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Polarization of Saturn's moon Iapetus

II. Comparison of the dark and the bright sides⋆

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ABSTRACT

Context. The surface properties of atmosphereless solar system objects can be constrained by investigating the nature of the polarized light scattered from their surfaces.

Aims. We provide new and precise measurements of the phase angle and the wavelength dependence of linear polarization on the leading side of Iapetus over the maximum phase angle range accessible from Earth (∼0.5−6.0°) and over a broad spectral range (400–800 nm), thereby identifying the polarimetric characteristics of its dark material. Moreover, we provide circular spectral polarization measurement of the same side of Iapetus at one phase angle, which was performed aiming at detection of chiral signatures on its surface. We also compare our new polarization measurements with those of the trailing hemisphere of Iapetus which were obtained in our previous work.

Methods. Using the FORS2 instrument of the ESO VLT, we performed spectro-polarimetric observations of Iapetus' leading side.

Results. While the linear polarization measurements of Iapetus' leading side show an opposite trend in phase angle dependence to that of its trailing hemisphere, the polarization values measured for the two hemispheres around similar phase angles (in the range ∼3.0−6.0°) differ by a factor of three. Besides this, the degree of negative linear polarization of Iapetus' leading hemisphere shows a slight dependence on the wavelengths of observations. Furthermore, like that of its trailing hemisphere, the circular polarization measurement of Iapetus' leading side indicates no evidence of a significant amount of optically active (chiral) molecules on its surface.

Key words. scattering – polarization – methods: observational – techniques: polarimetric – planets and satellites: surfaces

1. Introduction

With the goal of constraining the surface poroperties of Saturn's moon Iapetus, we carried out a series of linear spectro-polarimetric observations of both its leading and its trailing hemispheres, over the maximum phase angle range accessible from the Earth, $\alpha_{max} = \arcsin(1/r)$ (where r is the heliocentric distance in AU) – which is ∼6.0° for Saturnian satellites. Moreover, with the aim of detecting chiral signatures on Iapetus, we performed circular spectro-polarimetric observations of its two hemispheres, at a single phase angle for each. The spectro-polarimetric measurements of Iapetus' trailing hemisphere have already been reported in Ejeta et al. (2012, from here referred to as Paper I). In this paper, we report measurements of Iapetus' leading hemisphere in comparison with that of its trailing hemisphere, to investigate differences in the polarization behavior of the surface materials on its two hemispheres.

2. Observations, data reduction, and analysis

Linear spectro-polarimetric observations of the leading side of Iapetus have been obtained at five different epochs, using the FORS2 instrument of the European Southern Observatory (ESO) Very Large Telescope (VLT), from May 2009 to January 2012. We also performed circular polarization observations of the same side of Iapetus at one phase angle. The observing program of Iapetus' leading side was performed in a similar way to what was done for its trailing hemisphere (Paper I), i.e.,

Table 1. ESO VLT FORS2 instrument offset angle Θ_0 during our observation epochs of Iapetus' leading hemisphere.

Epoch	Observed STD	$\Theta_{measured}$ (°)	Θ_{real} (°)	Θ_0 (°)
2009-05-17	Hiltner 652	91.9	179.5	−87.6
2010-03-25	Ve 6-23	158.2	172.5	−14.3

Table 2. ϕ values calculated for each observation epoch of Iapetus' leading hemispheres.

Observation epoch	ϕ (°)
2009 05 17	−66.43
2010 03 25	−32.62
2010 06 10	−66.16
2011 02 12	−69.49
2012 01 02	−68.54

⋆ Based on observations made with ESO Telescope (UT1) at the Paranal observatory under program ID 383.C-0058(A), 384.C-0040(A), 385.C-0052(A), 386.C-0075(A), 087.C-0058(A), and 088.C-0019(A).

