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FAR-ULTRAVIOLET SPECTROSCOPY OF VENUS AND MARS AT 4 Å RESOLUTION WITH THE HOPKINS ULTRAVIOLET TELESCOPE ON ASTRO-2

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ABSTRACT

Far-ultraviolet spectra of Venus and Mars in the range 820–1840 Å at ∼4 Å resolution were obtained on 1995 March 13 and 12, respectively, by the Hopkins Ultraviolet Telescope (HUT), which was part of the Astro-2 observatory on the space shuttle *Endeavour*. Longward of 1250 Å, the spectra of both planets are dominated by emission of the CO fourth positive ($A\,^1\Pi$–$X\,^1\Sigma^+$) band system and strong O I and C I multiplets. In addition, CO Hopfield-Birge bands, $B\,^1\Sigma^+$–$X\,^1\Sigma^+$ (0, 0) at 1151 Å and $C\,^1\Sigma^+$–$X\,^1\Sigma^+$ (0, 0) at 1088 Å, are detected for the first time, and there is a weak indication of the $E\,^1\Pi$–$X\,^1\Sigma^+$ (0, 0) band at 1076 Å in the spectrum of Venus. The *B*–*X* band is blended with emission from O I λ1152. Modeling the relative intensities of these bands suggests that resonance fluorescence of CO is the dominant source of the emission, as it is for the fourth positive system. Shortward of Lyα, other emission features detected include O II λ834, O I λ989, H I Lyβ, and N I λλ1134 and 1200. For Venus, the derived disk brightnesses of the O I, O II, and H I features are about one-half of those reported by Hord et al. from *Galileo* EUV measurements made in 1990 February. This result is consistent with the expected variation from solar maximum to solar minimum. The Ar I λλ1048, 1066 doublet is detected only in the spectrum of Mars, and the derived mixing ratio of Ar is of the order of 2%, consistent with previous determinations.

Subject headings: molecular processes — planets and satellites: individual (Mars, Venus) — ultraviolet: solar system

1. INTRODUCTION

Ultraviolet observations of the atmospheres of Venus and Mars, primarily from flyby or orbiting spacecraft but also from platforms above the terrestrial atmosphere, have played an important role in the study of the composition and structure of the CO_2 atmospheres of these planets. Early spacecraft experiments were broadband photometers that provided information about the spatial distribution of the emissions in the passband but required remote spectroscopic measurements to assure the identity of the emitting species. A thorough review of this subject is given by Paxton & Anderson (1992). Once the emitting species were known, narrowband polychromators were developed and flown on missions such as *Mariner 10* (Broadfoot et al. 1974) and *Venera 11* and *12* (Bertaux et al. 1981), although the interpretation of the data from these instruments was far from unambiguous. With *Mariner 6*, *7*, and *9*, flown to Mars in the early 1970s, and *Pioneer Venus Orbiter*, launched to Venus in 1978, ultraviolet spectrometers were included in the payloads and provided modest spectral resolution. Very little additional spectroscopy, particularly from newer generations of Earth-orbiting observatories such as the *International Ultraviolet Explorer* (*IUE*) and the *Hubble Space Telescope* (*HST*), has been done and is also summarized by Paxton & Anderson (1992). In 1990 February, *Galileo* flew by Venus on its way to Jupiter, and the ultraviolet spectrometers on board made observations that were reported by Hord et al. (1991).

The flight of the Hopkins Ultraviolet Telescope (HUT) on the Astro-2 mission on the space shuttle *Endeavour* in 1995 March provided an opportunity to measure the ultraviolet disk spectra of both Venus and Mars at a spectral resolution (∼4 Å) significantly higher than any of the prior spacecraft observations. Moreover, since the first-order spectral range of HUT extended to wavelengths as short as 830 Å, the observations of Venus enabled the resolution of the identity of the emissions recorded in the narrowband photometric channels of the *Venera 11* and *12* EUV instruments that had been interpreted in terms of analog terrestrial spectra (Bertaux et al. 1981). This paper presents the HUT disk spectra of Venus and Mars together with the spectral identifications and the disk-averaged brightnesses. CO fluorescence in both the *B*–*X* (0, 0) and *C*–*X* (0, 0) Birge-Hopfield bands is identified in both Venus and Mars and shown to be consistent with current models of the CO/CO_2 mixing ratios in the atmospheres of these planets. Several other emissions are definitively identified for the first time.

