JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 89, NO. A1, PAGES 362–368, JANUARY 1984

Time Scales for the Decay of Induced Large-Scale Magnetic Fields in the Venus Ionosphere

J. G. Luhmann and C. T. Russell

Institute of Geophysics and Planetary Physics, University of California, Los Angeles

R. C. Elphic

NASA Goddard Space Flight Center

Observations from the Pioneer Venus Orbiter magnetometer suggest that a large-scale magnetic field is induced in the dayside ionosphere when the solar wind dynamic pressure is high. The persistence of the large-scale field structure is investigated by using realistic models of the neutral atmosphere and ionosphere. Under the assumptions that the magnetic field is horizontal with vertical gradients, the magnetic field evolution is described by a diffusion-convection equation where the diffusion coefficient depends on the sum of the electron-neutral and electron-ion collision frequencies. In this one-dimensional model the diffusion coefficient and the vertical plasma drift velocity together determine the time scale for the field disappearance. Numerical solutions of the field equation suggest that a large-scale field in the dayside Venus ionosphere disappears with a time scale of minutes for a vertical velocity of ~10 m/s, but that the lifetime increases to several hours if the vertical velocity is small. Above ~200 km altitude, the observed antisolar convection of the ionospheric plasma would cause the field to diminish more rapidly than these diffusion time scales, but at lower altitudes the diffusion process determines the rate of field decay. This result may explain some of the observations of quasi-steady, large-scale magnetic fields in the Venus ionosphere during steady solar wind conditions as remnants of fields previously induced by the solar wind interaction.

1. Introduction

Large-scale horizontal magnetic fields in the dayside ionosphere of Venus were first observed by the magnetometer on the Pioneer Venus Orbiter [*Russell et al.*, 1979; *Elphic et al.*, 1980]. The large-scale fields, which are present down to the periapsis altitude of ~150 km, occur when the magnitude of the solar wind dynamic pressure outside of the Venus bow shock is higher than average [*Luhmann et al.*, 1980]. Figure 1 shows some typical altitude profiles of these field structures from the Pioneer Venus magnetometer observations.

Cloutier and Daniell [1981] and *Cloutier et al.* [1983] have proposed that the observed magnetic structures are quasi-steady features produced by an ionospheric current system driven by the solar wind interaction. In their picture, the large-scale magnetic field structure shrinks and grows in rapid response to solar wind dynamic pressure changes, with no observable field resulting from the decay of currents induced at an earlier time. The latter deduction is based on the argument that the currents decay on very short time scales, much less than the 24-hour period of the Pioneer Venus Orbiter or the ~20-min ionosphere transit time, once the solar wind interaction ceases to drive them. From the viewpoint of this model, the various altitude profiles illustrated in Figure 1 are interpreted as observations of the same basic ionospheric current system at different spatial locations [*Cloutier et al.*, 1983].

Russell et al. [1983] examined the morphology of the large-scale dayside ionospheric field structure in detail. These authors suggested that the altitude profiles of the horizontal field on different orbits (see Figure 1) exhibit a pattern that can be interpreted as phases in the temporal evolution of an initial state in which the ionosphere was permeated with magnetosheath-like fields. The ionospheric currents producing the field were induced by the solar wind interaction at an earlier time, leaving a magnetized ionosphere in which the field evolves by a combination of convection and diffusion. In this paper the argument in favor of a temporal versus spatial explanation for some of the observed field structure is examined. A calculation is described which indicates that the diffusion time for ionospheric fields is long enough to justify attributing the observed large-scale fields to the "memory" of the Venus ionosphere in regions where the plasma convection speed is small.

2. Decay of Ionospheric Magnetic Fields: Theory

The rate of change of the ionospheric magnetic field $\bar{B}$ is given by Maxwell's equation

$$\partial \bar{B}/\partial t = \nabla \times \bar{E} \tag{1}$$

where $\bar{E}$ is the electric field. The electric field can be found, for known $\bar{B}$, plasma density n, and thermal pressure $\bar{p}$, by using the ion and electron momentum equations (subscript i denotes ion quantities; e denotes electron quantities):

$$-\nabla p_i + nm_i\bar{g} + \tfrac{1}{2}nm_i\nu_{in}(\bar{u} - \bar{V}_i) - nm_i\nu_{ie}(\bar{V}_i - \bar{V}_e) + en(\bar{E} + \bar{V}_i \times \bar{B}) = 0 \tag{2}$$

