DEPLETION OF THE F2 REGION IONOSPHERE AND THE PROTONOSPHERE BY THE RELEASE OF MOLECULAR HYDROGEN

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Abstract. Theoretical models have been used to investigate the effects of artificially injected H_2 gas on plasma densities in the ionospheric F region and the overlying protonosphere. Owing to large reaction rates between H_2 and ionospheric O^+ ions, plasma densities in both daytime and nighttime ionospheres can be greatly reduced by modest amounts of H_2 gas released. 100 kg of H_2 released at 300 km altitude reduces local O^+ densities by more than three orders of magnitude and produces ~5% depression in H^+ densities in the overlying protonosphere. These results suggest that it should be possible to conduct controlled chemical modification experiments for investigation of many outstanding ionospheric and magnetospheric problems.

Recent ionospheric observations during a Saturn rocket flight through the F region showed that the release of a small amount of chemically reactive gas can significantly modify the ionosphere [Mendillo et al., 1975a,b]. In this paper we examine theoretically the effects of such artificial gas injection on plasma densities in the ionosphere and the overlying magnetosphere. These effects are of interest because of increasing rocket and satellite activities at ionospheric heights and also because of possible controlled modification experiments that can be conducted for scientific investigation of the ionosphere. We consider the flow of injected gas and its reactions with the ionospheric plasma after the gas has thermalized with the background atmosphere. During this stage, gas flow is dominated by the diffusion process.

We assume instantaneous point releases of 10-100 kg of H_2 at 300 km altitude. Unlike other reactive gases such as H_2O, CO_2 amd NO_2, H_2 does not condense upon release. This is an advantage from the standpoint of both simplicity and efficiency in artificial ionospheric modification. Furthermore, photodissociation of H_2 is very slow [Banks and Kockarts, 1973, Chapter 13] so that a daytime release would produce chemical effects as efficiently as a nighttime release.

H_2 removes O^+ ions and electrons in the ionosphere through a two-step process:

$H_2 + O^+ \rightarrow OH^+ + H$ rate = 2×10^{-9} cm^3/sec
[Ferguson, 1973]

$OH^+ + e^- \rightarrow O + H$ rate = 1×10^{-7} cm^3/sec
[Biondi, 1973]

It is clear from the reaction rates that the removal process will be controlled by the first reaction, which is 50 times slower than the second, and that the intermediate product OH^+ will be present only in negligible concentrations. OH^+ ions also reacts with H_2 and O_2 to form heavier molecular ions, H_2O^+ and O_2^+, respectively, but the reaction rates are about two orders of magnitude slower than the competing dissociative recombination rate for OH^+ quoted above. For these reasons, molecular ions are ignored in this paper, although they may deserve better treatment in future studies. The loss rate of O^+ due to the injected H_2 molecules is about three orders of magnitude larger than the normal loss rate through reactions with N_2 and O_2 in the unperturbed ionosphere. It is because of this large loss rate associated with H_2 that it is possible to significantly modify the ionosphere with small amounts of injected gas. We will now calculate H_2 densities as a function of space and time following an assumed point release. These densities will then be used to evaluate the modification of the ionosphere-protonosphere system under several different sets of conditions.

The continuity equation for H_2 is written as

$$\frac{\partial n(H_2)}{\partial t} = D\left[\frac{\partial^2 n(H_2)}{\partial x^2} + \frac{\partial^2 n(H_2)}{\partial y^2}\right] + \frac{d}{dz}\left[D\left(\frac{\partial n(H_2)}{\partial z} + \frac{n(H_2)}{H_g}\right)\right] - K_r\, n(O^+) n\,(H_2) \qquad (1)$$

