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POLARIZATION MEASUREMENTS OF THE GALILEAN SATELLITES OF JUPITER

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Abstract

Polarization curves for the four Galilean Satellites are presented. They indicate that the surfaces of Io, Ganymede and Europa are covered mostly by a bright, transparent material, possibly frost. The surface of Callisto is different. It is more similar to that of the Moon, but some frost patches are also present.

1.) Introduction

Recently there has been renewed interest in the physical study of the Galilean satellites. Reflectivity measurements (Harris, 1961; Johnson, 1970) indicate that the surfaces are covered with some material which is very bright in the red, but which is much more absorbing in the blue and ultraviolet than ordinary water snow. The reflectivity curve of Io, for example, is very unusual: the geometric albedo drops from 1.15 at 0.82 μ to 0.19 at 0.35 μ (Harris, 1961). One suggestion (Veverka, 1970; Sagan, 1970) is that the surfaces are covered with a bright frost in which multiple scattering is important, but that in addition this frost contains very effective ultraviolet absorbers (such as organic compound, polymers, or free radicals). Photometric evidence (Harris, 1961; Johnson, 1970) and visual observations (Dollfus, 1962) indicate that all satellites are covered with patches of bright material, interspersed with darker regions. On Io, Europa and Ganymede the bright regions predominate, while the reverse seems to be true for Callisto.

Although the phase angle of Jupiter as seen from Earth never exceeds 11°, polarization measurements of the satellites should be very helpful in studying their surfaces. Since at small phase angles the degree of polarization, and hence its variation with color, are likely to be small, it is useful to begin such a survey with measurements in integrated white light.

2.) The Observations

The polarization curves of the satellites were determined using the Harvard two channel Wollaston prism polarimeter with the Harvard 16" and 61" telescopes. No filter was used. Since the polarimeter uses S20 photomultipliers all light between 0.3 and 0.8 μ is registered, thus appreciably increasing the signal to noise ratio. As the wavelength dependence of the polarization is probably small at small phase angles, little information is lost by not using a filter in a preliminary survey.

Observations were made during both the 1968 and 1969 oppositions. The major difficulty encountered was to allow correctly for the scattered light from Jupiter. In this respect the 1969 observations were definitely superior and only these are considered in this paper. The polarization curves of the four satellites are shown in Figure 1. The accuracy of the points is, with a few exceptions, $\pm$ 0.1%.

Since I will argue that these curves indicate the presence of frost or snow on at least the first three satellites, it will be well to review first what is known about the polarization properties of snow and frost.

3.) The Polarization Curve of Snow

The only published measurements of the polarization of water snow or frost are those of Lyot (1929) and Dollfus (1955). No polarization measurements of frosts of other compositions have been reported. Lyot studied a variety of natural snow surfaces in integrated white light. Between $\alpha = 0°$ and $10°$ the observed polarization was always small, increasing from values between -0.1 to 0.0% at $\alpha = 2°$ to 0.0 to +0.1% at $\alpha = 10°$ (here α is the phase angle).

Dollfus' measurements, also in white light, refer to laboratory frost layers viewed at 65°. Although for dark lunar-like surfaces the observed polarization depends on the phase angle only and is largely independent of the angle of incidence i or the angle of observation ε individually, this is not true for surfaces made up of bright, transparent particles in which multiple scattering is important (Dollfus, 1961). For example, according to graphs given by Dollfus (1955) for one particular frost layer at a phase angle of 70°, the observed polarization at $\varepsilon = 40°$ is over twice that at $\varepsilon = 10°$ for an azimuth angle of 90° between i and ε. However, for very small phase angles, the polarization of the frost is roughly independent of ε, except for very large values of ε. Thus we can probably use Dollfus' measurements here for guidance. His results indicate that between 0° and 10°, the polarization curve of frost will be concave upward and will lie between -0.4% and +0.4%, depending on the texture of the layer.

The weak polarization of a frost layer is evidently a result of the importance of multiple scattering within the surface. The addition of a strong absorber will hinder multiple scattering and hence enhance both the negative branches and the positive branches of the polarization curve. The polarization curves of snows or frosts cannot be diagnostic of composition, since any bright transparent substance will give very similar results. But it should be possible to detect the presence of even small admixtures of a strong absorber by the development and enhancement of the negative branch.

