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RECENT ADVANCES IN MODEL CALCULATIONS OF THE VENUS IONOSPHERE

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ABSTRACT

Our understanding of the physical and chemical processes which control the behavior of the Venus ionosphere has advanced significantly during the last few years. These advances are the result of a still growing data base and a variety of evolving theoretical models. This review summarizes some of these recent studies, especially those concerning the dynamics of the ionosphere, the maintenance of the nightside ionosphere, the energetics of the nightside ionosphere, and the time evolution of magnetic fields in the dayside ionosphere.

INTRODUCTION

This paper gives a brief review of recent advances in our understanding of some of the basic physical processes controlling the behavior of the ionosphere of Venus. More specifically this review is limited to summaries of theoretical model studies related to:

a) ionospheric dynamics,
b) nightside ionospheric densities,
c) nightside ionospheric temperatures, and
d) ionospheric magnetic fields.

IONOSPHERIC DYNAMICS

The early retarding potential analyzer (RPA) results /1/ from the Pioneer Venus Orbiter (PVO), which showed the presence of large horizontal day to night velocities, led to a series of attempts to model and thus establish the mechanisms responsible for these flows. The first effort in this direction was by Knudsen et al. /2/ who estimated the various force terms and who found that the plasma pressure gradient is the principal force accelerating the plasma across the terminator into the antisolar direction. This work was followed by more and more complete and sophisticated solutions of the horizontal momentum equations by Whitten et al. /3/ and Theis et al. /4/. Here we will only summarize the two most recent of these studies, namely the work of Elphic et al. /5/ and Whitten et al. /6/.

Elphic et al. /5/ solved a simplified version of the two dimensional momentum equation.

They carried out two sets of calculations; in the first one they assumed that the viscosity is zero and in the second that it has a value appropriate for vertical shear in the horizontal flow velocity aligned with the magnetic field. Figure 1 shows the solutions for both the viscid and inviscid cases. Below about 200 km the flow speeds are about the same in both cases, but at higher altitudes the viscous solution gives much lower flow speeds. In both cases the maximum calculated velocity is at the antisolar point which is contrary to observations (Knudsen et al. /1/) and is also unphysical because the convergent flow in the antisolar region must vanish. Figure 2 shows both the calculated and measured velocities for a solar zenith angle of 105°. The calculated flow velocities are smaller than the measured ones below about 300 km. The disagreement shown between the calculated and measured velocities at high altitudes may be an indication of the possibly important role of viscous drag by the ionosheath plasma, as advocated by Perez-de-Tejada /7/. Whitten et al. /6/ has just completed some calculations in which they solved the coupled two dimensional continuity and momentum equations. In order to fit their numerical code on their CRAY machine they had to make a number of simplifying assumptions and they also obtained only one set of solutions. Figure 3 shows their calculated and the measured horizontal velocities at 400 km. In comparing these results with those of Elphic et al. /5/, one needs to note that the solution of Whitten et al. /6/ is an inviscid one, that their boundary conditions impose zero flux at the antisolar point and that the calculations are bounded at 500 km.

