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THE DYNAMICS OF THE VENUS IONOSPHERE

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1. Introduction

Data from the Pioneer-Venus orbiter has demonstrated the importance of understanding ion dynamics in the Venus ionosphere. The analysis of these data has shown that during solar maximum the topside Venus ionosphere in the dark hemisphere is generated almost entirely on the dayside of the planet during solar maximum, and flows with super-sonic velocities across the terminator into the nightside. On the nightside, the ion density is maintained by the influx of ions, primarily O^+, from the dayside. The primary source of heat on the nightside is also thought to originate in the acceleration of the ions on the dayside, and to be deposited on the nightside by the conversion of kinetic energy to thermal energy on the nightside either by adiabatic compression as the ions converge in the anti-solar region, or by a re-compression shock as the ions are decelerated from super-sonic velocities. Since there is no strong internal magnetic field to constrain the motion of the ionospheric plasma, the ionosphere is able to respond freely to pressure gradients and possibly other internal and external forces.

The flow field in the ionosphere is mainly axially-symmetric about the sun-Venus axis, as are most measured ionospheric quantities [Brace, et al., 1983; Miller, et al., 1984; Theis, et al., 1984]. The thermal plasma is accelerated to super-sonic velocities as it crosses the terminator region. The flow then slows as it converges on the nightside. The deceleration to sub-sonic velocities is very localized in a statistical sense, suggesting the presence of a re-compression shock in the vicinity of 140 deg. solar zenith angle (SZA) [Knudsen, et al.,1980].

The primary data base used in this study consisted of the ion velocity measurements made by the RPA during the three years that periapsis of the orbiter was maintained in the Venus ionosphere. Examples of ion velocities have been published [Knudsen et al., 1980; Miller and Knudsen, 1986] and modeled [Whitten et al., 1982; Whitten et al., 1984; Theis et al., 1984]. This research examined the planetary flow patterns measured in the Venus ionosphere, and the physical implications of departures from the mean flow.

2. Data Used in This Study

Ion velocities were measured by the retarding potential analyzer (RPA) on board the Pioneer Venus orbiter for approximately three years after orbit insertion. During this time the altitude of periapsis of the orbit was maintained near 150 km, providing one north-to-south pass through the ionosphere in each 24-hour period. The latitude of periapsis was about 15 deg. north, so that the inbound legs spanned the northern midlatitudes, while the outbound legs spanned the equator.

The method by which the Pioneer Venus RPA measures the velocities of the ions is described by Knudsen et al. [1980]. Basically, it is the measurement of O^+ kinetic energies in three directions on three successive spacecraft rotations (Figure 1). The RPA is mounted at an angle of 25 deg. from the spacecraft spin axis. It is programmed to record data when the instrument is in the spacecraft ram direction in one spin period, 45 deg. earlier in the next spin period, and 45 deg. later in the third spin period. The line-of-sight of the second and third measurements are thus separated from the ram measurement line-of-sight by about 18.6 deg. The resolution of these three measurements into a Cartesian coordinate system provides the vector sum of the spacecraft and ion velocities. After subtracting the velocity of the spacecraft, the resultant vector formed from the three line-of-sight velocity measurements corresponds to the ion velocity of the ambient ions.

The spacecraft speed of approximately 9 km s^{-1} at periapsis insures that the flow is directed into the RPA for measurements when the spacecraft is in the ionosphere. Since the spacecraft spin period is about twelve seconds, this orbital velocity also means that the spacecraft has traveled about 100 km horizontally between measurements. In spite of approximately 200 km of horizontal distance separating the first and last measurement, the vectors formed from three successive measurements are usually self-consistent and in a nightward direction. The results suggest that there is a primary flow of ions that is global in scale, in spite of significant small-scale spatial and temporal variations.

The Pioneer-Venus Orbiter RPA was developed at Lockheed by Dr. W. C. Knudsen, Principal Investigator. Analysis and scientific studies have been carried out by Dr. Knudsen and Dr. K. L. Miller since the launch of Pioneer Venus in 1978. Dr. Knudsen is now at Knudsen Geophysical Research in Monte Sereno, California, and Dr. Miller at Utah State University. A set of RPA data through the period when periapsis was in the ionosphere is kept at Utah State as a backup to the complete data set maintained by Dr. Knudsen. Since the periapsis of the Pioneer-Venus orbiter is no longer at a low enough altitude to sample the ionosphere, the set of data at Utah State contains essentially all of the ion velocity measurements of the Pioneer-Venus mission.

3. Implementation on the CASS Harris 800 computer

In the first year, the most important software that had been developed at Lockheed was adapted to the particular computer configuration in the Imaging Spectroscopic Observatory (ISO) Laboratory at Utah State University. This was based around a VAX/750 and was similar to the computer environment used by the

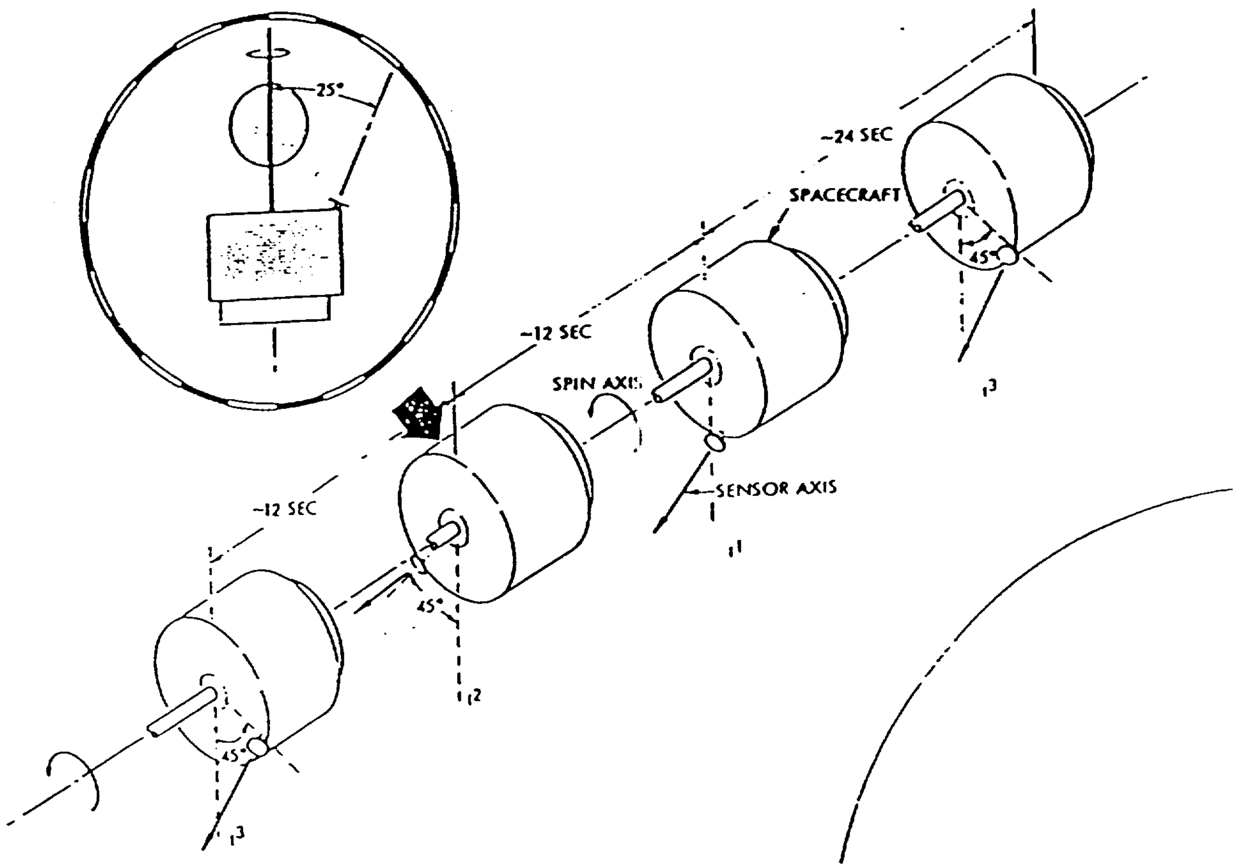

Figure 1.   Method of measuring ion velocities.

Principal Investigator to develop the analysis software at Lockheed. At the beginning of the second year, Dr. D. G. Torr, who was originally a co-investigator on this proposal, relocated his activities away from Utah State. In the meantime, CASS, acquired a Harris 800 as its primary computer. Much of the effort during the second year was the rewriting of the software that was developed on VAX computers at Lockheed and in the ISO laboratory to run either on a microcomputer or on the Harris 800, and to develop the capability of reading the previously-generated binary data files on the Harris 800.

The analysis software was also modified to take account of the results of the error analysis done the first year. A large vertical component of the ion velocity on the inbound leg of the orbit was found to be correlated with the angle of attack of the RPA. Since the angle of attack is large on the inbound leg and small on the outbound leg of the orbit, it was decided that, unless the inbound data are specifically required, only outbound data would be used in this research.

4. Summary of the Proposal

The absence of a strong planetary magnetic field and the lack of significant planetary rotation lead to very different conditions within the ionospheres of Venus than experienced on earth. Observations reveal large day-night differences in the ionospheric quantities, a strong solar wind influence at the upper boundary of the ionosphere, and near-axial symmetry of most of the measured quantities about the sun-Venus axis.

Measurements by the Pioneer-Venus RPA have shown that the ionization is flowing generally in an anti-sunward direction with average speeds that approach 4 km/s near the terminator. The ion flow field, like the ion density, is quite regular on the average at solar zenith angles less than 140 degrees. However, large variations are observed when individual orbits are considered.

The complexity of the Venus ionosphere is in many important areas strongly linked to dynamics. Although good agreement between data and theory was achieved by Cravens et al. [1983] and by Bougher and Cravens [1984], it applies only in regions where there is little variation in ion flow and only under average conditions. A more complete description of the ion flow at all solar zenith angles, as well as a consideration of the temporal variability of the flow, must be incorporated into any model which addresses these complex phenomena. The average or median conditions used to test the current models may themselves represent a perturbed state and not a ground state of an unmagnetized ionosphere.

In the original proposal, a study was outlined with the objective of increasing our knowledge of the characteristics of ion transport in the Venus ionosphere. In particular, this research addressed the following areas:

4.1 Characteristics of the mean ion flow:

Having established a basis for determining the subset of data that is most accurate, we began the more detailed studies outlined in the original proposal. Topics of study ranged from the global morphology of velocity and flux that indicate momentum and energy sources to the flow and determine the ion deposition pattern on the nightside to the day-to-day and intra-orbit variations typical of the nightside ionosphere.

We have generated a mean planetary ionospheric flow pattern using data from the outbound leg where uncertainty introduced by the systematic radial velocity component is small. Vertically-smoothed 50-km averages of the horizontal velocity components are listed in Table 1. The average ion velocities have an over-all axial symmetry about the sun-Venus axis that is consistent with the axial symmetry observed in ionospheric densities and temperatures. However, as is also the case with ion densities and temperatures, if the axisymmetric variation were removed from the velocities, significant asymmetries would remain.

