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The Venus Ultraviolet Aurora: A Soft Electron Source

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Abstract. The Pioneer Venus Orbiter Ultraviolet Spectrometer has recorded continuous but variable emissions of atomic oxygen at 1304 and 1356 Å in images of the nightside of Venus. We show that the observed intensities are consistent with the presence of precipitation of soft electrons into the nightside thermosphere. Model calculations are presented in which upper and lower limits to the magnitude of the electron flux necessary to produce the observed intensities are derived. Constraints are imposed on the energy spectrum of the electrons by the measured ion densities and by the predicted intensities of other emissions that have not been detected.

1. INTRODUCTION

Emissions of atomic oxygen at 1304 and 1356 Å have been detected by the Pioneer Venus Orbiter Ultraviolet Spectrometer (PVOUVS) in images of the nightside of Venus. Intensities of the 1304-Å emission are typically about 10 R, but excursions to 100 R have been recorded. This emission is continuously observed on the nightside and typically appears in patches that vary in size and intensity and occasionally fill the nightside. The observed spatial and temporal variability of the emissions and the inadequacy of the chemiluminescent sources suggest that particle precipitation produces the emissions.

The emissions at 1304 and 1356 Å arise from the transitions

$$O(^3S^o \rightarrow ^3P)$$

$$O(^5S^o \rightarrow ^3P),$$

respectively. The $^3S^o$ state lies 9.51 eV and the $^5S^o$ state 9.15 eV above the ground ^3P state of atomic oxygen. Emissions from these states are observed in the terrestrial equatorial nightglow, where they are produced principally by radiative recombination of O^+ [*Julienne et al.*, 1974]:

$$O^+ + e \rightarrow O + h\nu.$$

On Venus the ambient ion and electron densities are too low (10^4 – $10^5 cm^{-3}$) for this mechanism to be important. The expected intensities from this source are very small, of order 10^{-3} R. In addition, the terrestrial 1304- and 1356-Å emissions appear with comparable intensities, whereas the 1304/1356 ratio for Venus is about 6. Near the terrestrial magnetic equator, excess emissions at 1304 and 1356 Å have been observed by the EUV spectrometer on the satellite STP 78-1; *Abreu et al.* [1986] have suggested precipitation of O^+/O from the ring current as the source. The measured ratio of the emissions, about 4/3, is also unlike that on the Venus nightside. We propose that the Venus emissions are caused by the precipitation of very soft electrons into the nightside atmosphere. Suprathermal electrons of unknown origin have been detected above the atmosphere in the Venus umbra by the Pioneer Venus Orbiter Retarding Potential Analyzer (PVORPA) [e.g., *Knudsen and Miller*, 1985] and at altitudes between 1500 and 2000 km by the plasma detectors aboard the Soviet spacecraft Veneras 9 and 10 [e.g., *Gringauz et al.*, 1979]. We have modeled the excitation rates produced by the precipitation of soft electrons into the nightside atmosphere in order to determine the approximate magnitude of the electron number fluxes necessary to produce the observed emissions. The fluxes are also constrained by the limits on intensities of other emissions that have not been detected and by the ion production rates that would result from such precipitation.

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2. THE OBSERVATIONS

The PVOUVS instrument and its operations are described by *Stewart* [1980]. The spacecraft orbit plane is fixed in inertial space, so that the local time of a given observation advances by 24 hours every Venus year. The OUVS line of sight is offset 60° from the spin axis, which points at the south ecliptic pole. The line of sight scans across the planet during two periods on each orbit; the first occurs several hours before periapsis when the spacecraft is moving northward, and the second occurs near periapsis when the spacecraft motion is southward [see *Stewart et al.*, 1980]. In the present study we are concerned with spin-scan images at 1304 Å and 1356 Å obtained during the first period and with spectra covering the range 1800–3200 Å obtained during the second period. During image acquisition the combination of spacecraft spin and motion along the orbit allow the instrument to scan almost a complete hemisphere, from a vantage point about 30° north of the ecliptic. Early in the mission, the image acquisition lasted about 1.6 hours, centered about 1.5 hours before periapsis; over time the orbit evolved so that these times increased to 3.0 and 4.5 hours respectively. The instrument background (typically 1.0–1.5 counts/s) was measured during image acquisition, using data with neither the planet nor stellar UV sources in view. After subtraction of this background the images were rectified at a resolution of 500 km. Spectra were acquired near periapsis, when the proximity of the planet minimized the variations in local time and emission angle during the 1-s acquisition periods. The instrument background was obtained from signal-free portions of the spectra. The number of spectra per orbit varied from 3 to 20 depending on the telemetry rate and format. For the present study, only data from the nightside were considered.