where D is the diffusion coefficient, H_g is the scale height of H_2, K_r is the $O^+ + H_2$ reaction rate, and $n(H_2)$ and $n(O^+)$ are the H_2 and O^+ densities, respectively. We use a Cartesian coordinate system, centered at the point of gas release, with the z-axis pointing vertically upward. We assume an isothermal exponential atmosphere, $D(z) = D_o \exp(z/H_a)$, where D_o is the diffusion coefficient at the point of gas injection ($z = 0$), and H_a is the atmospheric scale height. The last term in Eq. 1 represents the chemical depletion of the injected gas by reactions with the ionospheric O^+. This term is negligible compared to the diffusion terms, which dominate the gas behavior until it is dissipated to an insignificant density level. For relatively small releases considered here, the chemical loss term has appreciable effects only during the last stage of the injection experiment when the ionosphere is already well on its way to recovery. Therefore we replace this small term with an approximation that will greatly simplify the solution of Eq. 1. We substitute a constant $\alpha = K_r < n(O^+)>$ for $K_r n(O^+)$, where $<n(O^+)>$ is the average O^+ density in the unperturbed ionosphere. Equation 1 then has an analytical solution [Yu and Klein, 1964].

$$n(H_2) = \frac{N_o H_a}{D_o t} \qquad (2)$$

$$\cdot \exp\left[-\frac{z}{2}\left(\frac{1}{H_a}+\frac{1}{H_g}\right) - H_a^2\left(\frac{1+e^{-z/H_a}}{D_o t}\right) - \alpha t\right]$$

$$\cdot\, 2\pi \int_0^\infty I_\gamma\left(\frac{2H_a^2 e^{-z/2H_a}}{D_o t}\right) J_o(2\pi\ rp)\ p\ dp$$

where $\gamma^2 = (4\pi H_a p)^2 + \left(\frac{H_a}{H_g} - 1\right)^2$, $r^2 = x^2 + y^2$,

N_o is the number of H_2 molecules released at the origin, $J_o(\cdot)$ is the Bessel function of the first kind, and $I_\gamma(\cdot)$ is the modified Bessel function of the first kind.

The integral in Eq. 2 can be evaluated numerically, but it turns out that during the time interval of our interest, the modified Bessel function inside the integral can be closely approximated by

$$I_\gamma(q) = \frac{e^q}{\sqrt{2\pi q}}\, e^{-\gamma^2/2q} \qquad (3)$$

With this approximation, the expression for H_2 density becomes

$$n(H_2) = \frac{N_o}{(4\pi D_o t)^{3/2}} \qquad (4)$$

$$\cdot \exp\left[-z\left(\frac{3}{4H_a}+\frac{1}{2H_g}\right) - \frac{H_a^2(1-e^{-z/2H_a})^2}{D_o t} - \alpha t - \frac{(x^2+y^2)e^{-z/2H_a}}{4D_o t} - \left(\frac{1}{H_a}-\frac{1}{H_g}\right)^2 \frac{D_o t e^{z/2H_a}}{4}\right]$$

This expression gives values of $n(H_2)$ within a factor of two of those given by Eq. 2 for $t < 1800$ sec under typical F2-region conditions. In the limit as time approaches zero, Eq. 4 reduces to

$$n(H_2) = \frac{N_o\, e^{-\frac{(x^2+y^2+z^2)}{4D_o t}}}{(4\pi D_o t)^{3/2}} \qquad (5)$$

which is the expression Mendillo et al. [1975a,b] used in their diffusive analysis.

The effects of the injected H_2 gas on the ionosphere-protonosphere system can now be examined by using a theoretical model developed by Park and Banks [1974]. In this model a magnetic flux tube is divided into three sections. The lowest section, between 150 and 500 km in altitude, is assumed to be populated by O^+ ions and electrons only. Their densities are calculated from a continuity equation including the effects of production, loss and flux. The uppermost section, extending from 3000 km altitude to the equatorial plane, is treated as a finite reservoir of H^+ ions and electrons. In the intermediate section, between 500 and 3000 km, a mixture of O^+ and H^+ ions exist along with electrons, subject to the charge exchange reactions, $O^+ + H \rightleftarrows H^+ + O$, diffusion, and the boundary conditions imposed by the adjacent sections. Further details of the model can be found in Park and Banks [1974 and 1975]. The only modification necessary for the present purpose is to change the recombination loss coefficient of O^+ ion below 500 km to read

$$\beta = \beta_a + 2\times10^{-9}\ n(H_2) \qquad (6)$$

where β_a is the recombination coefficient of the ambient atmosphere and $n(H_2)$ is given by Eq. 4.

