OPPOSITION EFFECTS OF JUPITER'S SATELLITES IO AND EUROPA

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Using long-term photoelectric observations of Io by Shavlovskij and Europa by Thompson *et al.* [10] at solar phase angles from 0° to 12° we determined solar phase functions for the leading and trailing hemispheres of the satellites. The obtained values of the half-width at half-maximum (HWHM) of the opposition peak prove that the opposition effects of Io and Europa are caused by coherent backscattering.

At small phase angles airless particulate surfaces can exhibit the opposition surge. The opposition effect (OE) is a rapid, nonlinear increase in brightness that occurs as the phase angle decreases to 0°.

Until recently, OE was interpreted [5–7] in terms of interparticle shadow-hiding in which particles of a surface cast shadows. If shadow-hiding opposition effect (SHOE) is only a geometric optics effect, OE surge should be weak in high-albedo materials. However, some highly reflective surfaces (the regoliths of the icy outer planet satellites) demonstrated narrow pronounced opposition surges. This phenomenon is attributed to coherent backscattering (CBOE) [2, 9].

The physical properties of the surfaces of Io and Europa have been studied by several authors [1, 3, 4, 8]. The solar phase curves were modelled by using Hapke's theory [5–7]. Buratti [1] examined Europa's phase curves based on Voyager images. Domingue *et al.* [3] combined telescopic observations with the Voyager image data and separated the data into leading and trailing hemisphere.

The different compaction states found by Buratti [1] and Domingue *et al.* [3] are due to the inclusion of telescopic data with a smaller phase angle than the Voyager data alone.

The observations of the Galileo spacecraft [8] indicate that Europa's surface reveals both SHOE and CBOE. All europan surface materials exhibit a narrow (less than 0.2° wide) coherent backscattering opposition surge.

The telescopic observations of Europa used in this study are taken from Thompson *et al.* [10].

The goal of this initial study is to examine our developing approach to correct the orbital brightness for bright surface of Europa. Within this approach, it was assumed that surfaces of the leading and trailing hemispheres differ by their (w, g, B_0, h) parameters. The contribution of each hemisphere to the total light flux scattered by the surface is accepted to be proportional to the square of the projection of the hemisphere on the image plane. This contribution may be calculated using Hapke's theory equations for the taken set of the parameters and α, θ values for time of observation.

The w, g, B_0, and h parameters were derived from the condition of the best accordance between the model and the observed reflectivity values. The derived values of parameters are presented in Table 1.

The observational data and our model curves at $\lambda = 0.47$ μm and $\lambda = 0.55$ μm are presented in Fig. 1 and Fig. 2, respectively.

The data presented in lines 1–4 (Table 1) were obtained using our approach and the observational data by Thompson *et al.* [10], the parameters in lines 5 and 6 are from Domingue *et al.* [3] for comparison.

Analysis of the results in Table 1 shows that our set of parameters is in agreement with those from [3]. This fact confirms the reality of the values of parameters derived by using our approach to correct the orbital brightness variations.

Domingue *et al.* [4] presented analysis of Io's disc integrated solar phase curve based on the combination of the ground-based telescopic observations with the Voyager data set. Using own long-term photoelectric observations at $\lambda = 0.54$ μm we obtained Hapke's parameters w, g, h, B_0 of the solar phase functions for the leading and trailing hemispheres of Io. To calculate the parameters, we used the approach introduced above.

The observational data and model curves are demonstrated in Fig. 3. The derived values of parameters are presented in Table 2. The data presented in the lines 1–4 are obtained from the observational data by Shavlovskij, those in the lines 5 and 6 from Domingue *et al.* [4].

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Table 1. Hapke's model parameters for Europa

Hemisphere	Hapke's model parameters				λ
	B_0	h	w	g	μm
leading					
1	0.409	0.0018	0.932	−0.410	0.470
2	0.350	0.0024	0.932	−0.410	0.470
3	0.410	0.0018	0.924	−0.440	0.550
4	0.410	0.0018	0.924	−0.440	0.550
5	0.490	0.0015	0.934	−	0.470
6	0.430	0.0016	0.964	−	0.550
trailing					
1	0.359	0.0030	0.924	−0.330	0.470
2	0.480	0.0027	0.948	−0.290	0.470
3	0.400	0.0028	0.936	−0.330	0.550
4	0.490	0.0022	0.920	−0.350	0.550
5	0.510	0.0016	0.897	−	0.470
6	0.521	0.0016	0.930	−	0.550

