Saturn's Ionosphere: Some Evidence of Equatorial Anomaly

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Electron density profiles obtained from radio science experiments on Pioneer-II, Voyager-1 and Voyager-2 have been analyzed to look for equatorial anomaly in the ionosphere of Saturn. Although there is no measurement right at the magnetic equator, the three southern latitude measurements provide some evidence for the existence of equatorial anomaly—a feature already seen in other magnetic planets like the earth and Jupiter. The extremely low electron densities observed in Saturn's ionosphere remain unexplained and require a faster H+ loss mechanism.

1 Introduction

The first measurement of electron densities in the ionosphere of Saturn was made on 1 Sep. 1979 by the Radio Science experiment on Pioneer-II (Ref.1). The entry profile gave a peak electron density of \(1.5 \times 10^4\) electrons cm\(^{-3}\), located at an altitude 1800 km above the 1-bar pressure level at 11.6°S latitude. The plasma scale height above the main peak corresponded to an exospheric temperature of about 1150 K for an H+ ionosphere. The time span covered by the exit data was rather short and therefore no meaningful electron density profile could be obtained, except for a qualitative profile for comparing the main features with the entry profile. The Voyager-1 radio occultation observations on 12 Nov. 1980 by Tyler et al.\(^2\), provided the high latitude (73°S) electron density profile for the entry data near the evening terminator. The peak electron density was \(2.3 \times 10^4\) electrons cm\(^{-3}\) and occurred at an altitude of about 2500 km above the 1-bar pressure level. The plasma scale height in the topside ionosphere gave an exospheric temperature of 750 K, lower than that observed on Pioneer-11. Electron density profile for the Voyager-1 exit data was not reported by the experimenters. Following these measurements, electron density profiles were provided by Voyager-2, both for the entry and exit data, on 26 Aug. 1981 by Tyler et al.\(^3\). The peak electron density was \(1.7 \times 10^5\) electrons cm\(^{-3}\) at 2150 km above the 1-bar pressure level for the exit profile at 31°S. The late afternoon entry profile at 36°N gave a peak electron density of \(6.4 \times 10^3\) electrons cm\(^{-3}\), at an altitude of about 2850 km above the 1-bar pressure level. The plasma scale heights above about 3000 km were around 1000 km for both these profiles and were higher than those on the earlier Pioneer-11 and Voyager-1 measurements. Fig.1 shows all the available electron density profiles for the ionosphere of Saturn.

These have been read for every 100 km from the data published by the experimenters and thus some fine structures might have been missed; however, the general shapes are expected to remain the same. Table 1 gives the sources of these profiles along with other relevant details.

2 Observed Profiles and Theoretical Models

The most surprising result about the ionosphere of Saturn is its extremely low electron densities—about a factor of 10 smaller than those obtained from model calculations. This can be noted from Fig.1 which compares the observed profiles with theoretical calculations of Atreya and Waite\(^4\). According to

![Figure 1](image-url)

Fig. 1—Electron density profiles in the Saturn's ionosphere obtained from Radio Science experiment on Pioneer-II and Voyager 1 and 2 spacecrafts.
various theoretical models, the major topside ion is $H^+$ which is produced by photoionization of atomic $H$ or photodissociative ionization of $H_2$. Both $H$ and $H^+$ have long life times above the homopause, which is about 2000 km above the 1-bar pressure level. Due to slow electron recombination reaction $H^+ + e \rightarrow H + \nu v$ at $2 \times 10^{-12}$ cm$^{-3}$ s$^{-1}$, and due to long diffusion time constant below the altitude of ionosphere peak, the time constant for loss of $H^+$ is many planetary rotations. As a result no diurnal variation in $H^+$ is expected. The major ion $H^+$ is only removed by downward diffusion to altitudes near homopause by charge exchange to heavier ions, particularly methane. With this simplified scheme, a peak ion concentration of $3 \times 10^5$ cm$^{-3}$ around 1800 km is obtained which, as already pointed out, is a factor of 10 larger than the observed values.