We examined 194 images at 1304 Å and 95 at 1356 Å, spread over the period 1980–1988. Images at 1304 Å show spatially and temporally varying emission patches [see *Phillips et al.*, 1986]; patches do not persist from one orbit to the next. When mapped into local time and latitude and averaged, the signal showed no latitude dependence but was brighter before midnight than after. The disc-averaged brightness declined from about 10 R at solar maximum to about 4 R at solar minimum. When plotted against emission angle, the averaged brightness increased by only 5-10% between 0° and 60°, indicating an optically thick emission. In the raw 1356-Å images, the signal noticeably exceeds the 5-6 R background only at and near the limbs, and indeed when the background was subtracted and the remaining signal was plotted against emission angle, the secant dependence characteristic of an optically thin emission was seen. After removal of this effect the disc-averaged brightness was about 1.6 R at solar maximum and about 0.8 R at solar minimum. The 1304/1356 Å brightness ratio, determined for 8 Venus years for for which both kinds of image were available, was 5.5 ± 2.7; most of the variation is due to scatter in the weaker 1356-Å signal.

The $1800 - 2300$ Å nightside spectrum is dominated by the $v' = 0$ progressions of the nitric oxide δ and γ bands [*Stewart and Barth*, 1979; *Stewart et al.*, 1980]. These chemiluminescent emissions mask many of the bands of the $CO(a^3\Pi \rightarrow X^1\Sigma^+)$ Cameron band system that should be excited by electron precipitation. Much of the strong $\Delta v = 0$ series should, however, be detectable in the $2160 - 2200$ Å region between the (0,3) and (0,4) δ bands. We have examined 685 spectra from 1979 and 1980 and found that these data were consistent with 50 ± 100 R of total emission in the Cameron system; the uncertainty derives from the counting statistics. This raw signal must be corrected for emission angle and for scattering from the planet's cloud deck. We estimate that the equivalent column excitation rate is $25 \pm 50 \times 10^6$ $cm^{-2}s^{-1}$.

We will argue below that the weakness of the Cameron bands and of nightside ionization levels relative to the observed oxygen emissions is evidence against energetic (keV or more) electrons as the source of the aurora. Electrons at the lower energies considered here will be stopped near 140 km, so that the bulk of the excitation of atomic oxygen will occur above this altitude. The absorption cross sections of CO_2 at 1304 and 1356 Å are about 9×10^{-19} and 6×10^{-19} cm^2, respectively [*Nakata et al.*, 1965]. Therefore unit opacity in CO_2 at 1304 and 1356 Å is not reached until below 120 km. The 1.6 R of 1356 Å emission seen at solar maximum therefore implies a column excitation rate of $1.6 \times 10^6 cm^{-2}s^{-1}$, and we use this as a representative value to which our auroral models will be normalized. In the case of the 1304-Å emission, even though the bulk of the initial excitations occur in the top few percent of the oxygen scattering medium, multiple scattering effects allow absorption by CO_2 to play a significant role. However, the same effects act to enhance the brightness of the signal emerging from the top of the atmosphere over what would be expected for an optically thin emission. In the next section we will estimate that a column excitation rate of $5 - 7 \times 10^6$ cm^{-2} s^{-1} is sufficient to produce an emerging brightness of 10 R. This provides a further constraint on the auroral models.