$$-\nabla p_e + nm_e\bar{g} + nm_e\nu_{en}(\bar{u} - \bar{V}_e) - nm_e\nu_{ei}(\bar{V}_e - \bar{V}_i) - en(\bar{E} + \bar{V}_e \times \bar{B}) = 0 \tag{3}$$

together with Ampere's Law for the current $\bar{J}$

$$\bar{J} = (1/\mu_0)(\nabla \times \bar{B}) = ne(\bar{V}_i - \bar{V}_e) \tag{4}$$

which ensures current closure. (Note the components of these three equations are sufficient to solve for the nine unknowns V_{ix}, V_{iy}, V_{iz}, V_{ex}, V_{ey}, V_{ez}, E_x, E_y, and E_z.) The standard definitions $\bar{V}$, plasma species velocity; $\bar{u}$, neutral velocity; e, electron

Paper number 3A1605.
0148-0227/84/003A-1605$05.00

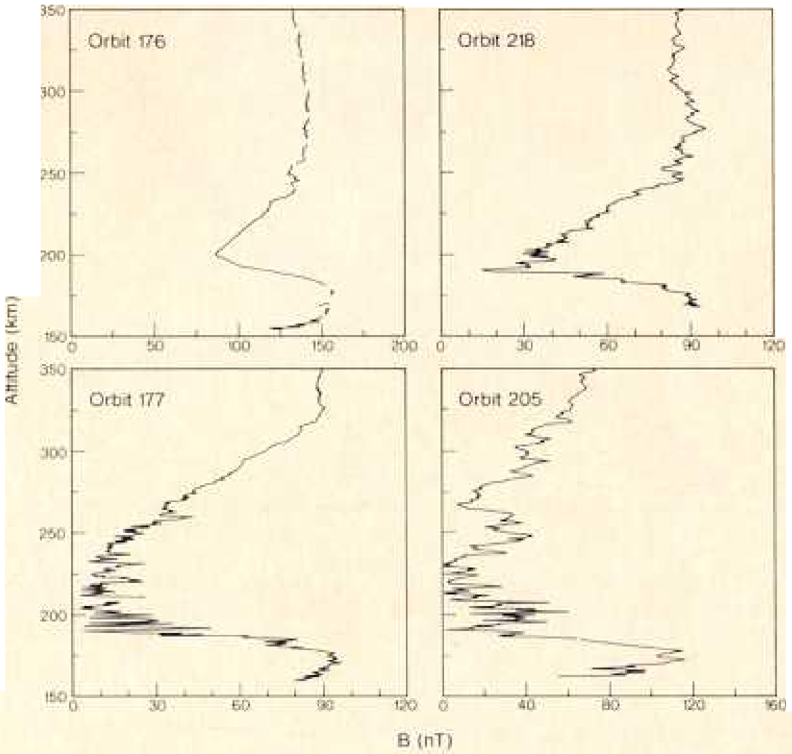

Fig. 1. Examples of altitude profiles of the magnetic field strength observed in the Venus dayside ionosphere by the Pioneer Venus Orbiter magnetometer. These large-scale fields, which are practically horizontal, look similar on the inbound and outbound legs of the orbit. Note the characteristic minimum near 200 km altitude.

charge; $\nu_{\alpha\beta}$, collision frequency between species α and β; m, mass; and g = gravitational acceleration are used above.

The inertial terms have been neglected in the momentum equations, since the ionospheric bulk velocities away from the terminator and below the ionopause are expected to be small during undisturbed times. In addition, the neutrals should also be described with a full system of similar equations. However, the neutral dynamics in a weakly ionized plasma like the Venus ionosphere can, to a first approximation, be considered as unaffected by the plasma dynamics. Hence $\bar{u}$ is regarded as a given parameter here.

If it is assumed that $\bar{B}$ is horizontal and varies only in the vertical (z) direction (implying that horizontal $\bar{J} \times \bar{B}$ forces are negligible and $J_z = 0$), and that all other quantities are also uniform in the horizontal directions but vary in z, $\partial\bar{B}/\partial t$ is given by

$$\frac{\partial \bar{B}}{\partial t} = -\nabla \times \bar{E} = \frac{\partial \bar{E}_x}{\partial z}\hat{j} + \frac{\partial \bar{E}_y}{\partial z}\hat{i} \qquad (5)$$