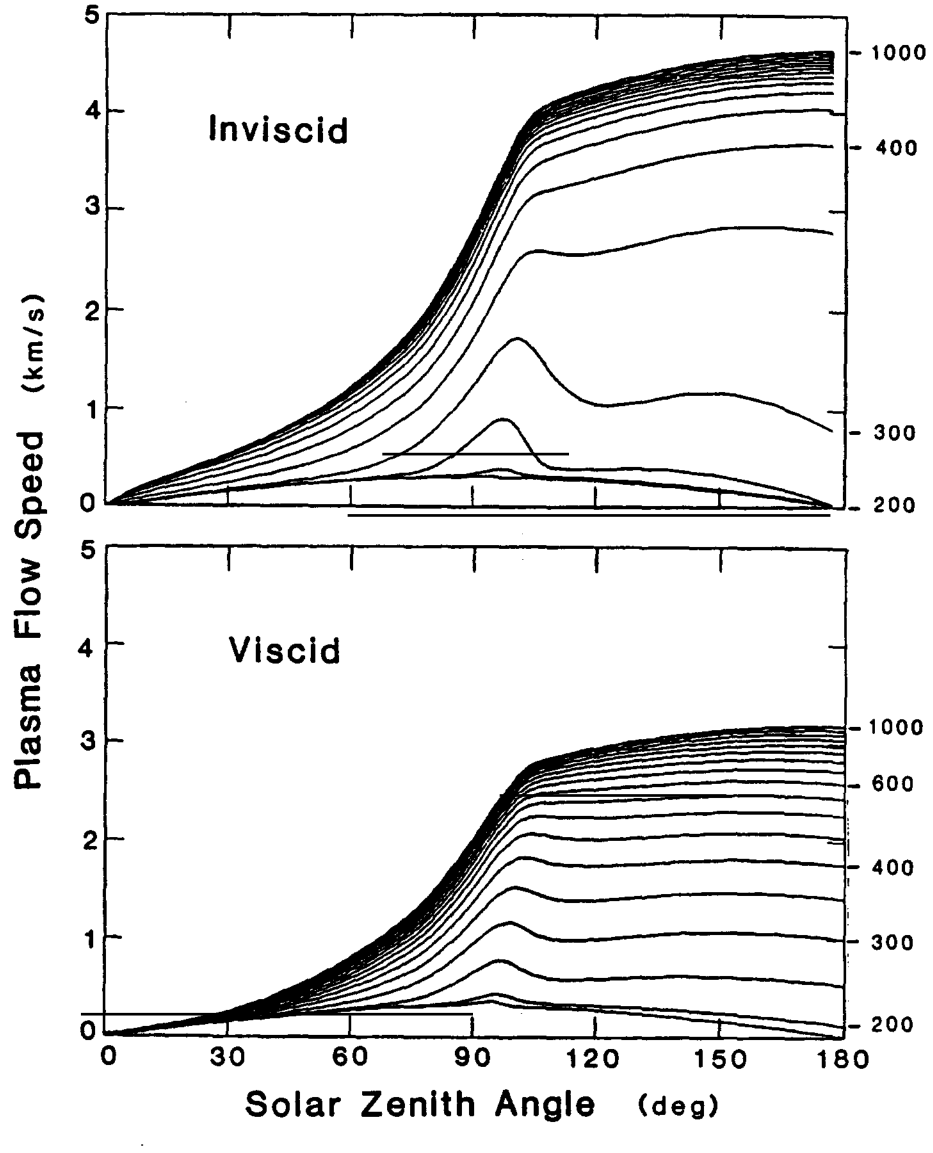

Figure 1

NIGHTSIDE IONOSPHERIC DENSITIES

Both theoretical calculations and direct observations have shown that there are large anti-solar horizontal flows in the ionosphere of Venus. The next logical topic of discussion concerns the mechanisms responsible for the maintenance of the nightside ionosphere. This question has been with us and it has been a controversial one since Mariner 5 observed an unexpected nightside ionosphere /8/. Of the various different mechanisms which were proposed to explain the observations, the two which stood the test of time best, are electron impact ionization and transport from the dayside. The most relevant and recent calculations aimed at answering the unresolved questions concerning the nightside ionosphere are those by Cravens et al. /9/. They solved the two dimensional continuity equation using calculated values for the vertical velocity and values based on observations for the horizontal velocity. One of the basic parameters in these calculations is height of the ionopause at the terminator. Calculations were carried out using three different assumed heights: 270 km (referred to as "low"), 500 km ("medium") and 880 km ("high"). Figure 4 shows the calculated O_2^+ densities for the low ionopause case; the result is a "disappearing" nightside ionosphere /10/. The calculated and measured O^+ densities at 200 km are shown in Figure 5 for all three assumed ionopause heights; horizontal transport for the "high" ionopause case and no H_2 in the neutral atmosphere is sufficient to maintain the nightside ionosphere. Another way of demonstrating this conclusion is shown in Figure 6, which gives the calculated and