To explain the discrepancy between the observed and the theoretical electron density profiles, one requires an additional and relatively fast loss mechanism for $H^+$ ions, since the production of $H^+$ through photodissociative ionization of $H_2$ and photoionization of atomic $H$ is now well understood. One such mechanism is the loss of $H^+$ through charge exchange with vibrationally excited $H_2$ ($\nu' \geq 4$). Atreya and Waite have argued that the low intensity of 700 R of the non-auroral $H_2$ band measured by the Ultraviolet Spectrometer on Voyager-1 implies rather low planetwide energy deposition rate of about $1.3 \times 10^{-2}$ ergs cm$^{-2}$ s$^{-1}$ by the precipitating electrons. This low deposition rate rules out the presence of vibrationally excited $H_2$. Another mechanism proposed is the presence of larger amounts of methane, in the upper ionosphere. For methane to be an effective $H^+$ loss molecule, unrealistically high values of eddy diffusion coefficient are needed.

One more mechanism proposed for the rapid loss of $H^+$ ions is by the OH and $H_2O$ molecules present in the rings, which could interact with the planetary ionosphere. Since these molecules would be concentrated in regions near the rings, one would then expect a latitudinal variation in the $OH + H^+$ loss process. However, no such latitudinal variation has been observed on the Pioneer and Voyager ultraviolet spectrometers.

### Table 1 — Radio Science Measurements of Saturn Ionosphere

<table>
<thead>
<tr>
<th>Date</th>
<th>Spacecraft</th>
<th>Latitude</th>
<th>SZA</th>
<th>$N_m$ cm$^{-3}$</th>
<th>$H_m$ km</th>
<th>Ref. No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Sep.1979</td>
<td>Pioneer-II</td>
<td>11.6 S</td>
<td>89</td>
<td>$1.14 \times 10^4$</td>
<td>1800</td>
<td>1</td>
</tr>
<tr>
<td>12 Nov.1980</td>
<td>Voyager-1</td>
<td>73 S</td>
<td>89</td>
<td>$2.3 \times 10^4$</td>
<td>2500</td>
<td>2</td>
</tr>
<tr>
<td>26 Aug.1981</td>
<td>Voyager-2</td>
<td>36.5 N</td>
<td>87</td>
<td>$6.4 \times 10^3$</td>
<td>2850</td>
<td>3</td>
</tr>
<tr>
<td>26 Aug.1981</td>
<td>Voyager-2</td>
<td>31 S</td>
<td>93</td>
<td>$1.7 \times 10^4$</td>
<td>2150</td>
<td>3</td>
</tr>
</tbody>
</table>

3 Equatorial Anomaly

The magnetic planets like the earth and Jupiter have shown the presence of equatorial anomaly in their respective ionospheres. Saturn also is a magnetic planet and the equatorial value of the magnetic field intensity is around 0.2 gauss. Also the planetary field is mainly dipolar with the dipole axis parallel to the rotation axis of the planet. In view of these magnetic features, we have tried to investigate if the equatorial anomaly also exists in Saturn’s ionosphere. Fig.2 shows a plot of maximum electron density against latitude for all the available measurements. The three measurements in the southern latitudes give some evidence for the presence of equatorial anomaly in Saturn’s ionosphere. Unfortunately there is no measurement right at the equator to prove our extrapolation of the peak electron density to the equator. However, such sharp latitudinal gradients are also indicated in the case of Jupiter’s ionosphere around $\pm 10^\circ$ latitude as seen in Fig.3 taken from the work of Mahajan. As a matter of fact, the Voyager-1 radio science measurement at 1$^\circ$N was the major

![Fig. 2 — Peak electron density as a function of latitude in the Saturn's ionosphere to show the presence of equatorial anomaly. (The dashed curve is author’s speculation based upon the large latitudinal gradients noted from 10°N to 10°S in the ionosphere of Jupiter. Saturn’s magnetic field is mainly dipolar with the dipole axis parallel to the rotation axis.)](image-url)
extremely low values of electron density as compared to theoretical models still remain unexplained and as pointed out by Atreya and Waite, some as yet unknown H$^+$ loss process may be the controlling factor at all Saturn latitudes.