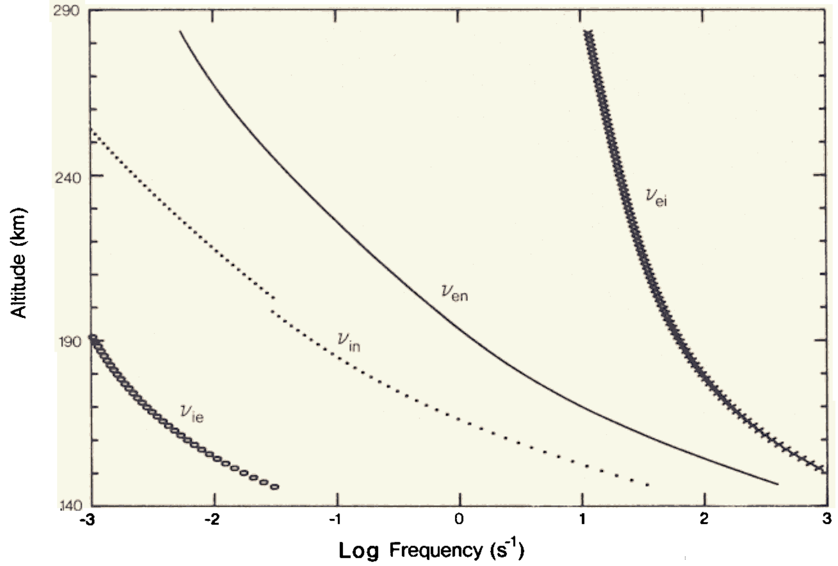

Fig. 2. Collision frequencies used in the present calculations: ν_{in} is the ion-neutral collision frequency ($\nu_{in} = 2.6 \times 10^{-15}\, N_n(m_i)^{1/2}$ (amu), N_n = neutral density), ν_{en} is the electron-neutral collision frequency ($\nu_{en} = 2. \times 10^{-16}\, N_n(T_e)^{1/2}$, T_e = electron temperature), ν_{ie} is the ion-electron collision frequency, and ν_{ei} is the electron-ion collision frequency ($\nu_{ei} = 1. \times 10^6\, n(59. + 4.18 \log (T_e^3/n))/T_e^{3/2}\ \mathrm{s}^{-1}$) [cf. *Ratcliffe,* 1972]. The discontinuity in the ν_{in} curve is from the assumption that the dominant ion changes from O^+ to O_2^+ at $\sim$160km.

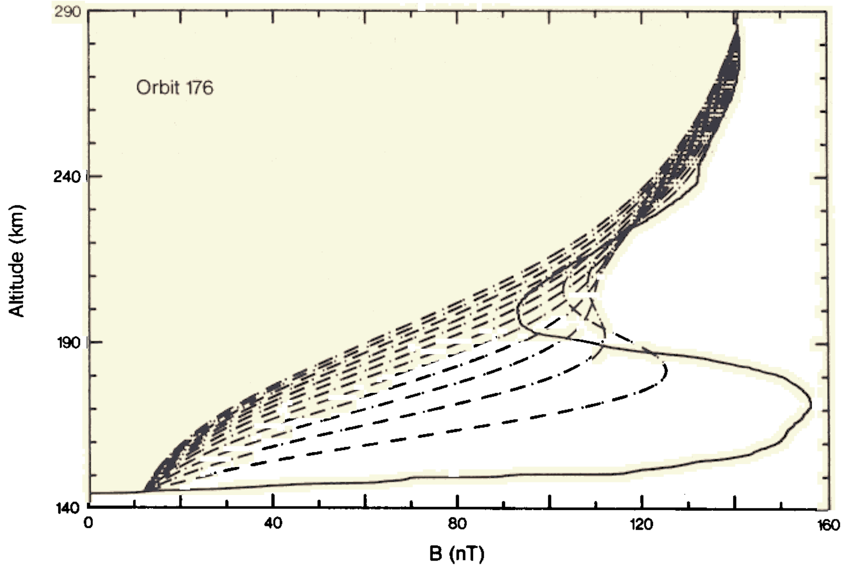

Fig. 3. The solid curve shows the altitude profile observed on the inbound leg of orbit 176 (the data have been extrapolated to 140 km from the periapsis altitude of ~150 km). The dashed lines show the solution for zero plasma velocity at 5000-s intervals for an initial condition given by the data. Upper and lower boundaries at which the field is held constant are at 290 km and 145 km, respectively.

No generality is lost by setting $\bar{B} = B_x(z)\hat{\imath}$, whence $E_x = 0$, and $\partial\bar{B}/\partial t$ is obtained by solving for E_y.