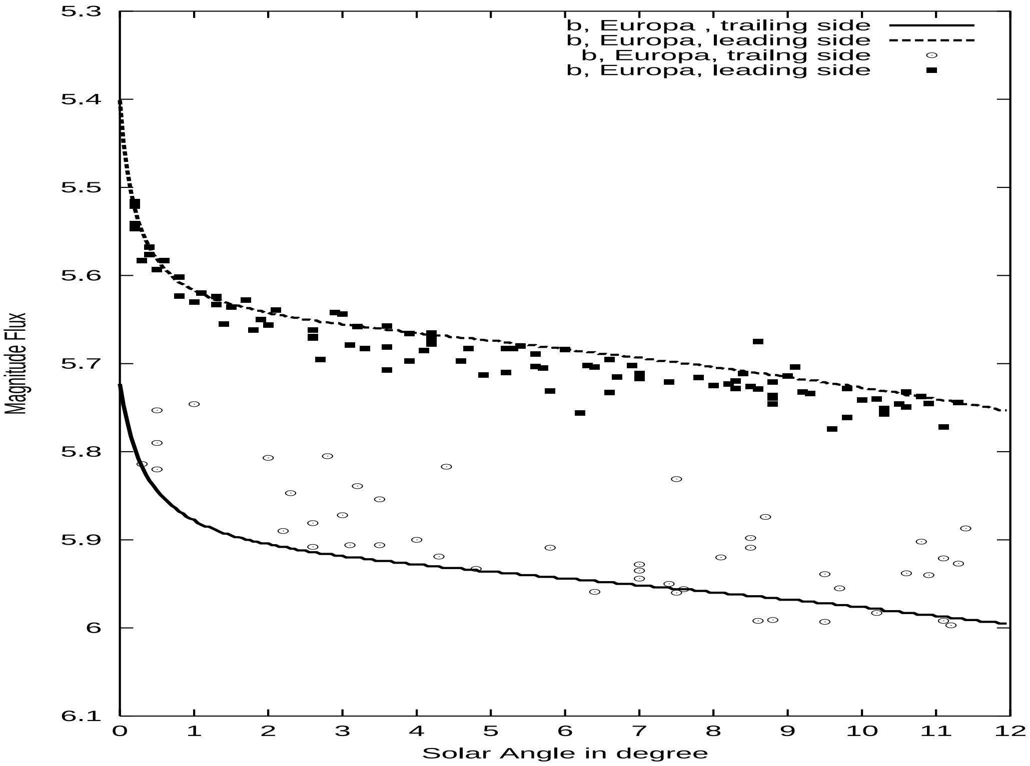

Figure 1. The observed magnitude flux (points) of Europa at $\lambda = 0.47$ μm as a function of solar phase angle. The model predictions are shown by dashed (leading side) and solid (trailing side) lines

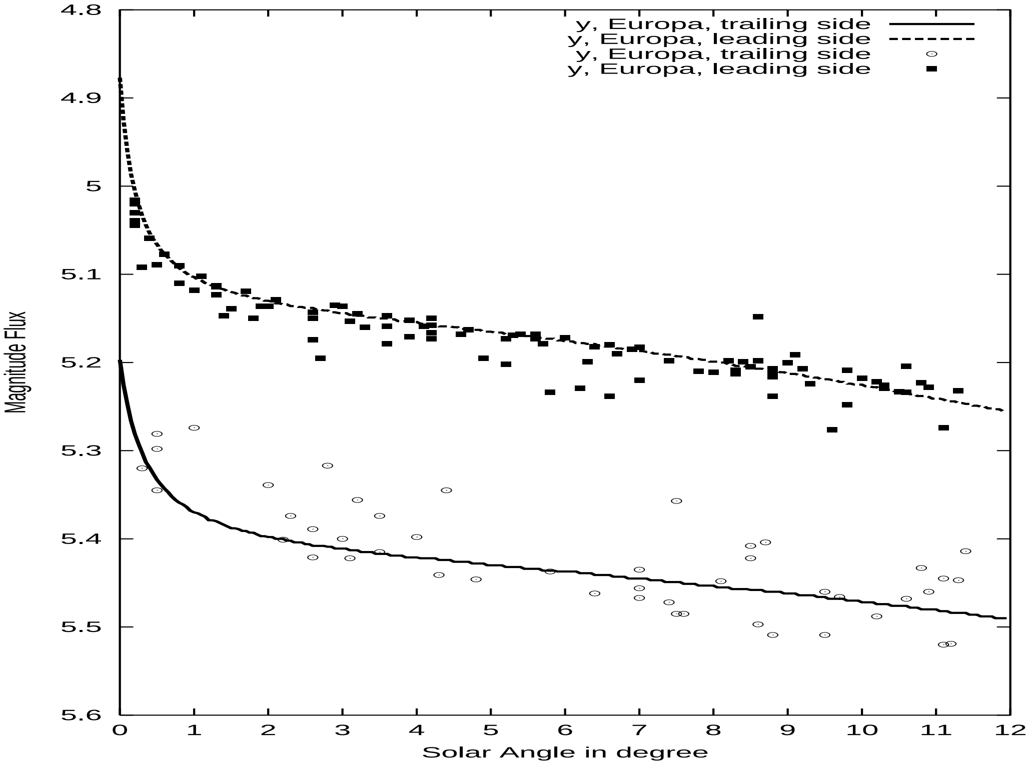

Figure 2. The observed magnitude flux (points) of Europa at $\lambda = 0.55\ \mu$m as a function of solar phase angle. The model predictions are shown by dashed (leading side) and solid (trailing side) lines

