planets. On the other hand, the equatorward boundary of Jupiter's aurorae matches the magnetic projection of Io's plasma torus onto the atmosphere, suggesting excitation by an interaction between the atmosphere and the plasma torus[11]. (Aurorae may be present nearer the poles, at the boundaries of the polar caps, as well.) The energy deposited in the Earth's atmosphere by aurorae is correlated with geomagnetic activity, ranging over more than 2 orders of magnitude[12]. The average value[13] is probably near 1.7 $\mathrm{erg\,cm^{-2}\,s^{-1}}$, which corresponds to about 3×10^{10} W, roughly 1/7 of the power deposited at Saturn. The interaction between the magnetosphere of a planet and the solar wind, the ultimate source of auroral energy on Earth and probably on Saturn, is important in determining the power available to auroral processes. This interaction transfers about 10^{11} W into Earth's magnetosphere[14], about 1/10 of the 10^{12} W injected into the saturnian magnetosphere, calculated using measurements of the saturnian magnetic field[6] and general scaling relationships for magnetospheric parameters[14]. Thus the ratio of power in aurora on the two planets is about the same as the ratio of the power transferred to the magnetosphere from the solar wind. This, and the occurrence of aurora near the edges of the polar caps on both planets, suggest that the aurorae result from similar magnetospheric processes.

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Saturn ionosphere: theoretical interpretation

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Voyager 1 high latitude and Pioneer 11 equatorial ionospheric structure indicate a solar EUV-controlled ionosphere with a possible molecular ion in the topside. Vibrationally excited H_2 in the high latitudes may be an important loss mechanism. Dynamical effects are expected to be important for determining the peak density and its location.

THE Voyager 1 coherent dual-frequency radio system (RSS) at wavelengths 3.6 and 13 cm provided the first look at a high latitude (~73 °S) ionospheric profile on Saturn[1]. The entry data reveal that near the evening terminator (solar zenith angle, $\xi = 89°$), the peak electron density of 2.3×10^4 electrons $\mathrm{cm^{-3}}$ occurred at a height of ~2,500 km from the 1 bar pressure level. Earlier observations on Pioneer Saturn measured a peak electron density of $1.1\times10^4\ \mathrm{cm^{-3}}$ at 1,800 km in the 10 °S latitude range[2]. The observed ionospheric characteristics point to a markedly different ionosphere from that expected on conventional theoretical grounds.

The RSS ionospheric measurements were accompanied by a simultaneous measurement of the neutral atmosphere by means of the Voyager UV spectrometer (UVS). Modelling studies suggest that the observed ionosphere is controlled principally by the ionization of the neutrals caused by the solar EUV.

The UVS solar occultation measurements yield a neutral exospheric temperature of 820 ± 100 K at 62,000 km (ref. 3). The large size of the Sun (~500 km) projected on Saturn means that the height level at which the temperature reaches its exospheric value cannot be determined accurately. The exospheric temperature, however, is nearly the same as the topside plasma temperature (750 K)[1].

Preliminary analysis of the UVS stellar occultation data indicates that the temperature is essentially isothermal (~150–200 K) in the mesosphere up to ~750 km ($H_2 \simeq 5\times10^{13}\ \mathrm{cm^{-3}}$) and an average temperature gradient of ~0.55 $\mathrm{K\,km^{-1}}$ prevails above this altitude resulting in an exospheric temperature of ~825 K at 2,000 km above the 1-bar pressure level. Indeed, the Saturn stellar occultation transmission characteristics are similar to those of the Jupiter stellar occultation data collected on Voyager 2 (refs 4, 5) when the height scale is corrected for the lower acceleration due to gravity on Saturn. With this information and the hydrostatic law, a working model of the atmospheric density profile at the ionospheric heights can be constructed. An important caveat is that the Voyager ionosphere was measured at high latitudes, while the neutral atmosphere used here is essentially from equatorial to mid-latitude measurements[3]. The auroral activity on Saturn, however, is confined to the latitude band 78°–81.5 °S which is well outside the latitude region (73 °S) of the ionospheric measurements discussed here. Therefore, no substantial change is expected in the neutral atmosphere at the ionospheric heights from the low to the high latitudes on Saturn.

