Outflow of ions from Ganymede: A reinterpretation

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Abstract. The cold, dense plasma in the polar magnetosphere of Ganymede has been observed to contain one species of positive ions. The usual assumption that they are protons leads to severe problems, e.g. finding an adequate ionization mechanism for hydrogen, or explaining why the expected oxygen ions are not found and what happens to the oxygen. We propose that the observed ions are in fact singly charged oxygen ions rather than protons, which immediately removes all these problems. We show that the assumption of O^+ instead of H^+ is fully consistent with the plasma ion measurements and, by multiplying the inferred number density by 4 and speed by 1/4, brings them into better agreement with independent estimates of electron density and ion bulk flow.

Introduction

A remarkable feature of the magnetosphere of Ganymede is a region of dense, cold plasma flowing over and away from the polar cap, observed with the Plasma Science (PLS) instrument on Galileo by *Frank et al.* [1997] who interpreted it as consisting entirely of outflowing hydrogen ions (protons). From the outset, this interpretation was recognized as giving rise to several puzzling difficulties. In this Letter we propose an alternative interpretation which avoids them.

Problems with Proton Outflow

The assumption that hydrogen ions are being lost from Ganymede at anything like the rate ($\sim 6 \times 10^{25}$ s^{-1}) inferred by *Frank et al.* [1997] leads to the following problems:

1. Although the presence of a cloud of *neutral* hydrogen around Ganymede is well established from Galileo Lyman α observations [*Barth et al.*, 1997] and has been confirmed by Hubble Space Telescope (HST) observations [*Feldman et al.*, 2000], there is no plausible mechanism for ionization of hydrogen at the rate required (recognized already by *Frank et al.* [1997] as well as by *Barth et al.* [1997]). Sputtering of protons directly from an icy surface, suggested by *Frank et al.* [1997] as another possible source, is grossly inadequate because the sputtering yields for producing ions are

lower, in comparison to those for producing neutrals, by some 3 to 4 orders of magnitude [*Johnson*, 1990].

2. It is well established (see, e.g., *Eviatar et al.* [2000] and references therein) that the atmosphere and the ionosphere of Ganymede consist almost entirely of oxygen in various forms, essentially all hydrogen (H and H_2) having escaped as neutral particles because of the excess energy available to them from the dissociation and sputtering processes. This is discussed in detail by *Eviatar et al.* [2000]; for our present purpose the important fact is that, as noted already by *Frank et al.* [1997], outflow of oxygen ions is expected, and their reported non-detection (with an upper limit of a few percent of the reported hydrogen ion flux) is remarkable indeed.

3. Since the ultimate source of material lost from the regions on Ganymede accessible to Jovian radiation belt ions is sputtering from the icy surface, outflow of hydrogen alone would leave oxygen behind, at a rate which would accumulate to the column density inferred from the HST observations ($10^{13} - 10^{15}\mathrm{cm}^{-2}$, [*Hall et al.*, 1998; *Eviatar et al.*, 2000]) in less than a year, and over geological time scales would lead to the absurd picture (also recognized by *Frank et al.* [1997]) of meter-deep layers of oxygen on the surface.

4. The cold ions are inferred by *Frank et al.* [1997] to have a flow speed perpendicular to the magnetic field $V_\perp$ of some 70 km s^{-1}, whereas the more energetic ions observed at the same time with the Energetic Particle Detector (EPD) instrument on Galileo show no detectable flow anisotropy, with an upper limit to $V_\perp$ of about 25 km s^{-1} [*Williams et al.*, 1998]. (The dominant mechanism of perpendicular flow on these scales is $\mathbf{E} \times \mathbf{B}$ drift, which acts equally on all charged particles.) Because the uncertainty in determining such relatively low bulk flows from EPD observations can be substantial, this discrepancy does not necessarily raise a problem of the same order of difficulty as those previously mentioned, but it still is a discrepancy.

Are Outflowing Ions Oxygen?

The above problems are all resolved if we assume that the observed ions are not protons but, instead, singly charged oxygen (O^+) ions. No mechanism to ionize hydrogen is now required, and no excess oxygen is left behind. The oxygen atmosphere provides a source for the outflowing ions through well-known processes of ionosphere formation and polar wind (or polar-wind-like) dynamics, such as photoionization, photodissociation, electron impact dissociation, dissociative recombination and ambipolar-like diffusion [*Eviatar et al.*, 2000]. As shown below, the inferred flow speeds are now reduced by a factor of four, to values below the upper limit from EPD. It remains only to examine whether the proposed reinterpretation is consistent with the PLS measurements and other relevant data.