3. Production Mechanisms and Cross Sections

The Venus nightside thermosphere near the turbopause is composed predominantly of CO_2 with smaller amounts of O, CO, and N_2. The neutral temperature is low (near 100 K), and the CO_2 scale height is less than 3 km; because of diffusive separation atomic oxygen becomes the major constituent above 140 km [*Hedin et al.*, 1983]. The $^3S^o$ and $^5S^o$ states of atomic oxygen may be produced in the Venusian thermosphere by electron impact on CO_2, O, and CO:

$$CO_2 + e \rightarrow CO + O^* + e \quad (1)$$

$$O + e \rightarrow O^* + e \quad (2)$$

$$CO + e \rightarrow C + O^* + e. \quad (3)$$

Cross sections for processes (1) and (3) have been measured by *Ajello* [1971*a*,*b*] and *Mumma et al.* [1972]. Emission cross sections for electron impact on atomic oxygen (2) were reported by *Stone and Zipf* [1974], and these cross sections have been recently renormalized by *Zipf and Erdman* [1985]; (see also *Zipf* [1986]). The emission cross sections are comprised of the cross sections for direct excitation of the $^3S^o$ and $^5S^o$ states and a contribution due to cascading from higher excited states. The major cascade contribution to the 1304-Å emission under optically thin conditions is from the $^3P^e$ state, which decays into the $^3S^o$ state with the emission of an 8446 Å photon; the main cascade contribution to the 1356-Å emission is from the $^5P^e$ state, which decays into the $^5S^o$ state with the emission of a 7774-Å photon. Several theoretical excitation cross sections are available for the $^3S^o$ and $^5S^o$ states and the states which cascade into them [e.g., *Rountree and Henry*, 1972; *Rountree*, 1977]. An experimental cross section for excitation of the $^3S^o$ state has been measured by *Gulcicek and Doering* [1988] (see also *Doering et al.* [1985], *Doering and Vaughan* [1986] and *Vaughan and Doering* [1986, 1987]), and for the $^5S^o$ state by *Doering and Gulcicek* [1989*a*], using electron energy loss spectroscopy. *Gulcicek et al.* [1988] have measured excitation cross sections for the $^3P^e$ and $^5P^e$ states. The excitation cross sections are in reasonable agreement with the emission cross sections.

For both features, emission cross sections have been employed in the calculations, since excitation cross sections are not available for all the states that cascade into the $^3S^o$ and $^5S^o$ states. The 1304-Å emission cross section reported by *Zipf and Erdman* [1985], which peaks at 1.7×10^{-17} cm^2, has been adopted, and for the 1356-Å feature the cross section of *Stone and Zipf* [1974] has been reduced by a factor of 2.8, as originally suggested by *Zipf and Erdman* [1985]. The peak value of the cross section is about 7.2×10^{-18}cm^2. The $^5S^o$ excitation cross section reported by *Doering and Gulcicek* [1989a] has a peak value of about 3×10^{-18}cm^2, but, as they discuss, cascading from higher quintet states could bring the total cross section to $9 - 12 \times 10^{-18}$cm^2. If so, the cross section used here is too small by 20–40%, and the estimated electron fluxes necessary to produce the observed 1356-Å emission should be correspondingly reduced.

The cross sections for electron impact dissociative excitation of CO_2 indicate that the ratio of 1304- to 1356-Å photon production from this source is less than 1. For soft electron impact on O the ratio depends on the energy spectrum of the electrons because the shapes of the cross sections differ substantially. Excitation of the $^3S^o$ state from the ground ^3P state is optically allowed and the cross section decreases gradually after peaking at about 20 eV. Excitation of O($^5S^o$) is spin forbidden; the cross section peaks near threshold at about 14 eV and then falls off rapidly with energy. The ratios of the 1304-Å column excitation rate to that at 1356 Å as a function of electron energy for both O and CO_2 are shown in Figure 1. These results were obtained using the emission cross sections in a discrete local energy loss calculation describing the injection of monoenergetic electrons into pure gases [cf. *Victor et al.*, 1976]. The 1304/1356 Å ratio for O increases from approximately 2 to 4.7 between 10 and 20 eV and is nearly constant above 30 eV. Because the 1304/1356 Å ratios for O and CO_2 differ substantially, and because the altitude to which an electron penetrates is determined by its energy, in the atmosphere the ratio will also vary with initial energy due to the changing composition of the atmosphere in the region of maximum absorption. Figure 2 shows the ratio of 1304/1356 Å column excitation rates for 20 eV electrons depositing their energy locally in a gas with composition characteristic of altitudes between 135 and 155 km, the range of probable maximum absorption. The ratio varies only slightly, from 4.2 to 4.6, because the efficiency for dissociative excitation of CO_2 is much less than for direct excitation of O and the O source therefore dominates.

