NOTE

Polar Frost Formation on Ganymede

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Received June 25, 1984: revised February 4, 1985

The suggested models of polar frost formation on Ganymede are reviewed. A model in which plasma bombardment changes the reflectance characteristics of the icy surface is proposed.

Introduction. The observation of a polar frost on Ganymede, which is often referred to as polar "caps," is well established from Voyager photographs (Smith et al., 1981). The frost covering is very light and may be only millimeters or less in thickness (Squyres, 1980), but, because it is clearly visible, it has received some attention as a possible clue to exogenic processes that might be affecting the surface. A number of models have been proposed for the formation of this distinctive feature which require transport of material from the equatorial to the polar regions. In this paper an alternate proposal for the origin and appearance of these caps is presented which does not depend on this transport and is based on observations of the surficial changes produced by ion bombardment. Before describing this model a review of the suggested mechanisms for establishing the polar frost on Ganymede is presented.

Purves and Pilcher (1978) considered a mechanism for production of the polar frost in which water molecules sublimated from the higher temperature equatorial regions are transported ballistically to the polar regions and redeposit as frost. They found, however, that a net accumulation of deposited water molecules would begin at much lower latitudes than that observed for the cap margins and, therefore, concluded that the process must be more complex. Subsequently Sieveka and Johnson (1982) pointed out that latitudinal variations in magnetospheric ion bombardment would also produce a net transport to the polar regions. As water molecules sputtered by the ion bombardment of the surface have much greater excursion distances across the surface than water molecules sublimated at those temperatures expected on Ganymede, such a process could, in principle, produce the observed cap margins. Based on recent laboratory measurements of the sputtered molecule energy spectra (Johnson et al., 1983a), it was concluded that a net accumulation of material of the correct order of magnitude would occur, due to ion sputtering, above latitudes close to those observed for the cap margins. Further, the calculated margins exhibited a leading/trailing asymmetry, due to sputtering by the corotating plasma–ion bombardment, not unlike that observed (Sieveka and Johnson, 1982).

Recently Shaya and Pilcher (1984) have rejected sputtering as a source of the cap margins. They base their objections on the estimates of the relative lifetime of bright (presumably icy) rays by Passey and Shoemaker (1982) and on the fact that the leading/trailing variation in the cap margins can be associated with differences in underlying terrain (Squyres and Veverka, 1981). They also reject the suggestion by Squyres (1980) that meteoritic impact gardening of the surface produced the caps, noting the absence of such a feature on Callisto which also has significant quantities of surficial ice (Spencer and Maloney, 1983; Clark, 1981). Shaya and Pilcher (1984) have proposed a model for the formation of the caps which has two aspects. First, the existence of grooved terrain suggests that there were upheavals which could have created large deposits of fresh ice as a bright frost, much like that deposited from impacts by large meteors. Second, the subsequent sublimation and redeposition of this material occurs at a rate that is latitudinally dependent and also depends on the underlying material. Based on an assumed surface temperature profile they show that one could expect complete removal of the frost up to latitudes consistent with the observed cap margins. In this model, the polar cap is a remnant of an earlier upheaval and the equatorial regions would lose the frost covering. The fate of the surface left behind in the equatorial regions, which is also icy (Clark, 1981), is not made clear.

In the above models, two important points have been neglected. First, even in regions from which a net loss of material occurs over long periods, the vast majority of the water molecules sublimated are redeposited close to their source (Sieveka and Johnson, 1982), indicating that the surface is reprocessed much faster.
than it is transported poleward. Second, no attention has been paid to the form the redistributed water molecules will take when they condense on the surface of Ganymede. That is, will such deposition produce a highly scattering surface like that observed?

Clark et al. (1983, 1984) have considered grain growth and destruction on the satellite surfaces. They suggest that, for a surface frost of mixed grain size, large grains should grow at the expense of small grains at a rate dependent on the substrate temperature and may eventually grow to form a solid. Further, they propose that smaller grains are lost more rapidly due to corotating ion bombardment (sputtering) than are larger grains. Using this they are able to show that the observed band depths for water ice on the leading and trailing hemispheres of the three icy Galilean satellites are consistent with expected temperature and ion bombardment rates, but they did not consider the latitudinal differences being discussed here.

Regarding grain formation, we note that in the laboratory even rather rapid (via a nozzle) depositions of water molecules on an extremely cold surface will result in the formation of a relatively clear surface which does not scatter light. (No band depth analysis of such deposits has been carried out yet.) The formation of a very irregular surface which appears highly reflecting apparently requires a flow onto a surface in which clusters already exist in the gas phase (Mayer and Pletzer, 1984). One would, therefore, expect that the slow ballistic transport (sputter or thermal) of molecules to higher latitudes would not form an irregular scattering surface if the underlying surface was not a scattering surface. Certainly, if the surface were covered with small grains then, by analogy with Clark et al. (1983), the thermal and sputter processes could result in grain metamorphism at different rates at the equator and at the poles, resulting in latitudinal differences in grain size. Whether the exchange is sufficient to explain the observations is not clear and what "initial" conditions would be required on the surface is also not clear. In the following, it is pointed out that ion bombardment itself can form a light-scattering surface if the underlying surface was not a scattering surface. Certainly, if the surface were covered with small grains then, by analogy with Clark et al. (1983), the thermal and sputter processes could result in grain metamorphism at different rates at the equator and at the poles, resulting in latitudinal differences in grain size. Whether the exchange is sufficient to explain the observations is not clear and what "initial" conditions would be required on the surface is also not clear. In the following, it is pointed out that ion bombardment itself can form a light-scattering surface, and this is used to account for the observed caps without requiring ballistic transport.