The balance between the influx of ionization from the dayside of Venus and the loss by transport and recombination on the nightside is described by the continuity equation. For steady state conditions, and assuming no local production on the nightside, the ion loss rate must be balanced by the divergence of the ion flux. Ion flux is a parameter that can be extracted from the RPA data, since ion density and velocity are measured simultaneously.

The mean O^+ flux has been determined using the local measurements of density and velocity. The local flux vectors were then averaged to allow statistical studies of the divergence throughout the nightside to determine whether the distribution is consistent with the ion densities measured on the nightside. Using O^+ flux measurements we find that the radial divergence is about a factor of ten larger than the horizontal component. Integrating vertically gives an equivalent ion column loss rate between 110 and 150 deg solar zenith angle of about 1.5×10^8 $cm^{-2}s^{-1}$.

We are beginning to use the knowledge gained of the magnitude and variability of the ion flux to examine the sources of energy and momentum, as well as the dissipation mechanisms. One topic that is currently being studied in detail is the importance of the interaction between the solar wind and the ionosphere in the momentum flux below the ionopause. Knudsen et

Altitude (km) \ Solar Zenith Angle (deg)	5	15	25	35	45	55	65	75	85	95	105	115	125	135	145	155	165	175
1000				0.2	0.5	0.8	2.1	-0.6		2.2	4.4	2.7	1.0	1.7	1.1	0.5		
950				0.2	0.4	0.8	2.3	1.4	2.9	3.0	4.3	2.7	1.7	1.9	0.2	0.7		
900				0.2	0.4	0.8	1.9	1.2	2.2	3.6	3.5	2.8	1.5	2.1	-0.7	1.0		
850				0.2	0.8	0.9	1.5	1.5	1.5	3.3	4.4	2.8	1.4	2.2	-1.6	1.2		
800			-0.6	0.2	0.6	1.1	1.4	1.5	1.4	2.7	4.4	2.8	1.1	2.4	1.8	1.1		
750			-0.4	1.1	0.4	1.3	1.4	1.5	1.4	3.4	5.6	5.2	0.8	2.6	-0.2	0.7		
700			-0.3	0.9	0.9	1.2	1.3	1.5	1.4	2.3	6.9	3.7	1.4	4.0	0.1	0.4		
650		0.1	-0.2	0.7	0.8	1.0	0.8	1.9	1.4	2.8	2.7	2.3	-0.8	3.3	0.3	0.4	2.8	
600		0.2	-0.1	1.0	0.7	0.9	0.7	1.6	1.9	2.2	3.7	0.8	-2.8	2.5	0.1	0.4	2.1	
550		0.3	0.5	0.6	0.3	0.7	0.7	1.2	1.6	2.3	4.1	1.9	-2.5	1.8	-0.1	0.5	1.3	
500		0.4	0.4	0.6	0.4	0.7	0.6	1.1	1.2	2.7	2.7	2.3	4.3	3.1	1.5	0.5	0.5	0.5
450		0.3	0.0	0.9	0.6	0.1	1.0	1.0	1.5	3.0	3.7	1.2	2.0	2.3	1.2	0.6	-0.3	0.7
400	-0.3	0.2	0.0	1.0	0.2	0.4	0.6	0.7	1.8	2.4	3.3	2.0	1.9	4.1	0.9	0.6	-0.8	0.9
350	-0.4	0.9	-0.2	0.0	0.2	0.1	0.9	0.8	0.9	2.0	2.3	2.8	2.1	2.0	0.6	0.7	-1.4	1.1
300	0.1	-0.7	-0.3	0.6	-0.3	0.4	0.2	0.1	0.1	1.5	2.9	1.4	2.8	1.7	0.3	0.9	-1.9	0.5
250	-0.1	0.6	-0.4	-0.6	0.0	-0.3	0.3	0.2	0.6	1.1	1.6	1.2	1.2	1.6	0.7	0.5	-2.4	0.9
200	-0.1	-0.3	-0.6		-0.4		0.3		0.5	0.5	1.0	-0.3	-2.0	1.8	0.8	-0.7	-0.4	2.0

Table 1: Horizontal O+ Velocity Averages (km s-1) of dawn and dusk, outbound only. Positive values indicate nightward velocities.

al., [1981] and Elphic et al. [1984b] have shown that the day/night pressure gradient is sufficient to accelerate the ionosphere to the measured velocities. At the same time, Perez-de-Tejada [1982, 1986] has shown that a viscous interaction between the solar wind and the ionopause could transfer momentum across the ionopause.

Research into the temporal variability of the flow across the terminator and its effects on the nightside ionosphere have suggested a test of the relative importance of the horizontal pressure gradient and the viscous interaction with the solar wind to the momentum flux. Knudsen et al. [1980, 1987] and Cravens et al. [1982] have shown that if the pressure gradient is the dominant mechanism, the flow into the nightside is increased if the ionopause is at a higher altitude. On the other hand, if viscous interaction with the solar wind is most important, then a low ionopause and the corresponding higher pressure above the ionopause would indicate a time of increased momentum flux into the nightside. A study of the momentum flux, ionopause height, and solar wind pressure on individual orbits, and a statistical treatment of the results was begun in an effort to resolve this question.

We are continuing to study the loss of flux on the nightside. We have shown that the ion flux averaged over the nightside is sufficient to account for the ion loss due to recombination. However, the manner in which this loss is distributed over the nightside hemisphere has interesting implications with respect to the loss of ions into the wake, the presence of a recompression shock, and the effect of ionospheric holes.

Analysis of ionospheric data from Pioneer Venus has shown that, for conditions of solar maximum, the ionization rate required to maintain the nightside ionosphere is consistent with the measured flux of ions from the dayside [Knudsen, et al., 1981, Whitten, et al., 1982; Theis et al., 1984]. We have made preliminary calculations of the flux of ions, as well as the momentum and energy flux, from median values of ion temperature, ion density, and electron temperature, and averages of ion velocity as measured by the retarding potential analyzer.

Figure 2 shows contours of ion flux as a function of solar zenith angle and altitude. The flux is greatest at lower altitudes, and decreases more slowly with altitude on the nightside than on the dayside. The calculation of number flux can be used to calculate an equivalent column production rate of ions across the nightside. Knudsen et al. [1980] calculated that an average column production rate of 2 x 10^8 cm^{-2} s^{-1} is needed to maintain the nightside ionosphere. Figure 3 shows the column production rate based on differences in the number flux from one solar zenith angle to the next. Although most of the ionization

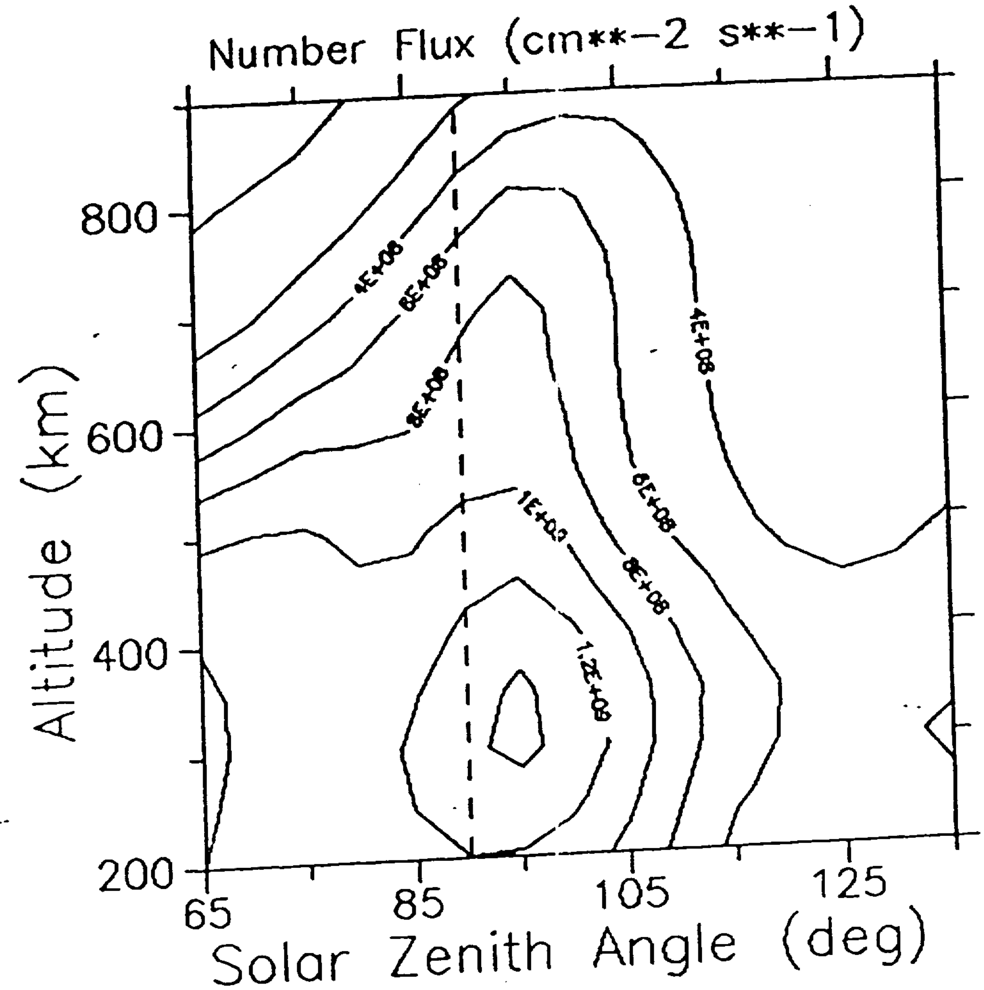

Figure 2. Horizontal component of ion flux measured in the vicinity of the terminator.