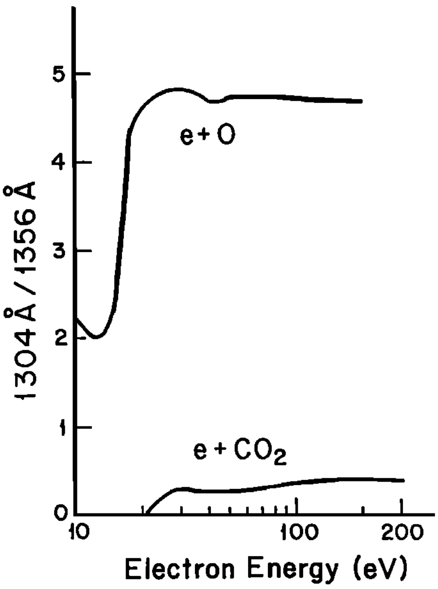

Fig. 1. Ratio of the 1034/1356 Å intensities as a function of electron energy for electron impact on O and CO_2, obtained from a discrete, local energy loss calculation for injection of monoenergetic electrons into the pure gases.

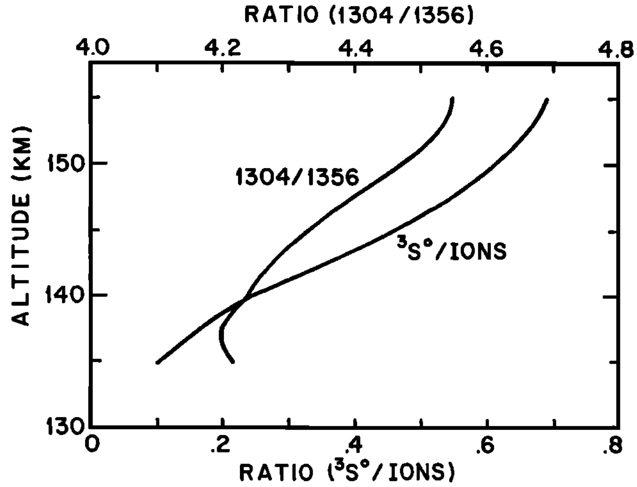

Fig. 2. Computed ratio of 1304/1356 Å excitation rates and the ratio of $^3S^o$ excitation to ionization for 20-eV electrons depositing their energy locally in a gas of composition characteristic of altitudes between 135 and 155 km, according to the neutral model of *Hedin et al.* [1983].

The 1304/1356 Å ratio will be enhanced in the Venus atmosphere by multiple scattering of 1304-Åphotons, to which the atmosphere is optically thick. *Strickland and Anderson* [1977] have discussed this effect in the terrestrial atmosphere; they show that the absorption of photons near the lower boundary of the O scattering medium (defined by O_2 in the terrestrial case) cannot be ignored. In our calculations most of the initial excitations occur in the top 2–20% (depending on energy) of the scattering medium. Similar conditions are found in the terrestrial atmosphere at altitudes between 120 and 200 km, where Strickland and Anderson, using a Voigt profile and complete frequency redistribution, calculate enhancement factors between 1.6 and 2.1. For the photoelectron-excited component of the 1304 Å emission in the Venus dayglow, whose excitation peaks at optical depths equal to about 20% of the total, *Alexander et al.* [1990] obtain an enhancement factor of 1.4. They used a Monte-Carlo calculation with partial frequency redistribution [*Meier and Lee*, 1982]. We adopt an enhancement factor range of $1.4 - 2.1$ as a reasonable estimate for the 1304-Å emission in the Venus aurora. Hence an observed brightness of 10 R can be accounted for by a column excitation rate of $5 - 7 \times 10^6$ cm^{-2}s^{-1}.