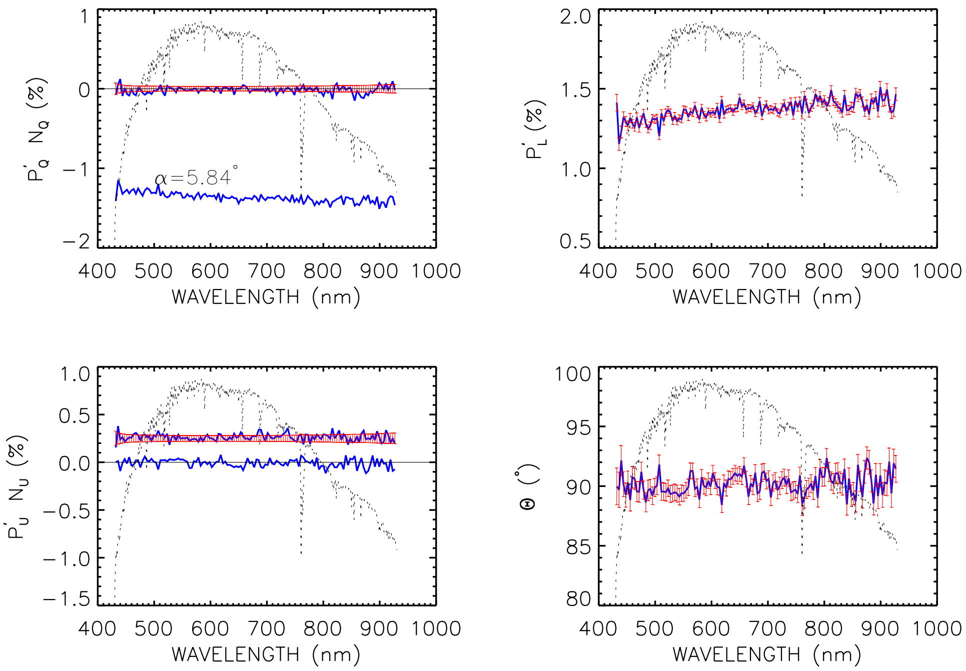


Fig. 1. Linear polarization of the leading side of Iapetus versus wavelength, observed with FORS2 at the ESO VLT during the night 2009 May 17 at a phase angle of 5.84°. In the P'_Q and P'_U panels, the red lines represent measurements obtained with respect to the reference direction perpendicular to the scattering plane. The null profiles, N_U (offset to +0.25 % for display purposes) and N_Q, are displayed in blue, superposed on the statistical error bars (in red). The right panels show the fraction of linear polarization and its position angle, together with their error bars. The stokes P'_U is well centered on zero, which is equivalent to the position angle of polarization centered on 90.0°. In all panels, the black dotted lines show the total flux (in arbitrary units).

Table 3. Observing log and results of polarimetric observations of Iapetus' leading side.

Date & time (UT) (yyyy mm dd) (hh:mm)	Program ID	Exp. (s)	α (°)	Filter	P'_Q(%)	P'_U(%)	Ob-lon & lat (°)
2009-05-17 01:05-01:30	383.C-0058(A)	1040	5.84	*B*	−1.28 ± 0.04	0.00 ± 0.04	106.90, 5.74
				V	−1.33 ± 0.03	0.00 ± 0.03	
				R	−1.37 ± 0.03	−0.01 ± 0.03	
				I	−1.40 ± 0.04	−0.01 ± 0.04	
2010-03-25 02:20-02:39	384.C-0040(A)	640	0.49	*B*	−0.46 ± 0.05	0.05 ± 0.04	70.45, 9.66
				V	−0.47 ± 0.03	0.02 ± 0.03	
				R	−0.48 ± 0.05	0.00 ± 0.03	
				I	−0.47 ± 0.04	−0.03 ± 0.04	
2010-06-10 01:56-02:37	385.C-0052(A)	800	6.0	*B*	−1.14 ± 0.06	−0.03 ± 0.07	59.61, 9.07
				V	−1.19 ± 0.04	−0.05 ± 0.06	
				R	−1.23 ± 0.04	−0.06 ± 0.06	
				I	−1.28 ± 0.05	−0.06 ± 0.07	
2011-02-12 04:32-04:57	087.C-0058 (A)	320	4.78	*B*	−1.24 ± 0.09	0.04 ± 0.10	81.93, 13.00
				V	−1.23 ± 0.06	0.05 ± 0.07	
				R	−1.27 ± 0.06	0.03 ± 0.07	
				I	−1.27 ± 0.07	0.06 ± 0.08	
2012-01-02 07:48-08:04	088.C-0019 (A)	400	5.58	*B*	−1.14 ± 0.09	0.02 ± 0.09	103.46, 14.88
				V	−1.21 ± 0.06	0.05 ± 0.06	
				R	−1.23 ± 0.07	0.03 ± 0.07	
				I	−1.26 ± 0.08	0.02 ± 0.08	