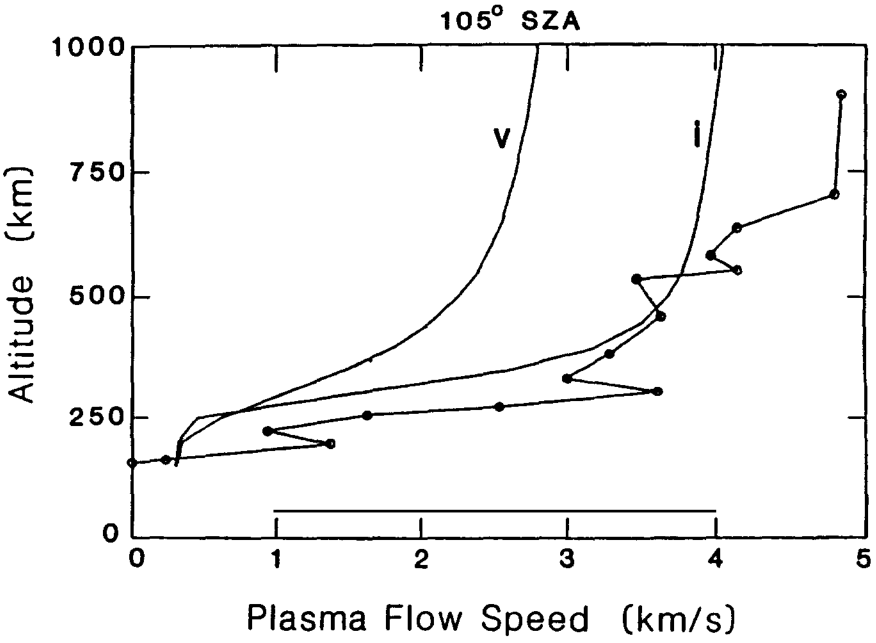

Figure 2

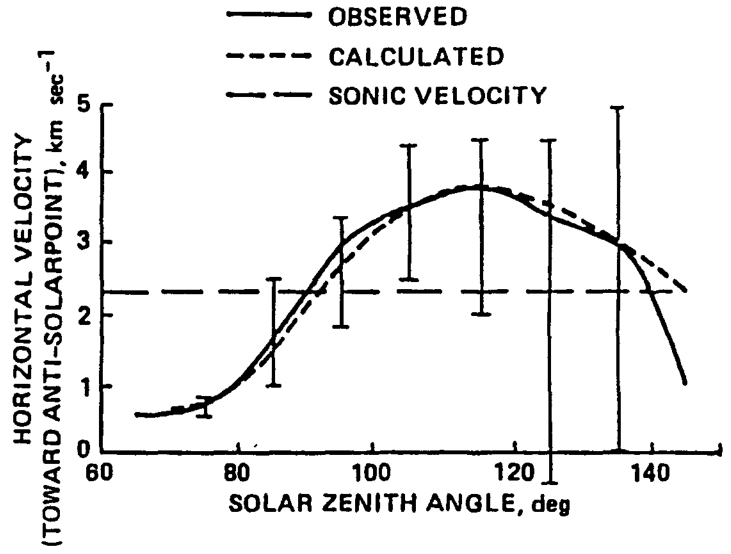

Figure 3

measured electron densities at the peak.

In order to evaluate the relative importance of electron precipitation in the maintenance of the nightside ionosphere, Cravens et al. /9/ calculated the impact ionization rate due to a precipitating flux consistent with both the Venera and Pioneer Venus observations. Figure 7 shows the calculated ionosphere due to this flux and it clearly shows that the measured and calculated densities are significantly different above the electron density peak. The calculations of Cravens et al. /9/ lead to the following conclusions:

a) Transport from the dayside, considering horizontal velocities of the order measured, is sufficient to maintain the observed mean nightside ionosphere.