As mentioned in section 2 above, the nightside ultraviolet spectrum indicates a column emission rate of $25\pm50\times10^6 cm^{-2}s^{-1}$ in the Cameron band system. These bands may be produced by electron impact on CO_2 or CO. For electron impact on CO we have adopted the cross section of *Ajello* [1971*b*], which was shown (due to a fortuitous cancellation of errors) to be correctly normalized by *Erdman and Zipf* [1983]. The excitation function for production of $CO(a^3\Pi)$ by dissociative electron impact on CO_2 has been measured by several workers, but the absolute magnitude of the cross section is uncertain. Estimates of the maximum of the cross section range from 3×10^{-17} to 3×10^{-16} cm^2 [*Ajello*, 1971*a*; *Freund*, 1971; *Wells et al.*, 1972; *Erdman and Zipf*, 1983]. We have adopted the normalization required by *Conway* [1981] to reproduce the Mariner 9 Martian dayglow measurements, for which the maximum cross section is 7×10^{-17} cm^2.

No emission of the atomic oxygen green line at 5577 Å was recorded by the visible spectrophotometers on the Venera 9 and 10 spacecraft. An upper limit of 10 R has been placed on its intensity [*Krasnopol'sky*, 1981, 1986]. The apparent intensity will, however, be enhanced by a factor of 2 by scattering from the cloud deck, so the upper limit to the column excitation rate is about $5\times10^6 cm^{-2}s^{-1}$. The green line arises from the transition $O(^1S)\rightarrow O(^1D)$. $O(^1S)$ may be produced by electron impact on CO_2, CO, or O. A cross section for electron impact dissociative excitation of CO_2 has been constructed by *Jackman et al.* [1977], but the normalization of the cross section is uncertain. It is not strongly constrained by the dayglow $O(^1S\rightarrow{}^3P)$ 2972-Å emission rates, since it contributes less than 10% of the total ^1S emission [*LeCompte*, 1984; *LeCompte et al.*, 1989; *Fox and Dalgarno*, 1981] (see also *Fox* [1986]). The cross section for excitation of $O(^1S)$ by electron impact on atomic oxygen has been computed by *Henry et al.* [1969] and measured recently by *Shyn et al.* [1986] and by *Doering and Gulcicek* [1989*b*] from threshold to 30 eV. We have used the *Doering and Gulcicek* [1989*b*] cross sections below 30 eV and the calculations of *Henry et al.* [1969] at higher energies.

The other cross sections for electron energy deposition in CO_2 that we have adopted are basically the same as those used by *Fox and Dalgarno* [1979*a*, *b*]. The cross sections for excitation of atomic oxygen, except where noted above, were taken from *Jackman et al.* [1977], updated using the oscillator strengths for allowed transitions measured by *Doering et al.* [1985]. Cross sections for ionization of O were compiled from *Burnett and Rountree* [1979], *Zipf et al.* [1985], and *Ziegler et al.* [1982].

4. THE MODEL

We have constructed a model atmosphere of the nightside of Venus, in which the neutral densities, including CO_2, O, CO, and N_2, and temperatures are taken from the model of *Hedin et al.* [1983] for high solar activity ($F_{10.7}=200$) and 165° solar zenith angle. This model is based on measurements made by the Pioneer Venus Orbiter Neutral Mass Spectrometer [e.g., *Niemann et al.*, 1980]. We examine the effect of a flux of precipitating electrons whose energy spectrum approximates that measured in the Venus umbra by the PVORPA and reported by *Knudsen and Miller* [1985]. They fitted the spectrum by a Maxwellian distribution with a characteristic energy of 14 eV. We define a "reference spectrum" which is based on the omnidirectional flux of *Knudsen and Miller* [1985]. While the PVORPA measurements and those of the Venera spacecraft [*Gringauz et al.*, 1979] suggest that the fluxes are roughly isotropic and invariant with solar zenith angle at altitudes above 1000 km, the fraction of the electrons that reach the thermosphere is uncertain and depends on the magnetic field configuration, as pointed out by *Cravens et al.* [1983]. We use only that portion of the PVORPA flux that has pitch angles less than 80,° measured from the nadir. A preliminary calculation of the intensity at 1304 Å that would be produced by the electron fluxes measured by *Gringauz et al.* [1979] was done by *Cravens et al.* [1983] using a two-stream method.

