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ATOMIC OXYGEN EMISSIONS OBSERVED FROM PIONEER VENUS

R. R. Meier, D. E. Anderson, Jr., and A.I.F. Stewart*

E. O. Hulburt Center for Space Research, Naval Research Laboratory, Washington, DC 20375

*Laboratory for Atmospheric and Space Physics, University of Colorado, Boulder, CO 80309

Abstract. Atomic oxygen features at 1304 and 1356 Å detected by the Orbiting Ultraviolet Spectrometer (OUVS) on Pioneer Venus are compared to theoretical emission models. Limb scans from three orbits of the OI 1304 Å emission were analyzed using an improved model which removes the restrictive assumptions of complete frequency redistribution and isothermal multiple scattering. Data-model comparisons indicate the OI 1304 Å emission rates observed are consistent with an O density 40% of the BUS model. It is also found that the emission at 1356 Å is consistent with the sum of the CO fourth positive band at 1352 Å and the OI doublet at 1356, 1358 Å, if an O density equal to 40% of the BUS model is used to calculate the OI emission rate.

Introduction

The atomic oxygen multiplets at 1304 and 1356 Å can provide valuable diagnostic information on excitation processes and densities in planetary atmospheres. The first positive detection of 1304 Å emission from Venus was made by Moos et al. (1969). This measurement was followed by two additional rocket measurements (Moos and Rottman, 1971; Rottman and Moos, 1973), and the Mariner 10 Fly-by of Venus (Broadfoot et al., 1974). Strickland (1973), in a theoretical analysis, found that the rocket measurements were inconsistent with the then currently accepted theory of the chemistry of CO_2 atmospheres. Anderson (1975) analyzed the Mariner 5 measurements of Rayleigh scattering near twilight and concluded that the excess signal of ~ 600R in the short wavelength photometer (λ > 1250 Å) was consistent with a 10% atomic oxygen model.

More recent measurements of Venus 1304 Å airglow by Bertaux et al. (1981) and Stewart et al. (1979), the Pioneer Venus (PV) mass spectrometer data (von Zahn et al., 1980; Niemann et al., 1980) and satellite drag data (Keating et al., 1980) leave little doubt that a larger concentration of atomic oxygen is present in the Cytherean thermosphere. However, until now, no direct comparison has been made between mass spectrometer measurements and the 1304 Å and 1356 Å orbiting ultraviolet spectrometer (OUVS) airglow observations. The initial analysis of the PV data by Stewart et al. required an unrealistically large contribution to the intensity from dissociative excitation of CO_2 or CO to reproduce the observed 1304 Å limb brightening.

An alternative explanation of the apparent discrepancy between the observed and computed limb brightening is the failure of the assumption of complete frequency redistribution (CFR) at large optical depths. Interpretation of the optically thick 1304 Å triplet emission requires solution of radiation transport equations. Previous work on Earth (Strickland and Donahue, 1970) and Venus (Strickland, 1973; Stewart et al., 1979) assumed CFR for resonant scattering of radiation in an isothermal atmosphere in order to facilitate solution of the transport equations. A recent model developed by Meier and Lee (1982) properly accounts for partial frequency redistribution (PFR) and allows for non-isothermal conditions. This new model provides an explanation for the limb brightening observed in the 1304 Å data without invoking substantial contributions from either CO_2 or CO.

In this paper we analyze a subset of OUVS data which consists of 1304 Å limb scans from within the atmosphere (spacecraft altitude less than 200 km). We also examine a limb scan at 1356 Å, although the data are contaminated by the 1352 Å (14,4) fourth positive band of CO at the limb and on the disc (Durrance, 1981). Important constraints on atomic oxygen densities and photoelectron fluxes can be provided by this type of analysis.

Model Calculations

The 1304 Å Monte Carlo radiative transport model of Meier and Lee (1982) was modified for the atmosphere of Venus. The model allows for partial frequency redistribution in a non-isothermal inhomogeneous atmosphere of multilevel atoms and absorbers. Very large optical depths (10^4-10^6) can be accommodated in reasonable computation times. Two versions of the code allow for the two principal sources of excitation: resonant scattering of the solar 1304 Å flux and photoelectron impact excitation of atomic oxygen. In the former case, the two major inputs to the model are the planetary atmosphere and the solar flux. The morningside Bus atmospheric model (von Zahn et al., 1980) of temperature, and CO_2 and O densities was used but the atomic oxygen density was allowed to vary as an independent parameter. Table 1 gives the model atmosphere, line center optical depths, and the optical depth for pure absorption by CO_2. The total solar 1304 Å flux was measured on 5 June 1979 to be 1.4×10^{10} photons $cm^{-2}s^{-1}$ at Earth, or 2.7×10^{10} photons $cm^{-2}s^{-1}$ at Venus (Mount and Rottman, 1981).