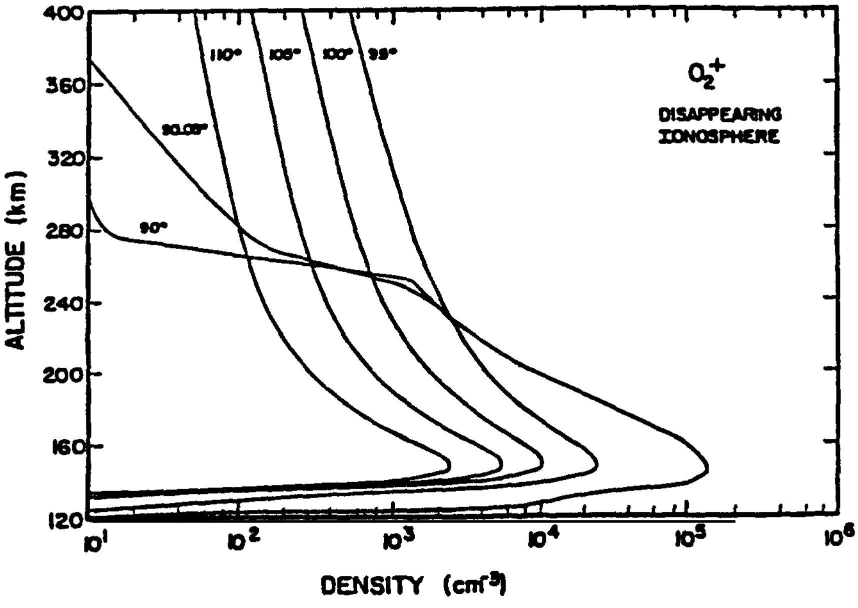

Figure 4

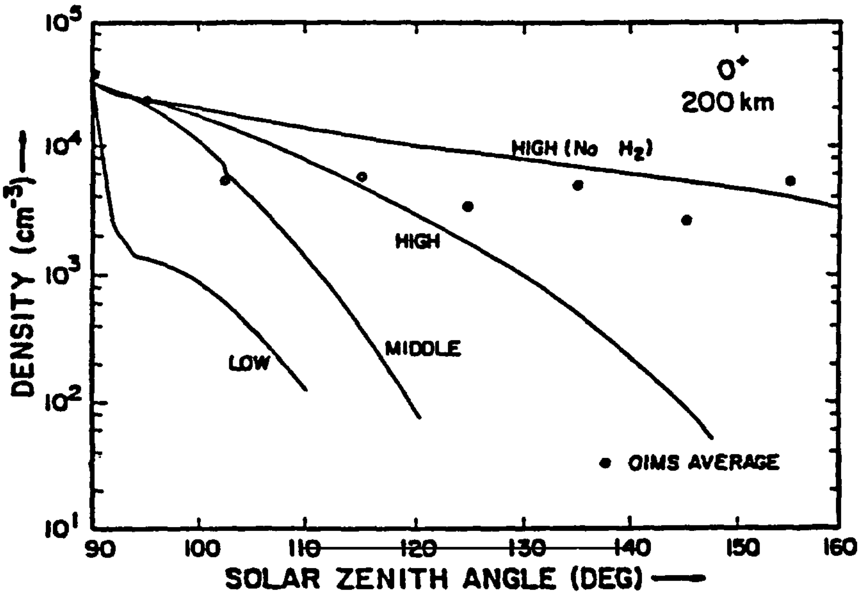

Figure 5

b) The effectiveness of the day to night plasma transport in maintaining the nightside ionosphere is controlled both by the magnitude of the horizontal velocity and by the dayside/terminator ionopause height.

c) The model can explain the sequence of events which leads to the "disappearing nightside ionosphere" /10/. High solar wind pressure causes a compressed dayside ionosphere, decreasing the dayside reservoir of ionization and thus the day to night transport cannot maintain the nightside ionosphere.

d) There is undoubtedly a significant low energy precipitating electron flux present on the nightside /11/, /12/, /13/. Electron densities of the right order are obtained at the peak, using accepted values of the flux, but it cannot explain the topside ionosphere. It appears that particle precipitation does not make a major contribution to the normal/mean nightside ionosphere but it is likely to be important when horizontal transport is small.

NIGHTSIDE IONOSPHERIC TEMPERATURES

The two dimensional ion energy equation was solved by Bougher and Cravens /14/ in a manner very analogous to the way in which Cravens et al. /9/ solved the two dimensional ion momentum equations. They assumed horizontal ion velocity values which are consistent with observations, and a mean calculated vertical velocity profile. Figure 8 shows some of the calculated ion temperatures obtained by Bougher and Cravens /14/ along with measured values from Miller et al. /15/. The calculated and measured temperatures are in good agreement for solar zenith angles less than about 150°. The calculations indicated that both horizontal and vertical advection of energy are important, but that horizontal heat conduction does not play an important role in the nightside ion energy balance. In effect, kinetic energy of the horizontal bulk flow is gradually and smoothly converted into thermal energy. The observed ion temperatures increase rapidly beyond 150°, which led Knudsen et al. /1/ to suggest that in this region the supersonic horizontal flow is rapidly decelerated through a shock, transforming most of the kinetic into thermal energy. This is a very plausible suggestion; however, no direct experimental indication of a shock has been found so far.