We have computed upper and lower limits to the necessary fluxes by modeling the production rates due to precipitating electrons in two ways. We first modeled the energy deposition of the primary electrons using the continuous slowing down approximation. In this calculation we adopted the the empirically determined shape of the differential ionization cross sections reported by *Opal et al.* [1971] and the secondary electrons were assumed to deposit their energy locally and discretely. In the continuous slowing down approximation, errors arise primarily from two sources. First, the electrons are considered to lose their energy continuously rather than discretely. Second, elastic scattering is ignored. For high-energy electrons, such as those associated with terrestrial auroras, the average energy loss is a small fraction of the total energy and the elastic cross sections are strongly forward peaked, so the errors are not serious. The assumption of continuous energy loss causes the electrons to appear to be absorbed over a more narrow altitude region than would be the case if the discrete and variable energy loss were taken into account. As the energy of the primary electrons decreases, the average energy loss becomes a larger fraction of the total energy and the differential elastic scattering cross sections become more isotropic. Consequently, the approximation breaks down for soft electrons. For very low energy electrons, elastic scattering accounts for a larger fraction of the total scattering, so the continuous slowing down approximation predicts that the electrons penetrate much farther than is observed. Because the efficiencies for production of photons are larger for electron energy loss in O than in CO_2, more deeply penetrating electrons will excite the emissions less efficiently, and a larger flux is necessary to produce the observed emissions. The continuous slowing down calculation therefore provides an upper limit to the necessary fluxes. A lower limit to the necessary number flux for a given spectral shape may be found by modeling electron precipitation into pure atomic oxygen, since the excitation efficiencies are largest for this case. Accordingly, our lower limit model is a discrete local energy loss calculation for our reference spectrum of electrons depositing their energy in pure atomic oxygen.

5. RESULTS

In Table 1 we present the optically thin emission rates for 1304- and 1356-Å photons due to a diffuse source of

TABLE 1. Column Excitation Rates ($10^6 cm^{-2} s^{-1}$) Computed Using the Continuous Slowing Down Approximation for Precipitation of Low-Energy Electrons into the Nightside Atmosphere of Venus

	Source			
Emission	$e + O$	$e + CO_2$	$e + CO$	Total
$O(^3S^o)$	24	0.021	0.0045	24
$O(^5S^o)$	5.8	0.066	0.0037	5.8
$O(^1S)$	9.9	8.7	—	19
$CO(a^3\Pi)$	—	29	40	69

The number fluxes and energies are those of our reference spectrum, with angles of incidence assumed isotropic from 0° to 80°.

electrons with an energy distribution determined by our reference spectrum impinging on the top of the atmosphere, which is at 235 km in our model. These values were computed using the continuous slowing down approximation. The major contribution to both emissions is from electron impact on atomic oxygen. The model predicts a 1304-Å photon production rate of 24 $\times 10^6$ $cm^{-2}s^{-1}$, but the observed intensities will be enhanced by radiative transfer. The predicted 1356-Å intensity is about 5.8 R and will not be affected by radiative transfer. An intensity of 1.6 R of 1356-Å emission will be produced by fluxes normalized to 28% of our reference spectrum.

The Cameron band intensities predicted using the continuous slowing down approximation are also shown in Table 1. If the cross section for electron impact dissociative excitation of CO_2 is as large as *Erdman and Zipf* [1983] suggest, the results will be larger by a factor of about 2. The total column excitation rate of about 69 $\times$ 10^6 $cm^{-2}s^{-1}$ is overestimated by the model because the source due to electron impact on CO_2 is sensitive to the depth to which the electrons penetrate. The limit on Cameron band emissions argues against electrons with energies of a kilovolt or more as the source of the emissions. Electrons which penetrate deeply will produce Cameron band emission quite efficiently, regardless of their energy. At least 6% of the energy of fast electrons injected into CO_2 appears as emission in this band system.

Table 1 also shows that the predicted column excitation rate of the green line for our reference spectrum is about 19×10^6 $cm^{-2}s^{-1}$. The green line is produced only slightly more efficiently by electron impact on CO_2 than on O for electrons with energies greater than 18 eV, so the computed intensity is not as sensitive to the depth to which the electrons penetrate as is the Cameron band intensity. The ratio of the emission to that at 1304 or 1356 Å depends on the depth of penetration, however, since the production of $O(^3S^o)$ and $O(^5S^o)$ is much more efficient for electron impact on O than on CO_2, for which the appearance potentials are greater than 20 eV. $O(^1S)$ is also produced by dissociative recombination of O_2^+, although the yield of $O(^1S)$ has been shown recently to be a strong function of the vibrational level of O_2^+ [*Guberman*, 1987]. We predict intensities of 1 − 2 R from this source [*Fox*, 1989].

