

8-1-2004

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Liemohn, M. W., Fox, J. L., Nagy, A. F., & Fang, X. (2004). Hot Carbon Densities in the Exosphere of Venus. *Journal of Geophysical Research-Space Physics*, 109, A10307.

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## Hot carbon densities in the exosphere of Venus

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Received 22 June 2004; revised 17 August 2004; accepted 30 August 2004; published 29 October 2004.

[1] The results of calculations of hot carbon densities in the exosphere of Venus are presented. The calculation is a two-step process. First a two-stream transport code is used to solve for the distribution function at the exobase, and then these results are used in a Liouville equation solution above the exobase. It is found that generally, photodissociation of carbon monoxide is the largest source of hot carbon atoms in the upper atmosphere of Venus, larger than dissociative recombination of  $\text{CO}^+$  and significantly larger than the creation of hot carbon through collisions with hot oxygen atoms. It is also found that the high solar activity densities are about 4 times larger than those for the low solar activity case. The results of these calculations are compared with the densities calculated by Paxton [1983]. *INDEX TERMS*: 5405 Planetology: Solid Surface Planets: Atmospheres—composition and chemistry; 5435 Planetology: Solid Surface Planets: Ionospheres (2459); 6295 Planetology: Solar System Objects: Venus; 6026 Planetology: Comets and Small Bodies: Ionospheres—composition and chemistry; *KEYWORDS*: carbon, exosphere, Venus

**Citation:** Liemohn, M. W., J. L. Fox, A. F. Nagy, and X. Fang (2004), Hot carbon densities in the exosphere of Venus, *J. Geophys. Res.*, 109, A10307, doi:10.1029/2004JA010643.

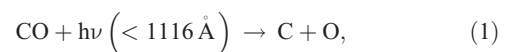
### 1. Introduction

[2] The changes in the carbon dioxide content of the atmospheres of Mars and Venus over time are determined either by the atmospheric escape of carbon via neutral atoms/molecules such as  $\text{CO}_2$ ,  $\text{CO}$ , and  $\text{C}$  corresponding ions or by the surface processes associated with carbon-bearing materials in the regolith and carbonate deposits. The escape energies of  $^{12}\text{C}$  at Venus and Mars are about 6.38 and 1.48 eV, respectively. The presence of a hot carbon exosphere at Venus was established by airglow measurements and related model calculations [Paxton, 1983, 1985]; the airglow measurements were carried out by the UV spectrometer, carried aboard the Pioneer Venus Orbiter [e.g., Stewart, 1980]. This work has established that the  $^{12}\text{C}$  escape fluxes at Venus are negligibly small. There is no observational information regarding hot carbon densities at Mars available at this time. The observed Venus emissions at 165.7 nm have been identified as arising from hot carbon atoms, and an exobase mixing ratio of  $\text{C}/\text{O}$  was estimated to be of the order of 1% at Venus. Two potential source terms for these hot  $\text{C}$  atoms were considered by Paxton [1983, 1985], namely, dissociative recombination of  $\text{CO}^+$  ions and collisions of thermal  $\text{C}$  with hot  $\text{O}$  atoms; he found that the latter source was the more important. Recently, Nagy *et al.* [2001] calculated hot  $\text{C}$  densities and fluxes for Mars. They

considered photodissociation of  $\text{CO}$ , in addition to the two sources considered by Paxton [1983, 1985] for Venus. It was found that for Mars the newly considered photodissociation source was the dominant one. Thus it is appropriate to recalculate the hot  $\text{C}$  densities and fluxes at Venus in order to assess the importance of the different source mechanisms and compare these new results with the Pioneer Venus observations.