In order to simulate the gas injection experiment, we first calculate steady state O^+ and H^+ density profiles satisfying all specified initial conditions. At time $t = 0$, we introduce the gas

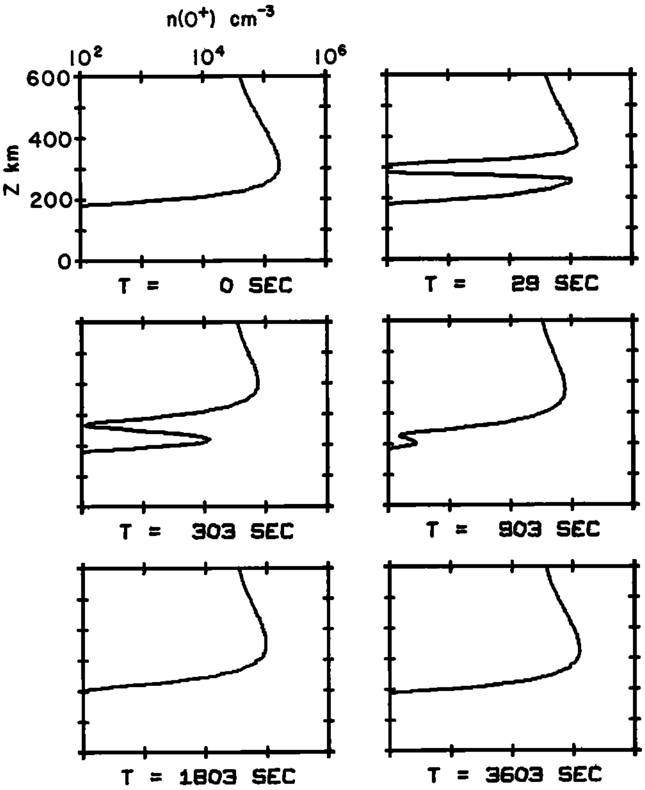

Figure 1. Modification of the nighttime ionosphere by the injection of 100 kg H_2 vapor at 300 km altitude and 60° invariant latitude. Protonospheric content is 3×10^{13} H^+ ions in a magnetic flux tube with 1 cm² base at 3000 km altitude and extending to the equator.

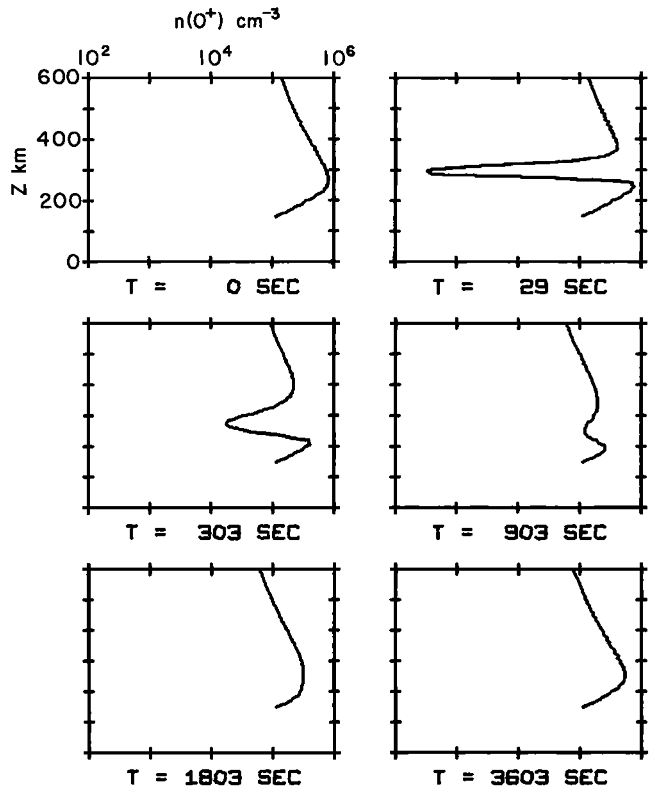

Figure 2. Modification of the daytime ionosphere. All other conditions are the same as in Figure 1.

according to Eq. 4 and then recalculate the ion density profiles as a function of time. Figures 1 and 2 show the results of sample calculations.

