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NOTE

Polar ‘‘Caps’’ on Ganymede and Io Revisited

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The polar spectral features on Ganymede and Io, often called polar ‘‘caps,’’ have been attributed to magnetospheric-ion irradiation of these surfaces. The recent discovery of an intrinsic magnetic field and the mapping of the surface temperatures at Ganymede by the Galileo spacecraft re-enforce this hypothesis. In this note we describe how the spectrally very different polar features at Ganymede and Io are both signatures of plasma precipitation along open field lines to the polar surfaces of these objects. © 1997 Academic Press

Introduction. The origins of the bright polar surface on Ganymede (e.g., Smith *et al.* 1981, Hillier *et al.* 1996) and the darkened polar region on Io (e.g., Fanale *et al.* 1982), often referred to as polar ‘‘caps,’’ have been a source of interest for almost two decades (e.g., Purves and Pilcher 1978) . These spectral features have both been attributed to magnetospheric ion bombardment of the surfaces of these satellites (Johnson 1985, Wong and Johnson 1996a, Hillier *et al.* 1996). The recent observation that Ganymede has an intrinsic magnetic field (Kivelson *et al.* 1996a, Gurnett *et al.* 1996), and that Io may also have a weak field (Kivelson *et al.* 1996b), re-enforces the idea that the polar ‘‘caps’’ are a signature of charged-particle impact. That is, jovian magnetospheric-plasma particles can spiral into the surface of both objects along ‘‘open’’ field lines which intersect the satellite in a region about the poles. This results in enhanced plasma bombardment of the polar surface (Kivelson *et al.* 1996a). The radiation damage produced by the plasma impact brightens the low-temperature H_2O in the polar region of Ganymede and darkens the SO_2 near the poles of Io. Another effect of the plasma near the poles of Ganymede was recently reported, a weak aurora (Hall *et al.* 1996) caused by the plasma electrons interacting with the oxygen produced by sputtering of the icy surface (e.g., Johnson 1990).

Brief History. The polar feature on Ganymede was initially thought to be a frost produced by poleward transport and condensation of water molecules, due either to sublimation (Purves and Pilcher 1978) or to sputtering (Sieveka and Johnson 1982). If this process *did* lead to brightening, then, as pointed out frequently (e.g., Fanale *et al.* 1982), Io should also have a bright polar frost due to the transport and condensation of SO_2. However, the surface in Io's polar regions is noticeably darker in the visible than is the surface at lower latitudes.

At Ganymede there *is* a slow net poleward transport of water molecules, but re-deposition of sputtered and sublimed water molecules occurs, primarily, at *mid-latitudes* (e.g., Sieveka and Johnson 1982). This led Shaya and Pilcher (1984) to suggest that Ganymede's ‘‘caps’’ were a residual frost from an early geologically active period. Johnson (1985), on the other hand, suggested the bombardment of the surface by the plasma trapped in the jovian magnetosphere would directly cause the icy surface of Ganymede to become light scattering (brighten) due to the damage produced in low-temperature water ice by keV ions. This plasma-induced brightening competes with annealing, a process which proceeds efficiently in regions where the temperature exceeds about 100 K (Johnson and Quickenden 1997). Such temperatures were recently found to occur at latitudes less than about 40°–50° (Orton *et al.* 1996). Therefore, even under uniform bombardment it was suggested that the surfaces in the equatorial regions would anneal and be less scattering, whereas the cold polar surface would remain bright. Johnson (1985) also noted that the O_2 produced by plasma-ion bombardment of water ice (e.g., Brown *et al.* 1982, Johnson 1990) would have long residence times near Ganymede's poles, which could also affect the reflectance.

Fanale *et al.* (1982) suggested that the dark polar surface of Io was caused by plasma-ion-induced sputter-removal of condensed SO_2, whereas Hapke (1989) suggested that it was due to polarward transport and deposition of photo-chemical products of SO_2. That is, although freshly deposited SO_2 at low temperatures could in principal form a bright frost, its photo-chemical products, such as S_2O, absorb efficiently in the visible and near UV. Recently, Belton *et al.* (1996) suggested that the spectral nature of Io's poles was due to the very slow thermal processing rate of *dark* volcanic deposits.

Wong and Johnson (1996b) developed an atmospheric transport model for Io which included photo-chemistry and tested the Fanale *et al.* (1982) and Hapke (1989) hypotheses. They also pointed out that plasma-ion impact could *directy* alter the albedo of an SO_2 surface (Moore 1984). Using their transport model they showed that energetic plasma bombardment of vapor-deposited SO_2 frost was more efficient at causing darkening of the polar regions than either sputter-removal of the frost or the pole-ward flow and deposition of photo-chemical products (Wong and Johnson 1996a). Therefore, they proposed that the Io polar feature was due to competition between the deposition of SO_2 (possible brightening) and radiation darkening of SO_2 by energetic ion impact. In their model the latter dominated above about 70° latitude.