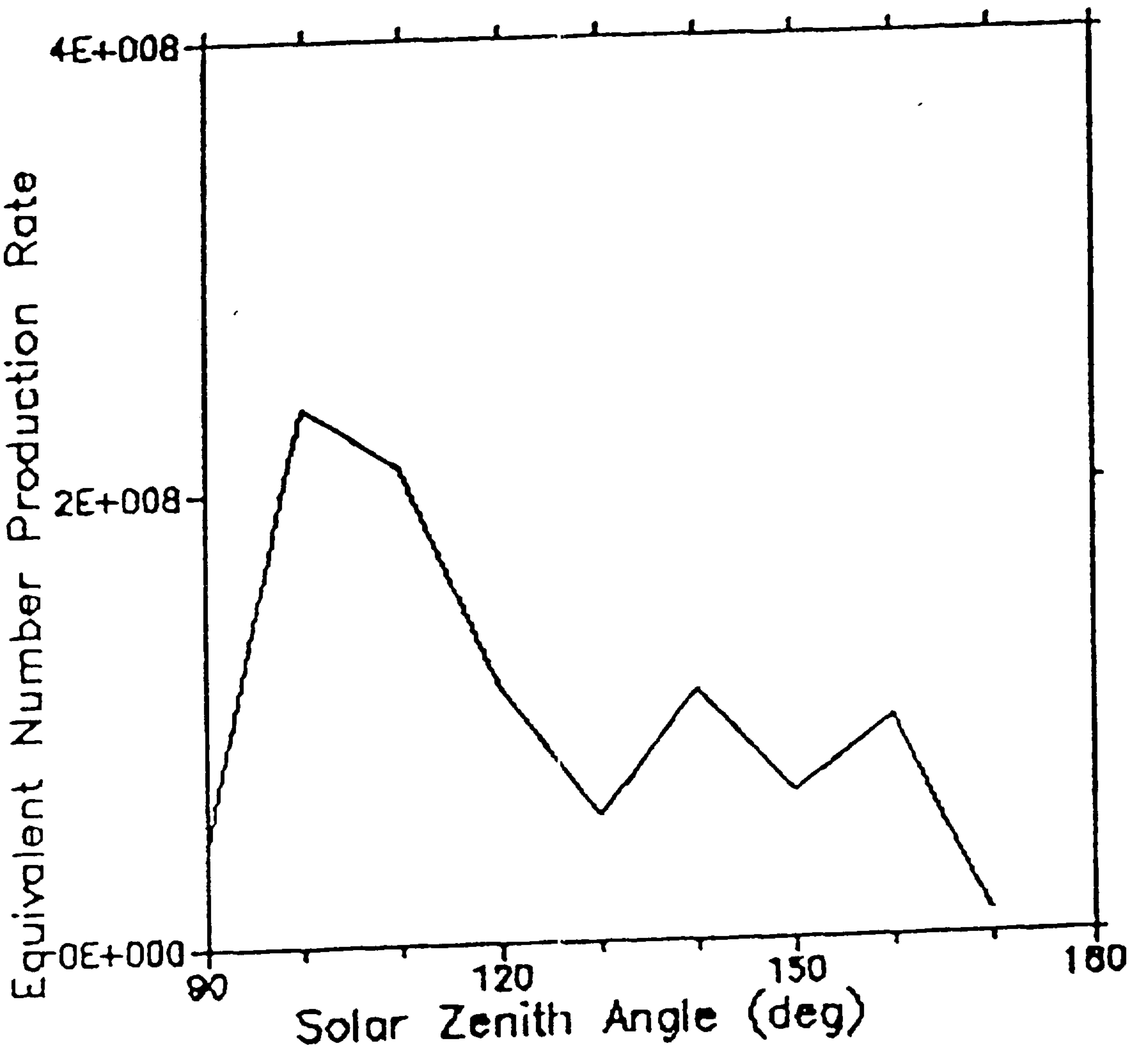

Figure 3. Column ion production rate on the nightside calculated from the divergence of the ion flux.

is lost from the flow in the first 30 deg from the terminator, the equivalent column production rate still stays near 10^8 cm^{-2} s^{-1} throughout the nightside.

The Venus ionosphere is clearly more complex than any of the current models indicate. This complexity can be better understood by including a global description of the dynamics involved. In particular, the rate at which ionization is being lost from the flowing ionosphere determines the spatial distribution of the main source of ionization and energy to the nightside.

Perez-de-Tejada [1982], using data from Venera 10, suggested that strong viscous coupling exists between the ionosheath and ionospheric flows. Knudsen et al. [1982] argued that if a viscous interaction does exist, it is unimportant in the acceleration of the ionospheric plasma into the nightside. This was supported by the work of Theis et al. [1984] and Elphic et al. [1984] who showed that calculation of ion velocity using empirical models of ionospheric temperature and density more nearly matched the measured values if viscosity is neglected.

If viscosity is included in the horizontal momentum equation, it adds a term of the form:

$$\frac{\partial}{\partial z} \eta \frac{\partial v}{\partial z}$$

where v is the horizontal ion velocity and η is the viscosity coefficient. A strong viscous interaction that is localized at the ionopause would thus be evident in the second derivative of the velocity with respect to altitude.

Figure 4 shows the momentum flux in the region of the terminator. This figure argues against the transfer of momentum through the ionopause. Nightward ion velocities actually appear to approach a constant value with altitude, with the result that the maximum momentum flux in the vicinity of the terminator occurs near 400 km altitude. This question must be studied by considering individual orbits, since a statistical approach tends to smear out any variations. It also biases high altitude values in favor of orbits when the solar wind pressure, and thus any momentum transfer, would be small. The statistical nature of the data in Figure 4 also masks any possible evidence for momentum transfer that affects the ionosphere on a smaller scale.

Energy flux is shown in Figure 5. It reaches nearly 1.5×10^{-3} erg cm^{-2} s^{-1} near the terminator, and drops by about a factor of three as it crosses the nightside. Bougher and Cravens [1984] showed that when the vertical diffusion velocity is included in the calculation, ion temperatures calculated for nighttime conditions are consistent with measured values except

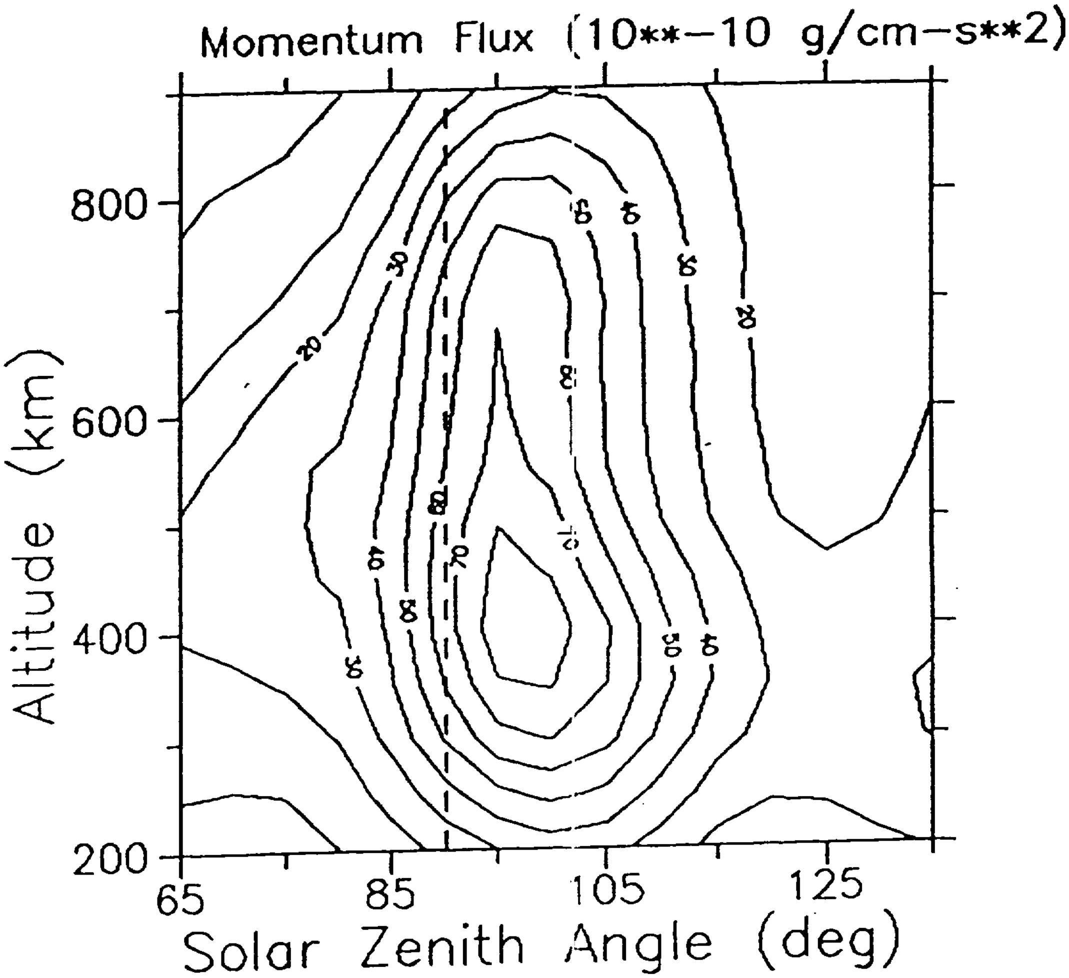

Figure 4. Horizontal component of momentum flux showing a decrease with altitude from a maximum at 400 km altitude.

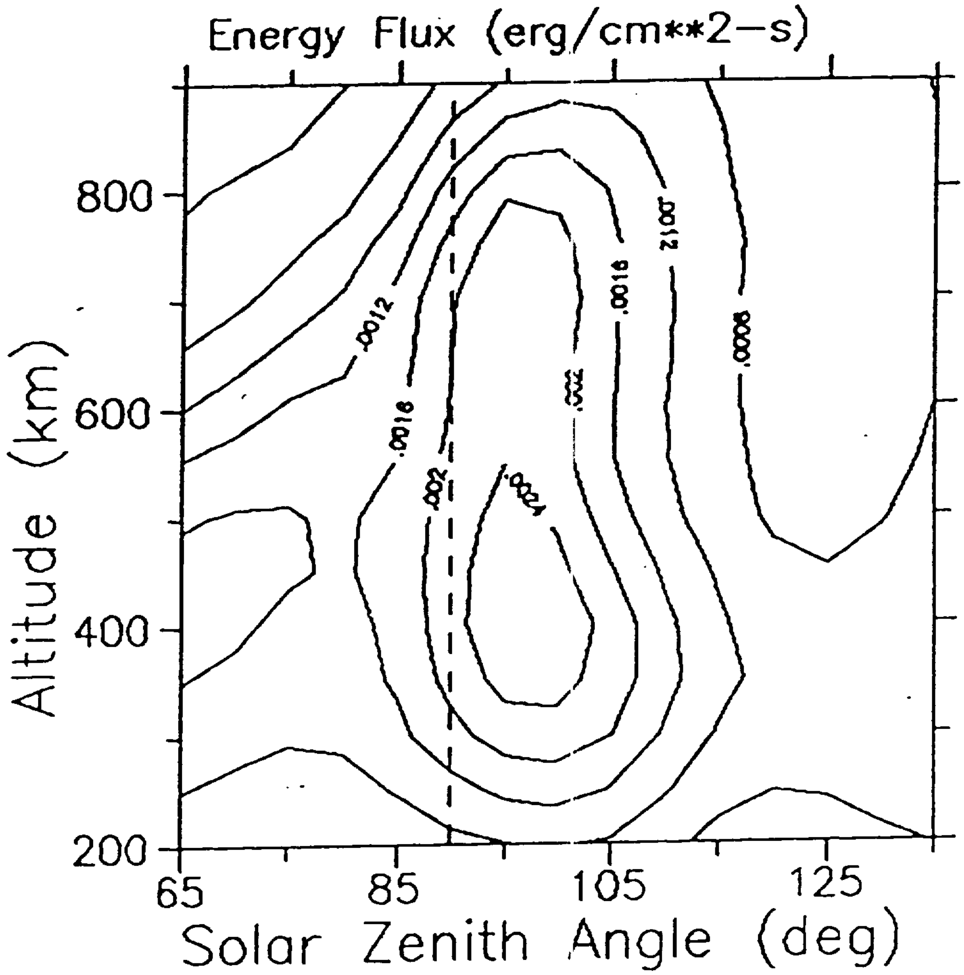

Figure 5. Horizontal component of energy flux in the vicinity of the terminator.

in the region surrounding the anti-solar point. Whitten et al. [1982] showed that an adiabatic compression of the ions as they converge at the anti-solar point would increase the temperature of the ions, but not sufficiently to reproduce the temperatures in excess of 10,000 K that are measured in this region.