IONOSPHERIC MAGNETIC FIELDS

Data from the magnetometer carried by the Pioneer Venus Orbiter has clearly indicated that at times strong (~150-200nT) and large scale magnetic fields are present in the ionosphere down to the periapsis altitude of about 150 km /16/. Extensive examination of the morphology of these fields led Russell et al. /17/, /18/ to suggest that they are decaying remnants of fields impressed on the ionosphere during conditions of high solar wind pressure. Luhmann et al. /19/ calculated decay time constants of the order of a couple of hours for these fields. Cloutier /20/ on the other hand argued that the fields at these low altitudes dissipate in the order of minutes and therefore the observed fields are an indication of a steady state phenomena resulting from solar wind ionosphere interaction processes.

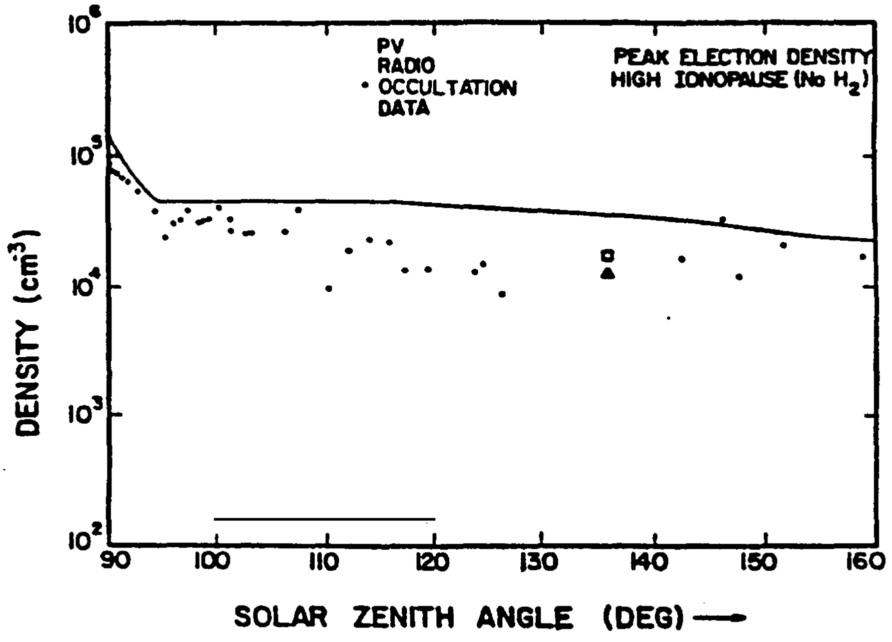

Figure 6

Cravens et al. /21/ undertook a more detailed and self-consistent study of these questions. The time rate of change of a uniform horizontal magnetic field, B, is controlled by convective transport and diffusion/dissipation of the magnetic field. Cravens et al. /21/ showed that the equations used by Luhmann et al. /19/ and Cloutier /20/ to solve for the time rate of change of B were effectively the same. The apparent differences were due to the fact that Luhmann et al. /19/ used the actual ion velocity, w, in their equation, while Cloutier /20/ used a velocity, w_o, which is the vertical ion velocity in the absence of vertical magnetic field gradients. In their first set of studies of the evolution and dissipation of the magnetic field, Cravens et al. /21/ used a calculated time independent value of w_o to solve the magnetic field equation, and they assumed that the field is constant at the upper boundary of 500 km. The results of these calculations, shown in Figure 9, indicate that initially the field increases near the peak, due to convection from higher altitudes, but then diffusion/dissipation takes over and the field decays. The value of w_o used in the calculations peaks near 200 km and that is the reason why B has a minimum at^{o}that altitude; B is swept down through and away from this region rapidly.

A more realistic set of calculations, in which B and w were calculated self-consistently, was also carried out by Cravens et al. /21/. They found, as shown in Figure 10, that the maximum B decays from about 100 nT to 50 nT rapidly (~ 700 sec), but then the decay slows down because the effective diffusion coefficient is proportional to B^2.