Notes. Ob-lon & lat refers to the longitude and the latitude of the sub-Earth point, α is the phase angle, while P'_Q and P'_U indicate the measured Stokes parameters with respect to the scattering plane.

close to its eastern orbital elongation around Saturn, to avoid contamination of light from its trailing side in the best possible way. The observing technique (the instrument set up), data reduction, quantification of the Stokes parameters, and measurement uncertainties for both the linear and the circular polarization were performed practically the same as described in Paper I, to which we refer the reader for further details.

Our measurements are transformed from the instrument reference system (in our case, the north celestial pole) to the reference system with the reference direction perpendicular to the scattering plane, using Eq. (4) of Paper I, with the quantities Θ_0 and ϕ, corresponding to our observation epochs of Iapetus' leading side indicated in Tables 1 and 2, respectively.

Figure 1 shows linear spectro-polarimetric measurement of Iapetus' leading side at a single observing epoch.

Table 3 shows the summary of our observation for Iapetus' leading side along with the polarization values in Bessel *BVRI* filters obtained by convolving the polarized spectra of Fig. 1 with the respective transmission function of each filter.

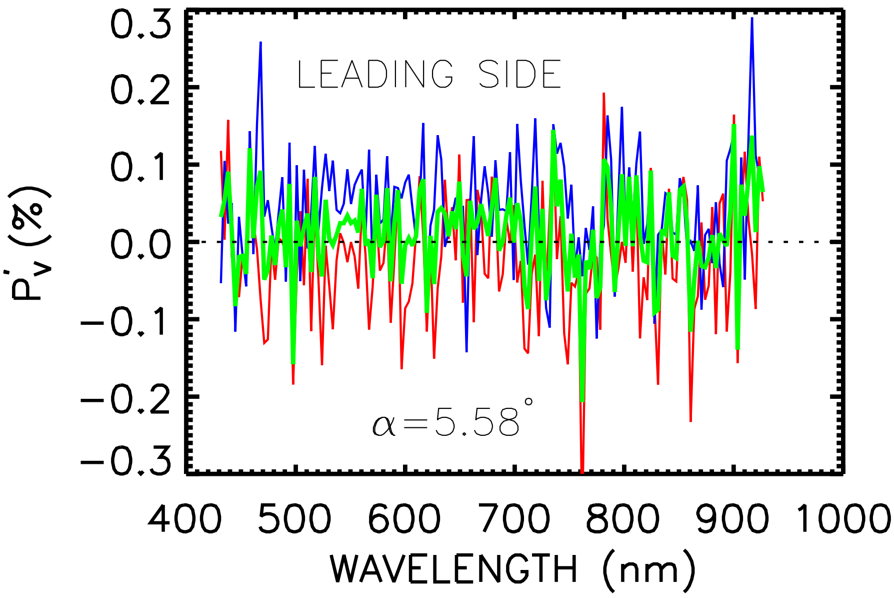


Fig. 2. Circular polarization of Iapetus' leading side versus wavelength, obtained with FORS2 at the ESO VLT during the night 2012 January 02 at phase angles of 5.58°. The measurement technique was performed the same way as reported in Paper I for the trailing hemisphere; i.e., the solid green curve represents the average of the value of the signals obtained at 0.0° and 90.0° instrument position angles on the sky, so as to reduce the cross-talk effect from linear to circular polarization of the FORS2 instrument (e.g., Bagnulo et al. 2009).