Figure 6 shows the energy density of the ion gas calculated from RPA data for an altitude of 450 km. The contributions of kinetic and thermal energy are shown separately. The total energy density remains nearly constant across the nightside, indicating a conversion of kinetic energy into thermal energy. At the same time Figure 5 shows a decrease in energy flux, due entirely to the decrease in velocity.

4.2 Sources of ionospheric variability:

One of the most often cited characteristics of the Venus ionosphere is its temporal variability. Experiments on Pioneer-Venus have shown large excursions in the height of the ionopause and in the local density, temperature, and velocity of a time scale comparable to the 24-hour period of the Pioneer-Venus orbit. Statistical studies, however, have shown the median ionosphere to be well-behaved, and to vary smoothly with solar zenith angle (SZA) [Miller et al., 1980; Theis et al., 1980; Miller et al., 1984; Knudsen et al., 1982].

Over three Venus years the variability of the dayside ion density is only about a factor of two. A similar variability is observed in the dayside ion temperature. However, the nightside ionosphere is found to be much more variable, with two-thirds of the measurements at a given altitude and within 10 degrees in SZA varying by approximately an order of magnitude [Knudsen et al., 1986]. The change of variability from the dayside to the nightside of Venus is expected, based on the differing ionization sources on the two hemispheres [Theis et al., 1984]. The dayside ionospheric variability is produced primarily by changes in solar EUV radiation [Bauer and Taylor, 1981, Elphic et al., 1984a], while changes in the nightside ionosphere are apparently the result of changes in the ion flux across the terminator [Knudsen et al., 1980; Cravens et al.,1982].

A direct comparison of the nightside ion density and the velocity of the ionization across the terminator is not possible with the Pioneer-Venus orbit. However, a correlation of the variability of the ion density within the Venus nightside ionosphere with the variability of the height of the ionopause suggests that a direct relationship exists between the ion density on the night side and the ion flow past the terminator [Miller and Knudsen, 1987].

The relationship between nightside ion density and ionopause

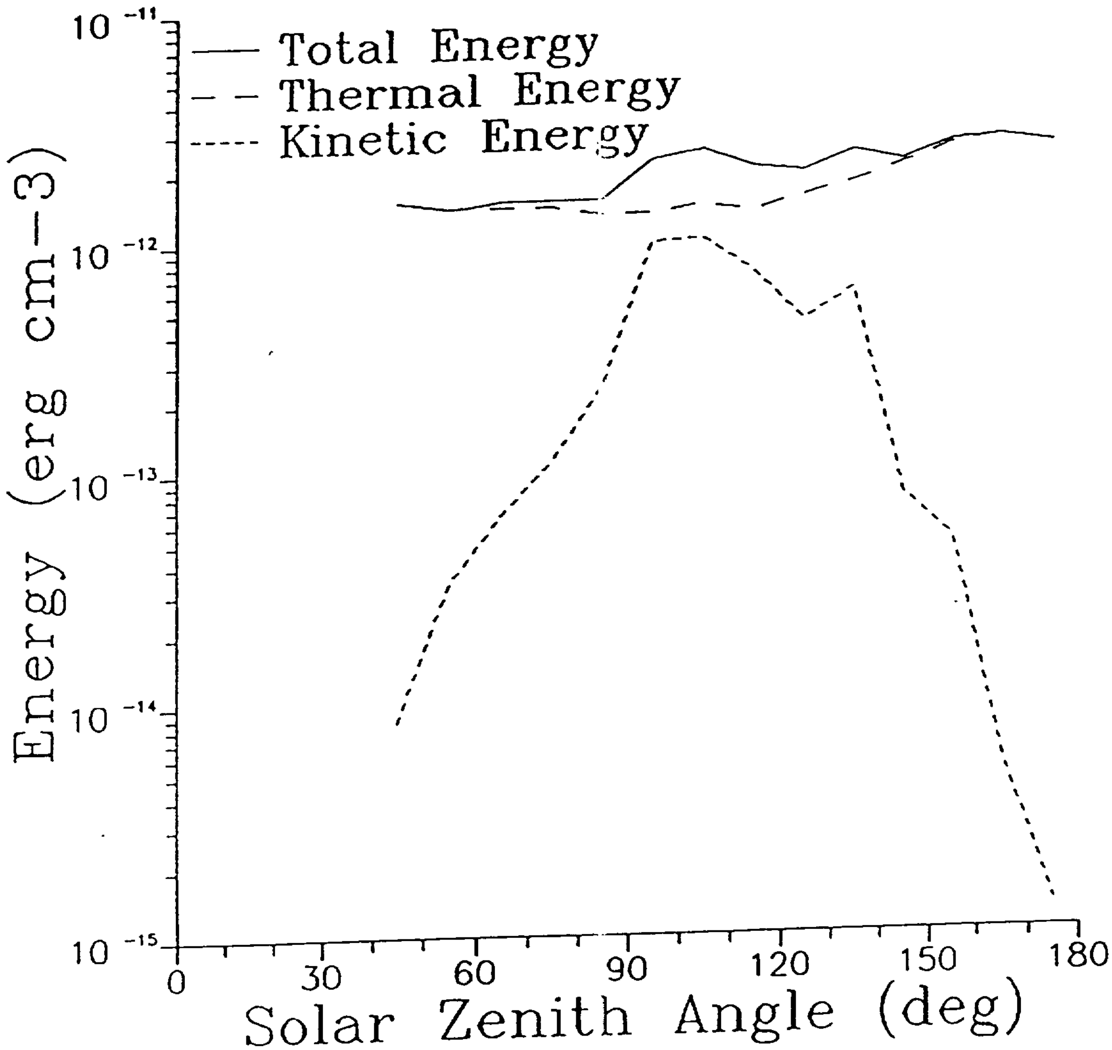

Figure 6. Energy density at 450 km altitude as a function of SZA. Long dashes show the contribution of thermal energy; short dashes show kinetic energy.

height can be shown by normalizing the measured ion density to the empirical model of Theis et al. [1984], and the corresponding ionopause height to the model of Knudsen et al. [1982]. We find essentially no correlation with ionopause height in the dayside ionosphere between 170 and 200 km altitude. On the nightside, however, the ion density and ionopause height are strongly correlated. Figure 7 is a scatter plot of normalized ionopause heights vs. normalized nightside ion density, illustrating this direct relationship. Strong temporal variability in the density of the nightside ionosphere is found to be directly correlated with the height of the ionopause. Knudsen et al. [1980] suggested that this relationship exists, and Cravens et al. [1982] predicted it, based on a two-dimensional ionospheric model. The increased nightside density at times of low solar wind (ie. high ionopause) seems to indicate that the viscous interaction between the solar wind and ionosphere is not the major force driving the nightward flow. However, it does show that the solar wind influences strongly the nightside ionosphere of Venus.

4.3 Ionospheric superrotation:

In general the flow into the nightside is symmetric about the sun-Venus axis. There are, however, differences in the velocity fields of the dawn and dusk hemispheres [Miller and Knudsen, 1986]. Figure 8 shows the horizontal eastward ion velocity at 250 km altitude as a function of the longitudinal angle from the sub-solar point. The dominant feature is the increase in the nightward velocity at the terminator. Although the flow is generally symmetric about the sub-solar meridian, it can be seen that the pattern is offset by a few hundred meters per second. This can be interpreted as a superrotation of the ionosphere superimposed on the axisymmetric flow. The superrotation is in the same sense as the superrotation of the neutral atmosphere.

The measured superrotation component generally decreases with altitude. The heavy curve in Figure 9 shows the difference between horizontal nightward velocities in the dawn and dusk hemispheres at 85 deg SZA. The difference is negative below about 400 km, indicating superrotation, but positive above 400 km, which indicates a prograde rotation component. This is not actually a superrotation, but a dawn/dusk asymmetry.

Since the magnetic field of Venus is negligible or non-existent, plasma flow is primarily in response to a pressure gradient. As a first approximation, this can be described by the horizontal component of the steady-state momentum equation [Elphic et al., 1984b],

$$\frac{Dv}{Dt} = v\frac{\partial v}{\partial t} = \nu_{in}\,(U - v) - \frac{1}{\rho}\,\frac{\partial P}{\partial x}$$