2. INSTRUMENT AND OBSERVATIONS

The HUT instrument consists of a 0.9 m SiC coated mirror that feeds a prime focus spectrograph with a photon-counting microchannel plate detector and photodiode array readout. Details of the instrument and its performance and calibration are given by Davidsen et al. (1992) and Kruk et al. (1995, 1999). The spectrograph covered 820–1840 Å in first order with a dispersion of 0.51 Å pixel^{-1}. The absolute calibration, monitored several times during the mission by observations of pure hydrogen white dwarfs, is considered accurate to better than 5% at all wavelengths longward of 912 Å (Kruk et al. 1999). For the observations reported here, the 20″ diameter spectrograph aperture was used and was underfilled by both Venus and Mars. The mean spectral resolution was determined by the diameter of the planet—15″.1 for Venus and 12″.2 for Mars—and the illuminated fraction, giving a resolution of 4–4.5 Å over the entire spectral band.

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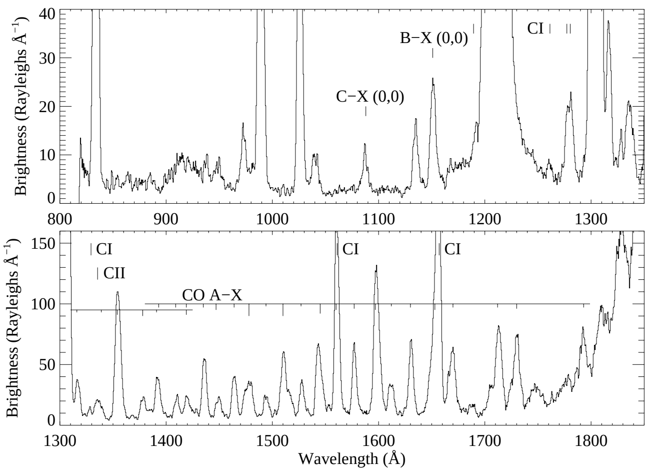

FIG. 1.—HUT spectrum of Venus obtained on 1995 March 13 beginning at UT 05:31. The integration time was 1080 s, and the data have been smoothed with a running mean over three 0.51 Å wide bins. Emissions of carbon and CO are indicated. The positions of the strongest solar Lyα and O I λ1304 pumped CO fourth positive bands are indicated separately. The spectrum also contains emission from the daytime terrestrial atmosphere.

At the time of the Astro-2 mission, Venus was at a solar elongation slightly inside the 45° solar avoidance constraint of HUT. Nevertheless, since the performance of HUT and the supporting Instrument Pointing System was nominal after 10 days of the mission, it was decided to attempt to observe Venus at a solar elongation of 40°.2. This observation occurred at UT 05:25 on 1995 March 13 and produced no adverse heating of the telescope assembly nor appreciably elevated scattered light. A second observation was made about 9 hr later. Both observations were made during orbit day.

A spectrum of Venus from the first observation is shown in Figure 1. It includes not only the desired disk spectrum of Venus but also contributions from the terrestrial day airglow. The Earth's dayglow includes H I Lyα, Lyβ, and Lyγ as well as emissions of atomic and ionic oxygen and atomic nitrogen that are also present in the dayglow of Venus. Fortuitously, it took longer to acquire and lock onto Venus during the second observation, so there are $\sim$500 s of background data taken during this observation that correspond to approximately the same viewing geometry (with respect to the Earth's atmosphere) as when Venus was in the aperture during the first observation. This is illustrated in Figure 2, which shows the count rates for two of the brighter emissions, O I λ1304 and N I λ1200, as a function of time for both observations. Figure 3 shows two 516 s integrations, Venus + Earth and Earth alone. The difference spectrum is then the true spectrum of Venus, and this spectrum is used to derive the disk brightnesses for the O I, N I, and H I emissions listed in Table 1. For the other emissions, the longer exposure spectrum of Figure 1 is used. The error bars given in Table 1 are 1 σ statistical uncertainties in the observed counts within a given emission feature.