Recently, electron densities in Saturn's ionosphere have also been inferred from an analysis of radio bursts detected on the planetary radio astronomy (PRA) experiment onboard the two Voyager spacecrafts. These radio bursts, called as Saturn electrostatic discharges (SED), which appear to have originated from atmospheric lightning storms, exhibit a sharp but variable low frequency cut-off below which no bursts are detected. These low frequency cut-offs have been analyzed by Kaiser et al. to infer about electron density in the ionosphere of Saturn. They have obtained electron densities varying from less than 100 electrons cm$^{-3}$ during the night to more than 5 x 10$^5$ electrons cm$^{-3}$ during the day, with average day-to-night ratio of about 150. In addition there are large fluctuations from one measurement to the next. Fig. 4 shows a plot of all the electron densities inferred by Kaiser et al. from SED measurements. Observation Nos. 6, 7, 8a and 8b (open circles) were not included by Kaiser et al. in Fig. 4 of their paper, as three of these corresponded to non-equatorial latitudes. These have also been included now in Fig. 4 of this paper. Except for the fact that the inferred electron densities during the day are in agreement with theoretical models, the

4 Discussion

The equatorial anomaly in Saturn's ionosphere can be explained by the 'fountain effect', where the plasma at the equator is lifted up by dynamo electric fields. This plasma then settles down under diffusion along field lines, leading to decrease in equatorial peak density and an increase in density at higher latitudes. The presence of fountain effect leading to equatorial anomaly in Saturn's ionosphere was speculated earlier by Kliore et al. and Waite to explain the low electron density values measured at 11.6°S by Pioneer-11. This hypothesis was then not seriously taken up when subsequent measurements on Voyager-1 and Voyager-2 also gave lower values of electron density at higher latitudes. In our opinion, the electron density at the equator might be a factor of 10 lower than at mid and high latitudes due to the fountain effect. The
other features, like the large diurnal variation and the hour-to-hour fluctuation in the electron density, are rather difficult to explain.

Connerney and Waite\textsuperscript{14} have, however, suggested a new model of Saturn's ionosphere to explain the electron densities inferred from the SED measurements, and also those obtained from Radio Science on Pioneer and Voyager spacecrafts. They have suggested that water plays a major role as a minor constituent in the formation of Saturn's ionosphere and have proposed a planetwide influx of $4 \times 10^7$ molecules cm$^{-2}$s$^{-1}$ from the rings. According to them the H$^+$ ion gets lost via charge exchange with H$_2$O. The H$_2$O$^+$ ion is very shortlived and it reacts with H$_2$ to produce H$_3$O$^+$, which after electron recombination produces H$_2$O and/or OH. The OH again produces H$_2$O after reacting with H$_2$. Thus, in this model, water acts as a catalyst in the rapid removal of H$^+$. Connerney and Waite\textsuperscript{14} have proposed that a classical 'Bradbury layer', analogous to the earth's F2 layer, can occur at an altitude where the chemical and diffusive time constants are comparable and the peak forms well above the level of maximum ion production. They have found that the observed daytime peak electron density of $10^5$ electrons cm$^{-3}$ and its altitude of about 2500 km are consistent with this hypothesis. They have explained the rapid post-sunset decay of electron density, by assuming a downward drift related to the ionosphere-protonosphere exchange. According to Connerney and Waite, the very low electron densities of 200 electron cm$^{-3}$, inferred from the SED observations by Kaiser \textit{et al.}\textsuperscript{13}, could occur because of increased local water influx at these latitudes, which are magnetically connected to the inner edge of Saturn's B-ring.

The SED inferred electron densities from Voyager-1 show an unrealistically large diurnal as well as hour-to-hour variations. Further, the near-dusk measurement at observation No.3 indicate electron densities larger by about a factor of 4, while the near-dawn measurements at observation Nos. 12 and 15 indicate electron densities smaller by factors of 2 to 4 as compared to the Radio Science results from Voyager-1. It is rather difficult to explain this disagreement. The planetwide influx of $4 \times 10^7$ molecule cm$^{-2}$s$^{-1}$ of water required by Connerney and Waite is approximately an order of magnitude larger than expected from photosputtering of the rings\textsuperscript{15}. They have, however, involved micrometeorite bombardment of Saturn's rings\textsuperscript{16} as a possible mechanism to obtain the required influx of water molecules.

It follows from the above that no clear picture of Saturn's ionosphere has yet emerged. However, the electron densities, observed by the Radio Science experiment on Pioneer-11 and Voyager 1 and 2, give some evidence on the existence of equatorial anomaly in the ionosphere of Saturn. The extremely low values of electron density observed by the radio science experiments still remain unexplained although a planetwide influx of water molecules to explain the observed results, is an attractive mechanism for a faster H$^+$ loss process.

\textbf{Acknowledgement}

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\textbf{References}