### 2. Model Description

[3] The photodissociation of  $\text{CO}$ ,

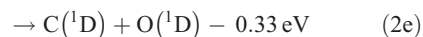
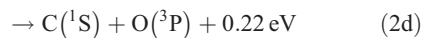
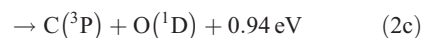
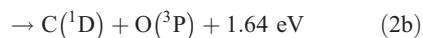
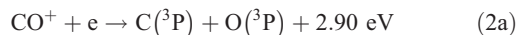


provides excess kinetic energy available to the atomic products, the amount of which depends on the wavelength of the dissociating photon and the electronic state of the dissociation products. The hot  $\text{C}$  production rates caused by this photodissociation process were calculated by assuming that the products are in their ground state and using the photodissociation cross sections presented by Fox and Black [1989]. The energy distribution of carbon atoms from the photodissociation of  $\text{CO}$  were calculated in the center-of-mass frame. A transformation to the laboratory frame would broaden the peaks, owing to the thermal motion of the  $\text{CO}$  molecules, which are characterized by neutral

temperatures of 200–300 K. We believe that this broadening will not have a significant effect on our final results; our finite energy “box size” results in some broadening, as do collisions encountered by these hot C atoms, as they move upward toward the exobase.

[4] The solar flux values used were the 79050 and the SC21REFW EUV fluxes of *Hinteregger et al.* [1981], for high and low solar activities, respectively, combined with the X-ray values given by *Ayres* [1997]. We have used the Hinteregger solar flux models, because the current Solar 2000 models of *Tobiska* [2004] are still undergoing recalibrations in both the EUV and soft X-ray range that are not insignificant. Until the “final” S2K solar fluxes, which are calibrated to the TIMED SEE and other recent data, are available, it is not unreasonable to use the *Hinteregger et al.* [1981] solar fluxes. We expect the differences to be less than a factor of 2 due to the use of different solar flux models. This is of the order of the general uncertainties inherent in the models caused by all the various input parameters. Furthermore, the use of the Hinteregger solar fluxes facilitates comparison with previous models, such as that of *Paxton* [1983, 1985] in which the Hinteregger solar fluxes were used. The thermospheric models used were similar to those used previously [e.g., *Fox and Sung*, 2001]. Both the high and low solar activity densities come from the VTS3 model [*Hedin et al.*, 1983]; they correspond to the equatorial 1600 LT values. The solar maximum model assumes an  $F_{10.7}$  cm flux of 200, while the solar minimum one is for  $F_{10.7}$  equal to 80.

[5] The dissociative recombination of  $\text{CO}^+$ ,



results in carbon atoms with excess kinetic energy, the amount of which depends on the electronic excitation state of the products, as indicated above. Detailed Monte Carlo calculations of the altitude-dependent velocity distributions of the C atoms resulting from reaction (2), similar to the ones carried out by *Fox and Hac* [1999] for Mars, were also done for Venus, corresponding to both high and low solar cycle conditions, using the relevant plasma temperatures. In these calculations we adopted the latest available rate coefficients and branching ratios [*Rosen et al.*, 1998]. The total dissociative recombination rate coefficient used was  $2.76 \times 10^{-7} (300/T_e)^{0.55}$ . At 0 eV relative energy the branching ratios given by *Rosen et al.* [1998] are 0.761, 0.145, 0.094, and 0.0 for channels 2a, 2b, 2c, 2d, and 2e, respectively. At 0.4 eV the endothermic channel 2e is energetically possible and the measured branching ratios are 0.53, 0.34, 0.08, 0.0 and 0.05, respectively. In the

calculations presented in this paper, a linear interpolation between these branching ratio values was used, which depended on the temperatures corresponding to a given altitude. We assumed that the rotational and vibrational temperatures are the same as the adopted ion temperatures [see *Fox and Hac*, 1999]. We took into account the decrease in the cross section for dissociative recombination due to the relative velocity of the ions and electrons [*Rosen et al.*, 1998]. The assumed ionospheric densities and temperatures for the low and high solar activity conditions are presented by *Fox and Sung* [2001].

[6] Collisions between energetic oxygen atoms and cold, thermal carbon atoms can result in hot carbon production:



We calculated the hot oxygen distribution functions below the exobase, in the manner described by *Kim et al.* [1998], but now using the atmospheric/ionospheric parameters adopted for the present Venus calculations. We used a collision cross section of  $1.2 \times 10^{-15} \text{ cm}^2$ , which is a reasonable choice based on the calculations of *Kharchenko et al.* [1997].