For photoelectron excitation we used the photoelectron flux, F(E) electrons $cm^{-2}s^{-1}eV^{-1}sr^{-1}$ observed by Knudsen et al. (1980) above 200 km. (For the range of O densities used in this work, little variation of the photoelectron flux is expected.) An isotropic photoelectron flux was

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TABLE 1. Bus Model Atmosphere

Z	T	[O]	[CO_2]	τ_1	τ_3	τ_5	τ_{CO_2}
km	K	cm^{-3}	cm^{-3}	(1306.03Å)	(1304.86Å)	(1302.17Å)	
120	183	9.6(+ 10*)	4.00(+ 12)	442	2210	12100	1.63(+ 0)
135	197	1.27(+ 10)	1.32(+ 11)	86.7	403	1880	5.80(- 2)
150	238	2.50(+ 9)	5.30(+ 9)	27.4	119	473	2.83(- 3)
200	275	1.05(+ 8)	1.62(+ 6)	1.4	5.8	22.3	1.00(- 6)

* 9.6 (+ 10)= 9.6 x 10^{10}

assumed. The excitation rate s^{-1} or g-factor was computed from $g = \int\sigma(E)F(E)dE$, where the inelastic cross sections of Stone and Zipf (1974) were used. These cross sections, which peak at 5.3×10^{-17} and 2.5×10^{-17} cm^2 for excitation of $O(^3S)$ and $O(^5S)$, respectively, successfully account for the terrestrial airglow (Meier and Lee, 1982) and aurora (Meier et al., 1982). The 1304 and 1356 Å g-factors obtained are 3.5×10^{-7} and 1.23×10^{-7} s^{-1}, respectively. The altitude profiles of the g-factors come from the photoelectron model of Cravens et al. (1977). The initial column excitation rate is defined as $I_o = \int gn(O)dz$. At 42° solar zenith angle $I_o = 5.2 \times 10^9$ and 1.8×10^9 ph $cm^{-2}s^{-1}$ for 1304 and 1356 Å, respectively using the Bus model O density.

In Figure 1, we illustrate the effects of including partial frequency redistribution in the radiative transport model. The example is for a limb scan, in which the intensity is plotted as a function of local zenith angle from an observing altitude of 170 km at 14.5° solar zenith angle. The Bus model with one half of the atomic oxygen density was used. While there are not large differences between the CFR and PFR solutions for photoelectron excitation (PE), the solar case shows much more limb brightening in the PFR model. With photoelectron excitation, photons are created near line-center, resulting in substantial imprisonment and relatively greater isotropy of the internal radiation field in both the CFR and PFR cases. In the solar source case, scattering of the wings of the broad solar line is important. Also, the scattering process becomes more monochromatic (less frequency redistribution) in the wings. Neither of these latter considerations is incorporated in the CFR model. The net effect of PFR is to enhance the limb brightening because of the changing character of the scattering process in the optically thinner wings. Meier and Lee (1982) and their references discuss additional details of the multiple scattering problem.

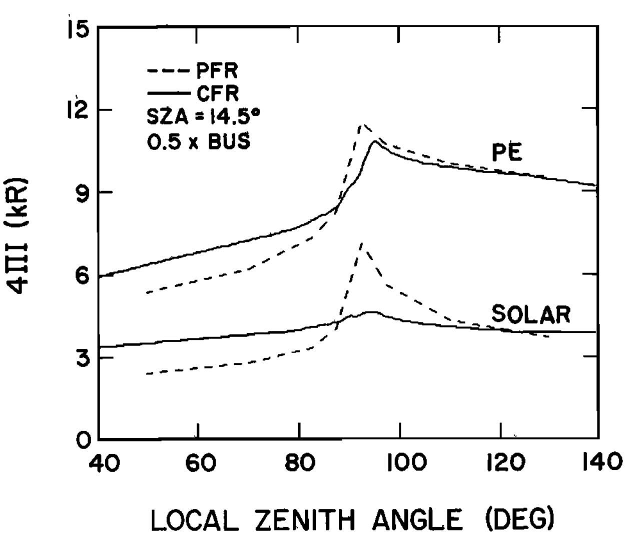

Figure 1. Comparison of theoretical 1304 Å intensities calculated for PFR and CFR plotted as a function of local zenith angle. SOLAR and PE refer to the solar resonance and photoelectron impact excitation sources, respectively.