Ionization will also result from precipitation of electrons with energies greater than 13.6 eV. Table 2 shows the integrated ionization rates computed for our reference electron spectrum, using the continuous slowing down approximation. Figure 2 shows the ratio of $^3S^o$ excitation to ionization for 20-eV electrons. The ratio increases with altitude of absorption because ^3S production is much less efficient for CO_2 than for O. The ratio also varies with electron energy. Figure 3 shows the ratio of $O(^3S^o)$ production to ionization as a function of electron energy for both gases. The values for electron impact on O are much larger than for electron impact on CO_2, so the deeper in the atmosphere the electrons penetrate, the more ionization will be produced for a given $O(^3S^o)$ emission rate. For electron energy loss in pure atomic oxygen, Figure 3 shows that, independent of penetration depth, the ratio rises steeply with decreasing electron energy for energies less than 20 eV, becoming infinite below the ionization threshold at 13.6 eV. Thus softer electrons will produce a higher ratio of excitation to ionization than more energetic electrons; the excess ionization produced by precipitation of electrons with hundreds or thousands of eV is another argument against electrons in this energy range. Table 2 shows the integrated ionization rates produced by our reference spectrum computed using the continuous slowing down approximation. The composition of the nightside ionosphere is similar to that of the dayside, with a high-altitude O^+ peak near 155 km and lower peak due mostly to O_2^+ at 148–150 km [e.g., *Taylor et al.*, 1980, 1982]. Significant variability is seen in the location and magnitudes of the peaks. At times the nightside ionosphere is highly disturbed or disappears completely [*Cravens*, 1982]. The peak value of the median total ion density measured by the ORPA is about 1.5 $\times$ $10^4 cm^{-3}$ [*Knudsen et al.*, 1986]; the average peak in the electron density recorded by the PV orbiter radio occultation experiment is about 1.67 $\times$ $10^4 cm^{-3}$ [*Kliore*, 1979]. The nightside ionosphere is generally believed to be maintained by transport of ions, mainly O^+ from the dayside, at least at times of high solar activity [e.g., *Knudsen et al.*, 1980; *Cravens et al.*, 1983]. *Spenner et al.* [1981] computed the O^+ and O_2^+ profiles that resulted from downward fluxes of O^+ ions. They showed that a flux in the range $1 - 2 \times 10^8 cm^{-2}s^{-1}$ was sufficient to reproduce the observed nightside O^+ and O_2^+ peaks. The

TABLE 2. Integrated Column Ionization Rates for the Major Species in the Nightside Thermosphere of Venus Computed Using the Continuous Slowing Down Approximation for a Homogeneous Diffuse Source of Electrons with Energies of our Reference Spectrum[a]

Species	Ionization Rate, $10^6 cm^{-2}s^{-1}$
O	43
CO_2	23
N_2	5.4
CO	9.5
Total	81

[a]See text.

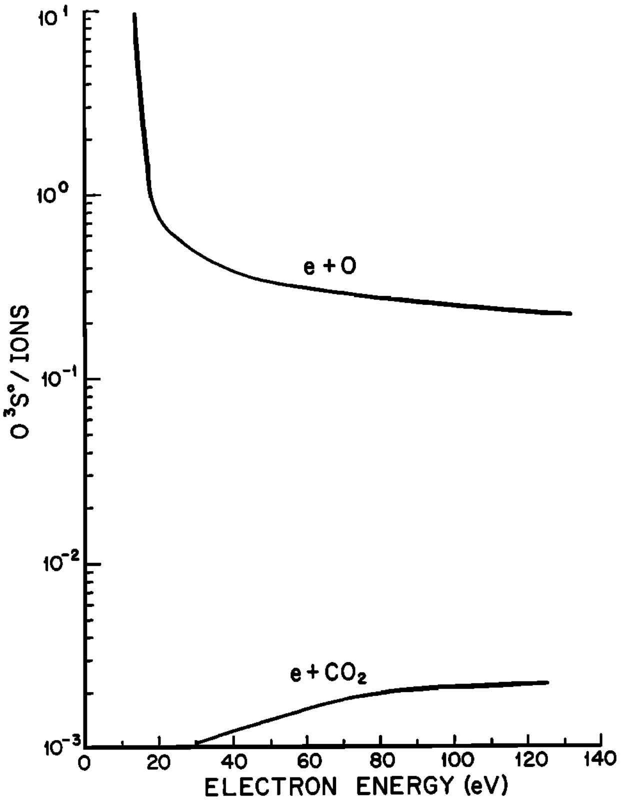

Fig. 3. Computed ratio of O($^3S^o$) excitation to ion production as a function of electron energy for both O and CO_2.