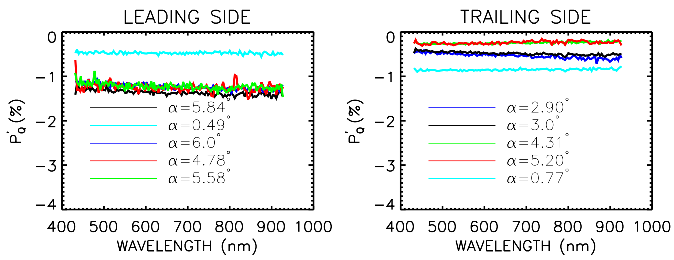
Besides the linear spectro-polarimetric observations, we also performed circular spectro-polarimetric observations of Iapetus' leading side at one phase angle (see Fig. 2).

3. Discussion

The wavelength dependence of the observed degree of linear polarization for Iapetus' leading side is less noticeable (Fig. 3a), but there is a slight tendency to increase in polarization with increasing wavelength for most of our observing epochs (see also Fig. 4). In this respect, the trend to wavelength dependence of the polarization for Iapetus' leading side shows similarity to those of S and M type asteroids (e.g., Belskaya et al. 2009). Moreover, as can be seen from Fig. 3, the effect of phase angle on the polarimetric spectral slope for Iapetus' two hemispheres is insignificant, which might be attributed to the fact that, in our case, the range of phase angle under consideration is very narrow (from ~0.5–6.0°).

Figure 4 shows the linear polarization measurements of Iapetus' leading side versus phase angles in Bessel *BVRI* filters. The measurements show that the linear degree polarization for Iapetus leading side varies from ~–0.50% at a phase angle of ~0.50°, which is consistent with the value obtained by Rosenbush et al. (2002), to ~–1.30% at a phase angle of ~6.0°, which is a value consistent with measurements by Zellner (1972). In contrast to that of its trailing side (Paper I), the polarization of Iapetus' leading side therefore shows a clear trend to increase with increasing phase angle, possibly reaching a minimum at a phase angle of about ~5.90°. However, even though the sub-Earth longitude of our observation epochs for Iapetus' leading side were all performed close to the longitude of its maximum eastern elongation, 90.0° (see Table 3) – when its dark hemisphere can be viewed exclusively, polarization is also strongly longitude dependent, an effect that we cannot disentangle at this moment owing to lack of measurements corresponding to different longitudes at a fixed phase angle.

The albedo value of Iapetus' leading side (~0.04) reported by Spencer & Denk (2010) is in the range of the typical albedo values of F-type asteroids, i.e., 0.03–0.07 (Tedesco et al. 2002). However, the polarization minimum of Iapetus' leading side is



(a) (b)

Fig. 3. Linear polarization of Iapetus' leading side **a)**, and trailing side **b)** versus wavelength, at each phase angle of our observing epochs.

slightly shallower than the typical value for low-albedo asteroids, which is ~−1.6%, and slightly deeper than that of the F-type asteroid 419 Aurelia, which is ~1.0% (Belskaya et al. 2005). However, the surface reflectance of Iapetus' leading side is red, while the F-type asteroids are characterized by an almost flat reflectance spectrum (Tedesco et al. 2002).

While the polarization minimum of Iapetus' leading side is similar to that of Chiron, it is deeper than that of Chariklo and shallower than that of Pholus (Bagnulo et al. 2006; Belskaya et al. 2010). Moreover, the minimum of negative polarization of three Centaurs occurs at smaller phase angles than for Iapetus' leading side. For comparing the measurements for Iapetus' leading side with those of trans-Neptunian objects (Boehnhardt et al. 2004; Bagnulo et al. 2006, 2008; Belskaya et al. 2008), and the nucleus of a comet Encke (Boehnhardt et al. 2008), the limited respective data points within the same phase angle range is a constraint, given that there is only one data point for each of Iapetus' hemispheres at phase angles ≤2.0°. The phase angle dependence of the measured polarization for Iapetus' leading side shows a trend that is quite consistent with that of 133P/Elst-Pizarro (Bagnulo et al. 2010), within similar phase angle ranges.