Experience has shown that the plane parallel model (particularly in the solar case) underestimates the intensity when viewing through long atmospheric slant paths. Even though the opacity is quite large at line center, photons scattered in the wings of the solar line can pass through large columns of atomic oxygen with less attenuation in the optically thin wings of the planetary line. For the present case of an observation within the emitting region at 170 km, the interval of underestimated intensities corresponds to 90-100° local zenith angle. Thus, the PFR intensity in Figure 1 (and the subsequent figures) is low for those viewing angles.

Comparison with Data

Examples of computed limb scans at 14.5° solar zenith angle are shown in Figure 2 for the solar and photoelectron sources. The magnitude of the PE component is much larger than that used previously (Strickland, 1973) due to the larger g-factor and larger O density in the Bus model, especially at lower altitudes. There is not a large change in the brightness of the solar component as the O density is decreased. However, the intensity due to the PE source varies more strongly because the initial excitation rate depends linearly on the product of the O density and the g-factor.

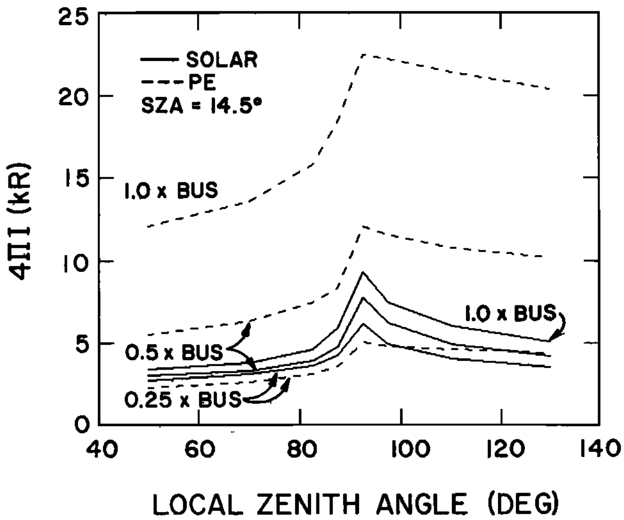

Figure 2. Theoretical 1304 Å intensity calculated using PFR, plotted as a function of local zenith angle.

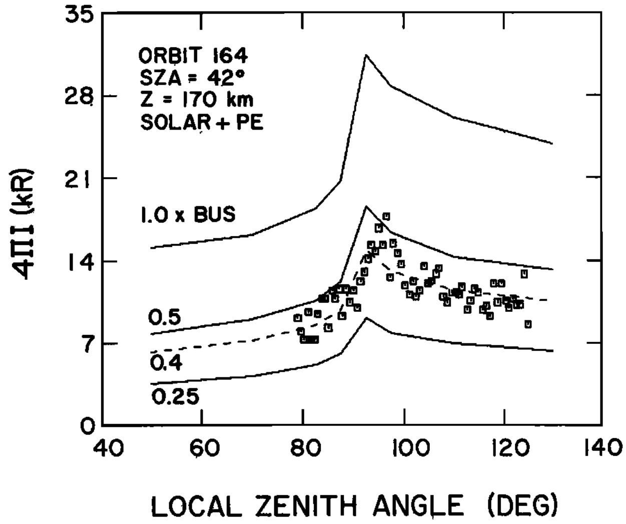

Figure 4. Comparison of data to the total theoretical intensity for four different O density profiles for Orbit 164.

Figures 3 and 4 show comparisons of the models with data taken on orbits 188 and 164. Clearly the combination of the Bus model density and the photoelectron g-factor predicts too much intensity. The model with 40% of the O density reproduces the data reasonably well. (As noted above, the mismatch in the vicinity of 95° local zenith angle is a result of geometric approximations in the plane parallel model.) These conclusions apply also to the analysis of orbit 206 (not shown).

The optical depth of O at 1356 Å is much less than at 1304 Å, so a CFR model is accurate. The OI 1356 Å emission rates were evaluated using spherical geometry. Figure 5 shows a comparison of the 1356 Å data and model for orbit 185 with 0.4 of the O density in the Bus model. The bottom curve represents the CO(14,4) band at 1352 Å. This curve was obtained by scaling an average of six limb scans obtained on orbit 395 of the CO(14,5) band at 1390 Å. The scaling included a sec θ solar zenith angle adjustment from 28° to 19° and the ratio of the g-factors for the two bands (Durrance, 1981). High frequency fluctuations were filtered out for clarity. The middle curve represents the OI 1356 Å emission rate calculations, and the dashed curve represents the sum of the CO and OI emissions. Above the limb the model appears slightly higher than the data and on the disc, slightly lower. The 50% increase in the pure