Combining the momentum equations and Ampere's Law, one finds the solution for E_y:

$$E_y = \rho_e \nu_{en}\left(\frac{\rho_i \nu_{in}/2}{(\rho_i \nu_{in}/2 + \rho_e \nu_{en})}\right)\frac{1}{(ne)^2\mu_0}\frac{\partial B_x}{\partial z} + \rho_e \nu_{ei}\frac{1}{(ne)^2\mu_0}\frac{\partial B_x}{\partial z}$$
$$- B_x\left[u_z + \frac{1}{(\rho_i \nu_{in}/2 + \rho_e \nu_{en})}\right.$$
$$\left.\left(-\frac{\partial}{\partial z}(p_i + p_e) + (\rho_i + \rho_e)g - \frac{1}{2\mu_0}\frac{\partial B_x{}^2}{\partial z}\right)\right] \quad (6)$$

The derivative, $\partial E_y/\partial z$, of this expression is equal to $\partial B_x/\partial t$. Considering that the approximations

$$(\rho_i \nu_{in}/2 + \rho_e \nu_{en}) \simeq \rho_i \nu_{in}/2 \quad (7)$$

can be made, this result can be written in the form

$$\frac{\partial|B|}{\partial t} = \frac{\partial B_x}{\partial t} = \frac{\partial}{\partial z} D \frac{\partial B_x}{\partial z} - \frac{\partial}{\partial z}(B_x V_{pz}) \quad (8)$$

where $V_{pz} = V_{iz} = V_{ez}$ is the vertical plasma drift velocity (given by the expression in brackets in equation (6) above), and the diffusion coefficient D is given by

$$D = \frac{m_e(\nu_{en} + \nu_{ei})}{(ne^2\mu_0)} \quad (9)$$

Thus the diffusion time scale in the present formulation depends on the electron-neutral and electron-ion collision frequencies, while the time scale for vertical convection is determined by the vertical plasma drift velocity V_{pz}. The collision frequencies are shown in Figure 2 for the subsolar neutral atmosphere and ionosphere given by the empirical Hedin

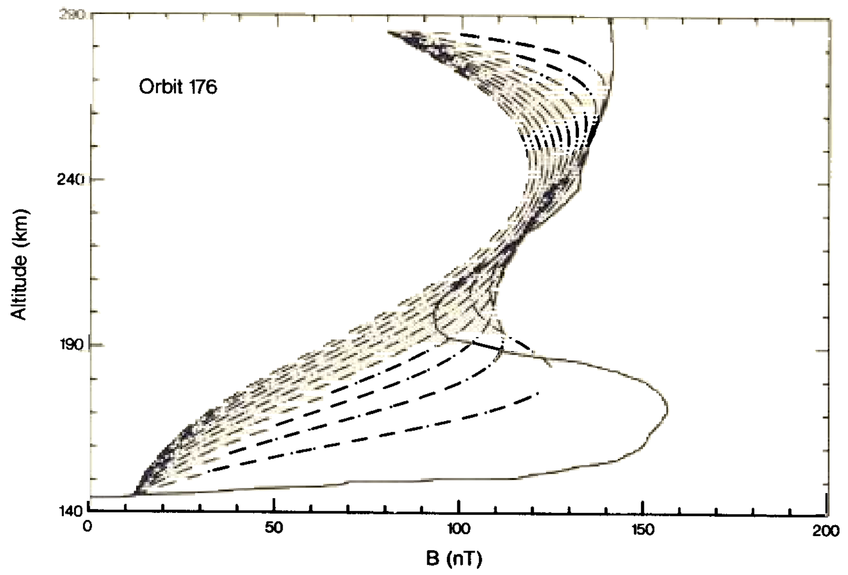

Fig. 4. Same as Figure 3, but with the field at the upper boundary (290 km) decaying to 80 nT with a time constant of 1 hour.