Proposed model. Experiments on ion and electron bombardment of water ice at low temperatures have shown that not only do these particles sputter significant quantities of water molecules (Brown et al., 1982; Reimann et al., 1984) but that they also change the visual characteristics of the surface significantly (Brown et al., 1978; Johnson et al., 1983b; Smythe, 1985). That is, deposits of water ice at very low temperatures which are initially nonscattering become highly scattering after being subjected to fast ion bombardment (~10^6 ions/cm^2). The change in the reflectance property is due to the surface becoming very irregular (Johnson et al., 1984a) with an increase in the defects in the surficial ice and some indication of dendritic crystal growth in the region bombarded (Brown et al., 1978). The laboratory observations suggest that any irregularities produced by ion bombardment are gradually enhanced during subsequent irradiation as the ions increase the mobility of the surface molecules and defects. The fast ion bombardment, therefore, is a source of observable irregularities on a surface which initially is not a scattering surface. This effect is not seen for low-energy heavy ions like the corotating ions which only penetrate the ice a few hundred angstroms (J. W. Boring, 1984, private communication).

Based on the above, an icy surface at the equator or at the poles of Ganymede experiencing the expected level of ion bombardment (Johnson et al., 1981, 1983a) would acquire a scattering surface unless the thermal reprocessing and annealing of this surface is rapid compared to the bombardment rate. In the latter case the surface will remain nonscattering, like frosts deposited in the laboratory. Using the laboratory dose given above and the LECP fluxes, the time for acquiring a highly reflecting surface due to ion bombardment at Ganymede would be years. Care should be taken, however, in applying this observation to the satellite surfaces as the ion fluxes used in the laboratory are chosen so that the sputtering rate dominates the sublimation rate. These fluxes are, however, kept low enough so that the sputtering results are due to individual particles. Although the growth of a light-scattering surface is certainly related to the sputtering rate, the mechanism for formation of the irregularities is not known and, therefore, the rate of formation caused by the much lower fluxes at the satellite is not certain.

The thermal reprocessing rate of a volatile surface on a satellite does, of course, depend both on latitude and on the thermal properties of the substrate in the same manner as the loss rate discussed by Shaya and Pilcher (1984) does. In fact, in regions where a net loss of volatiles occurs over long periods, the relative concentration of impurities can increase (Haff, 1980), enhancing these thermal processes. Therefore, ion bombardment competing with thermal reprocessing may be sufficient to explain the latitudinal differences observed on Ganymede. Because the laboratory data on the formation of a scattering surface and the plasma data at the surface of the satellite are incomplete, it is only possible to roughly estimate the latitude at which the production of a scattering surface by ion bombardment dominates thermal reprocessing. Here we note that, based on available calculations (Johnson et al., 1982, 1984b; Sieveka and Johnson, 1982), the sputtering and diurnally averaged sublimation rates become comparable at midlatitudes on Ganymede. On the other hand, the sputter rate dominates the diurnally averaged sublimation rate over most of the surface of Europa, resulting in a global scattering surface, whereas at Callisto the extremely low level of ion bombardment does not compete with thermal processes.

The model proposed is, therefore, seen to be consistent with the discussion of Shaya and Pilcher (1984) without, however, the need to invoke a massive event.
and ballistic transport. Whereas ion bombardment would produce a frost-like surface at the millimeter level [based on penetration depths (Johnson et al., 1983b)], one might expect a thicker mantle to be produced by a massive event, a covering much more similar to the bright ejecta rays. In the model given here, the polar frost would be a permanent feature of Ganymede, a reflection of the fact that the surface of Ganymede is subjected to ion bombardment which creates a light-scattering surface in the absence of rapid thermal processes.

A second laboratory observation may also help explain the observations on Ganymede. At the highest temperatures expected in the equatorial region on Ganymede ion bombardment of water ice produces and ejects oxygen molecules nearly as efficiently as it sputters water molecules (Brown et al., 1983; Reimann et al., 1984; Haring et al., 1983; Bar-Nun et al., 1985). As the loss (to space) of the heavier O$_2$ molecule is much smaller than that for H$_2$O molecules (Johnson et al., 1983a), and as the O$_2$ will not efficiently absorb on the surface at those temperatures expected in the equatorial region, the much colder surface layer in the polar region may accumulate a significant amount of condensed O$_2$ (Johnson et al., 1982; 1984a). The implications of this for the reflectance properties under consideration is not yet understood. However, the presence of oxygen and water molecules being deposited on the rough surface produced by ion (electron) bombardment should modify the band depth and the gross reflectance characteristic of the surface of Ganymede at the higher latitudes.

In this note an alternative scenario for the formation and maintenance of the polar frost on Ganymede is proposed. It employs certain aspects of the previous model of bombardment of millimeter or less grains and comets. Frost grain size metamorphism: Implications for remote sensing of planetary surfaces. Icarus 56, 233–245.