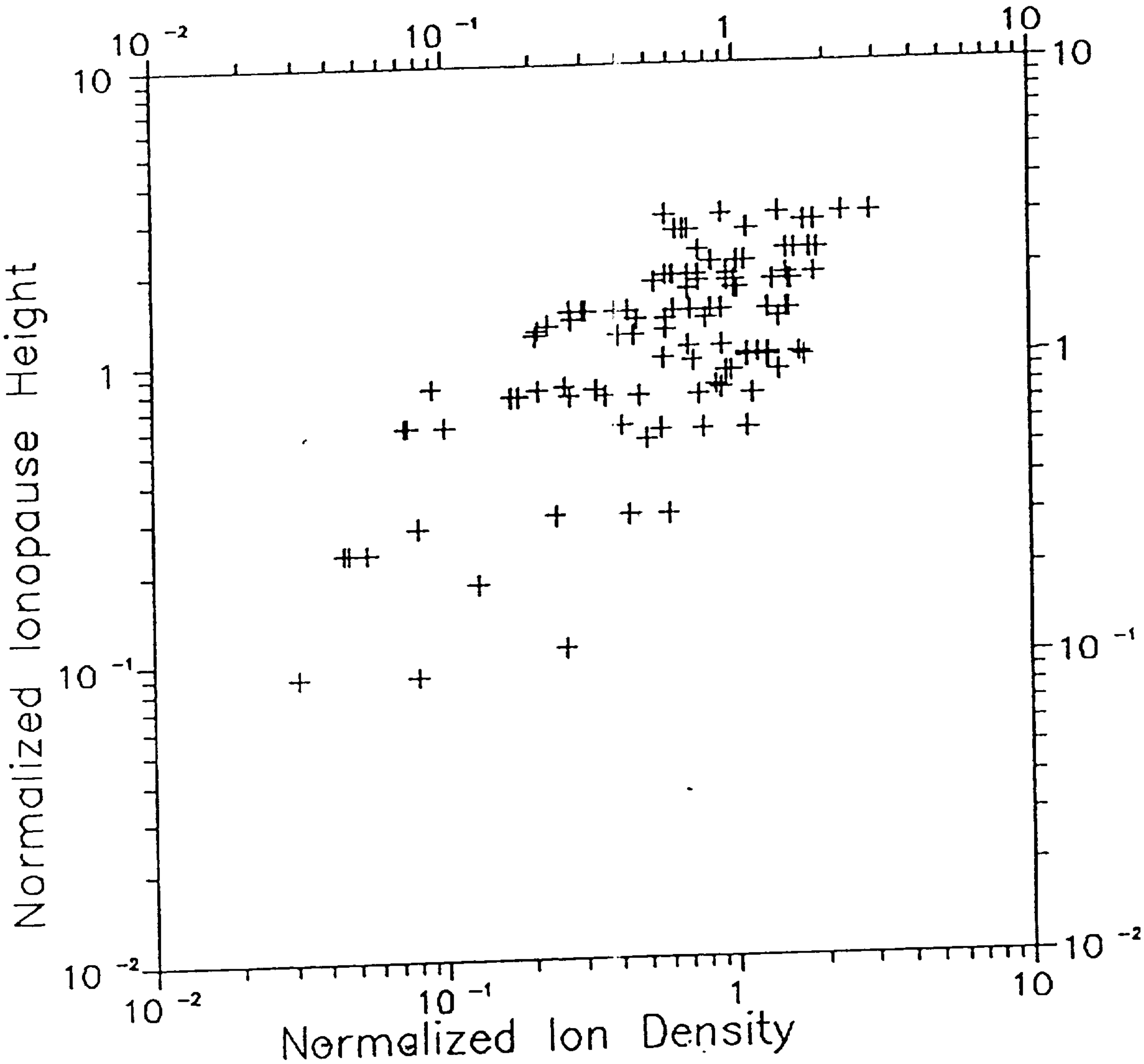

Figure 7. Normalized nightside ion density medians between 170 and 200 km altitude plotted against the normalized ionopause height from the same orbit.

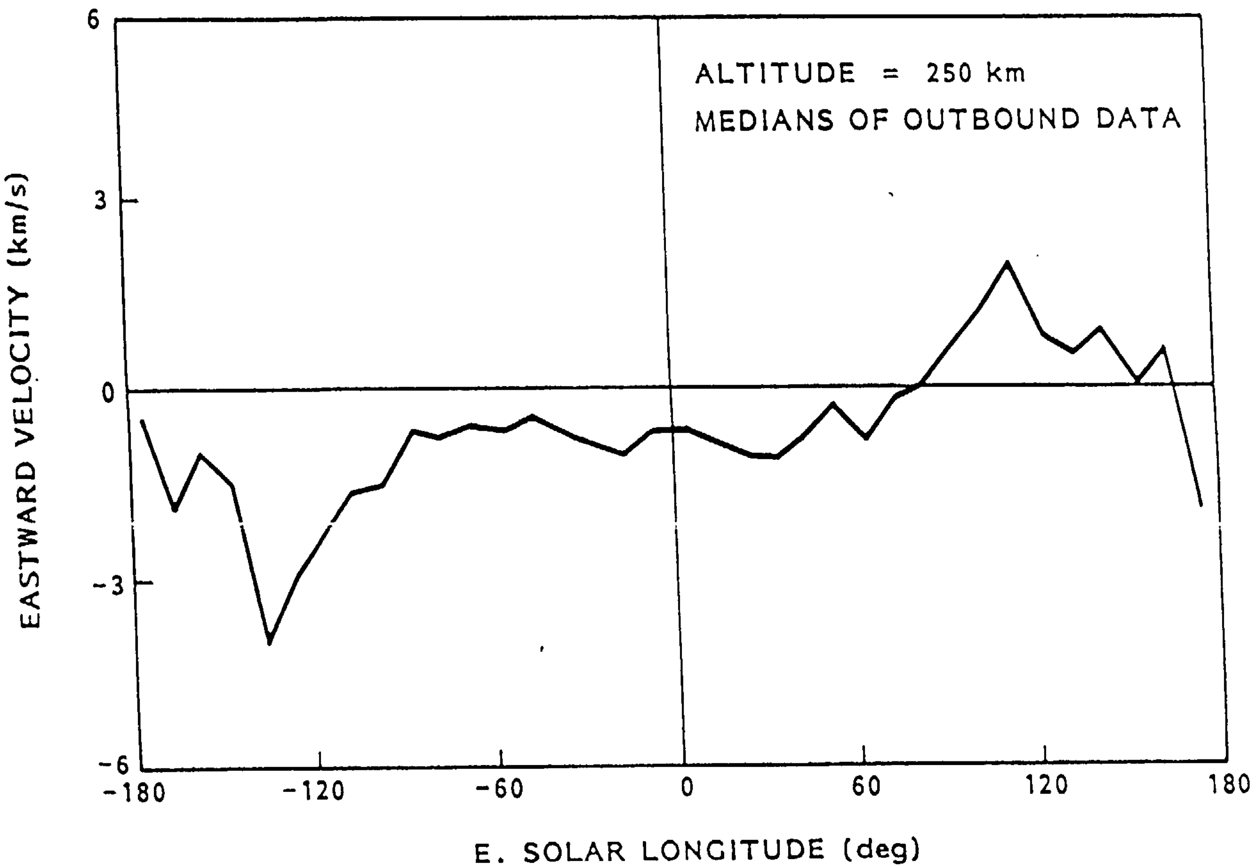

Figure 8. Horizontal eastward ion velocity at 250 km altitude. Solar longitude is measured in degrees eastward from the sub-solar meridian.

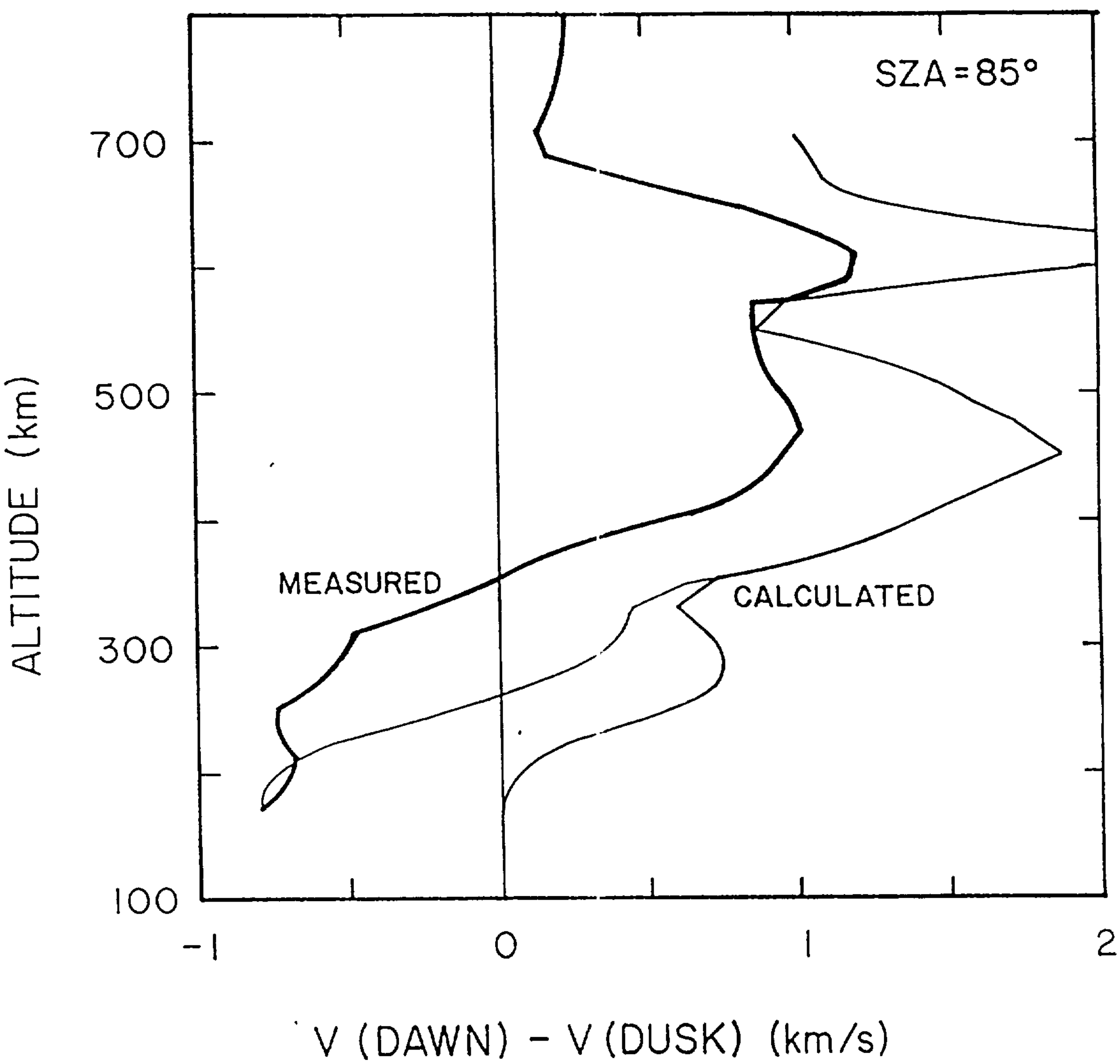

Figure 9. Difference between dawn and dusk horizontal ion velocity at 85 deg SZA. The heavy curve is the difference in the measured averages of velocity between 80 and 90 deg SZA. The lighter curves were calculated from Equation 1, with and without superrotation in the neutral atmosphere.

where v and U are the horizontal components of the ion and neutral velocities; ν_{in} is the ion-neutral collision frequency; P and ρ are plasma pressure and mass density.

The advection is thus affected by the ion pressure gradient and by collisions with neutrals. We have used ion concentration and temperature measurements by the RPA [Miller et al., 1984], together with the neutral atmosphere model of Hedin et al. [1983] to evaluate this equation. In order to balance the cumulative contribution of advection, we begin the calculation at the location of the median ionopause [Knudsen et al., 1982]. We have calculated the velocity field based on the momentum equation and compare our results with measured average velocity at all SZA in Figure 10.

The dayside results are consistent with measurements, both qualitatively and quantitatively. Contours in Figure 10 show the velocity to increase with altitude on the dawn side, while remaining nearly constant with altitude on the dusk side. The calculated results for the nightside are probably inaccurate because of, among other things, a strong downward flow behind the terminator and a suspected recompression shock at about 135 deg solar zenith angle [Knudsen et al., 1980].