Figure 1 shows the evolution of the O^+ density profile in the ionosphere at 60° invariant latitude following a 100 kg release at 300 km. The profiles shown are for the field line passing through the point of the gas release. We assume no electric field or neutral wind so that there is no net horizontal motion of the expanding gas or the ionospheric plasma with respect to the chosen field line. This case represents an idealized winter night ionosphere, which is maintained solely by downward flow of plasma from the overlying plasmasphere. A 'full' plasmasphere (or 'high content' plasmasphere) is assumed with the initial H^+ density of 10^4 cm^{-3} at 3000 km and the H^+ content of $3x10^{13}$ in the tube reservoir with a 1 cm^2 base at 3000 km and extending to the equator. It can be seen in Fig. 1 that a deep 'hole' is created within 30 seconds of the gas release, thus splitting the F layer into two distinct layers. Increased loss rates of O^+ induces more plasma to flow downward from the plasmasphere, which helps maintain the upper layer. The lower layer, however, is cut off from the plasmaspheric flux and disappears after 900 sec. At t = 1 hr the profile has almost fully recovered, but the peak density is somewhat lower than the initial peak density for two reasons: (1) the recombination rate is still slightly higher because of residual H_2 molecules, and (2) the plasmasphere, which has been drained by increased downward flux, cannot provide as much plasma as before the gas release.

Figure 2 shows a sequence of O^+ profiles for similar conditions as in Figure 1 but for the

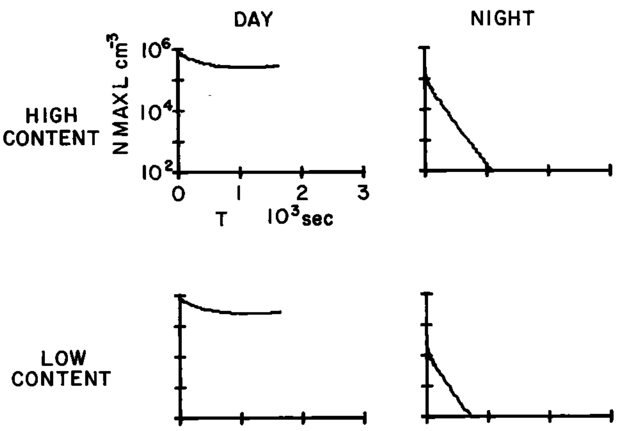

Figure 3. Temporal variations of the lower peak density. High and low content refers to protonospheric content of $3x10^{13}$ and $6x10^{12}$, repectively.

