According to the above discussion, the grain accretion hypothesis requires sharp decreases in the nebular gas pressure and fairly constant temperatures from the region where Venus formed to that for Earth to that for Mars. Currently available laboratory data suggest that temperature differences of no more than several tens of degrees Kelvin would be permitted by either the adsorption or solid-state dissolution mechanism of rare gas incorporation in order to keep the fractionation pattern the same, with temperatures of about 150 and 500 K required, respectively (*8*). Are such constraints on the nebular conditions reasonable? We believe they are. The required circumstances could obtain in one of two possible scenarios: one involving the instantaneous structure of the solar nebula, and the other involving the entropy evolution of the inner solar system. Regarding the first, current models of solar system formation may be characterized by three stages (*13*): initially, there is no central condensation and temperatures are fairly isothermal, but the pressure gradients are quite shallow. As a central condensation that is to become the sun forms, pressure gradients build up dramatically, but the temperature gradients remain small because the central condensation is not yet a dominant energy source. Finally, the sun becomes the dominant energy source and both the nebular pressure and temperature gradients become steep. If the grain accretion hypothesis is correct, then it would appear that volatile incorporation occurred during the second stage of nebular development. The second scenario is one where the volatile incorporation in the terrestrial planets was not coeval but rather occurred (or was terminated) at essentially the same temperature for each of the planets. If the entropy of the inner regions was higher than that of the outer regions, the required pressure differences could be realized without implying a high instantaneous pressure gradient.

The grain accretion hypothesis is not without problems. Much more work needs to be done on nebular evolution to determine whether the pressure-temperature conditions required under either scenario can be realized. Moreover, a reasonable way must be worked out to yield the observed significant variations in bulk density among the terrestrial planets. This probably will require that not all of the planet formation took place during the epoch of volatile incorporation; that the grains of the volatile stage accreted to planetesimals prior to the next stage, so that they no longer equilibrated with the solar nebula; and that planet formation was not accomplished until well into the next stage, so that the volatiles were not segregated toward the center of the planets.

If the grain accretion hypothesis is correct, then we can make several interesting inferences. As the ratios of the rare gases for the chondritic meteorites are similar to those for the terrestrial planets, their volatiles were formed in a region of the solar nebula having a very similar temperature to that characterizing comparable regions for the planets. Hence, nebular pressure was also the dominant factor in determining their $^{36}Ar/^{12}C$ and $^{36}Ar/^{14}N$ ratios. On the basis of the values for these ratios given in Table 2, we infer that the nebular pressure in the region where these meteorites' parent bodies formed could not be much lower than that where Mars formed. Thus, an origin in the asteroid belt is to be favored over one much farther out. Because only modest temperature differences are permitted at the time of volatile incorporation, an amount of H_2O not much less than that for Earth was incorporated into Venus. In this case, the amount of H_2O in the Venus atmosphere at the present time is much less than the initial endowment and substantial sinks are required. Both reincorporation into the lithosphere (*11*) and early rapid exospheric escape (of H) (*14*) need to be critically reevaluated to determine the plausibility of this inference. Finally, it appears to be reasonably safe to use the N/C ratio but not the $^{36}Ar/^{12}C$ ratio found for other objects to infer the amount of CO_2 outgassed over the history of Mars. Using the model parameters given above, we obtain an amount equal to ~ 1 to 3 bars, enough to create much warmer conditions in the early history of Mars (*15*). Also, by analogy to terrestrial H_2O/N_2 ratios, Mars outgassed an amount of H_2O equivalent to an ice layer 80 to 160 m deep, uniformly covering the planet. Such an amount could supply enough H_2O to carve the fluvial channels observed on the Mariner 9 and Viking spacecrafts (*15*).