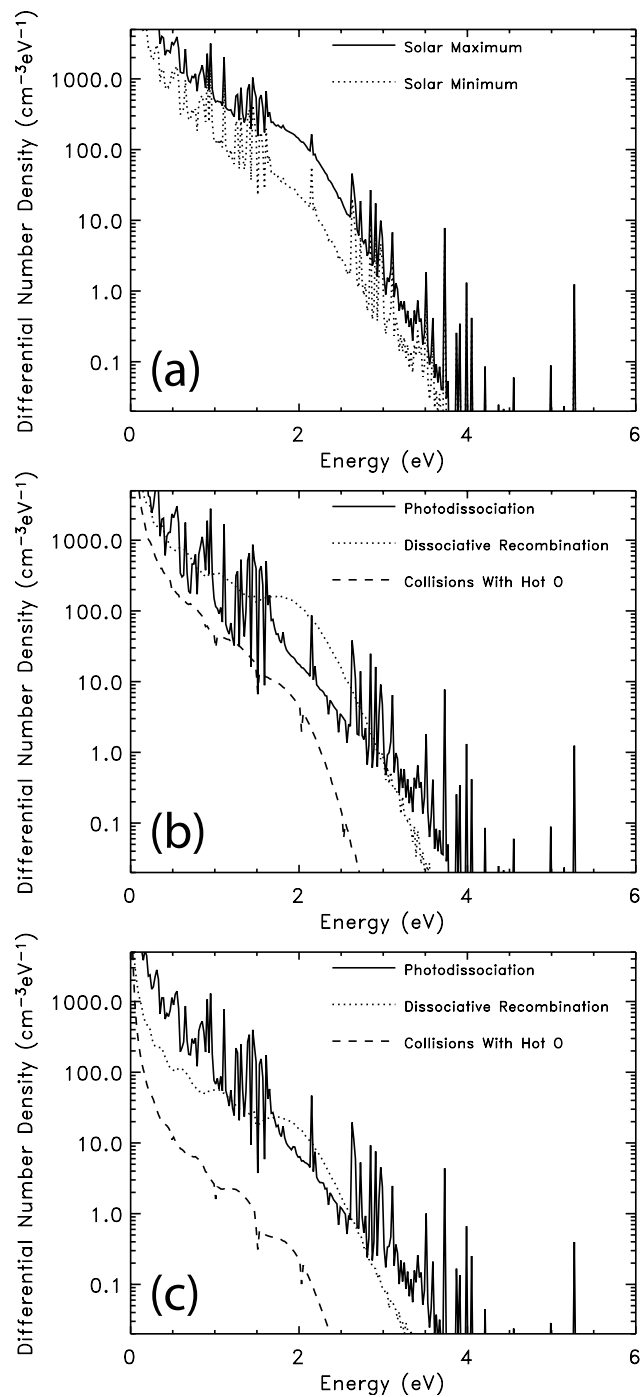
[7] We combined these three hot C production rates as a function of altitude and energy. We then used these production rates in our two-stream model to calculate the hot C fluxes as a function of altitude. This two-stream model [cf. *Schunk and Nagy*, 2000] has been used widely and successfully to calculate electron, ion, and neutral particle fluxes [e.g., *Cravens et al.*, 1980a; *Nagy and Cravens*, 1988; *Kim et al.*, 1998]. Specifically, it has been used to calculate hot oxygen and carbon at Mars and hot oxygen densities at Venus. In these applications, hard sphere collision approximations were used. The hot C total cross sections adopted for collisions with  $\text{CO}_2$ , O, and H were  $1.9 \times 10^{-15}$ ,  $1.2 \times 10^{-15}$ , and  $1.9 \times 10^{-15} \text{ cm}^2$ , respectively. The calculated hot oxygen densities at Venus agreed well with the observed values [*Nagy and Cravens*, 1988]; the Mars results [*Nagy and Cravens*, 1988; *Kim et al.*, 1998] are in reasonably good agreement with the values calculated by *Lammer and Bauer* [1991] and *Hodges* [2000], who used a Monte Carlo method. (There is a factor of about 13 difference in the escape fluxes given in Table 1 of *Kim et al.* [1998] and *Hodges* [2000], which is due to an error in compiling that table; the densities and the distribution function presented by *Kim et al.* [1998] are correct.)

[8] Using this two-stream approach, we obtained the hot C fluxes at the exobase. The classical definition of the exobase, namely, the location where the mean free path equals scale height, places it somewhere between 180 and 220 km. The exact choice of the exobase altitude does not affect our calculated densities to any significant degree, as long as that choice is “reasonable,” as evidenced in the results presented below.