However it is difficult to compare laboratory measurements accurately with the disk-integrated polarization of a snow or frost covered planet, since the polarization on such a planet will vary significantly with position on the disk. This is because for such a surface the polarization depends not only on α but also on i and ε separately. This effect will be most important at large phase angles.

4.) Discussion

In interpreting the polarization curves, I will assume that atmospheric contributions are negligible. There is no spectroscopic evidence that any of the Galilean satellites has a significant atmosphere, and photometric observations of post-eclipse brightness anomalies are still uncertain (Binder and Cruikshank (1964); Franz and Millis (1970)).

From the absence of a pronounced negative branch in the polarization curves of Io, Europa and Ganymede, it can be inferred that the surfaces of these satellites consist mostly of a bright multiply scattering material, such as snow. It is true that this is also a property of solid (that is, non-particulate) surfaces but these tend to have larger polarizations near $\alpha = 10°$. To keep the polarization at $\alpha = 10°$ low, multiple scattering within the layer is required. Furthermore, the phase curves of the satellites measured by Stebbins (1927) and Stebbins and Jacobsen (1928) reveal the presence of opposition effects (Veverka, 1970) which are incompatible with solid smooth surfaces, but indicate rather surfaces which are microscopically rough and probably particulate.

The polarization curve of Callisto has a definite negative branch. The presence of a well developed negative branch can be interpreted as indicating that the surface is particulate and sufficiently dark for multiple scattering to be unimportant (Lyot, 1929). This agrees with photometric evidence: The reflectivity of Callisto is low (Harris, 1961) and quite compatible with that of a rocky surface; and Callisto shows a very strong opposition effect (Stebbins and Jacobsen, 1928), indicating that the surface is particulate.

The minimum polarization is -0.8%, compared with -1.2% for the Moon, but the cross-over angle is probably much smaller than the lunar 23°. Certainly, the phase angle at which the minimum polarization is observed ($\simeq$ 6°) is much smaller than the lunar 11°. The unusually small values of the cross-over angle and of the angle of minimum polarization require an explanation since Callisto has a well developed branch. A possible explanation is that part of the surface is covered with frost. In this case the negative branch of the dark soil would be in fact even more pronounced than indicated in Figure 1. It is also possible that the entire surface is covered with frost contaminated with a strong admixture of a dark absorbing substance which hinders multiple scattering and leads to the production of a negative branch. The amount of this contamination would vary from place to place since visual observations (Dollfus, 1961) and photometric measurements (Harris, 1961; Johnson, 1970) indicate patches on Callisto.

Either this model, or the one above in which a rocky surface of a fairly dark particulate material is covered in places by patches of uncontaminated frost could explain the observed negative branch, the small cross-over angle, the pronounced opposition effect, and the shape of the reflectivity curve.

The two sides of Callisto differ by 0.2 mag in V (Harris, 1961). Since the leading (darker) side has fewer bright regions than the trailing (brighter) side, the negative branch of the leading side should be more pronounced than that of the trailing side. Unfortunately only two measurements of the trailing side are available (Fig. 1) and it is as yet impossible to determine whether this indeed is true.

Vapor pressure arguments suggest that water frost is likely to be the most common frost on the Galilean satellites (Moroz, 1966). However it is difficult to explain the observed reflectivity curves in terms of patchy surfaces of snow and silicate rock (Johnson, 1970). The problem is that the satellite surfaces tend to be very bright in the red, but quite dark in the UV. This is not a behaviour of snow. By changing the particle size a layer of snow can be made bluish, but not red (Veverka, 1970). For this reason, and since the drop in reflectivity from the IR to the UV increases systematically from Ganymede to Europa to Io, Veverka (1970) has suggested that the surfaces originally consisted of water frost with small amounts of impurities such as CH_4 and NH_3, and have been modified by the action of the charged particles in the Jovian radiation belts. A similar suggestion has been made independently by Sagan (1970, 1971). This has led to the formation in the surface layer of organic compounds, polymers and free radicals, which strongly absorb in the UV. Suggested materials include NH and CH (Ramsey, 1970); CH_3I (Papazian, 1958); $(NH_2NH)_n$ and CH_3CS (Rice, 1956); polymers of HCN, C_2N_2 and $HCN.NH_3$ (Woeller and Ponnamperuma, 1969); and complex organic molecules such as azobenzene (Sagan et al., 1967). (Callisto can be left out of this discussion since its reflectivity changes only from 0.31 at 0.82 μ to 0.14 at 0.35 μ, and is therefore not unlike that of a silicate material).