Radiation effects. Johnson and Quickenden (1997) recently reviewed the effects produced in low temperature water ice by charged-particle bombardment. These include the formation, diffusion, and trapping of new molecular species, as well as the formation of point defects, voids, and bubbles. In water ice those molecules formed by the incident radiation which can be stable at low temperatures [e.g., OH, HO_2, H_2O_2, etc. (Johnson and Quickeden 1997)] absorb efficiently in the UV and the IR but *not* in the visible. On the other hand, *surface damage*, *voids*, *and bubbles* are also formed (Johnson and Jesser 1997). Depending on the

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size and density of these features, a clear surface can become become brighter due to enhanced scattering in the visible.

That plasma-irradiated ice can brighten in the visible was first noted in the laboratory work of Brown *et al.* (1978) for MeV ions and subsequently by others for keV ions (e.g., Johnson *et al.* 1985, Smythe 1985). In a study of the change in reflectance due to ion impact of vapor-deposited water ice at 60 K, Sack *et al.* (1991, 1992) showed that 30 keV He^+ and S^+ brightened the surface above about 450 nm, whereas 30 keV Ar^+ caused brightening above about 290 nm. Whether this brightening is primarily surficial or is due to the damage produced below the surface has not been established, although it has been noted that ions with very small penetration depth do not brighten the laboratory ices (e.g., Johnson 1985). It was also shown that the brightening produced by bombardment can be removed by annealing (Sack *et al.* 1991). [Note: films deposited at low temperarures and warmed to 200 K appear to brighten by cracking (Westley 1994), a process different than that proposed here.] The increase in reflectivity produced by ion bombardment in low-temperature, small-grain (submicrometer) laboratory samples will also occur in the much larger grains (tens of micrometers) comprising the polar ice on Ganymede.

The production of damage, which can cause the surface to become scattering (bright), was also studied using a transmission electron microscope. Johnson *et al.* (1985) reported that samples irradiated at 95 K with a large dose of keV He^+ viewed in such a microscope had developed submicrometer to micrometer surficial and internal structure. Independently, Heide and Zeitler (1985) showed that very small vacancy aggregates (voids) were formed in a very low temperature, dense-phase, amorphous ice produced by the keV electrons. [The keV electrons may also have contributed to the damage reported by Johnson *et al.* (1985).] The voids produced in the dense-amorphous ice studied by Heide and Zeitler disappeared with increasing temperature during conversion to a less-dense form of amorphous ice. However, Heide and Zeitler (1985) also reported that voids formed and grew at higher temperatures (up to 160 K) in crystalline ice grains.

The production of voids and bubbles was recently described by Johnson and Jesser (1997) to account for the trapping in ice of a density of O_2 as inclusions in Ganymede's surface (Calvin *et al.* 1996, Calvin and Spencer 1997). The multiple defects produced in the track of a fast heavy ion or a keV electron form vacancy aggregates (voids) which are nanometer features at low temperature ($\ll 100$ K). Voids can grow by irradiation-induced or thermal diffusion and can be stabilized at higher temperatures becoming bubbles by trapping of a volatile, such as O_2 which is formed during irradiation (e.g., Johnson 1990). The void size achieved is typically limited by grain size, due to competition between void growth and diffusion of irradiation-produced vacancies to the grain boundaries. Hence, lower temperatures give smaller grains and smaller voids and bubbles. Recently, Calvin and Spencer (1997) found the "dense O_2" spectral feature on Ganymede had a latitudinal dependence. This is opposite to that of the polar "cap" brightening, suggestive of the differences in void size and distribution with temperature (Johnson and Quickeden 1997, Johnson and Jesser 1997).

In the SO_2 ice on Io, void and bubble formation must also occur, and, as in water ice, radiation damage of SO_2 produces new molecular species. However, the absorbing properties of the radiation products formed in SO_2 ice differ markedly from those produced in water ice. That is, products such as S_2O and S_n absorb efficiently in the visible and near UV (Hapke 1989, Johnson *et al.* 1988) causing the surface to darken, as seen in laboratory samples (e.g., Moore 1984). Therefore, although plasma precipitation produces physical damage which can *brighten a water ice surface*, it also produces chemical damage which *darkens SO_2 surfaces* in the visible.