### 3. Results and Discussion

#### 3.1. Two-Stream Model Results

[9] The calculated energy distribution functions at the nominal exobase altitude (200 km), for the two solar cycle conditions, are shown in Figure 1a. The differential number densities for each source are shown in Figures 1b and 1c for high and low solar activity conditions, respectively. These



**Figure 1.** (a) Hot carbon differential number density versus energy for the high and low solar activity cases. Spectra are shown for the 200-km altitude bin in units of  $\text{cm}^{-3} \text{eV}^{-1}$ . Also shown are the differential number densities versus energy for the three sources at (b) high solar activity and (c) low solar activity.

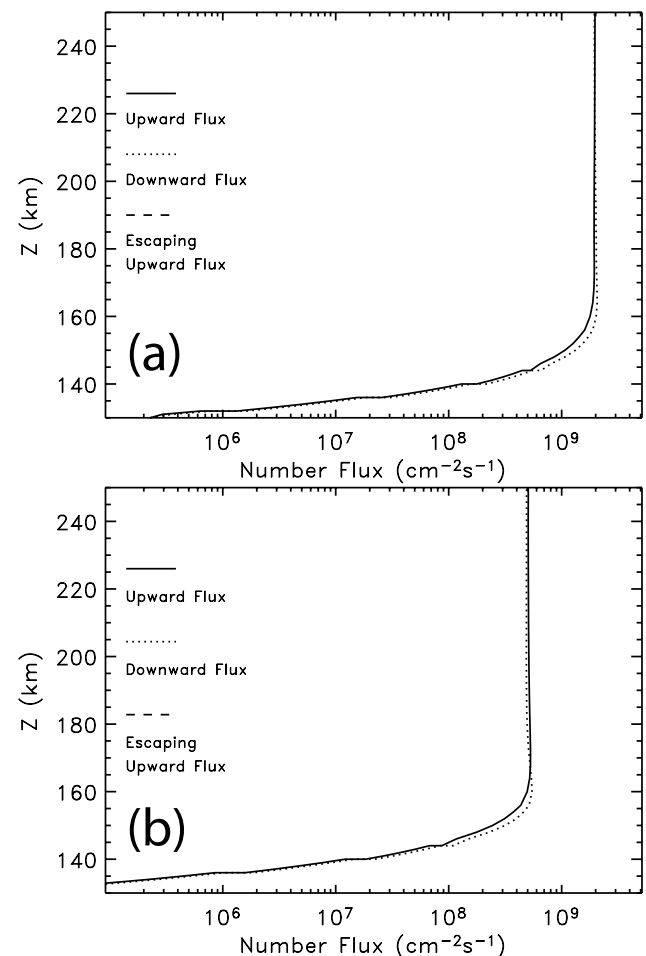
two-stream model results show the fine structure of the hot C source. Photoionization produces dozens of spikes in the distribution, as discussed in the previous section. Collisions between hot O and cold C are only a minor source of hot C particles at the exobase. The high activity spectrum is roughly a factor of 4 larger than the low activity densities.

Note that the differential number densities become negligibly small at energies above about 4 eV.