Knowledge of the atmospheric mixing as represented by the eddy diffusion coefficient, K, is important for determining the distribution of the hydrocarbons which act as an important sink to the major ions, H^+, H_2^+ and H_3^+ (refs 6, 7). K_h at the homopause may be determined from the atomic hydrogen abundance deduced from the planetary Lyα intensity[4,8,9]. The UVS data yield 3.3 kR for Saturn Lyα dayglow[3] implying $5\times10^{16}\ \mathrm{cm^{-2}}$ H atoms above the homopause, and consequently K_h of $(1.5\text{–}5.0)\times10^5\ \mathrm{cm^2\,s^{-1}}$.

The hydrocarbon density distributions were calculated considering CH_4 photolysis with the eddy diffusion coefficient varying inversely as the square root of the atmospheric number density[7].

The important chemical reactions for the Saturn ionosphere were taken from previous work[6,10]. We consider here low-pressure, low plasma temperature (T_e) approximation for the radiative recombination reaction rate of the major topside ion, H^+; the new rate is $4\times10^{-12}\,(250/T_e)^{0.7}\ \mathrm{cm^3\,s^{-1}}$ (ref. 11). The calculated ionospheric profile with a comparison with the Pioneer equatorial[12] and Voyager high latitude[1] data are shown in Fig. 1. Protons (H^+) comprise the major ions in altitudes >750 km. Below 750 km, a transition to H_3^+ and heavy hydrocarbon ions such as $C_2H_5^+$ and CH_5^+ occurs. Conversion to the higher order hydrocarbon ions, $C_3H_5^+$ and $C_4H_5^+$, is also probable in the lower ionosphere[8].

Although the Pioneer and Voyager data differ in details, there is general agreement about the location and magnitude of the peak, and the extent of the ionosphere. The observed peak electron density in the Voyager data is about a factor of 10 lower than the calculated one. A similar low density jovian ionosphere profile measured by Voyager 1 was interpreted as being due to the reaction of H^+ with vibrationally excited H_2 (ref. 10). The

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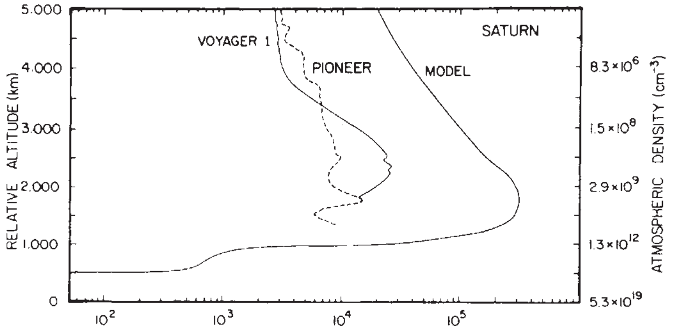

Fig. 1 Model calculations and observations of the Saturn ionosphere. The Pioneer data refer to low latitude (~10 °S), while the Voyager data are for the high latitude (~73 °S).

relatively low exospheric temperature (~800 K) on Saturn results in a small population of H_2 in $v' \geqslant 4$ vibrational state so that the charge exchange reaction between H^+ and H_2 ($v' \geqslant 4$) would not be expected to be as important on Saturn as on Jupiter. However, the H_2 vibrational levels may be non-thermally populated due to electron precipitation processes. Such non-thermal vibrational distributions were suggested by Cravens[13] from modelling of jovian electron precipitation processes. Such processes could be important in interpreting the Voyager/Saturn data provided that the effects of auroral precipitation extend beyond the observed latitude band in which significant (~5 kR) H_2-Lyman and Werner band auroral emission have been observed by the Voyager UVS[3]. The observed H_2 auroral emission imply an energy input of ~0.5 erg cm^{-2} s^{-1} (in the 78°–81.5 °N and S latitudes) on Saturn which is about a factor of 10 lower than in the jovian auroral region.