The effect of the charged particle radiation should be largest on Io, and appropriately Io is not only the reddest of the four Galilean satellites, but the reddest known object in the solar system.

Unfortunately polarization measurements can tell us little about the composition of the surface frosts. Here near IR spectrophotometry seems more promising. However polarimetry remains a powerful way of studying the texture and general nature of the surfaces.

The next step in the polarimetry of the Galilean satellites is a series of color measurements between 0.3 and 1.0 μ, with special emphasis on Io and Callisto. Measuring the polarization of Callisto at various points in its orbit is another important project.

Laboratory measurements of the polarimetric (and photometric) properties of various snows and frosts (water, carbon dioxide, methane, ammonia, etc.) are urgently needed. In addition, frosts contaminated with various chemicals and mineral powders should be carefully studied.

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References

Binder, A.B. and Cruikshank, D.P. (1964). "Evidence for an atmosphere on Io." Icarus 3, 299.

Dollfus, A. (1955). "Study of the planets by means of the polarization of their light." NASA TTF-188.

Dollfus, A. (1961). "Polarization studies of the planets" Chapter 9 in Planets and Satellites. (Kuiper and Middlehurst, eds.) Chicago.

Dollfus, A. (1962). "The surfaces of the Moon and planets." Handbook of Physics, 54, 180.

Franz, O.G. and Millis, L. (1970). "A search for an anomalous brightening of Io after eclipse." Icarus, in press.

Harris, D.L. (1961). "Photometry and colorimetry of planets and satellites." Chapter 8 in Planets and Satellites. (Kuiper and Middlehurst, eds.) Chicago.

Johnson, T.V. (1970). "Albedo and spectral reflectivities of the Galilean satellites of Jupiter." California Institute of Technology Ph.D. Thesis.

Lyot, B. (1929). "Research on the polarization of the light from planets and from terrestrial substances." NASA TTF-187.

Moroz, V.I. (1966). "Infrared spectrophotometry of the Moon and the Galilean satellites of Jupiter." Soviet Astronomy A. J. 9, 999.

Papazian, H.A. (1958). "Free radical formation in solids by ion bombardment." J. Chem. Phys. 29, 448.

Ramsey, D.A. (1960). "Optical spectroscopy of trapped radicals" Chapter 6 in Formation of Free Radicals. (Bass and Broida, eds.) Academic Press.

Rice, F.O. (1956). "Colors on Jupiter" J. Chem. Phys. 24, 1259.

Sagan, C. (1970). "The star that failed" in Science Year: 1971 (Field Enterprises Educational Corporation).

Sagan, C. (1971). "The solar system beyond Mars: an exobiological survey." Sp. Sci. Rev., in press.

Sagan, C., Lippincott, E.R., Dayhoff, M.O., and R.V. Eck (1967) "Organic molecules and the coloration of Jupiter." Nature 213, 273.

Stebbins, J. (1927). "The light variations of the satellites of Jupiter and their application to the measures of the solar constant." Lick Obs. Bull. 13, 1.