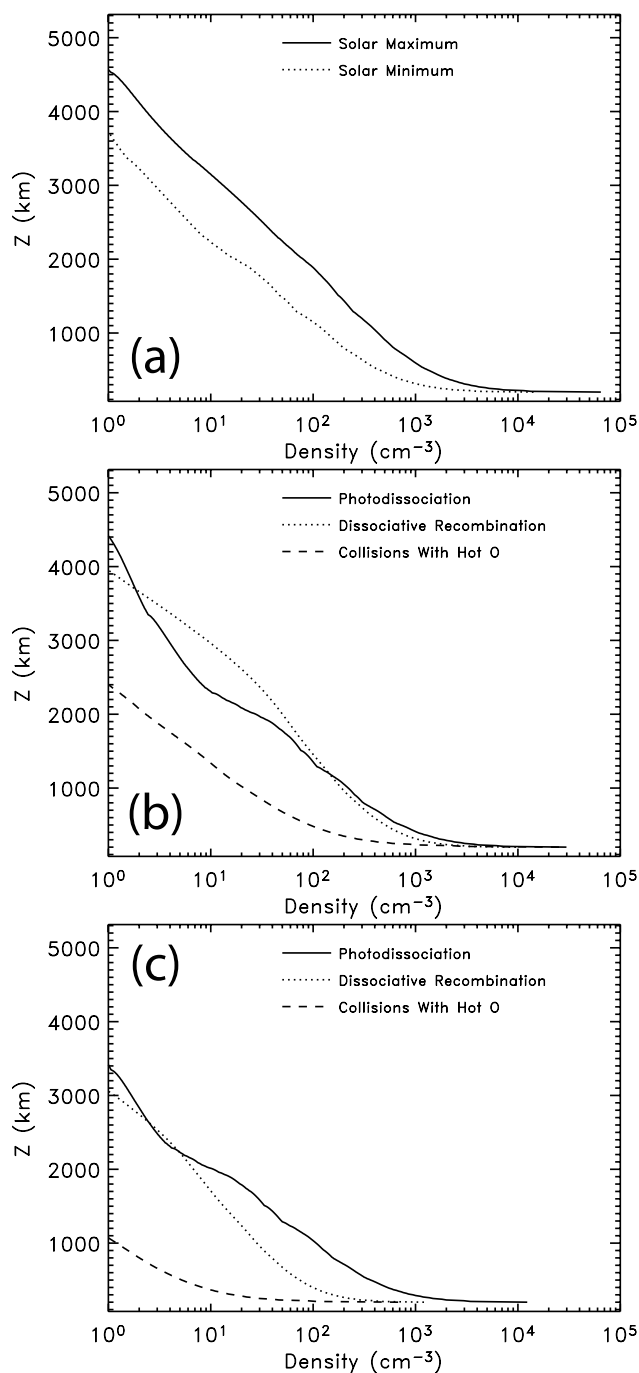
[10] The upward and downward hemispheric fluxes are plotted in Figures 2a and 2b for the high and low solar activity conditions, respectively. One can obtain the total density by adding the upward and downward hemispheric fluxes and dividing it by the appropriate velocity. The upward and downward fluxes are essentially equal and unchanging above  $\sim 170$  km, and they rapidly drop to zero below 150 km. Comparing Figures 2a and 2b confirms the factor of 4 difference in the fluxes between high and low solar activity. The escape energy for C at Venus is 6.46 eV at 200 km, well above the energy range of the hot C sources. This means that hot carbon atoms (at least from the three sources considered here) effectively cannot escape the Venus gravitational well.

### 3.2. Exosphere Model Results

[11] Having calculated the distribution functions at the exobase, we used Liouville's theorem [cf. *Schunk and Nagy, 2000*] to calculate the hot carbon densities in the exosphere of



**Figure 2.** Hot carbon number flux versus altitude for (a) high solar activity conditions and (b) low solar activity conditions. Upward and downward flux values are integrated over all energies, while the escaping upward flux values are integrated above 6.46 eV (note that it is below the scale on both plots).



**Figure 3.** (a) Hot carbon densities in the exosphere of Venus versus altitude for the high and low solar activity cases. The exobase altitude was chosen to be 200 km for these calculations. Also shown are the densities for the three sources at (b) high solar activity and (c) low solar activity.

Venus, as we have done for hot hydrogen and oxygen cases before [e.g., *Cravens et al.*, 1980b; *Nagy and Cravens*, 1988; *Nagy et al.*, 2001]. The resulting hot carbon densities are shown in Figure 3a for the two solar activity levels. The hot C densities decrease from about  $6.5 \times 10^4$  and  $1.5 \times 10^4$   $\text{cm}^{-3}$  near the exobase for the high and low solar activity conditions, respectively. As a comparison, it should be noted that the hot O densities at 200 km are  $1.36 \times 10^6$  and  $1.37 \times$