TABLE 1

DISK BRIGHTNESSES OF VENUS AND MARS

Species	Wavelength (Å)	Venus (R)	Mars (R)
O II	834	91 ± 41	7 ± 4
Ar I	867	<4.0[a]	<1.7[a]
H I Lyγ	973	25 ± 18	3.6 ± 2.0[b]
O I	989	45 ± 33	9.4 ± 2.6
H I Lyβ + O I	1026	115 ± 23	36 ± 5[b]
O I	1040	21 ± 7	3.7 ± 1.1
Ar I	1048	<1.9[a]	2.4 ± 1.0
Ar I	1066	<2.4[a]	5 ± 2
N I	1134	35 ± 11	~1.4
N I	1200	77 ± 16	~12
O I	1304	2800 ± 110	280 ± 10
O I	1356	605 ± 28[c]	50 ± 5[c]
C I	1561	800 ± 27[c]	57 ± 7[c]
C I	1657	1500 ± 50[c]	110 ± 30[c]
CO *C*–*X* (0, 0)	1088	44 ± 6	3.4 ± 1.7
CO *B*–*X* (0, 0) + O I	1152	128 ± 10	6.3 ± 1.9
CO *A*–*X* (0, 1)	1597	754 ± 30	52 ± 8

[a] 1 σ statistical limit.
[b] Includes terrestrial nightglow contribution.
[c] Includes blended CO *A*–*X* band.

Mars was observed during orbit night beginning at UT 22:33 on 1995 March 12. The HUT spectrum of Mars is shown in Figure 4, and the derived disk brightnesses are also listed in Table 1.

3. DISCUSSION

The HUT observations of Venus and Mars represent the highest quality spectra, in terms of both spectral resolution and instrument sensitivity, obtained to date for the ultraviolet below 1800 Å. The present discussion will focus on the identification of spectral features and comparison with previous observations. Future work will concern the modeling of these spectra in terms of current atmospheric models based on in situ measurements made over the past two decades (Paxton & Anderson 1992).

3.1. *Carbon Monoxide and Atomic Carbon*

Below 2000 Å, the ultraviolet dayglow of Venus and Mars is dominated by emissions of carbon monoxide and carbon (Durrance 1981; Fox 1992). From both Figure 1 and Figure 4 we see that a large number of individual bands of the CO fourth positive ($A\,^1\Pi$–$X\,^1\Sigma^+$) system are clearly identified. When compared with calculated optically thin fluorescence efficiencies ("*g*-factors") for this system (Tozzi, Feldman, & Festou 1998), the effect of the 20-fold increase in the mean CO_2 absorption cross section from 1700 to 1500 Å (Yoshino et al. 1996) is clearly seen in the enhancement of the weaker longer wavelength bands. In addition, the CO is optically thick in that the expected strong $(v', 0)$ bands are particularly weak, implying that photons are being pumped out of these bands into other members of the (v', v'') progression by repeated absorption and reemission. Bands of the $(14, v'')$ and $(9, v'')$ progressions, pumped by solar H I Lyα and O I λ1304, respectively (Kassal 1976; Durrance 1981; Wolven & Feldman 1998), are clearly seen, particularly the (14, 3) band at 1316 Å and the (9, 2) band at 1378 Å, both of which are free of blending by other CO bands or atomic emissions. The strong emission feature at $\sim$1355 Å is a blend of O I λ1356 and the CO (14, 4) band at 1352 Å, the strongest in the solar Lyα pumped progression, with most of the observed emission due to CO.