JAMES B. POLLACK, DAVID C. BLACK
NASA Ames Research Center, Moffett Field, California 94035

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Ultraviolet Night Airglow of Venus

Abstract. *The night airglow spectrum of Venus in the ultraviolet is dominated by the* v′ = 0 *progressions of the gamma and delta bands of nitric oxide. The bands are produced by two-body radiative recombination of nitrogen and oxygen atoms. Since the source of these atoms is in the dayside thermosphere, the night airglow is a tracer of the day-to-night thermospheric circulation. The airglow is brightest at equatorial latitudes, and at longitudes on the morning side of the antisolar meridian.*

During the early orbits of the Pioneer Venus orbiter mission, the ultraviolet spectrometer experiment detected ultraviolet emissions from the dark limb of Venus. These were tentatively identified (*1*) as the Cameron bands of carbon monoxide excited by the precipitation of charged particles into the Venusian thermosphere. Since then, the orbit's periapsis has traversed the dark side of the planet, and we have obtained spectra of the night airglow. These spectra are dominated by bands of the nitric oxide delta and gamma systems, confirming an earlier detection of some members of the delta band system from the Earth-orbit-

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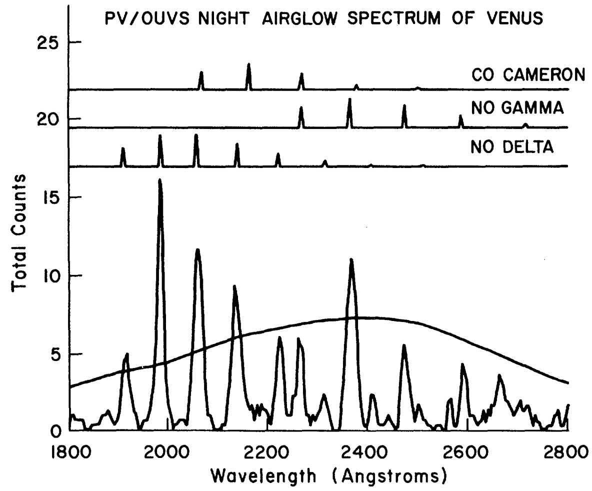


Fig. 1. The far ultraviolet spectrum of the night airglow of Venus. The spectrum is the sum of 96 spectra obtained on five separate orbits, and has been smoothed by a three-point running average. The overplotted line is the response expected for white light at an intensity of 0.25 kR per bandpass. Also shown are the predicted relative responses for bands in the $v' = 0$ progression of the nitric oxide delta and gamma systems and the carbon monoxide Cameron system.

ing International Ultraviolet Explorer satellite (*2*).

Figure 1 shows the sum of 96 spectra of the night airglow of Venus. Because of the weak signals involved, it has not been possible to resolve spatial or temporal variations in the spectra themselves, so that the spectrum in Fig. 1 is, in effect, averaged over all viewing geometries. The intensities are therefore upper limits on the average zenith intensities of the various bands.

The spectrum contains six clearly identifiable members of the $C^2\Pi$-$X^2\Pi$ delta system of nitric oxide. All six belong to the $v' = 0$ progression, starting with the (0, 0) band at 1909 Å. Included in Fig. 1 are the relative signals from these bands expected on the basis of the Franck-Condon factors (*3*). The intensity match is within the statistical uncertainties, with the exception of the (0, 0) band itself, which appears to be ~40 percent weaker than expected. This is most probably because of the partial absorption of this band by the ambient CO_2, which has an absorption cross section of 5×10^{-23} cm^2 at 1909 Å, declining to 5×10^{-24} cm^2 at the (0, 1) band (1980 Å) (*4*). The $v' = 1$ and higher progressions do not appear; this is also the case with the same band system in Earth's night airglow (*5*).

A further five features can be identified with the $v' = 0$ progression of $A\ ^2\Sigma^+$-$X^2\Pi$ gamma system of nitric oxide, NO. Figure 1 contains the expected relative signals. The measured signals match the expected signals less well than in the case of the delta bands; in particular, the (0, 1) band at 2365 Å and the (0, 4) band at 2713 Å are stronger than predicted. The discrepancy may be due to blending with other emissions; if this is so, then 20 to 50 percent of the 2365-Å feature and 40 to 80 percent of the 2713-Å feature may be ascribed to the blended emission. The weakness or absence of the $v' \geq 1$ progressions is characteristic of the gamma bands produced in Earth's airglow and in the laboratory by the two-body radiative recombination of oxygen and nitrogen atoms (*6*).

Table 1 shows the observed signal, the best-fit synthetic signal, and the equivalent intensities of each band. The possible residual intensities near 2365 Å and 2713 Å are also included.