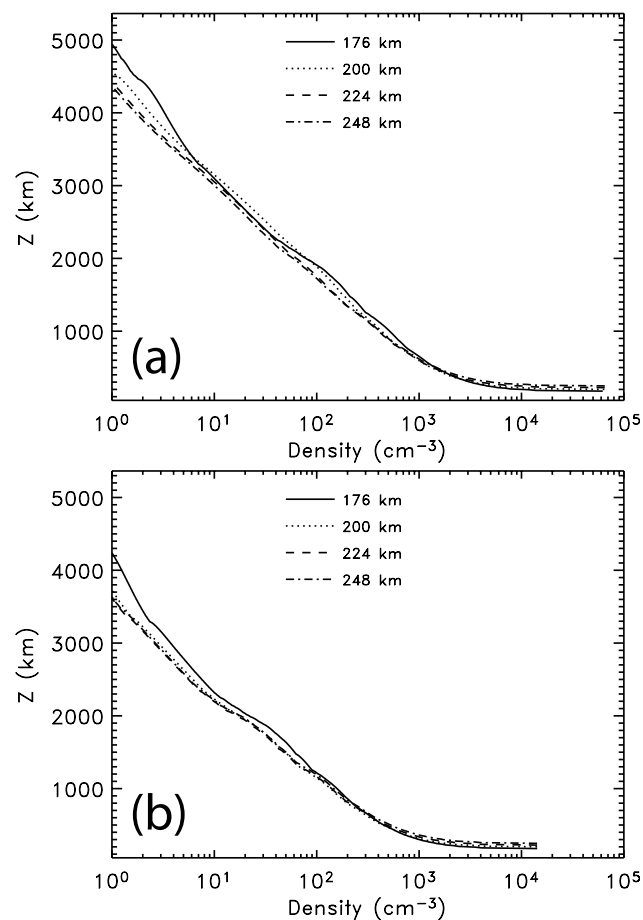
$10^5$   $\text{cm}^{-3}$  for solar cycle maximum and minimum conditions, respectively, significantly greater than the hot C densities.

[12] We have found that photodissociation is basically the most important source mechanism, over the whole altitude range, followed by dissociative recombination, while the hot oxygen impact source appears to be rather small at Venus, just as we found for Mars [*Nagy et al.*, 2001]. In order to demonstrate this conclusion in Figure 3b and 3c we have plotted the exospheric densities due to the three possible sources separately, for the high and low solar activity conditions, respectively. The spectral features in the energy distributions govern the flatness or steepness of the exospheric density profile with altitude. That is, higher-energy particles reach higher altitudes, and so the spikes, knees, and other structure seen in Figure 1 directly translate to the structure seen in Figure 3.

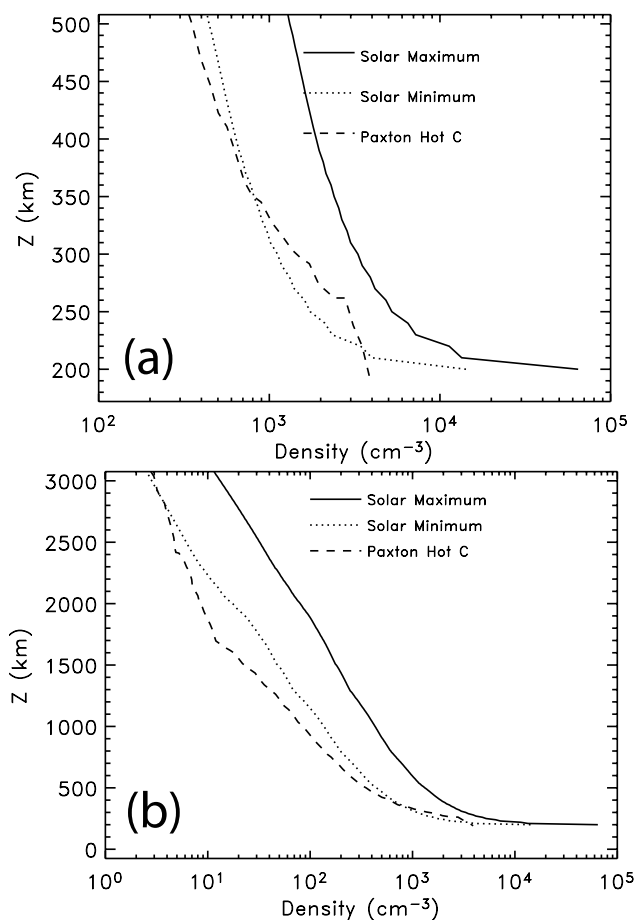
[13] In Figures 4a and 4b we have plotted the calculated high and low solar activity densities, respectively, for four different assumed exobase altitudes. These results clearly demonstrate that the choice of the exobase altitude has only a small influence on our calculated hot carbon densities.