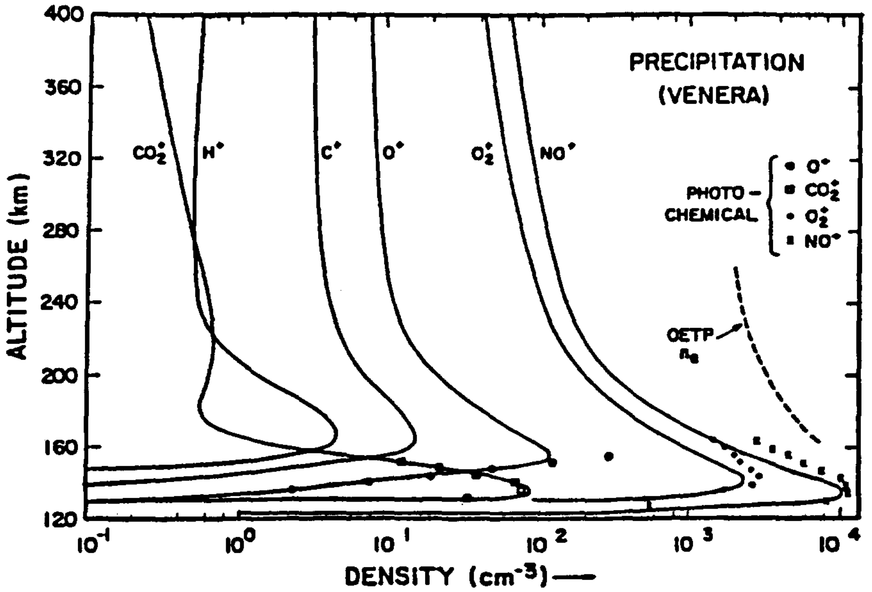

Figure 7

Having discussed the question of how an existing magnetic field decays, one can next consider the generation of this field in the first place. When the solar wind pressure is high, the ionopause is pushed downward, increasing the downward velocity in the ionosphere, which in turn results in increased convection of magnetosheath fields down deep into the ionosphere. This "conveyor belt" effect was demonstrated by Cravens et al. /21/ who obtained the t=0 profile, shown in Figure 10, in about 2500 sec, using reasonable assumptions for the downward velocities.

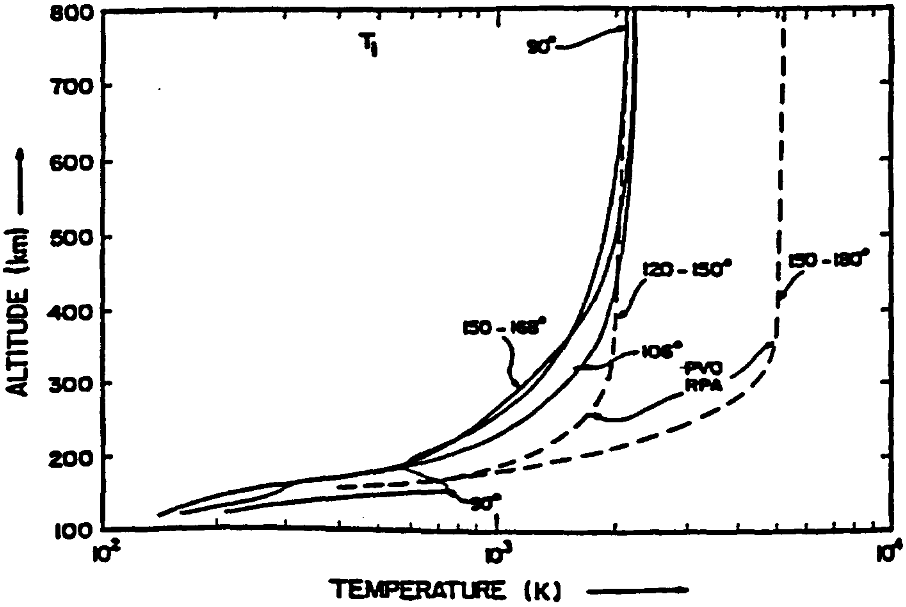

Figure 8

Some preliminary calculations have been carried out /22/ in which the magnetic field, B, the vertical ion velocity, w, and the ion density, n, are solved simultaneously and self-consistently. These calculations indicate that there are strong couplings among B, w, and n, but the end result for relatively simple field decay is not significantly different from the case in which the density coupling was neglected.