It is worth noting that the polarization of Iapetus' leading side is three times higher than that of the trailing side (Paper I) in the same phase angle range of ~3.0–6.0°. This agrees with the general expectation that the negative branch of polarization tends to get deeper for low albedo objects. At the same time, the measurements of Iapetus' trailing side are deeper than that

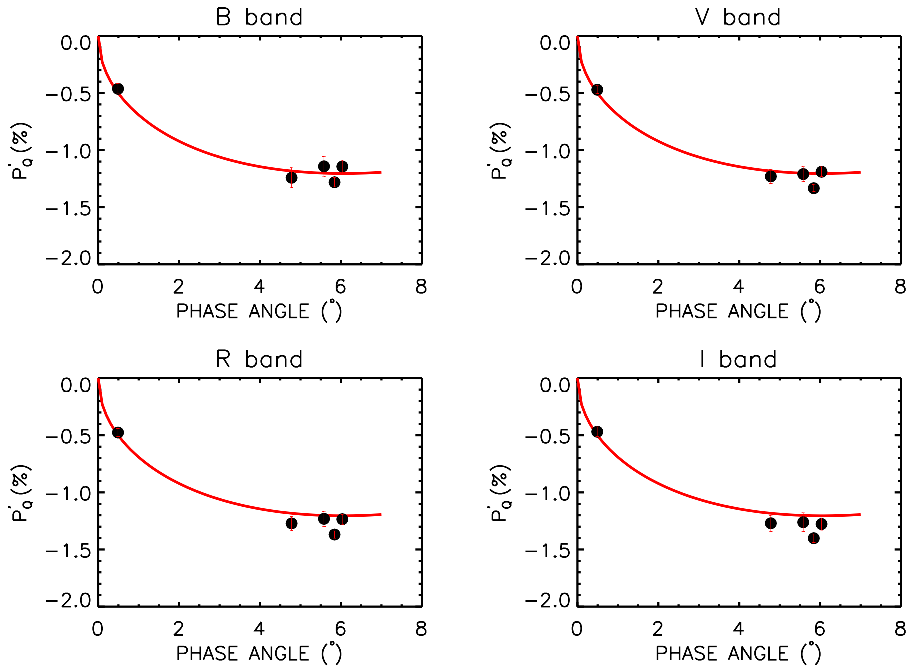


Fig. 4. Degree of linear polarization P'_Q of Iapetus' leading side in four Bessel filter bands, obtained after convolving the polarized spectra, versus the phase angle of observation. The data points were fitted by the trigonometric polynomial proposed by Lumme & Muinonen (1993): $f = b\sin^{c_1}(\alpha)\cos^{c_2}(\frac{\alpha}{2})\sin(\alpha - \alpha_0)$, where b and the inversion angle α_0 are considered as free parameters, while c_1 (affecting the position of the minimum) and c_2 (influencing the asymmetry of the curve) can be fixed to 0.5 and 0.35, respectively, for satellites (e.g., Belskaya et al. 2010). Note that we fitted all data points with the curve generated for the case of one spectral band (B band) to help see the spectral variation in the measurements in different filter bands.

of the leading side at very low phase angles (≤1.0°), indicating that brighter objects exhibit the so-called polarization opposition effect at very small phase angles, thus confirming the prediction of the coherent backscattering model, as noted in Paper I.