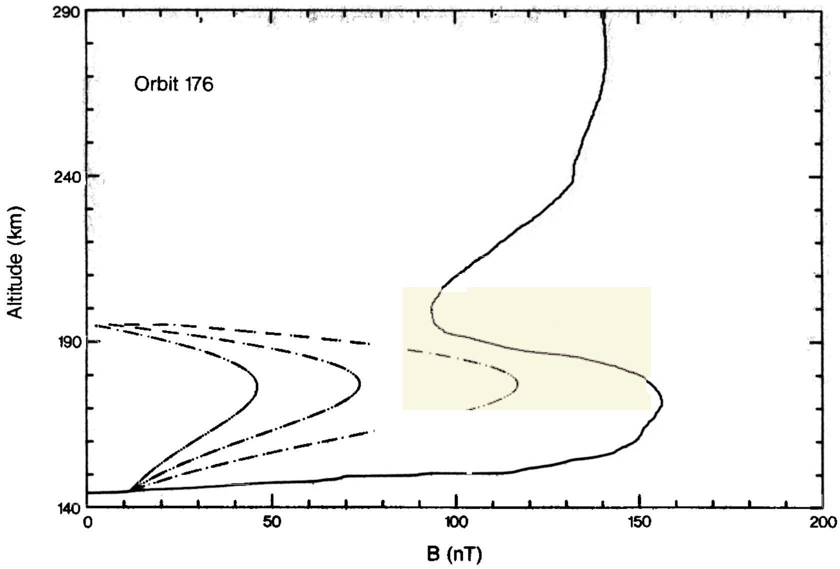

Fig. 5. Same as Figure 3, but with the upper boundary at 195 km instead of at 290 km, and with the field strength at that upper boundary decaying with a 10-min time constant.

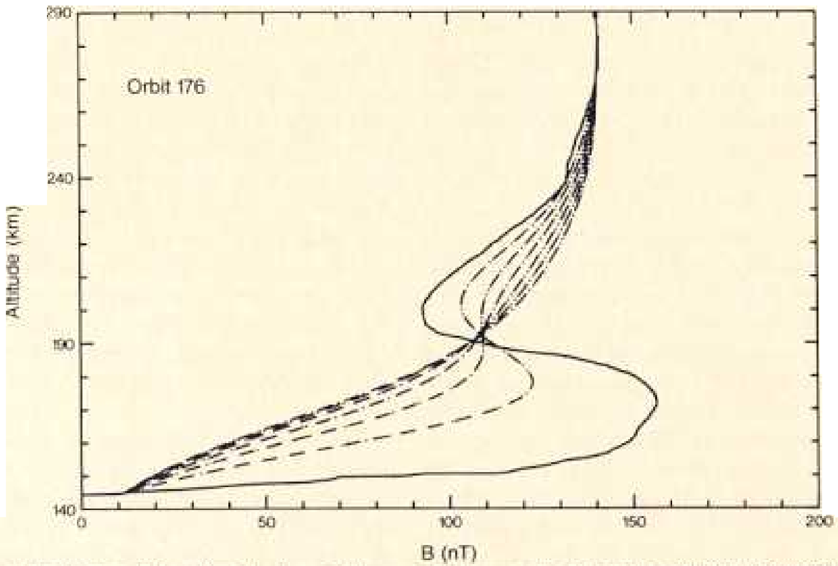

Fig. 6a Illustration of the effect of a 1-ms^{-1} downward plasma velocity on the solution of the diffusion equation

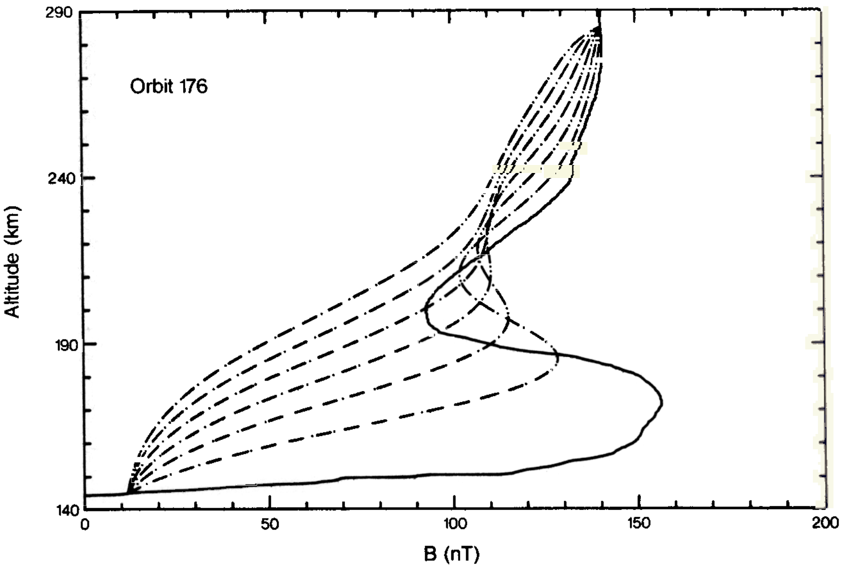

Fig. 6*b*. Solutions for 1-ms^{-1} upward plasma velocity.