total column ionization rate produced by our auroral reference spectrum is about $8 \times 10^7 cm^{-2}s^{-1}$. Only 28% of the reference spectrum is, however, required to explain the 1356-Å emission. The precipitation of soft electrons would increase the production rate by only 10–20%, and the O_2^+ peak by 10% or less, if the energy is deposited in the region of the peak.

Using the discrete, local loss approximation for electron energy deposition in a pure O atmosphere, the production rates of photons and ions for our reference spectrum scaled to produce the observed 1356-Å emissions are obtained. The results are presented in Table 3 as the "lower limit" case. Table 3 also shows the production rates for the upper limit case, those obtained using the continuous slowing down approximation, scaled to a 1356-Å column production rate of 1.6×10^6 $cm^{-2}s^{-1}$. Values for the deposition of 300-eV electrons are shown for comparison. If the precipitating electrons have a spectral shape similar to our reference spectrum, then a lower limit to the magnitude of the flux necessary to produce the observed emissions (1.6 R of 1356-Å emission) is 8% of our reference spectrum, i.e., of the downward traveling portion of the omnidirectional flux measured by *Knudsen and Miller* [1985]. The ion production rates are about one half those of the upper limit case.

6. CONCLUSIONS

We have presented evidence for precipitation of very soft electrons into the nightside atmosphere of Venus. The main arguments in favor of soft electrons are threefold. First, the high ratio of the 1304- to 1356-Å intensities rules out radiative recombination and precipitation of O^+, the major sources of these emissions in the terrestrial nightglow. Radiative recombination is also unable to produce sufficient intensity. Second, the weakness of the possible Cameron band emission limits the depth to which the electrons can penetrate and therefore limits their energy. Third, the low ion densities also rule out more energetic electrons, which produce a too high ratio of ionization to excitation.

We have modeled the energy deposition of a flux of electrons incident on the atmosphere at 235 km, with a distribution of angle of incidence assumed isotropic from 0° to 80°. Our reference spectrum is the downward traveling portion of the omnidirectional flux reported by *Knudsen and Miller* [1985] from measurements of suprathermal electron fluxes in the Venus umbra. We find that 1.6 R of 1356-Å emission are produced by number fluxes that are factors of 8 – 28% of our reference spectrum. It can be seen that the lower and upper limit photon and ion production rates for our reference spectrum bracket numbers that are consistent with the emission data and observed ion densities. In contrast, for 300-eV electrons,

TABLE 3. Upper and Lower Limits to the Integrated Production Rates of Photons and Ions Compared to the Experimental Values or Upper Limits

	Integrated Production Rates, 10^6 cm^{-2} s^{-1}			
Species	Upper Limit[a]	Lower Limit[b]	300-eV Electrons	Observed[c]
O($^5S^o$)	1.6	1.6	1.6	1.6
O($^3S^o$)	6.4	6.4	5.5	5 – 7
O(^1S)	5.2	2.8	10	< 5
CO($a^3\Pi$)	18	—	32	25 ± 50
Ions	22	12	125	< 50

The values for precipitation of 300 eV electrons are shown for comparison.

[a] Obtained by using the continuous slowing down method in a model atmosphere for our reference spectrum multiplied by 0.28.

[b] Obtained by using the discrete, local loss method for our reference spectrum multiplied by 0.079.

[c] See text.

the production rates of 5577-Å and Cameron band photons and ions are larger for the same emission rate of 1304- and 1356-Å photons and are only marginally consistent with the observations; for higher energies the situation is worse. More detailed calculations, which will employ a more accurate solution of the electron transport equations, including elastic scattering and discrete energy loss, are in progress.

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