Our motivation for measuring the circular polarization of Iapetus' leading side (Fig. 2) follows the report of Cruikshank et al. (2008) regarding the identification of traces of organic compounds (e.g., PAHs) on this hemisphere of Iapetus. In fact, PAHs are not chiral, and thus no circular polarization from such molecules would be expected even if its presence on Iapetus is real. As can be seen from Fig. 2, the consistency of our measurement of circular polarization of Iapetus' leading side with zero therefore implies that chiral organic compounds are likely to be absent on its surface. Moreover, it is worth mentioning that, despite the difference in the phase angle of observations, this value is similar to the circular polarization measurements of Iapetus' trailing side (Paper I). Masiero & Cellino (2009) have also tried to measure the circular polarization of two main belt asteroids, (234) Barbara and (387) Aquitania, but did not detect any circular polarization of the light scattered from these asteroids.

4. Conclusions

To measure the polarization of Iapetus with an accuracy level of ∼±0.1% per spectral bin (bin size of ten pixels over which the maximum intensity counts are integrated) for each Stokes parameter, a signal-to-noise ratio of ∼500 is needed. To meet this end, we exploited the full capability of the FORS2 instrument of the ESO VLT in spectro-polarimetric mode.

With this work, we have presented the analysis of both linear and circular polarimetric observations of the leading side of Saturn's moon Iapetus, which were obtained using the FORS2 instrument of the ESO VLT. We also compared our polarimetric measurements of Iapetus' leading side with that of the trailing hemisphere obtained in our previous work (Paper I). The observations were performed from 2009 to 2012 at five different phase angles (for each hemisphere), covering the maximum accessible phase angle range from the ground (i.e., ∼6.0°) and over a broad spectral range (400–800 nm).

The main results are summarized as follows.

- The linear polarization of both the leading and trailing sides of Iapetus are negative over the accessible phase angle range.
- The polarization of Iapetus' leading side shows a clear trend to increase (in absolute terms) with increasing phase angle from ∼0.50% at a phase angle of ∼0.50 to ∼−1.30% at a phase angle of ∼6.0°, reaching likely a minimum at ∼5.90°. This trend contrasts to that of the trailing side, which varies from ∼−0.90° at 0.77° to ∼−0.3% at 5.20°, as reported in Paper I.
- The variation in polarization of Iapetus' two hemispheres with wavelength is in general very small. However, in particular for the leading side of Iapetus, there is a slight tendency to increase in polarization with increasing wavelength for most of our observing epochs, showing similarity, in this regard, to the trend toward wavelength dependence of polarization for S and M type asteroids (e.g., Belskaya et al. 2009). Besides this, no clear trend in the variation of polarimetric spectral slope with phase angle can be drawn for both hemispheres of Iapetus.
- The negative polarization of Iapetus' leading side is three times higher than that of the trailing side within the same phase angle range (between ∼3.0–6.0°), in agreement with the general expectation that the linear degree of negative polarization tends to get deeper for low-albedo objects. At the same time, for observations at phase angles <1.0° (i.e., near exact backscattering direction), the polarization value of the bright side of Iapetus is deeper than that of the dark side, indicating that brighter surfaces exhibit the so-called polarization opposition effect (i.e., a sharp surge in polarization depth) at very low phase angles.
- Our circular polarization measurements of Iapetus' two hemispheres are consistent with zero, indicating that a significant number of optically active (chiral) molecules are not present on its surface.

- Our polarimetric measurements of Iapetus' leading side are similar to those of 133P/Elst-Pizzaro (Bagnulo et al. 2010), which in turn resembles F-type asteroids more. This similarity in the behavior of the polarization phase curve might indicate a similarity in at least certain scattering parameters of the surfaces (e.g., particle size, composition, albedo, compactness, etc.), even though the effect of each parameter cannot be disentangled from our measurements alone (without modeling the observed polarization).

In summary, our measurements of circular polarization of Iapetus' hemispheres, combined with their respective linear polarization measurements, would therefore allow one to translate this polarimetric characteristic of typical water ice (on its trailing side) and that the dark material (on its leading side) to the light scattering behavior of other solar system bodies whose surface materials are unknown.

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