Miller et al. [1984] reported a dawn/dusk asymmetry in the ion density on the dayside. This is reflected in a pressure asymmetry that affects the acceleration of the ions toward the nightside of Venus. The higher pressure on the dusk hemisphere means that there is a smaller pressure gradient from the sub-solar point to the terminator on the dusk side. The dawn/dusk density asymmetry was originally thought to be the result of variability of the ion density within the Venus ionosphere with superrotation. It is now seen to be the probable cause of the ionospheric sub-rotation component at high altitude. The asymmetry in ion density may be related to a similar asymmetry in neutral oxygen that is measured at lower altitudes [Hedin et al., 1983; Niemann et al., 1980].

The difference in the computed velocities of the two hemispheres shows that the result of the momentum equation gives a prograde asymmetry that disappears at low altitude. The superrotation component at low altitude can be simulated by introducing a superrotation in the neutral atmosphere. The effect of collisions with the neutral atmosphere is dominant below 250 km, but decreases rapidly with altitude and becomes negligible above about 350 km. Figure 9 compares the measured dawn/dusk velocity difference at 85 deg SZA with the difference calculated with and without a neutral atmosphere that superrotates at a speed of 400 m/s.

The velocity differences at all SZA are compared with the calculated differences in Figure 11. It can be seen that the

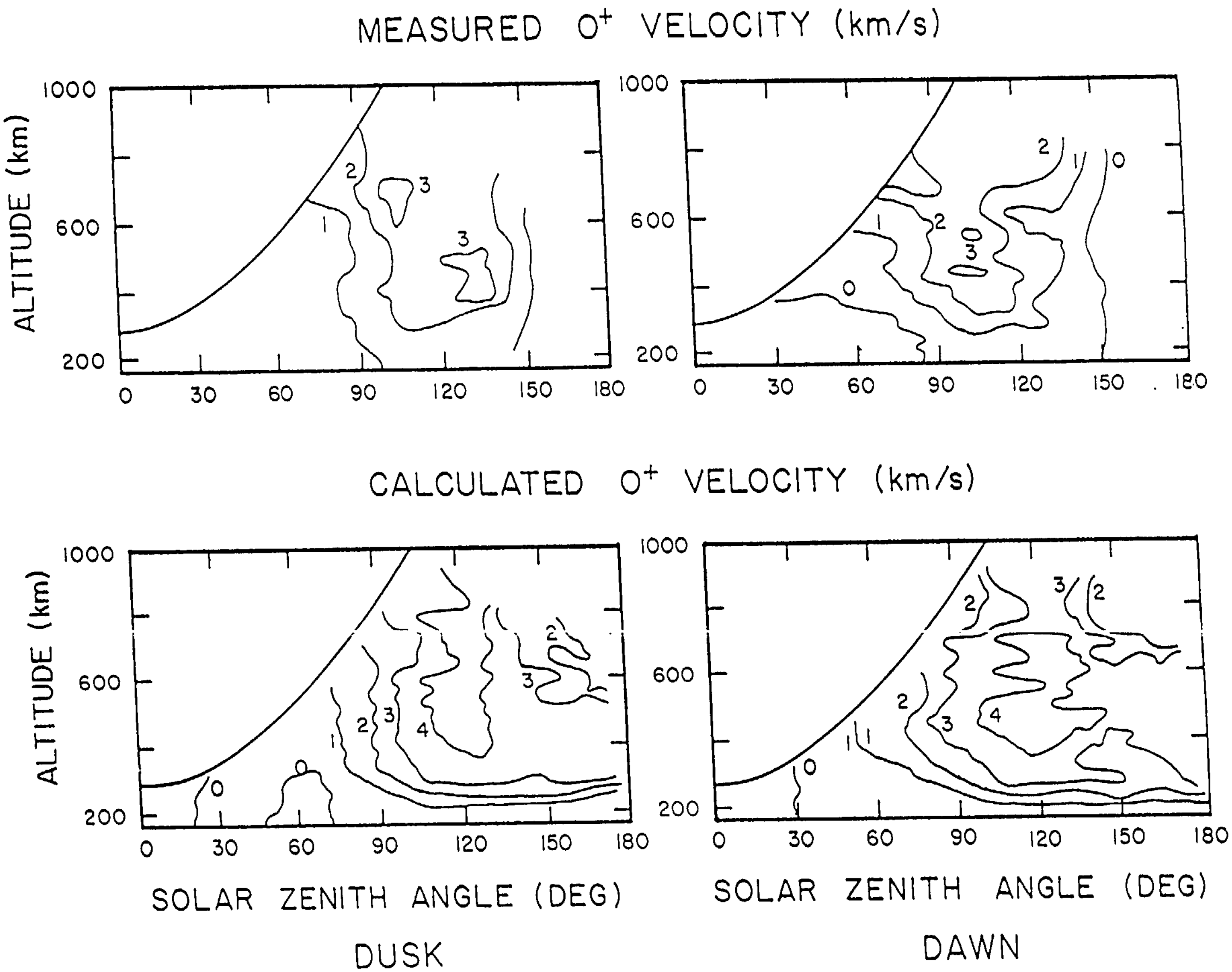

Figure 10. Measured and calculated average horizontal ion velocity (km/s) for dawn and dusk hemispheres. The boundary in the upper left is the median location of the ionopause.

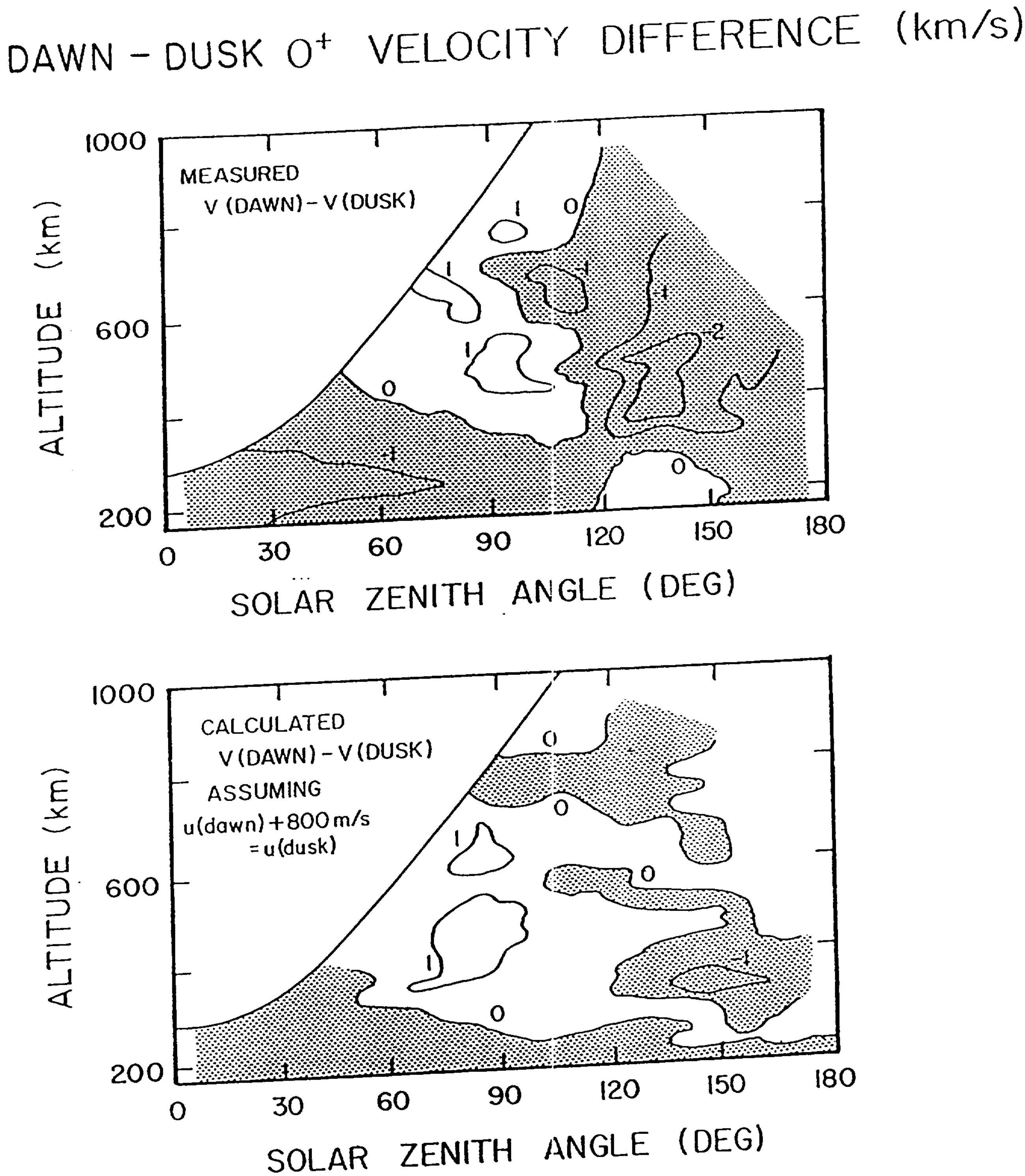

Figure 11. Measured and calculated dawn/dusk differences in the horizontal ion velocity (km/s). A 400 m/s superrotation of the neutral atmosphere is included in the calculation.

calculations agree quite well with the measurements. As before, calculated velocities on the nightside are probably in error because of influences on the velocity that are not directly related to the pressure gradient and not included in the model. For SZA less than approximately 110 deg, the calculation reproduces the general features shown in the measurement.

4.4 Nightside recompression shock:

At present, the primary evidence of the recompression shock includes the abrupt ending of the strong anti-sunward flow at about 145 deg SZA, and the rapid increase in the ion temperature nightward of this point. A preliminary orbit-by-orbit search of the ion velocity, temperature, and density data was made to determine if the signature of a shock could be recognized in the data, but without success. A more detailed search will be made, but this time to determine the characteristics of the flow near the anti-solar point that result in the average flow becoming small. This change in the ion velocity field could result from a redirection of the flow, as well as the decrease in the velocity that is usually associated with a shock. A better understanding of the ion dynamics in this part of the Venus ionosphere would be important in the eventual understanding of the source of other phenomena such as high ion temperatures, ionospheric holes, and radial magnetic fields that are observed at high solar zenith angles on Venus.

The ion temperature on Venus is nearly independent of solar zenith angle throughout most of the ionosphere. Figure 12 shows median ion temperatures for the first Venus year of the Pioneer Venus mission [Miller et al., 1980]. Although temperatures at low altitudes show the effect of the decreased cooling rate on the nightside, temperatures above about 500 km show very little change, except near the anti-solar point. A more detailed examination of orbits 1 through 780 is shown in Figure 13. This figure shows a slight decrease in the ion temperature nightward of the terminator, and then a strong increase, especially at higher altitudes, beginning at about 135 deg. SZA.

Figure 6 shows the total energy density as a function of SZA at 450 km altitude. The total energy is constant on the nightside, suggesting that the increase in temperature is being supplied by the conversion of bulk kinetic energy to thermal energy. The contributions of kinetic and thermal energy to the total are also shown in Figure 6.