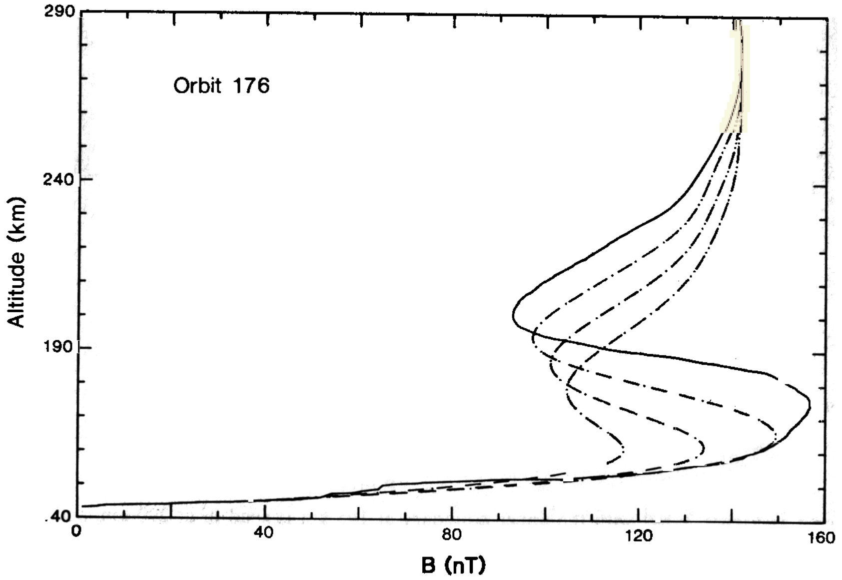

Fig. 6*c*. Solutions for 10-ms^{-1} downward plasma velocity. Here curves are separated by 1000 s instead of 5000 s as in Figures 6*a* and 6*b*.

model [cf. *Cravens et al.*, 1981] and the *Theis et al.* [1980] model, respectively. These altitude profiles indicate that electron-ion collisions determine the diffusion coefficient throughout the region of interest.

3. RESULTS

Equation (9) can be integrated numerically by using a standard finite-difference scheme [cf. *Smith*, 1965]. For an initial condition given by observations, one can then study the time scales for the field evolution under a variety of conditions. Here the initial condition is always taken as the observed field on the inbound leg of orbit 176, since the sensitivity of the solution to various parameters is under investigation. If it is assumed that the vertical plasma velocity is zero and that the magnetosheath magnetic field is constant at 290 km (near the ionopause), the integration of (9) produces the curves shown in Figure 3. Each curve is separated by 5000 s, with curves for successively later times increasingly to the left. For this calculation the field was kept at a constant value at the ionopause boundary and at the base of the ionosphere at 145 km. Diffusion smooths out the altitude structure between the two boundaries. Hence the local minimum at about 200 km evident in the initial profile disappears with time, as does the local maximum at about 170 km. The important feature of Figure 3 is that the time scale for decay is several hours. Sometimes the observations suggest that the field magnitude at the ionopause decreases while diffusion is in progress. Figure 4 shows the solution for the case in which the field at the ionopause was decreased exponentially to 80 nT with a 1-hour time constant. The essential features of the solution are unchanged by this complication and the time scales are basically unaltered.

In the scenario envisioned by *Russell et al.* [1982] the local minimum in the magnetic field at about 200 km is a result of the convection of the magnetized plasma from the dayside to the night and its replacement by fresh photoionization. It is beyond the capabilities of the present simple model to simulate this process of horizontal transport. However, if such con-

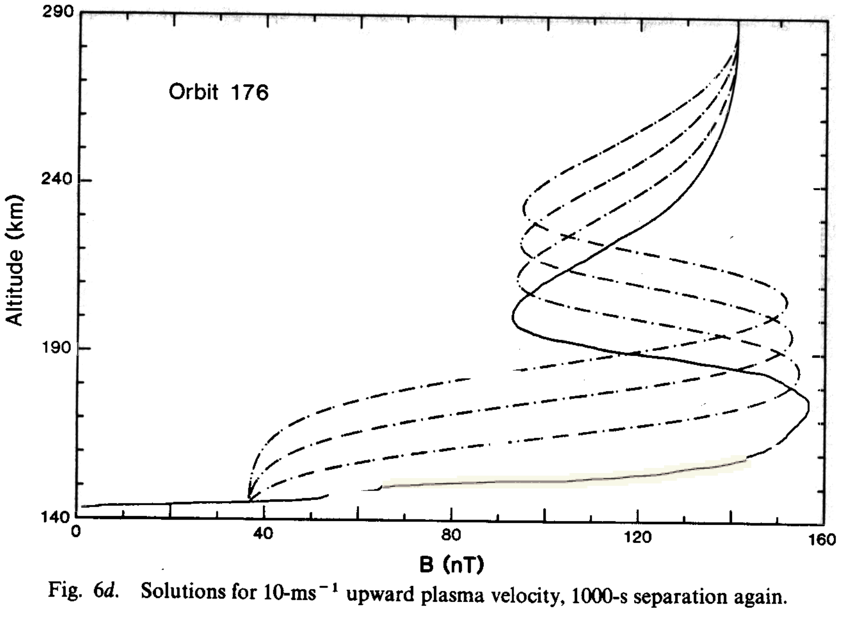

Fig. 6*d*. Solutions for 10-ms^{-1} upward plasma velocity, 1000-s separation again.