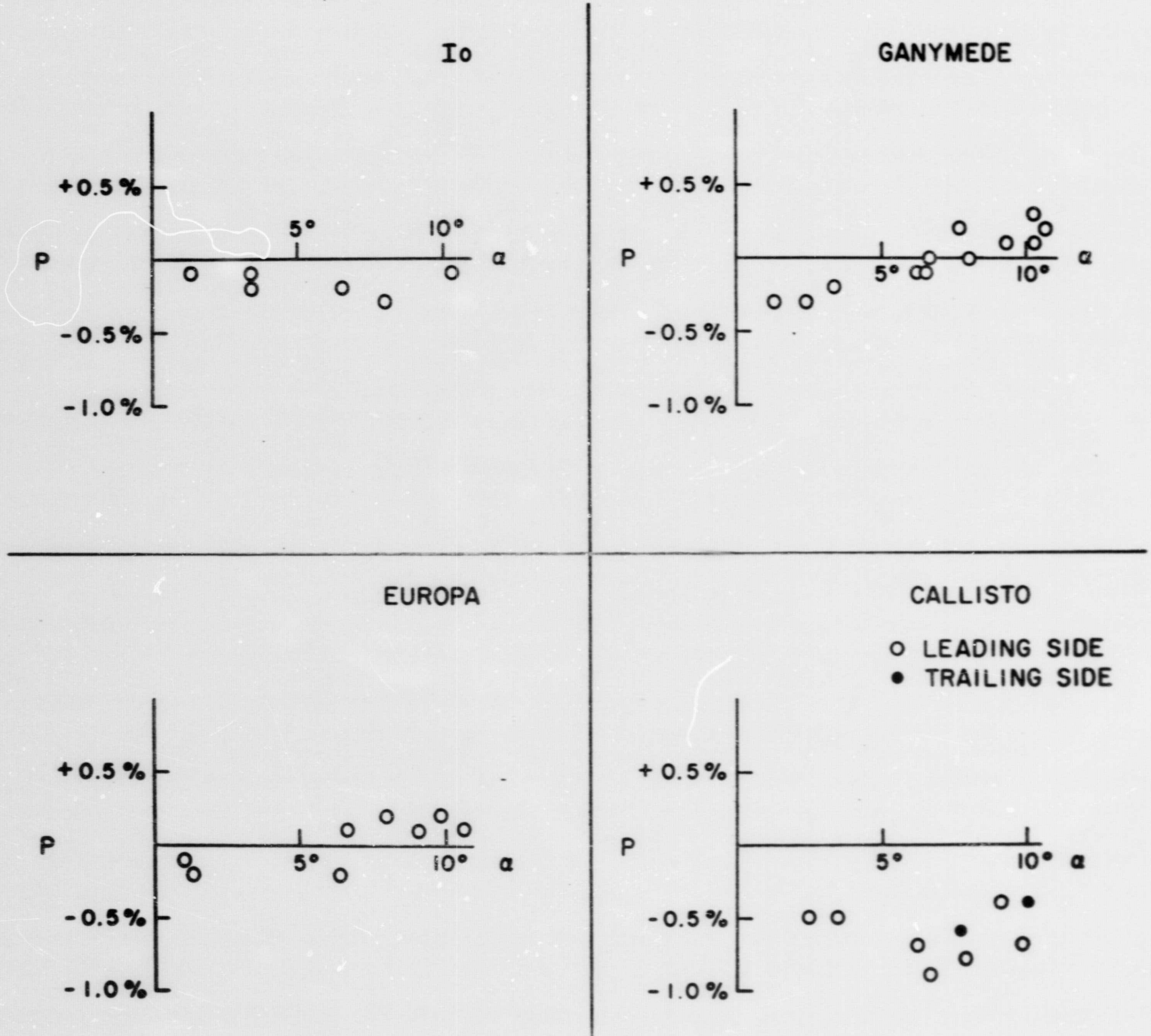
Stebbins, J. and Jacobsen, T.S. (1928). "Further photometric measures of Jupiter's satellites and Uranus, with tests for the solar constant." Lick Obs. Bull. 13, 180.

Veverka, J. (1970). "Photometric and polarimetric studies of minor planets and satellites." Harvard Ph.D. Thesis.

Woeller, F. and Ponnamperuma, C. (1969). "Organic synthesis in a simulated Jovian atmosphere." Icarus 10, 386.

Figure Caption

Polarization curves of the four Galilean satellites of Jupiter.



Io
GANYMEDE
EUROPA
CALLISTO
○ LEADING SIDE
● TRAILING SIDE
P
+0.5 %
-0.5 %
-1.0 %
5°
10°
α