POLARIMETRIC OBSERVATIONS OF THE GALILEAN MOONS OF JUPITER: EUROPA, IO, GANYMEDE. A. A. Savushkin[1], N. N. Kiselev[1,2], V. K. Rosenbush[3,2], N. V. Karpov[4]. [1]Crimean Astrophysical Observatory, Nauchny, 298409 Crimea, sharrakka@gmail.com, [2]Main Astronomical Observatory of the National Academy of Sciences of Ukraine, 27 Zabolotnoho Str., 03143 Kyiv, Ukraine, [3]Taras Shevchenko National University of Kyiv, Astronomical Observatory, 3 Observatorna Str., 04053 Kyiv, Ukraine, [4]International Center for Astronomical, Medical and Ecological Research, Peak Terskol Observatory, Ukraine.

Introduction: Intensive polarimetric observations of the Galilean moons began in the 70s of the last century [1–4]. In works [5–7], it was found that satellites Io, Europa, and Ganymede show a sharp minimum of negative polarization at phase angles less than 1°, the so-called polarization opposition effect (POE). It was believed [8] that the negative polarization branch (NPB) for these satellites consists of the POE at phase angles of about 0.2° – 0.7° superimposed by a regular parabolic NPB with smaller values of polarization (about –0.2% to –0.3%). However, despite the high brightness of these satellites, the accuracy of most of the past observations was insufficient, (0.05 – 0.1%) [9], to determine the exact shape of the POE and NPB for the Galilean satellites.

At present, the need to study the physical properties of the regolith surfaces of planetary satellites is becoming increasingly relevant and important. This is due to the new results of the study of satellites obtained by several space programs, ground-based and Hubble Space Telescope observations. Among them subsurface oceans on Europe and Ganymede, signs of geyser activity (cryovolcanism) on Europa, volcanic activity on Io. Complex organic matter on the surface and subsurface ocean makes Europa one of the best candidates for extraterrestrial life in the Solar System. These results have renewed scientific interest in the study of Europa both by the ground-based and space-based means, including the planned NASA Europa Clipper and ESA JUICE missions.

Therefore, the main purpose of our work was to obtain high-precision measurements of the polarization of the Galilean satellites at the whole range of accessible phase angles and in a wide spectral range.

Instruments and observations: The polarization of the moons was measured in the UBVRI bands with the two identical two-channel photoelectric polarimeters "POLSHAKH" [10] mounted on the 2.6-m telescope of the Crimean Astrophysical Observatory and the 2-m telescope of the Peak Terskol Observatory (North Caucasus) during 2018–2021 years. These polarimeters based on the principle of synchronous detection which makes the polarization measurements almost independent on the weather conditions and ensures their high accuracy: usually, errors in the polarization degree do not exceed 0.05% in the UB filters and 0.02% in the VRI filters. The range of phase angles at which the observations were obtained extends from 0.1° to 11.2°.

Results: *Europa.* The icy surface makes Europa one of the most reflective in the Solar System, its geometric albedo ρ_V=0.67. The light scattered by Europa shows two interesting opposition phenomena: a strong spike-like brightness opposition effect (BOE) at phase angles less than 1° [11] and a pronounced and asymmetric POE. We found that the phase-angle dependence of polarization for Europe in all spectral bands are highly asymmetric curves with sharp polarization minimum $P_{\min} \approx -(0.3 \div 0.4)\%$ at phase angles $\alpha_{\min} \le 0.4°$ and practically independent of the wavelength. The polarization measurements of Europa in the R band are shown in Fig. 1 (top panel). After the minimum, the polarization degree gradually increases to positive values, passing the inversion angle at $\alpha_{\text{inv}} \approx (6–7)°$. In general, the phase polarization curve for Europa is similar to the phase curve obtained by Lyot in the laboratory for MgO [12].

Ganymede. Unlike the almost homogeneous surface of Europa, the surface of Ganymede ($\rho_V = 0.43$) is highly heterogeneous and is only partially covered with ice. There are two types of regions: ancient dark areas and younger lighter areas [1, 2]. The results of the polarimetry of Ganymede in the R band are shown in Fig. 1 (middle panel). Despite the difference in composition and albedo of the surfaces, the polarization curve for Ganymede is morphologically similar to the polarization curve for Europa. However, the NPB parameters are different from those for Europa. For Ganymede, as well as for Europa, there is also a sharply asymmetric branch with a minimum of polarization $P_{\min} \approx -0.4\%$ at $\alpha_{\min} \approx 0.5°$, but it asymptotically tends to a much larger inversion angle $\alpha_{\text{inv}} \approx 10°$.