Knudsen et al. [1980] suggested that the rapid rise in ion temperature occurring at the same solar zenith angle as the nightward boundary of strong anti-sunward flow indicates the presence of a re-compression shock. We have begun to test this hypothesis by considering whether the expansion of the ion gas

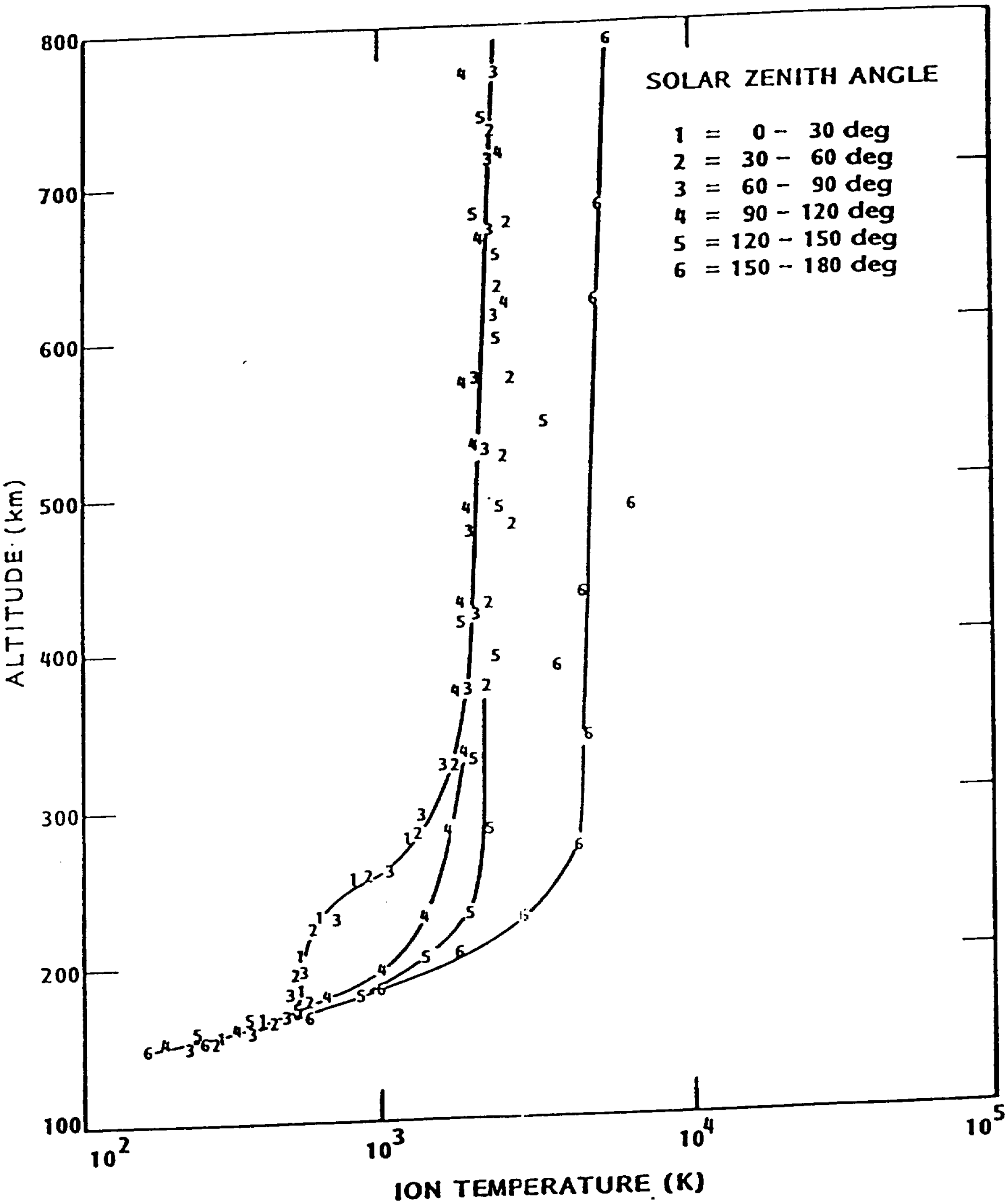

Figure 12. Median ion temperature from 30 deg intervals in SZA (Miller, et al., 1980).

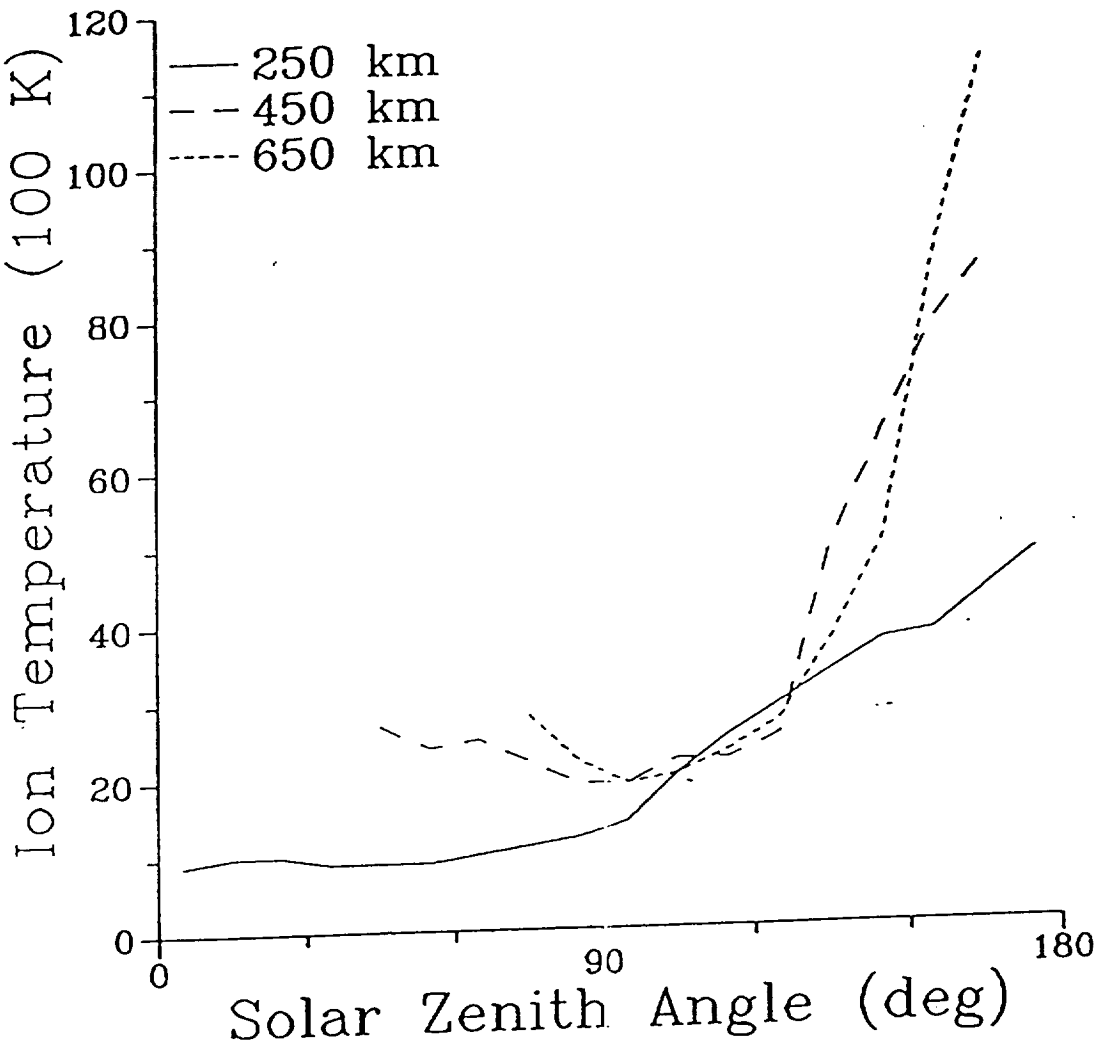

Figure 13. Median ion temperatures at three altitudes showing, at the higher altitudes, the cooling of the ions at the terminator and the dramatic increase in temperature in the anti-solar region.

into the nightside is adiabatic, and, if not, where diabatic processes are important. For example, both a re-compression shock and an adiabatic compression of the ion gas converging in the anti-solar region would conserve energy and convert bulk kinetic energy into thermal energy. The variability in the data and the weakness of any re-compression shock makes it unlikely that a shock signature would be unambiguous in data from individual orbits in the region. However, the determination of where entropy is constant and whether there are regions where it is not constant would indicate which process is responsible for the high ion temperatures.

In an adiabatic process such as the expansion of a gas in response to a pressure gradient, the ratio

$$\alpha = \frac{P}{\rho^{\gamma}}$$

is conserved, where P is the pressure of the gas, ρ is mass density, and γ is the ratio of specific heats. This ratio is called the adiabatic constant, α. Figure 14 shows ratios of α from adjacent SZA bins for altitudes of 250, 450 and 650 km in the Venus ionosphere. For this calculation we have used $\gamma = 5/3$, which is appropriate for a monatomic gas. This figure shows α to be approximately constant in the region nightward of the terminator. The drop in ion temperature in this region has been shown by Bougher and Craven [1984] to be consistent with an adiabatic expansion of the gas into the less dense nightside. However, α shows a strong increase at the higher altitudes in the region of the suggested re-compression shock.

The average ion velocity above about 500 km altitude in the terminator region is about 4 km/s. This is about twice the sound speed in this region, but only about 75% of the Alfven speed of O^+ if a magnetic field of 100 nT is assumed. Knudsen et al. [1981] suggested that the gradient in the ionospheric pressure across the terminator is sufficient to accelerate the ions to the observed velocities. This was confirmed in calculations based on the momentum equation by Elphic et al. [1984b]. In neither of these studies was the question of transonic flow addressed.