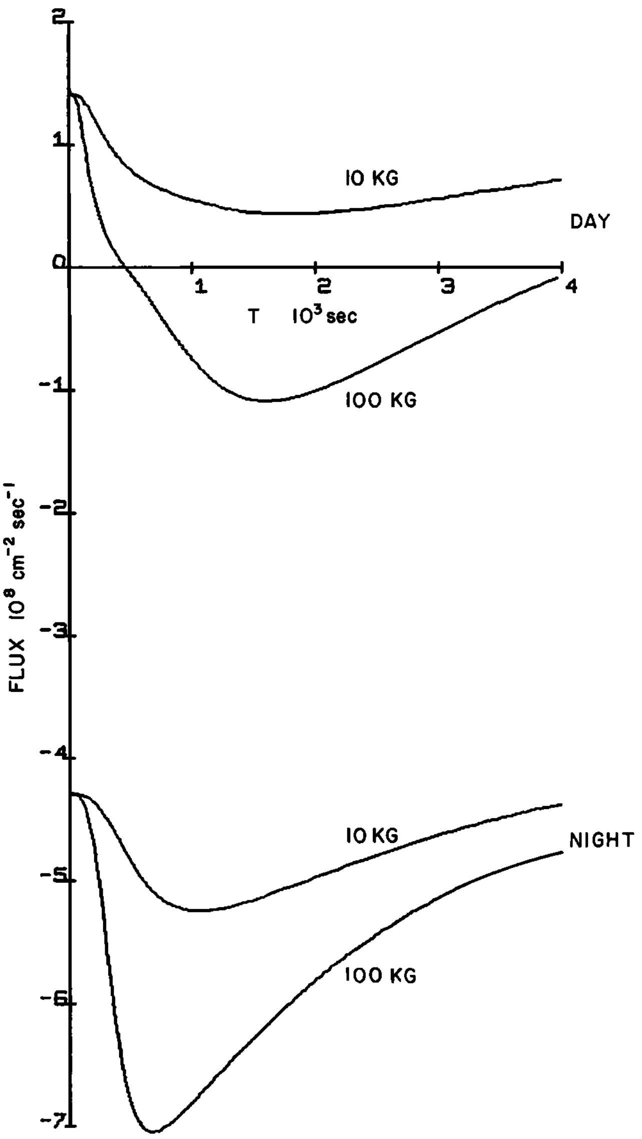

Figure 4. Changes in protonospheric fluxes at 3000 km altitude induced by the release of H_2 vapor at 300 km. Protonospheric content is $3x10^{13}$.

TABLE 1. Percentage Protonospheric Depletion

Protonospheric Content	H_2	Day	Night
High	100 kg	3.5%	4.6%
Low	100 kg	8.3%	4.1%
High	10 kg	1.0%	2.4%

summer day ionosphere with an overhead sun. Since there is continuous production of O^+ by photoionization, the lower layer is maintained throughout the experiment, in contrast to the nighttime case. This day-night difference is better illustrated in Fig. 3, where the peak density of the lower layer (NMAXL) has been plotted for different conditions of simulation. The two upper plots represent the day and night cases of Fig. 2 and 1, respectively. The two lower plots assume an 'empty' (or 'low content') protonosphere with an initial H^+ density of 10^3 cm^{-3} at 3000 km and protonospheric content of $6x10^{12}$ protons. It is clear that the protonospheric content makes no qualitative difference. At night the peak density of the lower layer decreases exponentially with a time constant of ~300 sec. This time constant is approximately equal to $1/\beta$ due to H_2 molecules because chemical equilibrium prevails at these low altitudes. Recall that our nighttime model assumes no production. If there is appreciable production, i.e., by corpuscular ionization, the peak density would level off at a certain point after initial period of exponential decay. Observations of such behavior with an incoherent scatter radar or an HF sounder should provide quantitative information on production and loss rates in the nighttime ionosphere.

Figure 4 shows H^+ fluxes across the 3000 km level as a function of time, for day and night conditions and for 10 and 100 kg releases. A 'full' protonosphere is assumed in all four cases, and positive flux in the figure flows upward. A 100 kg release induces an additional downward flux of up to ~ $3x10^8$ protons/cm^{-2} sec^{-1}. This is large enough to reverse the direction of normal daytime upward flux and nearly double the nighttime downward flux. (The unperturbed nighttime flux is somewhat too large because neutral winds are ignored in these calculations.) It is clear that such modulations in proton fluxes will produce field-aligned density depressions in the protonosphere. Table 1 summarizes the calculated percentage depression along the field line passing through the gas injection point. These field-aligned structures should be investigated to find out if they can guide hf and vlf waves for interhemispheric propagation.

It appears from these calculations that the release of modest amount of H_2 gas, well within the capabilities of present rocket and satellite technology, can produce significant perturbations in the ionosphere and the protonosphere. This offers new opportunities for controlled experiments.

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