Io. Jupiter's moon Io ($\rho_V = 0.63$) is the most geologically active body of the Solar System. The surface of Io is constantly renewing due to the eruption of several dozen volcanoes which eject sulfur compounds onto the satellite's surface. Fig.1 (bottom panel) displays the phase-angle dependence of polarization which is almost flat ($P \approx -0.2\%$.) between the phase angles ~3° and ~12°.

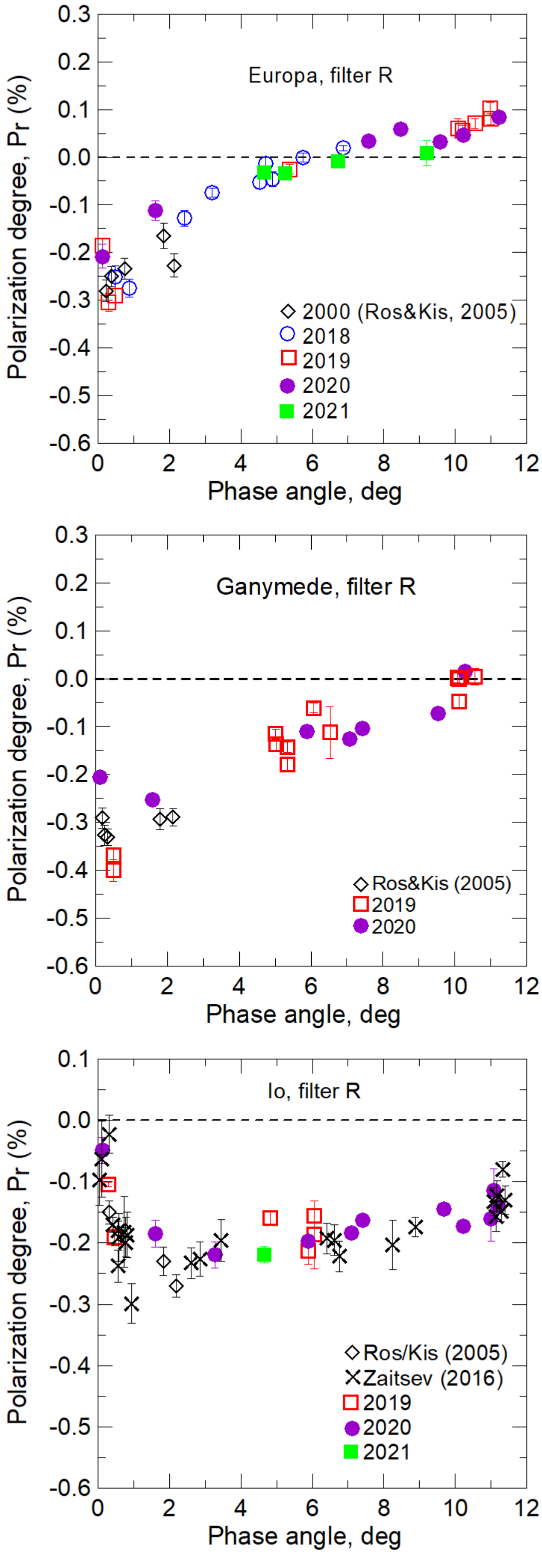

Fig. 1. The phase-angle dependence of polarization for Europa (top panel), Ganymede (middle panel), and Io (bottom panel) in the R band.

Conclusions: There were numerous attempts to model the polarization of high-albedo bodies at low phase angles to reveal the characteristics of the regolith particles from the measurements of the polarization. However, because of the lack of high-precision polarization measurements, our knowledge on the surfaces of the Galilean satellites remains limited and fragmentary. Almost all computer or laboratory modeling showed that the high-albedo media exhibit a narrower and less deep negative branch of polarization. Laboratory measurements of layers formed by MgO [12], Al_2O_3 [13, 14], or ice particles [15] showed very asymmetric phase curves of polarization which are similar to those we observed for Europa at phase angles <3°, however, at larger phase angles they demonstrated a very shallow NPB with the inversion point around 20°.

Our observations show that despite the close values of albedo of Europe and Io, the shape of the polarization curves are very different. At the same time, Ganymede and Europa have a similar shape of the polarization curve, although their albedo differs greatly. Apparently, the composition of the surface regolith layer (water ice for Europa, water ice + silicates for Ganymede, sulfur dioxide for Io) and its porosity have a greater effect on the formation of the morphological features of the polarization curve than the albedo of satellites.

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