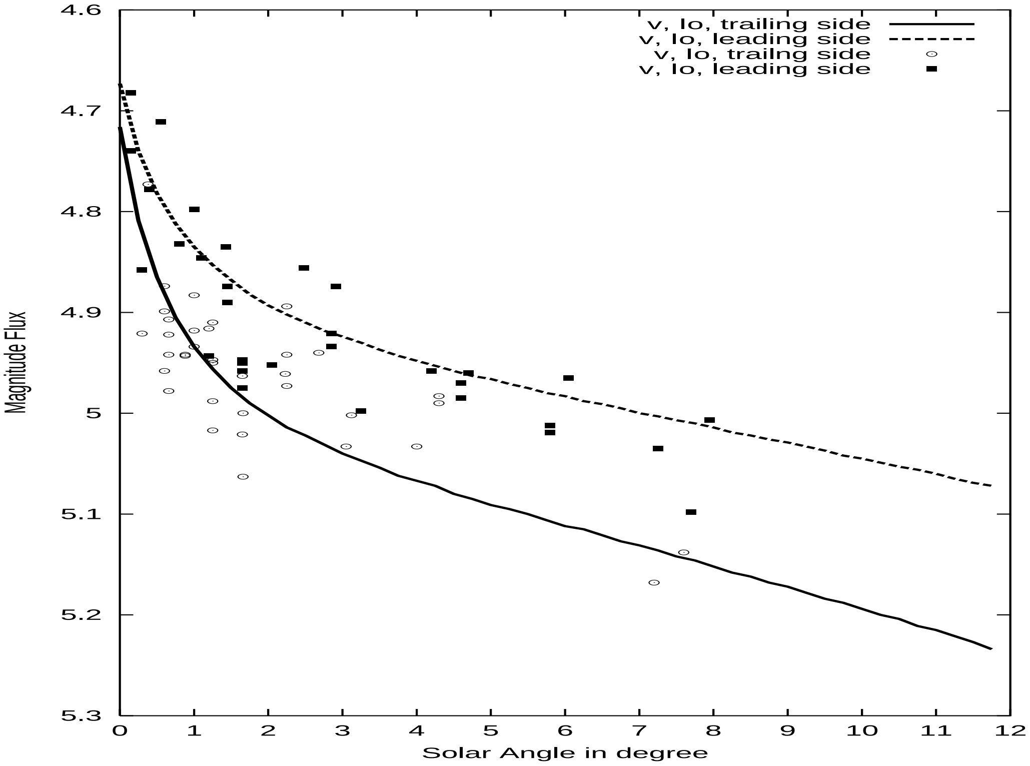

Figure 3. The observed magnitude flux (points) of Io at $\lambda = 0.54\ \mu$m as a function of solar phase angle. The model predictions are shown by dashed (leading side) and solid (trailing side) lines

Table 2. Hapke's model parameters for Io

Hemisphere	Hapke's model parameters				λ
	B_0	h	w	g	μm
leading					
1	0.499	0.0048	0.869	-0.440	0.540
2	0.499	0.0030	0.869	-0.450	0.540
3	0.599	0.0045	0.949	-0.375	0.540
4	0.500	0.0075	0.949	-0.375	0.540
5	0.340	0.0065	0.958	–	0.470
6	0.467	0.0108	0.944	–	0.550
trailing					
1	0.200	0.0030	0.750	-0.500	0.540
2	0.300	0.0044	0.829	-0.450	0.540
3	0.375	0.0089	0.799	-0.450	0.540
4	0.500	0.0060	0.799	-0.450	0.540
5	1.0	0.0145	0.910	–	0.470
6	1.0	0.0180	0.925	–	0.550

Using our model curves for the leading and trailing side for Io and Europa, we obtained the values of the HWHM of the OE at several wavelength.

The values of the HWHM for Europa at $\lambda = 0.47$ μm are 0.166° and 0.257° for leading and trailing side, respectively, and at $\lambda = 0.55$ μm they are 0.171° and 0.260°.

The values of the HWHM of the OE for Io at $\lambda = 0.54$ μm are 0.48° and 0.40° for leading and trailing side, respectively.

The obtained values of the HWHM for Europa are in good agreement with those derived by Dlugach and Mishchenko [2]. Mishchenko [9] concluded that the HWHM of the coherent OE for the surfaces covered by submicrometer-sized water ice particles was of the order of several tenths of degree.

The values of the HWHM of the opposition surge of Io and Europa which were obtained with the use of observational data of Shavlovskij and Thompson *et al.* [10] and our approach for correction of the orbital brightness variations confirm that the coherent backscattering may be a possible explanation of the OE exhibited by Io and Europa.

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