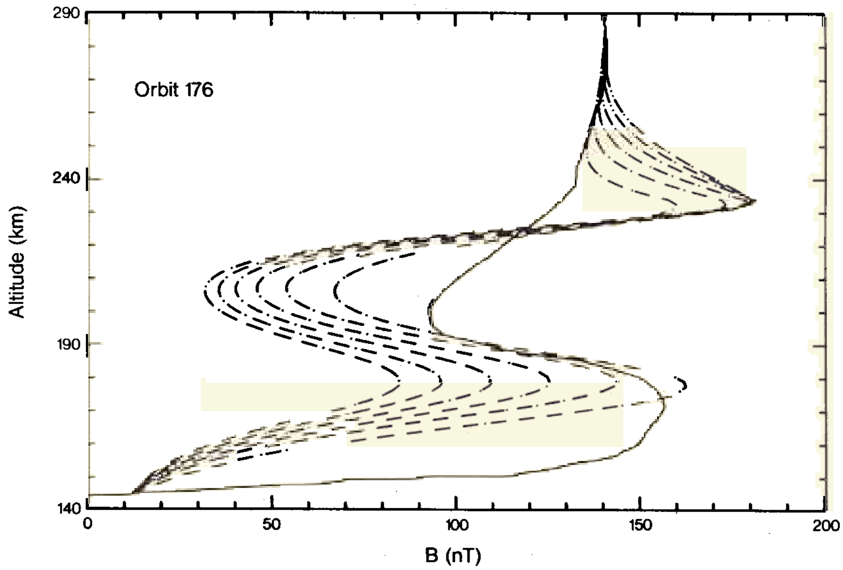

Fig. 7. Same as Figure 3, but with a 1-ms^{-1} vertical velocity which varies sinusoidally with altitude with a 60-km wavelength.

vective losses do occur above about 200 km, they will speed up the apparent decay of the field at those altitudes. Our solution was altered to approximate this convective loss by establishing an upper boundary condition at 195 km, rather than at 290 km, and allowing the field magnitude there to decay to zero with a 10-min time scale. Because this is much more rapid than would be expected for convective losses at 200 km, this assumption determines the fastest possible decay time for the low-altitude field under the condition of zero vertical plasma velocity. The resulting altitude profiles in Figure 5 indicate how this device speeds up the decay of the low altitude field. However, the decay time is still the order of hours. One important qualitative difference is in the location of the peak field. With fixed minimum field strength boundaries at 195 and 145 km, the peak field altitude no longer drifts upward with time, but remains fixed at ~170 km, as is observed [cf. *Russell et al.*, 1982]. It is also notable that the calculated profiles for a boundary condition at a normal subsolar ionopause location of 290 km (e.g., see Figure 3) decay to a smooth shape which resembles the thick low-altitude ionopauses discussed by *Elphic et al.* [1981].

However, the vertical plasma velocity may be as large as tens of ms^{-1} (T. E. Cravens, personal communication, 1983). The effect of a nonzero vertical velocity on the time scale is illustrated by Figure 6, which shows the effect of assuming constant vertical plasma velocities of 1 ms^{-1} (Figures 6*a* and 6*b*) and 10 ms^{-1} (Figures 6*c* and 6*d*). The curves for the 10 ms^{-1} velocity case are separated by 1000 instead of 5000 s. It is apparent from these examples that the time scale for the persistence of the ionospheric field can decrease by an order of magnitude or more if the ionospheric plasma has a substantial vertical drift. Self-consistent models of the magnetized ionosphere, in which the plasma and field properties are determined together, are necessary to determine the magnitude of the vertical plasma velocity. A modeling treatment of this scope is beyond the level of the present effort. However, some preliminary data analyses [*Luhmann et al.*, 1983] suggest that the vertical velocity within the ionosphere has a range of values that may reach magnitudes of tens of ms^{-1}. Thus the possibility of both long and short time scales for the ionospheric field persistence should be considered. It is also important to appreciate that altitude-dependent vertical velocities can grossly modify the large-scale field structure during its evolution. As an example, Figure 7 shows the field for a sinusoidal vertical wind shear.