Particle precipitation. Open field lines that intersect the surface of a satellite will enhance the flow of plasma to the surface. On Ganymede the presence of the intrinsic field results in open field lines which intersect the surface above about 40° latitude (Kivelson *et al.* 1996a). Quite remarkably, the polar "caps" begin about 35°–50° (e.g., Smith *et al.* 1981, Hillier *et al.* 1996) with some variations in the cap "edge" between the leading and trailing hemispheres. Temperatures for which *annealing* takes place efficiently ($T \gtrsim 100$ K) *also* occur below about 40°–50° latitude (Orton *et al.* 1996). This agreement is very suggestive that Ganymede's polar "caps" are a signature of plasma bombardment, but this must be analyzed in more detail. A damage/annealing calculation is needed, since the spectral character of the radiation damage depends not only on the plasma flux to Ganymede's polar surface but also on the local composition and temperature.

At Io, present modeling of Galileo data indicates that open field lines also reach the polar surface, whether or not there is an intrinsic field (Kivelson *et al.* 1996b). This re-enforces the arguments in Wong and Johnson (1996b) that radiation darkening by those ions which can penetrate the very thin atmosphere near the poles alters the spectral character of the surface in the polar regions. When the particle flux data is eventually determined, that comparison of atmospheric transport and deposition with radiation damage should be repeated.

In evaluating radiation damage for either surface it is important to remember that although the jovian magnetospheric-particle *flux* is dominated by the lower energy plasma ions ($\lesssim$1–10 keV), the plasma *energy transport* (Mauk *et al.* 1996) is dominated by the *very* energetic ion flux [e.g., for Io $>$ 100 keV (Wong and Johnson 1996a, Fig. 3)]. Since the gyroradius of a charged particle is proportional to its mass and speed, the plasma electrons and slower ions essentially "flow" along the field lines, whereas the *very* fast heavy ions do not and can have access to Ganymede's surface at low latitudes. Since the electrons and the lower energy ions have smaller penetration depths, the quality of the change produced in the surface can differ from that for the very fast ions. Such differences were seen in the experiments of Sack *et al.* (1992). The brightening produced in water ice by 30 keV Ar^+ was somewhat *greater* than that produced by the *lighter, more penetrating* 30 keV He^+, both of which are non-reactive on implantation. Since the surface at low latitudes on Ganymede is partially protected from the plasma, the ion flux is low and annealing dominates resulting in larger grains and, hence, a darker surface [i.e., an anti-correlation of albedo with temperature (Orton *et al.* 1996)]. Similarly larger bubbles containing trapped O_2 are formed at low latitudes. For comparison, at Europa the bulk of the plasma appears to have access everywhere, which may contribute to the fact that its surface is brighter gobally than is Ganymede's surface but is similar to Ganymede's polar surface (Johnson 1985, Hillier *et al.* 1996). If the grains in the polar region are ~50–100 μm, as suggested, and the diffusion of radiation damge is small, then the optical depth of the scattering region measured by Hillier *et al.* (1996) is produced by a ~1 μm layer of radiation damage in each ice grain exposed in the porous surface to the plasma.

Summary. The origin of the spectral character of the polar surfaces on Ganymede and Io has been an issue of long-standing interest. Earlier we proposed that, even if the plasma flow onto Ganymede and Io was uniform, the polar reflectance for these objects might be accounted for by plasma precipitation to the surface (Johnson 1985, Wong and Johnson 1996a). At Ganymede the *brightening* of the ice in the visible produced by plasma bombardment competes with annealing at temperatures above about 100 K [<40°–50° latitude (Orton *et al.* 1996)] producing a polar "cap," whereas the poleward transport of H_2O makes a negligible contribution. At Io, on the other hand, the more rapid sublimation, poleward transport, and deposition of SO_2 competes with radiation-induced *darkening* by the plasma ions. The recent mapping of open field lines onto the surfaces of these two objects by Kivelson *et al.* (1996a,b) suggests that the charged particles do have access to these surfaces and that the fluxes in the polar regions are larger than in the equatorial regions, so that the "caps" are a signature of plasma impact. This is especially convincing at Ganymede where the rough latitudinal scale of the polar feature compares closely with the average latitudinal region in which open field lines intersect the surface. Since the flux in the equatorial region on this object is lower than previously thought, the effect of annealing is more pronounced, which can also account for the latitudinal dependence of trapped O_2 seen by Calvin and Spencer (1997). Therefore, although the cause of the polar features on these two objects may be the same, *the spectral ramifications are very different* due to the very different absorbing properties of the radiation products produced in low-temperature H_2O and SO_2.

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