### 3.3. Comparison With Previous Studies

[14] The UV spectrometer carried by the Pioneer Venus Orbiter (PVO) measured the 1657-Å carbon emission at



**Figure 4.** Hot carbon densities in the exosphere of Venus for the high solar activity case using various altitudes for the exobase height for (a) high solar activity and (b) low solar activity.



**Figure 5.** Hot carbon densities in the exosphere of Venus for high and low solar activity cases compared with the exospheric densities calculated by Paxton [1983]. Two views are shown, highlighting (a) the low-altitude exosphere and (b) the high-altitude exosphere.

Venus [Stewart, 1980]. Paxton [1983] calculated hot carbon densities considering only the sources due to the dissociative recombination of  $\text{CO}^+$  and collisions with hot O, using data from the early Pioneer Venus epoch, which is about 3 years past the solar maximum conditions of 1979. Figure 5 compares our solar cycle maximum and minimum results with the calculated densities of Paxton [1983]. Figure 5a shows the comparison in the low-altitude exosphere (200–500 km altitude) while Figure 5b shows the comparison for entire altitude range of the Paxton [1983] results (up to 3000 km). The Paxton [1983] results are in reasonable agreement with our solar cycle minimum density values but roughly a factor of 3 below our solar maximum results. As demonstrated before (see Figures 3b and 3c), we found that the hot O source is the least important of the three likely ones, in contrast to the conclusion of Paxton [1983]. The reason for the difference regarding the hot O source is somewhat puzzling, because both hot O models predict similar densities, which are consistent with the observed values [cf. Nagy and Cravens, 1988], and the collision cross section used in our and Paxton's calculations are similar,  $1.2 \times 10^{-15}$  and  $1.5 \times 10^{-15} \text{ cm}^2$ , respectively. Paxton [1983, 1985] found that his calculated hot C densities matched the observed 1657-A intensities in the 300–400 km region (the upper

limit of the measurements) reasonably well, when he used a g factor of  $3.56 \times 10^{-5} \text{ s}^{-1}$  and a C/O ratio of 1–1.5% at the exobase. His model assumed a C/O ratio of 1% at the exobase. Thus it appears that if we assume that the 1657-A observations correspond to conditions between solar cycle maximum and minimum conditions, then the predicted intensities from our model are within the observed constraints, assuming the g factor used by Paxton [1983].

#### 4. Summary and Conclusion

[15] The results of calculations of hot carbon densities in the exosphere of Venus were presented. We performed a two-step calculational process. First, a two-stream transport code was used to solve for the distribution function at the exobase, and then these results were used in a Liouville equation solution above the exobase. It was found that generally, photodissociation of carbon monoxide is the largest source of hot carbon atoms in the upper atmosphere of Venus, larger than dissociative recombination of  $\text{CO}^+$  and significantly larger than the creation of hot carbon through collisions with hot oxygen atoms. It was found that essentially no hot C (from these three sources) can escape the gravitational well of Venus. While the combined-source profiles of the exospheric densities smoothly decrease with altitude, the profiles of the exospheric densities from each source flatten and steepen with altitude according to the fine structure of the energy spectra at the exobase. It was also found that the high solar activity densities are roughly a factor of 4 larger than those for the low solar activity case. The results of these calculations were compared with the densities calculated by Paxton [1983] and deduced from the 1657-A emissions observed by the Pioneer Venus Orbiter Ultraviolet Spectrometer (OUVS). There are discrepancies between our results, which show that photodissociation is the most important source of hot carbon, and those of Paxton [1983, 1985], who found that collisions with hot oxygen are the dominant source.

[16] **Acknowledgments.** We thank Larry J. Paxton for providing information relevant to this paper. The work at the University of Michigan was supported by NASA grant NAG5-13332 and at Wright State University by NASA grant NAG5-12755 and NSF grant AST-9802007.

[17] Arthur Richmond thanks Thomas Cravens and Vasili Kharchenko for their assistance in evaluating this paper.

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