The Cameron bands of CO have been observed in the Martian dayglow by Mariners 6, 7, and 9 (*7*). They are vibrationally and rotationally well developed and, at ~15 Å resolution, appear broad, with half-widths of approximately 50 Å. The absence of a measurable signal near 1940 Å, 2080 Å, and 2340 Å in Fig. 1 rules out such well-developed Cameron bands in the Venus nightglow. The possibility of a relaxed emission, however, remains; such an emission could occur from altitudes where the pressure exceeds ~10 μbar, provided that the excited molecules (which are metastable) are not quenched. Figure 1 contains the expected relative signals in the $v' = 0$ progression of the Cameron bands. It can be seen that the stronger bands are blended (at ~12 Å bandpass) with members of the nitric oxide systems, except for the (0, 1) band at 2158 Å. The signal at this wavelength, ~100 rayleighs, provides an upper limit for this band. This in turn implies an upper limit of 25 R on the contribution of the (0, 3) Cameron band to the feature at 2365 Å, and an upper limit of ~80 R on the contribution of the (0, 0) Cameron band at 2063 Å to the feature identified as the (0, 2) delta band of NO. Although this vertical intensity implies a maximum limb intensity of ~4 kilorayleighs, it seems likely that the signal identified earlier (*1*) as the (0, 0) Cameron band was in fact the (0, 2) delta band.

The spectrum in Fig. 1 is so similar to spectra of the delta and gamma bands produced in the laboratory by the two-body radiative recombination of N and O (*6*) that there can be little doubt concerning the excitation mechanism (*2*). The pseudomolecule formed during collisions of N and O atoms is occasionally stabilized by radiation in either the $C^2\Pi$-$X^2\Pi$ delta bands or in the infrared $C^2\Pi$ $A\ ^2\Sigma^+$ band. Progressions other than the $v' = 0$ do not appear in the delta bands because the higher vibrational levels are energetically inaccessible at thermal energies. These higher progressions are also weak or absent in the gamma bands; only the $v' = 0$ level of the $A^2\Sigma^+$ state is populated by the infrared cascade.

Monochromatic disk traces yield a better measure of the zenith airglow intensities than do the spectra. Figure 2 shows the average of 18 traces in the

Table 1. The intensities of the bands shown in Fig. 1. The total counts (from 96 individual spectra) are obtained by integrating under the curve in Fig. 1 (before smoothing). The "excess intensity" column contains the intensities of blended emissions that would account for departures of the data from the expected relative intensities.

Band	Wave-lengths (Å)	Total counts	Best-fit counts	Intensity (kR)	Excess intensity (kR)
			Delta system		
(0, 0)	1909	20	33	0.38	
(0, 1)	1980	60	58	0.99	
(0, 2)	2054	54	58	0.77	
(0, 3)	2134	44	43	0.52	
(0, 4)	2219	25	24	0.27	
(0, 5)	2310	11	11	0.11	
(0, 6)	2406	8	4	0.08	
			Gamma system		
(0, 0)	2262	25	25	0.25	
(0, 1)	2365	55	36	0.54	0.19
(0, 2)	2471	24	27	0.24	
(0, 3)	2587	16	13	0.19	
(0, 4)	2713	11	4	0.18	0.11

(0, 2) delta band taken near periapsis on orbit 118. Before averaging, each trace was decalibrated and plotted in such a way that the limbs from all the traces coincided. Also shown are the same data with the effects of viewing geometry removed; the zenith intensity thus obtained varies little across the disk in this particular case. The average value is 0.5 kR.

We can combine such measurements with measurements of atomic oxygen by the orbiter mass spectrometer to arrive at an estimate of the atomic nitrogen abundance. The column product of N and O implied by Fig. 2 is

$$\int_0^\infty [\mathrm{N}]\cdot[\mathrm{O}]\,dz = (0.5 \times 10^9)/(3.7 \times 10^{-18}) = 1.4 \times 10^{26}\ \mathrm{cm}^{-5}$$

where the integral is over altitude, z, and we have invoked the reaction rate for the production of the (0, 2) band (6). The O concentration is $\sim 5 \times 10^8$ cm^{-3} at 150 km, and shows a scale height of ~ 9 km (8). If the N/O ratio is f, then $\int_z^\infty [\mathrm{N}]\cdot[\mathrm{O}]\,dz = 1 \times 10^{23} f$ at 150 km and will increase with a scale height of ~ 4 km. The integral will reach the required value of 1.4×10^{26} at ~ 105 km if $f = 0.01$. We do not yet have a sufficiently accurate altitude scale to determine the altitude at which the emissions are strongest, but preliminary indications place it in the 100 to 120 km region. Thus, an N/O ratio of a few percent seems likely, and such a value might also be expected from the N_2/CO_2 ratio in the daytime thermosphere (9) (which is the source region for both N and O atoms).