Gasdynamic theory holds that a steady adiabatic flow can attain the speed of sound only at a throat [Liepman and Roshko, 1957]. In one dimension, this relation can be written as

$$\frac{du}{u} = \frac{-dA/A}{1-M^2}$$

where u is the velocity of the gas, M is the Mach number, and A is the area in which the flow is contained. This relationship holds for isentropic processes, such as the expansion of a gas in

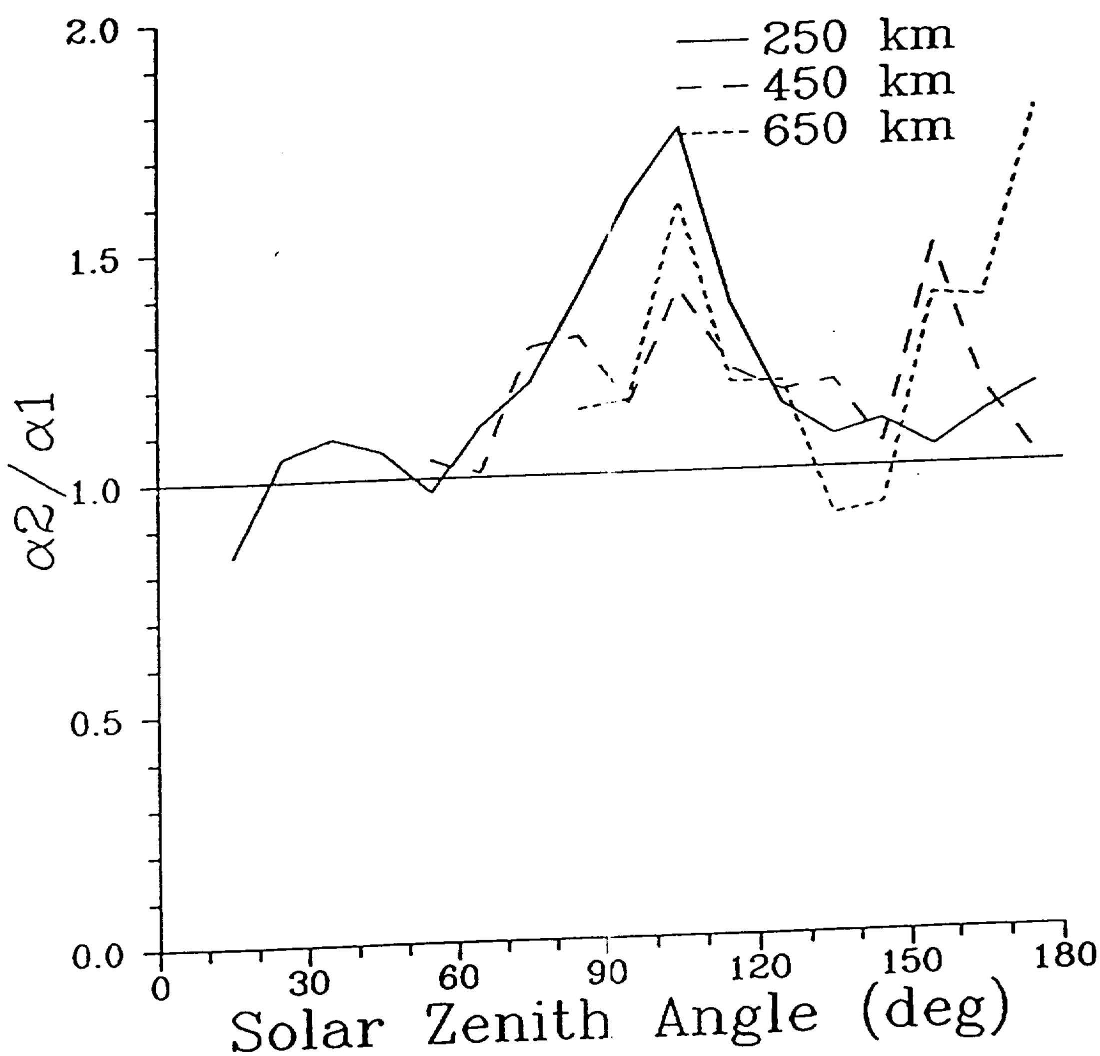

Figure 14. Ratios of the "adiabatic constant" P/ρ^{γ}, from successive 10-degree intervals in solar zenith angle.

response to a pressure gradient.

We are in the process of studying the applicability of this constraint in the Venus ionosphere. There is no throat near 70 deg. SZA through which the ion gas passes to attain supersonic velocities. If it were a simple gasdynamic situation, attaining super-sonic speeds under these conditions would require an external momentum source.

It is, however, not an adiabatic problem. Energy and mass are being added to the ionosphere through photochemical processes on the dayside. As a result of solar heating and ionization, the ionized gas will increase in entropy as it flows toward the nightside. This contribution to the change in entropy would be expected to be greatest at low solar zenith angles, while Figure 14 shows the greatest percentage change in α occurring at the terminator. Understanding the acceleration mechanism of the ions to super-sonic velocities is almost certainly linked to understanding the source of entropy at the terminator.

5. Publications and Presentations

Papers discussing Pioneer-Venus data that have been published or submitted for publication since the beginning of this project include the following:

W. C. Knudsen, K. L. Miller, Pioneer Venus suprathermal electron flux measurements in the Venus umbra, J. Geophys. Res., 90, 2695-2702, 1985.

W. C. Knudsen, and K. L. Miller, Median density altitude profiles of the major ions in the central nightside Venus ionosphere, J. Geophys. Res., 91, 11936-11950, 1986.

K. L. Miller and W. C. Knudsen, Spatial and temporal variations of the ion velocity measured in the Venus ionosphere, Adv. Space Res., 7, (12)107-(12)110, 1986.

Relevant presentations in the same time period include:

W. C. Knudsen and K. L. Miller, The Venus nightside ionosphere, EOS, 66, 294,1985.

W. C. Knudsen and K. L. Miller, Venus ionospheric recompression shock, presented at IAGA, Prague, CZ., August, 1985.

C. T. Russell, J. L. Phillips, M. R. Arghavani, J. D. Mihalov, W. C. Knudsen, and K. L. Miller, A possible observation of a cometary bow shock, presented at IAGA, Prague, CZ., August, 1985.

K. L. Miller and W. C. Knudsen, Zonal non-axisymmetric flow in the Venus ionosphere, EOS, 66, 1037, 1985.

K. L. Miller and W. C. Knudsen, Spatial the temporal variations of the ion velocity measured in the Venus ionosphere, presented at COSPAR, Toulouse, FR, July, 1986.

K. L. Miller and W. C. Knudsen, Ion number, momentum, and energy flux at the Venus terminator, to be presented at the Fall AGU Meeting, San Francisco, CA, December, 1986.

K. L. Miller, W. C. Knudsen, Energy flux and trans-sonic flow in the nightside ionosphere of Venus, presented at the Fall AGU Meeting, San Francisco, CA, December, 1987.

6. References

Bauer, S. J. and H. A. Taylor, Modulation of Venus ion densities associated with solar variations, Geophys. Res. Lett., 8, 840-842, 1981.

Bougher, S. W., and T. E. Cravens, A two-dimensional model of the nightside ionosphere of Venus: Ion energetics, J. Geophys. Res., 89, 3837-3842, 1984.

Brace, L. H., T. I. Gombosi, A. J. Kliore, W. C. Knudsen, A. F. Nagy, and H. A. Taylor, The ionosphere of Venus: Observations and their interpretation, in Venus, D. M. Hunten, L. Colin, T. M. Donahue, and V. I. Moroz, eds., Univ. Arizona Press, Tucson, 779-840, 1983.

Cravens, T. E., L. H. Brace, H. A. Taylor, Jr., C. T. Russell, W. C. Knudsen, K. L. Miller, A. Barns, J. D. Mihalof, F. L. Scarf, S. J. Quenon, and A. F. Nagy, Disappearing ionospheres on the nightside of Venus, Icarus 51, 271-282, 1982.

Cravens T. E., S. L. Crawford, A. F. Nagy, and T. I. Gombosi, A two-dimensional model of the ionosphere of Venus., J. Geophys. Res., 88, 5595-5606, 1983.

Elphic, R. C., L. H. Brace, R. F. Theis, and C. T. Russell, Venus dayside ionospheric conditions: Effects of ionospheric magnetic field and solar EUV flux, Geophys. Res. Lett., 11, 124-127, 1984a.

Elphic, R. C., H. G. Mayr, R. F. Theis, L. H. Brace, K. L. Miller, and W. C. Knudsen, Nightward ion flow in the Venus ionosphere: Implications of momentum balance, Geophys. Res. Lett., 11, 1007-1010, 1984b.

Hedin, A. E., H. B. Niemann, W. T. Kasprzak, and A. Seiff, Global empirical model of the Venus thermosphere, J. Geophys. Res., 88, 73-83, 1983.

Knudsen, W. C., K. Spenner, K. L. Miller, and V. Novak, Transport of ionospheric O+ ions across the Venus terminator and implications, J. Geophys. Res., 85, 7803-7810, 1980.

Knudsen, W. C., K. Spenner, and K. L. Miller, Anti-solar acceleration of ionospheric plasma across the Venus terminator, Geophys. Res. Lett., 8, 241-244, 1981.

Knudsen, W. C., K. L. Miller, and K. Spenner, Improved Venus ionopause altitude calculation and comparison with measurement, J. Geophys. Res., 87, 2246-2254, 1982.

Knudsen, W. C. and K. L. Miller, Median density altitude profiles of the major ions in the central nightside Venus ionosphere, J. Geophys. Res., 91, 11936-11950, 1986.

Knudsen, W. C., A. J. Kliore, and R. C. Whitten, Solar cycle changes in the ionization sources of the nightside Venus ionosphere, J. Geophys. Res., in press, 1987.

Liepmann, H. W., and A. Roshko, Elements of Gasdynamics, p. 41-61, John Wiley & Sons, Inc., New York, 1957.

Miller, K. L., W. C. Knudsen, K. Spenner, R. C. Whitten, and V. Novak, Solar zenith angle dependence of ionospheric ion and electron temperatures and densities on Venus, J. Geophys. Res., 85, 7759-7764, 1980.

Miller, K. L., W. C. Knudsen, and K. Spenner, The dayside Venus ionosphere I. Pioneer-Venus retarding potential analyzer experimental observations, Icarus, 57, 386-409, 1984.

Miller, K. L. and W. C. Knudsen, Ion number, momentum and energy flux at the Venus terminator, Abstract in EOS, 67, 1171, 1986.

Miller, K. L. and W. C. Knudsen, Spatial and temporal variations of the ion velocity measured in the Venus ionosphere, Adv. Space Res., in press, 1987.

Niemann, H. B., W. T. Kasprzak, A. E. Hedin, D. M. Hunten, and N. W. Spencer, Mass spectrometric measurements of the neutral gas composition of the thermosphere and exosphere of Venus, J. Geophys. Res., 85, 7817-7827, 1980.

Perez-de-Tejada H., Viscous dissipation at the Venus ionopause, J. Geophys. Res., 87, 7405-7412, 1982.

Perez-de-Tejada, H., Fluid dynamic constraints of the Venus ionospheric flow, J. Geophys. Res., 91, 6765-6770, 1986.

Spitzer, L., Physics of Fully Ionized Gases, Interscience, N.Y., 1967.

Theis, R. F., L. H. Brace, R. C. Elphic, and H. G. Mayr, New empirical models of the electron temperature and density in the Venus ionosphere with application to transterminator flow, J. Geophys. Res., 89, 1477-1488, 1984.

Whitten, R. C., B. Baldwin, W. C. Knudsen, K. L. Miller, and K. Spenner, The Venus ionosphere at grazing incidence of solar radiation: Transport of plasma to the night ionosphere, Icarus, 51, 261-270, 1982.

Whitten, R. C., P. T. McCormick, D. Merritt, K. W. Thompson, R. R. Brynsvold, C. J. Eich, W. C. Knudsen, and K. L. Miller. Dynamics of the Venus ionosphere: A two-dimensional model study, Icarus, 60, 317-326, 1984.