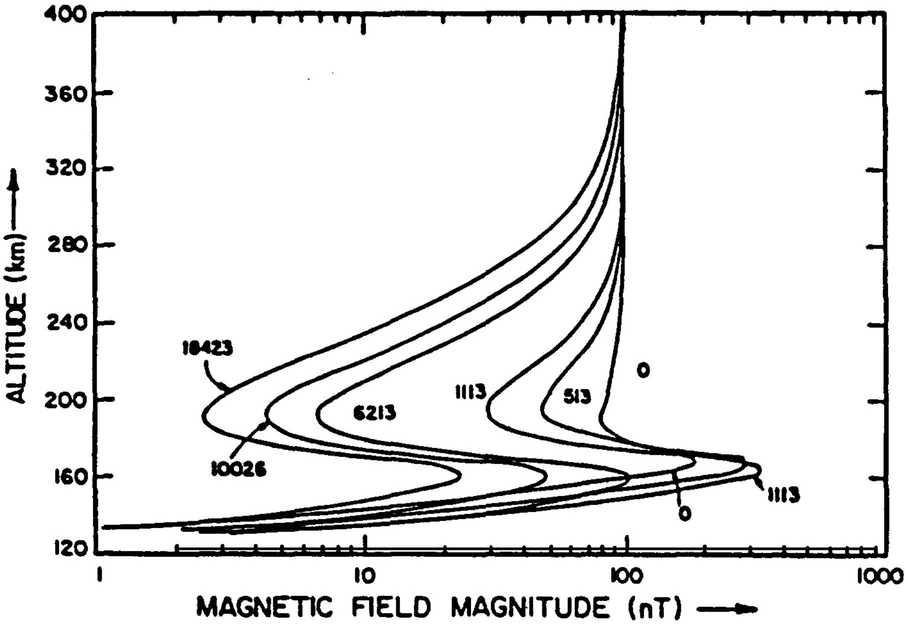

Figure 9

The calculations of Cravens et al. /21/ have indicated that the convection of field lines increases the effective lifetime of observed magnetic structures in the lower ionosphere. Thus the observed ionospheric fields of 50-75 nT do not need to be continuously and actively maintained in a steady state manner, but could be remnants of fields recently convected down from the ionopause region.

CONCLUSION

The above highlights of theoretical studies of the Venus ionosphere indicates that we are now beyond the discovery phase and that we are making important strides towards a better understanding of the physical processes controlling its behavior.

ACKNOWLEDGEMENTS

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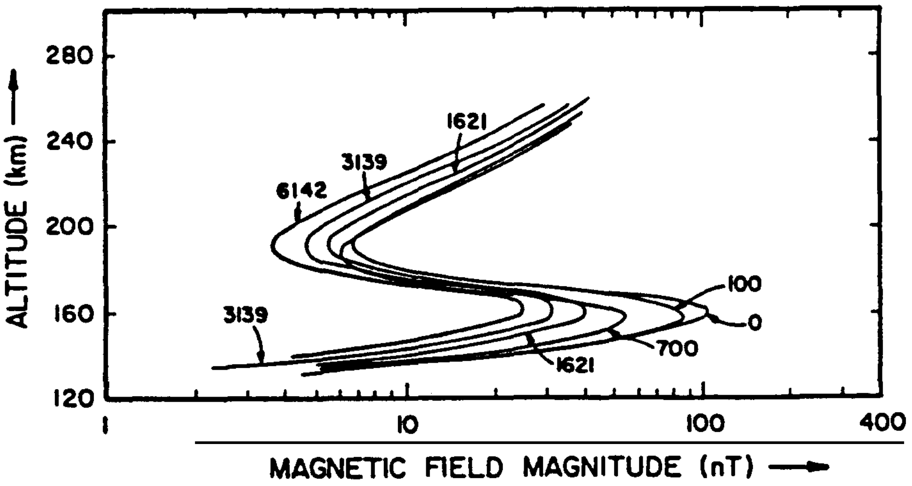

Figure 10

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