4. CONCLUDING REMARKS

The simple one dimensional model of magnetic field diffusion in the Venus ionosphere described here suggests that the time scales for the disappearance of the observed large-scale horizontal fields can be as long as hours or as short as minutes, depending on the vertical plasma drift velocity. To reproduce the details of the observed profiles, such as the fixed position of the magnetic field peaks and minima, horizontal ionospheric convection or a vertical plasma velocity with a special altitude structure must be invoked. These influences can only be approximated within the framework of this simple model. In reality, the three-dimensional nature of the solar wind interaction with Venus makes both magnetic tension (horizontal $\bar{J} \times \bar{B}$ force) and horizontal convection potentially important in the evolution of the ionospheric field. Moreover, the ionospheric density and temperature, which are treated as fixed quantities here, can be affected by the field at the higher altitude. It is beyond the capability of the present effort to simulate such effects. Nevertheless, the simple model can be used to address the important question of the time scales for the persistence of the ionospheric field at altitudes below ~200 km, where these other effects may play a minor role. From the results described above, it is expected that although active induction must occur, temporal effects in the form of remnant solar wind induced currents can on some occasions determine the observed large-scale ionospheric field at Venus.

Acknowledgments. The authors wish to acknowledge enlightening discussions with D. J. Southwood, A. F. Nagy, T. E. Cravens, and P. A. Cloutier and several useful exchanges with R. S. Wolff. This research was supported by NASA grant NAA 2-9491.

The Editor thanks the two referees for their assistance in evaluating this paper.

REFERENCES

Cloutier, P. A., and R. E. Daniell, An electrodynamic model of the solar wind interaction with the ionospheres of Mars and Venus, *Planet Space Sci.*, *27*, IIII, 1981.

Cloutier, P. A., T. F. Tascione, R. E. Daniell, Jr., H. A. Taylor, and R. S. Wolf, Physics of the interaction of the solar wind with the ionosphere of Venus: Flow/field models, in *Venus*, edited by D. Hunten, University of Arizona Press, Tucson, Ariz., in press, 1983.

Cravens, T. E., A. J. Kliore, J. U. Kozyra, and A. F. Nagy, The ionospheric peak on the Venus dayside, *J. Geophys. Res.*, *86*, 11,323, 1981.

Elphic, R. C., C. T. Russell, J. A. Slavin, and L. H. Brace, Observations of the dayside ionopause and ionosphere of Venus, *J. Geophys. Res*, *85*, 7679, 1980.

Elphic, R. C., C. T. Russell, J. G. Luhmann, F. L. Scarf, and L. H. Brace, The Venus ionopause current sheet: Thickness length scale and controlling factors, *J. Geophys. Res.*, *86*, 11,430, 1981.

Luhmann, J. G., R. C. Elphic, C. T. Russell, J. D. Mihalov, and J. H. Wolfe, Observations of large-scale steady magnetic fields in the dayside Venus ionosphere, *Geophys. Res. Lett.*, *7*, 917, 1980.

Luhmann, J. G., R. C. Elphic, C. T. Russell, L. H. Brace, and R. E. Hartle, Effects of large scale magnetic fields in the Venus ionosphere, *Adv. Space Res.*, *2*, 17, 1983.

Ratcliffe, J. A., *An Introduction to the Ionosphere and Magnetosphere*, Cambridge University Press, New York, 1972.

Russell, C. T., R. C. Elphic, and J. A. Slavin, Initial Pioneer Venus magnetic field results: Dayside observations, *Science*, *203*, 745, 1979.

Russell, C. T., J. G. Luhmann, and R. C. Elphic, The properties of the low altitude magnetic belt in the Venus ionosphere, *Adv. Space Res.*, *2*, 13, 1983.

Smith, G. D., *Numerical Solution of Partial Differential Equations*, Oxford University Press, New York, 1965.

Theis, R. F., L. H. Brace, and H. G. Mayr, Empirical models of the electron temperature and density in the Venus ionosphere, *J. Geophys. Res.*, *85*, 7787, 1980.

R. C. Elphic, NASA Goddard Space Flight Center, Greenbelt, MD 20771.

J. G. Luhmann and C. T. Russell, Institute of Geophysics and Planetary Physics, University of California, Los Angeles, CA 90024.

(Received January 28, 1983;
revised October 4, 1983;
accepted October 4, 1983.)