailing hemispheres [4].

We found (see Fig. 5, right panel) that for the Uranian moons the polarization phase dependencies are in a good agreement with the measured polarization of the group of small trans-Neptunian objects (Ixion, Huya, Varuna, Orcus, 1999 TD10, 1999 DE9) which are characterized by a large gradient of negative polarization, approximately 1% per degree in the $0.1-1°$ range of phase angles, according to [14].

4 Summary

The extensive polarimetric observations of moons of the outer planets, obtained during the past two decades, demonstrate that the behavior of the phase-angle dependence of polarization near the opposition is highly various. It is ranging from a bimodal curve consisting of a secondary minimum distinctly separated from the main minimum of the NPB (the Galilean satellites of Jupiter) to an asymmetric negative polarization branch (Saturn's and Uranian satellites). A quantitative analysis of these observational data in terms of specific physical parameters is hardly possible at this time because of the still limited data (limited range of phase angles and wavelengths). Nevertheless the data can be qualitatively interpreted in terms of the currently available light scattering mechanisms on the regolith surfaces. Shadow hiding, coherent backscattering, near-field effects, and anisotropic scattering by single particles are often considered as the dominant mechanisms that define the characteristics of the scattered radiation (intensity and polarization) at small phase angles. The shape of the NPB, as well as characteristics of BOE and POE, depend on the relative contributions of the mentioned mechanisms which, in turn, depend on the physical characteristics of the regolith layer and the scattering geometry. The packing density and the refractive index, as well as size and shape of the monomers constituting the aggregate particles, determine the effectiveness of each of the scattering mechanisms and, hence, the behavior of brightness and polarization near the opposition. This is what draws significant interest in the study of light scattering effects on surfaces of ASSBs, including planetary satellites, in terms of both observations and their modeling and development of light scattering theory.

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