Atomic nitrogen is produced in the sunlit thermosphere of Venus by dissociation of N_2, which is present at about the 3 percent level in the lower atmosphere (10), and about 10 percent at 150 km (9). The dissociation of N_2 produces metastable $N(^2D)$ as well as ground state $N(^4S)$, and the former will react with CO_2 to produce nitric oxide. The nitric oxide removes $N(^4S)$ in a reaction producing molecular nitrogen:

$$\mathrm{N}(^4S) + \mathrm{NO} \rightarrow \mathrm{N}_2 + \mathrm{O}$$

but it is also subject to dissociative processes that return the nitrogen. The overall distribution of N and NO in the thermosphere of Venus has not been studied, although some work has been done for Mars (11). It is certain that the circulation of the Venus thermosphere plays an important role in this distribution. Current two-dimensional models of this circulation (12) predict an upwelling near the subsolar point, a high-altitude flow across the terminator, and a descending flow under an antisolar stagnation cell on the nightside. The nightside detection of the Herzberg II bands of molecular oxygen in the visual by Venera 9 (13) lends support to the importance of this circulation in carrying dissociation products from dayside to nightside, since the excitation mechanism has been identified (13) as:

$$\mathrm{O} + \mathrm{O} + \mathrm{CO}_2 \rightarrow \mathrm{O}_2(c^1\Sigma_u^-) + \mathrm{CO}_2$$

The circulation will carry N with it as well as O, and the emission will occur where the flow descends and the concentrations increase. Both the molecular oxygen and nitric oxide emissions serve to trace the descending part of the circulation.

The Venera measurements were confined to equatorial latitudes, and showed that the molecular oxygen emissions brightened as one went from the evening toward the morning terminator, indicating that the two-dimensional model (which is symmetric about the Sun-Venus line) does not fully describe the circulation. From Pioneer Venus, we have obtained many orbits' worth of traces of the nitric oxide emission from the dark disk of Venus. Figure 3 shows three of these orbits, with the data presented as unrectified "three-dimensional" images. The viewing geometry changes greatly as the spacecraft descends from high altitudes at high northern latitudes, to periapsis at 18°N, and then ascends as it crosses the equator. The latitude coverage is from 60°N at the top to 60°S at the bottom; the longitude range decreases from $\sim 70°$ at the top to $\sim 10°$ at periapsis (18°N) and increases again to

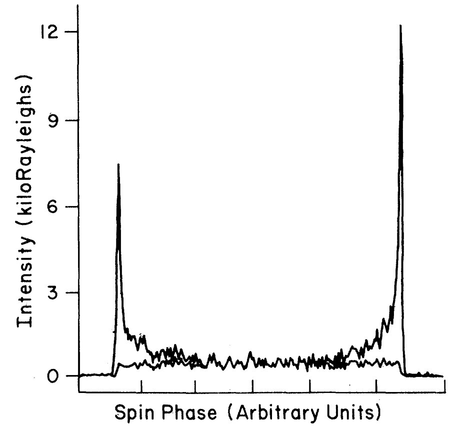
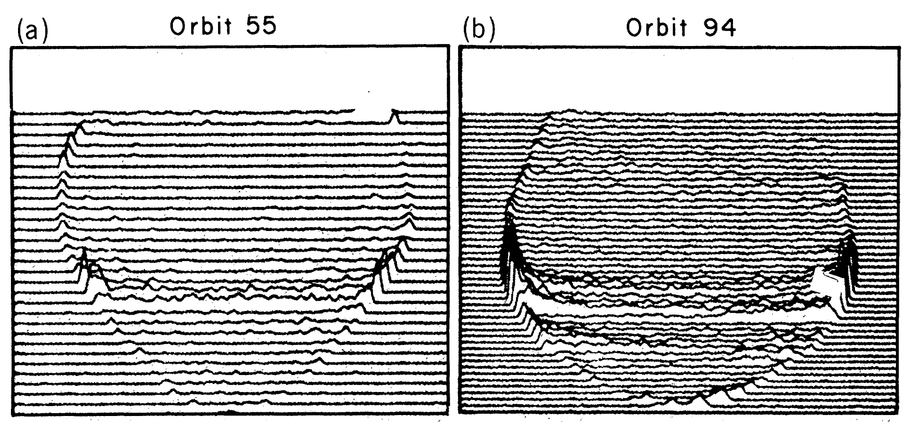