An electron precipitation event composed of 2 keV electrons with a flux of 1.5×10^8 cm^{-2} s^{-1} could reproduce the 3–5 kR of H_2-Lyman and Werner band emission seen by the UVS[3]. Such an aurora produces a model ionosphere with a peak electron density of 2×10^6 cm^{-3} near 2,400 km when the effects of the charge exchange reaction ($H^+ + H_2$ ($v' \geqslant 4$)) are omitted. However, if a rate constant of 10^{-9} cm^3 s^{-1} is assumed for the reaction of H^+ with H_2 ($v' \geqslant 4$), and a vibrational temperature of ~2,000 K, the peak electron density can be brought into rough agreement with the RSS high latitude ionosphere measurements.

Even if the loss of H^+ by charge exchange with H_2 ($v' \geqslant 4$) could explain low peak electron density in the high, non-auroral latitudes, similar low peak electron densities have been measured by the Pioneer 11 spacecraft near 10 °S latitude[2,12] also, and they apparently need an alternative explanation due to the unlikely occurrence of a significant vibrationally excited H_2 population in the Saturn equatorial ionosphere. The 700 R intensity of the non-auroral H_2 bands measured by the UVS[3] implies a planetwide precipitation of electrons resulting in a relatively low energy deposition rate of 1.3×10^{-2} erg cm^{-2} s^{-1} on Saturn. Relatively good agreement between the Pioneer equatorial and the Voyager high latitude Saturn ionospheric data suggests a common H^+ loss process missing from current theoretical models. Moreover, the loss of the major ion H^+ after the charge exchange with vibrationally excited H_2 ($v' \geqslant 4$) even in the high latitudes is only a remote possibility as the measured ionosphere is ~5°–10° removed from the auroral latitude band.

The most obvious choice for reconciling the calculations and the measurements is an ion–molecule reaction which would convert some of the H^+ into relatively short-lived molecular ions. Although methane reacts rapidly with H^+ to form molecular ions, it is not distributed high in the atmosphere due to the relatively low value of the eddy diffusion coefficient, $K_h \sim 10^6$ cm^2 s^{-1}. Even an extremely high K_h (~10^9 cm^2 s^{-1}) falls short of the required H^+ loss rate[7]. An alternative explanation is that water vapour in the rings could provide an important loss to the ionospheric H^+ (ref. 14). The OH would, however, be concentrated in the region near the rings suggesting a latitudinal variation in the OH + H^+ loss process, a variation not supported by the Pioneer and Voyager data. Furthermore, the large OH production rates might force unacceptable limits on the longevity of the rings. We also find that the depletion of the peak electron density due to the ring shadow occurs in low latitudes; the effect, however, is minimal (≤10% depletion in the electron density) at the latitudes of the Pioneer observations[7].

There is no adequate common explanation for the low peak electron densities observed at both the low and high Saturn latitudes. Dynamical effects may have an important role in the low latitude ionosphere and auroral effects may be important at high latitudes. However, some as yet unknown H^+ loss process may be the controlling factor at all Saturn latitudes.

The location of the peak in electron density seems to be ~500 km higher than calculated (Fig. 1); this is, however, questionable as the calculated peak is quite broad. But many theories for reconciling this apparent discrepancy are possible. Calculations indicate that an average diurnal vertical drift velocity of ~14 m s^{-1} for H^+, produced by an electrical field of ~3 mV m^{-1}, southward neutral winds of ~140 m s^{-1}, and/or vertical winds of ~14 m s^{-1} are capable of raising the peak by 500 km (refs. 7, 15).

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C_3H_8 and C_3H_4 in Titan's atmosphere

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Four bands of propane C_3H_8 and two of methyl acetylene C_3H_4 have been identified in the Voyager IR spectrum of Titan. Stratospheric abundances of 2×10^{-5} for C_3H_8 and 3×10^{-8} for C_3H_4 have been determined for the mid-latitude region. A feature at 1,154 cm^{-1}, previously assigned solely to CH_3D, is now identified at least in part due to C_3H_8.

THE Voyager 1 IR instrument (IRIS)[1] obtained several hundred spectra of Titan when the angular diameter of the disk was at least five times the angular field of IRIS. Spectra of the centre of the disk, the polar regions, and both limbs all revealed the signatures of many hydrocarbons and of HCN in emission, indicating the presence of these gases in a warm stratosphere. In

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