Reinterpretation of Plasma Measurements

The analysis of *Frank et al.* [1997] is based entirely on measurements of ion energy/charge, and the derived parameters scale with the assumed ion species (see, e.g. *Vasyliūnas* [1971]). A spectrum whose analysis (whether by model fitting, moments, or any other method) yields an ion distribution with concentration (number density) N, bulk velocity **V**, and thermal energy T under the assumption that the ions are protons will, under the assumption that the ions have charge number Z and atomic mass number A, yield a distribution of the same form with bulk velocity $\sqrt{Z/A}\,\mathbf{V}$, concentration $\sqrt{A/Z}$ N, and thermal energy Z T. Thus the ion species cannot be identified directly but must be inferred by indirect arguments.

One indirect argument is based on the possibility of detecting several peaks in the energy/charge spectrum when the various ion species have a common bulk velocity large compared to their thermal speeds. In the Jovian plasma sheet just outside the region of interaction with Ganymede, *Frank et al.* [1997] observe two peaks differing in mass/charge by a factor of 16, and there can be no reasonable doubt that the lower peak is H^+ and the higher O^+ (with possible admixture of other heavy ions). Near Ganymede, however, *Frank et al.* [1997] observe only one peak, so this argument cannot be applied. The energy/charge of this one peak is an order of magnitude lower than that of the H^+ peak in the adjacent plasma sheet, so no argument can be made on the basis of continuity (which is not expected, anyway).

If the one detected ion species is the dominant constituent of the plasma, charge quasi-neutrality requires Z N to be equal to the electron concentration n_e. Since the measured ion concentration is really $\sqrt{A/Z}$ N, comparison with an independently determined n_e should discriminate between H^+ and O^+ by a factor 4. The Plasma Wave Science instrument (PWS) on Galileo can determine the local n_e from the frequency of upper hybrid emissions [*Gurnett et al.*, 1996]. *Frank et al.* [1997] invoke the direct comparison of the two concentrations as providing " a robust identification of the ion mass," but they do not cite specific numbers and reference the PWS observations only from the Galileo G1 pass [*Gurnett et al.*, 1996] , which extend down to an altitude of 835 km above the surface of Ganymede and need therefore to be extrapolated to the 261 km minimum altitude of the G2 pass from which the PLS data were analyzed. Values of n_e obtained from the PWS observations are now available from the G2 pass as well and were kindly provided to us by D. A. Gurnett (they are discussed in detail in *Eviatar et al.* [2000] and can also be read off from the UH band in figure 1 of *Kurth et al.* [1997]). Near closest approach to Ganymede, $n_e \approx 200 - 230$ cm^{-3}, whereas the ion concentration at the same time obtained by *Frank et al.* [1997] (from a Maxwellian model fit) is $N \approx 65$ cm^{-3} if the ions are H^+, or, therefore, $N \approx 260$ cm^{-3} if O^+. Although neither is perfect, O^+ obviously agrees much better than H^+.

(Note: If, instead of a Maxwellian model fit, the ion concentration is evaluated by a direct moment calculation, the value obtained [*Frank et al.*, 1997] is $N \approx 100$ cm^{-3} if the ions are taken to be H^+. This method, however, gives the concentration at the surface of the spacecraft, which may differ from that in the undisturbed plasma because of effects from spacecraft potential. Such effects are evident in the significant discrepancy between the Maxwellian model and the count rates at low energy/charge, as pointed out by *Frank et al.* [1997]. Hence we consider the value of N from the Maxwellian model fit as the more reliable estimate, to be compared with n_e determined from plasma wave observations which are unaffected by spacecraft charging.)

Discussion

The outflowing cold ions of a single species observed by *Frank et al.* [1997] in the polar magnetosphere of Ganymede are most reasonably identified as singly ionized oxygen ions (rather than protons as first assumed). Typical values of ion concentration extend then up to $N \approx 250$ cm^{-3}, consistent with values of electron concentration determined simultaneously by plasma wave observations, and typical values of ion flow speed perpendicular to the magnetic field are at most $V_\perp \approx 18$ km s^{-1}, comfortably below the upper limits inferred from energetic ion observations. In contrast to the well-nigh insurmountable problems posed by the proton assumption, the presence of these ions, when interpreted as O^+, makes sense in terms of our current understanding of processes that shape the atmosphere and ionosphere of Ganymede, as discussed in detail elsewhere [*Eviatar et al.*, 2000].

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