SATURN'S IONOSPHERE: A CORONA OF ICE PARTICLES?

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Abstract. There is an order-of-magnitude discrepancy between the observations and theoretical calculations of electron density in Saturn's ionosphere. Since the lower observed values are prevalent regardless of latitude, there must be a loss process operating over the entire planet which is missing from current theoretical considerations. A corona of ice particles is suggested here as a possible explanation.

Observations of the vertical profile of electron density distribution in Saturn's ionosphere by radio occultation on Pioneer (Kliore *et al.*, 1980a) and Voyager (Tyler *et al.*, 1981; 1982) spacecraft have revealed topside peak densities of the order of $1–3 \times 10^4$ cm^{-3} at an altitude of 2300 to 3000 km above the cloud top over latitudes ranging from 11.6° S to 73° S (Figure 1). Theoretical calculations of electron density, however, produce peak densities an order of magnitude larger, but at altitudes in accord with the observations (Waite, 1981). It is clear that an electron loss process of a dynamic or chemical nature is missing from the theoretical interpretations. Possible explanations include (1) an equatorial anomaly (Kliore *et al.*, 1980b), (2) the loss of the major ion (H^+) to vibrationally excited molecular hydrogen, (3) a neutral atmosphere constituent distribution which is radically different from current models, and (4) the reaction of H^+ with the hydroxyl radical OH produced from sputtering of ice particles in Saturn's rings (Shimizu, 1980). A brief discussion of each of these explanations follows.

The equatorial anomaly, which occurs in the Earth's ionosphere, is caused by the vertical transport (Hall current) of ions resulting from a near normal orientation of the electric and magnetic fields in the ionosphere. It occurs only within a few degrees of the equator and is thus highly latitude-dependent. Vertical drifts may occur at greater latitudes but a driving mechanism has not been found and, based upon our experience with other planets, the drifts should be highly latitude-dependent. The loss of H^+ to vibrationally excited H_2 occurs through the reactions (McElroy, 1973)

$$H^+ + H_2(v'' \geqslant 4) \rightarrow H_2^+ + H,$$

$$H_2^+ + H_2 \rightarrow H_3^+ + H,$$

$$H_3^+ + e \rightarrow H_2 + H.$$

In order for the first reaction to be exothermic, the H_2 molecule must be excited to the fourth or higher vibrational level (denoted by v''), the population of which is described by the vibrational temperature (T_v). Atreya and Waite (1982) have noted that it would

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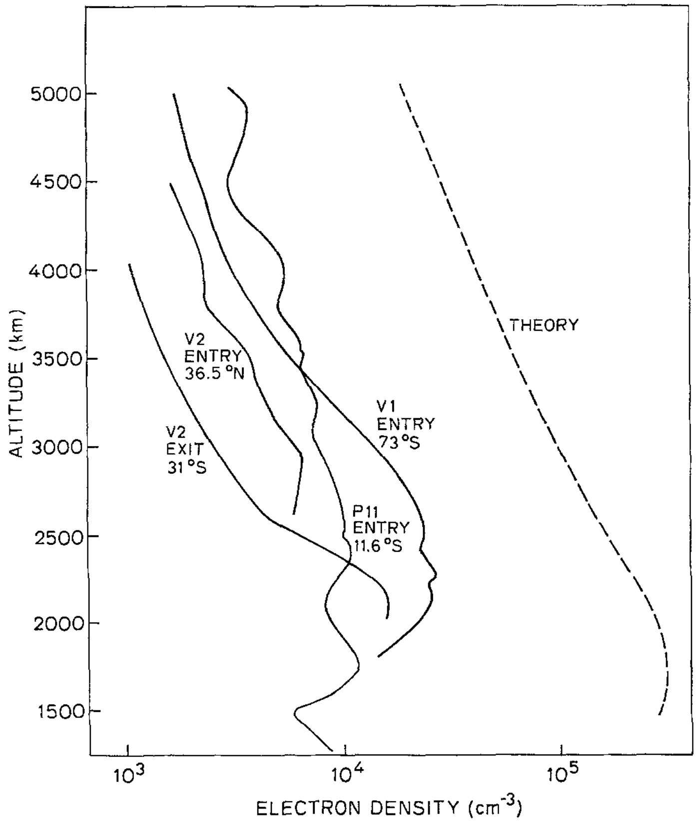

Fig. 1. Electron density observations from Pioneer 11 and Voyagers 1 and 2 (solid lines) and theory (dashed line) in Saturn's ionosphere.

require a T_v of 2000 K to reduce the electron density at the observed peak to match the observations by Voyager 1, and that such high temperatures are unlikely to exist outside of the auroral zone (where particle bombardment would excite the H_2 molecules). In fact, I have calculated that above 3000 km vibrational temperatures of several thousands of degrees are necessary to reduce the electron density on the topside sufficiently, thus making this mechanism even more unlikely.

These two processes, as well as the ring sputtering mechanism to be discussed below, depend strongly upon latitude and, as can be seen in Figure 1, the low values for electron density are manifested uniformly over a considerable latitudinal range.

The distribution of neutral constituents has been inferred from the Voyager 2 ultraviolet spectrometer observations (Atreya, 1982; Festou and Atreya, 1982) and no major discrepancies with current model distributions have been found.