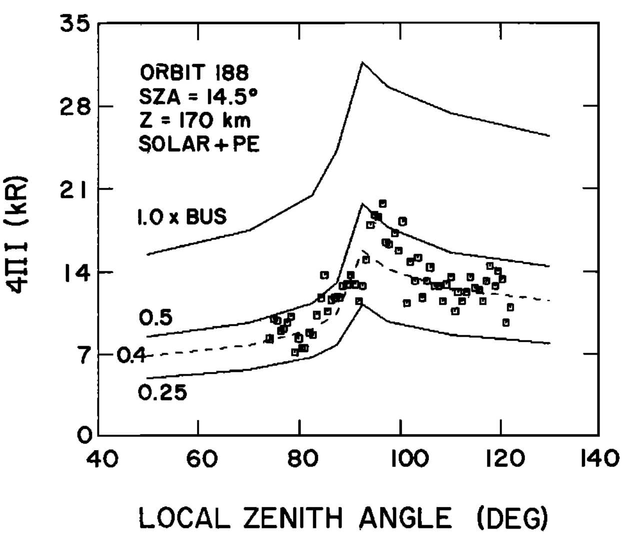

Figure 3. Comparison of data to the total theoretical intensity for four different O density profiles for Orbit 188.

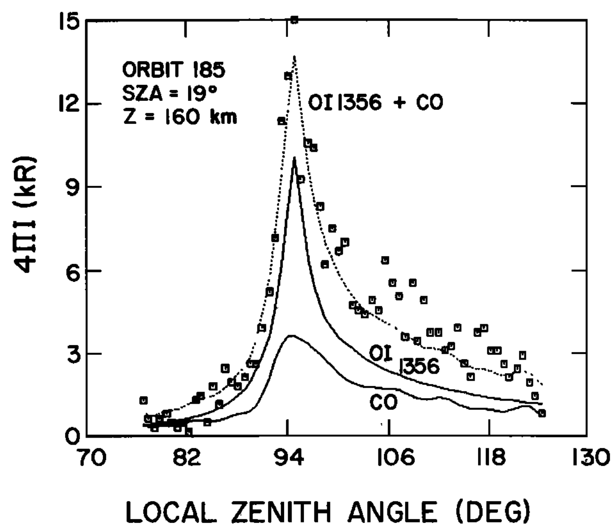

Figure 5. Comparison of data at 1356 Å for Orbit 185 with a theoretical OI 1356 Å emission rate and the expected CO(14,4) fourth positive emission rate. The CO(14,4) emission rate was obtained by scaling of the CO(14,5) data for Orbit 395 using the respective population rates and branching ratios. No correction was made for differences in pure absorption at the two wavelengths, but correction was made for the change in solar zenith angle (~10°).

absorption cross section between 1390 Å and 1352 Å (not included since CO(14,5) data were used) may account for this discrepancy by decreasing the limb to disc ratio (Durrance, 1982). Also, the 1390 Å data are somewhat noisy at smaller zenith angles above the limb.

Discussion

Analyses of both the 1304 and 1356 Å limb scans suggest that an O density, which is 40% of the Bus model, is consistent with the OUVS observations. On the other hand, if the photoelectron flux were different than our scaling to the Knudsen et al. (1980) observations, the factor of 0.4 would change. (A complete photoelectron flux computation for each change in the atmospheric composition is required for internal consistency.) We estimate that the factor of 0.4 is unlikely to be in error by more than about 25%, because of the consistency of the solar and photoelectron contributions with the 1304 Å emission, and the agreement of the model with 1356 Å data.

The atomic oxygen densities in the various models depend upon photochemistry considerations and assumptions about eddy diffusion. There are important differences among the altitude profiles from the Bus model (von Zahn et al., 1980), the orbiting mass spectrometer model (Niemann et al., 1980) and the satellite drag model (Keating et al., 1980). Furthermore, variations of the order of a factor of two in the relative O density are seen in 1304 Å disk images, so that real changes may also contribute to apparent discrepancies.

In summary, we find that 1304 Å and 1356 Å intensities observed on several orbits by the OUVS can be explained with a reduction in the Bus model O density by a factor of 0.4. This corresponds to a 4% atomic oxygen composition at 140 km. Although this value is the same as that used by Stewart et al. (1979), now no significant contributions from dissociative excitation of CO_2 or CO are required to account for the observed limb brightening. Future work on this problem will include the development of a new photoelectron model for the calculation of initial excitation rates and the inclusion of spherical geometry in the multiple scattering code. From the altitude dependence of limb scans, it should be possible to distinguish between different O (and CO) models, both in absolute value and altitude profile.

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