Fig. 2. Intensity of the (0, 2) delta band of nitric oxide across the dark disk of Venus, showing the strong limb-brightening expected from an optically thin emission. Note that the eastern limb (toward the antisolar meridian) is brighter than the western (toward the morning terminator). Plotted is the average of 18 disk traces obtained near periapsis on orbit 118 (1 April 1979). Also plotted is the same average with the limb-brightening removed; the average zenith intensity obtained from this curve is 0.5 kR.



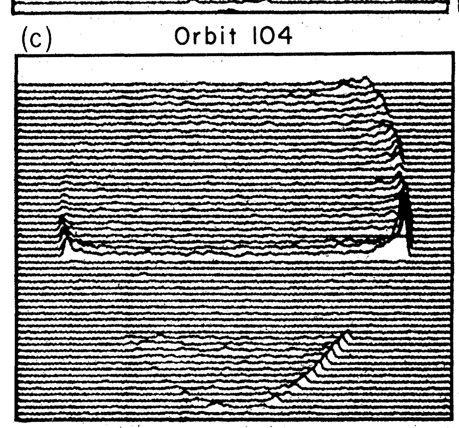


Fig. 3. Unrectified "three-dimensional" plots of the brightness of the (0, 2) delta bands of nitric oxide in the night airglow of Venus. The top of the figure is near 60°N and the southern limb is at 60°S. The equator lies about one-third of the way up. (a) Orbit 55, 28 January 1979. The equator is noticeably brighter than higher latitudes, and the western limb (toward the antisolar meridian) is brighter than the eastern (toward the evening terminator). (b) Orbit 94, 8 March 1979. Again the equator is bright, and bright patches can be seen in both hemispheres. The limbs are of comparable brightness. (c) Orbit 104, 18 March 1979. The equatorial region was observed at 2082 Å, where the spectrum in Fig. 1 is dark, but a brightening toward the equator is seen in the northern hemisphere. Periapsis is now only 42° from the morning terminator, and the eastern limb (toward the antisolar meridian) is brighter than the western limb.

~30° in the southern hemisphere. The equator is well below the center of the images.

There is a distinct tendency for the equatorial region to be brighter than other latitudes (see Fig. 3, a to c). There is also a tendency for the western limb to be brighter than the eastern limb, before orbit 90 or so, and for the eastern to be brighter than the western thereafter, suggesting that at any given time the brightest emission occurs about 30° in longitude beyond the antisolar meridian toward the morning terminator. ("Morning" and "evening" are used on the basis of the observed retrograde circulation of the cloud tops.) Occasional isolated bright patches are seen in both hemispheres; one example appears as a band sweeping across the upper part of Fig. 3b. The overall signal level fluctuates from orbit to orbit, with the brightest signals being seen on orbits 94 and 114; this suggests temporal fluctuations superimposed on the spatial variations.

We conclude on the evidence of the night airglow observations reported here that the overall circulation of the Venusian thermosphere is temporally irregular and, in addition, its convergence on the nightside is largest near the equator at all longitudes and ~30° beyond the antisolar meridian at latitudes between 60°N and 60°S.

A. IAN STEWART, CHARLES A. BARTH
Department of Astrogeophysics and Laboratory for Atmospheric and Space Physics, University of Colorado, Boulder 80309

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15 May 1979

Short-Term Cyclic Variations and Diurnal Variations of the Venus Upper Atmosphere