In the ring sputtering theory, Shimizu (1980) suggested that relatively small amounts of oxygen-hydrogen compounds work efficiently to remove electrons from the ionosphere: i.e.,

$$H^+ + OH \rightarrow OH^+ + H,$$

$$OH^+ + H_2 \rightarrow H_2O^+ + H,$$

$$H_2O^+ + H \rightarrow H_3O^+ + H,$$

$$H_3O^+ + nH_2O \rightarrow H_3O^+(H_2O)_n$$

and

$$OH^* + H_2 \rightarrow H_2O + H,$$

$$H^+ + H_2O \rightarrow H_2O^+ + H;$$

where OH^* denotes vibrationally excited radicals. Water ions including the hydrated H_3O^+ recombine efficiently with electrons thereby serving to decrease the electron density and to produce water molecules. Shimizu assumed that the rings are the source of the OH and this is what makes the effect latitude-dependent. Another criticism is the possible effect upon the life-time of the rings (Atreya and Waite, 1981). These problems can be eliminated if there is another source for the OH radicals; that is, a planet-wide envelope of microscopic ice particles from which the hydroxyl radicals may be sputtered.

Any explanation of the discrepancy between theory and observation of electron density distribution must consider the fact that Jupiter's measured daytime topside peak electron densities are of the order of 10^5 cm^{-3} (Fjeldbo *et al.*, 1975; 1976; Eshlemen *et al.*, 1979a; b), generally in agreement with theoretical calculations which contain the same fundamental physical and chemical processes used in Saturn studies (Chen, 1982). Thus the mechanism that explains the discrepancy must be operating in Saturn's system but not in Jupiter's. The ice corona hypothesis presented here meets this criterion because the potential sources of ice are unique to Saturn. One source could be Saturn's icy moons. Brown *et al.* (1982), in a study of ion bombardment of icy surfaces, found that the relatively low gravitational escape velocities of Saturn's moons will cause ice eroded by ion impact to leave the moons and fall into Saturn's magnetosphere. In contrast, the Galilean satellites have a higher escape velocity and eroded ices will fall back to the satellites' surfaces. This then is a continuous source of ice which operates in the Saturnian system and not in the Jovian system. Once in Saturn's magnetosphere, the ice may be distributed over the planet through collisions with charged particles in the radiation belts. Another source of ice may have been initiated from collisions of cometary nuclei with Saturn and its satellites in the early days of the Solar System. At that time, comets were more numerous near Saturn's orbit than Jupiter's. With some infall of ice particles into Saturn's atmosphere, the oxygen-hydrogen system described above will recycle some H_2O to help maintain the required amounts of ice. The rings may be a source of ice also; the 'spokes' observed by Voyager are evidence of apparent collisional processes resulting in the detachment of ice particles from the rings.

Using a mathematical model similar to one used for Jupiter (Chen, 1982), I have calculated that in order to reduce the electron density by an order of magnitude requires a constant (with altitude) density of 10^4 OH radicals cm^{-3} (Figure 2). This value is a thousand times higher than that suggested by Shimizu as sufficient. It is difficult to assess

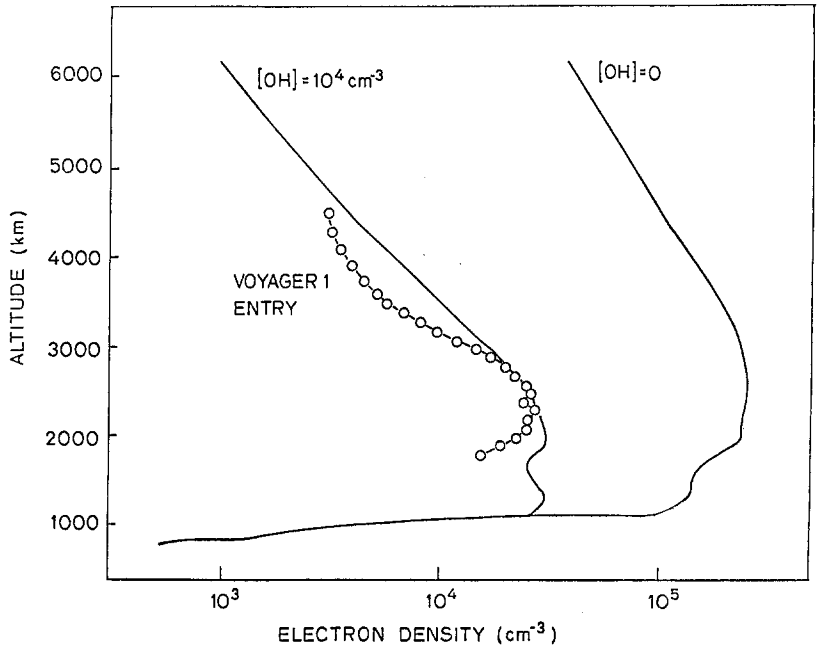

Fig. 2. Theoretical calculations of electron density with no OH and 10^4 OH cm^{-3}. The circles are the electron density as measured by Voyager 1 radio occulation.

the density of ice particles necessary to produce this amount of OH; the Earth's atmosphere (which has large and variable amounts of water ice and vapor) contains OH densities of the order of 10^3–10^7 cm^{-3}.

Planet-wide concentrations of OH radicals can be confirmed by identifying the OH Meinel bands in the visible and infrared spectra of Saturn. The Saturn spectra should be different from those of Jupiter in these wavelength regimes. Clark and McCord (1979) have found a smaller continuum slope and limb brightening in the infrared spectral albedos of Saturn. I suggest that these differences could be due to OH emissions and a water ice haze respectively. Santer and Dollfus (1981) have also determined from polarisation studies that there is a fine haze of submicron-size particles which covers the entire planet above the main cloud layer and which is variable from year to year.

Of the planets visited by spacecraft thus far, Saturn is unique in its environment pervaded by water ice (including the rings and moons) and its distance from the Sun at formation. While evidence for an ice corona is scant, in light of the magnitude of the discrepancy between observation and theory of the ionospheric electron density distribution, it appears that satisfactory explanation requires a major departure from the well-known processes occurring in the ionospheres of the other planets.

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