Abstract. *Measurements of satellite drag obtained from the orbital decay of the Pioneer Venus orbiter on the nightside of Venus indicate an atomic oxygen atmosphere near 155 kilometers (an order of magnitude less dense than expected) with nighttime inferred exospheric temperatures averaging as low as 110 K. Densities at these altitudes decrease sharply from day to night, contrary to the predicted nighttime oxygen bulge. This decrease may be indicative of an unexpectedly weak transport across the evening terminator or a very strong heat sink at night that is possibly related to vertical eddy heat transport. Large periodic oscillations in density and inferred exospheric temperature are detected with a period of 5 to 6 days. We have subsequently discovered temperature variations of the same period in the stratosphere, which are tentatively interpreted as planetary-scale waves that may propagate upward producing the periodic variations in the thermosphere and exosphere. The peak-to-peak amplitude of the temperature oscillations associated with these waves apparently increases with altitude approximately as follows: 1 K (70 kilometers), 3 K (90 kilometers), 40 K (155 kilometers). Inferred nighttime exospheric temperatures are found to be asymmetric relative to midnight, minimizing on the morning side. The possibility of superrotation of the thermosphere and exosphere is discussed.*

From the orbital decay of the Pioneer Venus orbiter, atmospheric densities on Venus have been determined at altitudes ranging between 140 and 175 km near a latitude of 18°N. The method by which densities are determined near periapsis from changes in the orbital period caused by atmospheric drag was discussed in (*1*). In the present report we discuss a study of the vertical structure of the nighttime thermosphere and exosphere, the results of which verify the atmospheric model [see (*1*)] that indicated nighttime exospheric temperatures below 150 K. We then study temporal variations identifying (i) a very sharp density decrease from day to night contrary to predictions, (ii) the existence of a large amplitude periodic variation in the exosphere with a period of 5 to 6 days, (iii) preliminary evidence of a 5-day temperature wave in the stratosphere interpreted as a planetary-scale wave which may be the cause of the oscillations in the exosphere, and (iv) a significant asymmetry with respect to midnight of the diurnal variation. Some of the implications of these results, including the possible coupling between the upper and lower atmosphere of Venus, are discussed.

Shown on the right of Fig. 1 is the observed altitudinal variation of densities on the nightside of Venus over the period 1 January through 1 April 1979. Densities were obtained nearly every day except for days when large tracking errors occurred. It may be seen that conditions are highly variable. The observed mean altitudinal variation near 155 km is consistent with a density scale height of 7 km. The model developed in (*1*) from altitudinal variations of dayside density data gave, for any density, correspond-

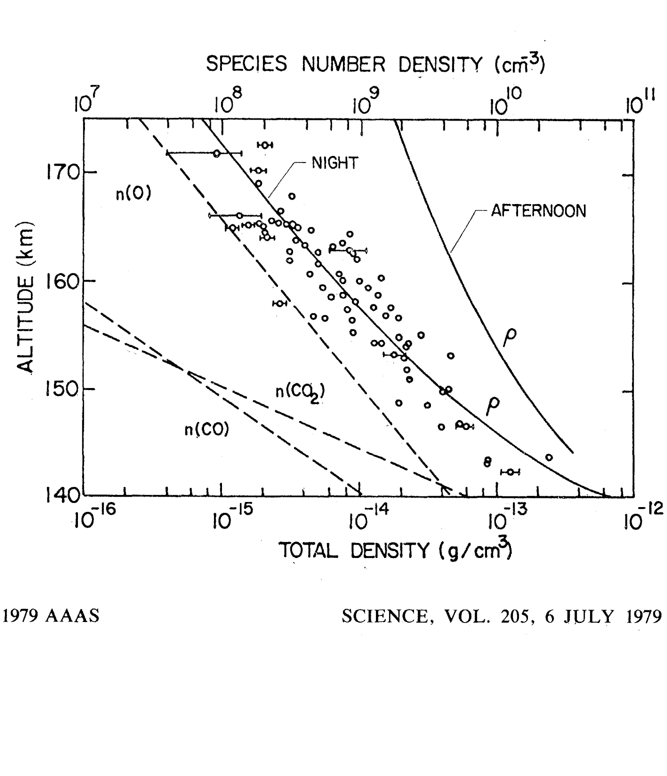

Fig. 1. Variation of nighttime density (ρ) (solid line labeled "night," bottom scale) and composition (dashed lines, top scale) with altitude based on the model described in (*1*) and an exospheric temperature of 110 K. The "afternoon" density profile from (*1*) is also shown. Tracking error bars are shown for drag measurements of density when errors exceed 10 percent. Measured densities are shown between periapsis pass 28 and 118 (local solar times 7:00 p.m. to 4:00 a.m.).