Other observed features include the CO Hopfield-Birge bands, $B\,^1\Sigma^+$–$X\,^1\Sigma^+$ (0, 0) at 1151 Å and $C\,^1\Sigma^+$–$X\,^1\Sigma^+$ (0, 0) at 1088 Å, which are identified for the first time in the spectra of Venus and Mars. They appear to be present in the *Galileo* EUV spectrum of Venus (Hord et al. 1991) but

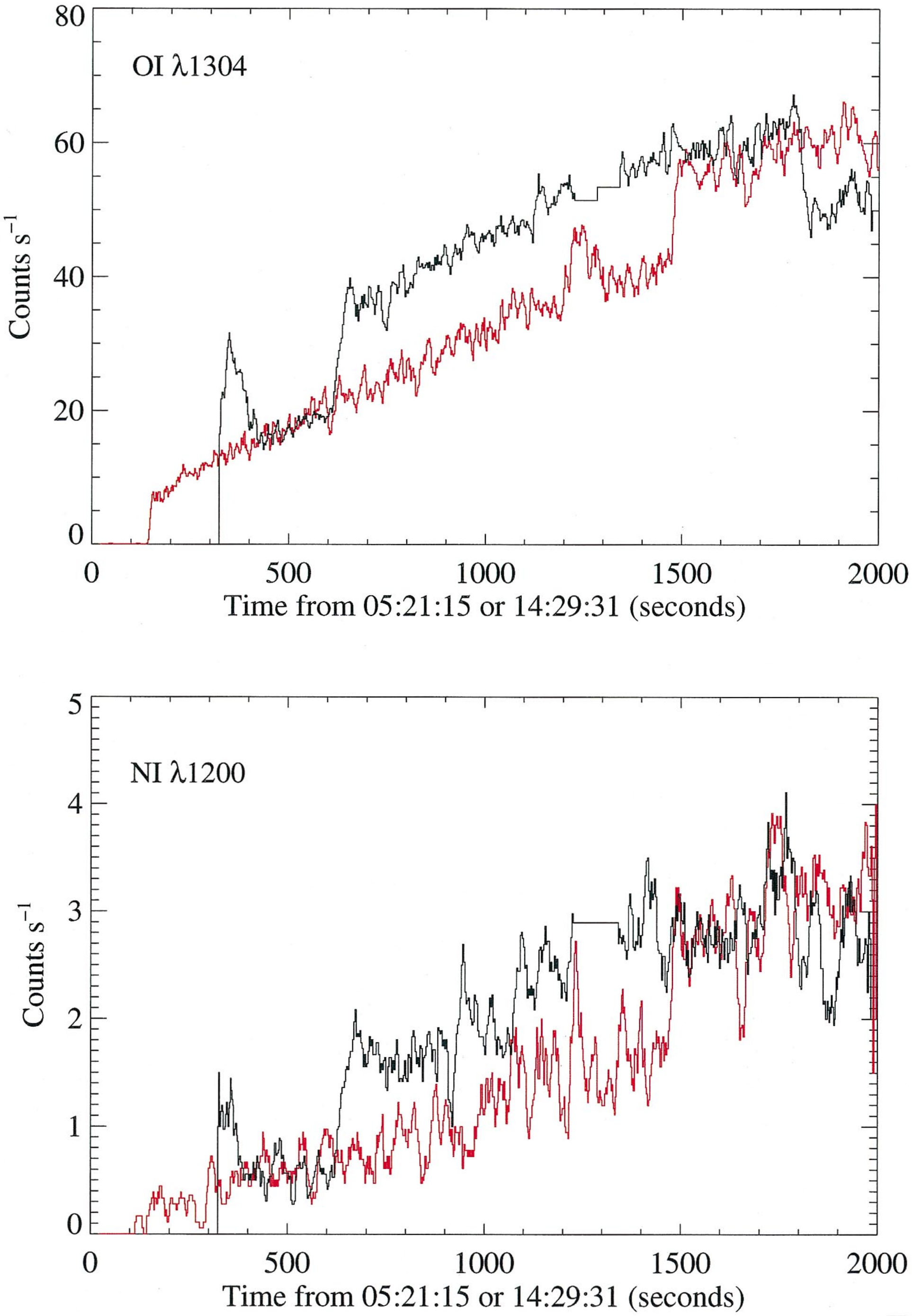

FIG. 2.—Time variation of the O I λ1304 and N I λ1200 emissions from the two Venus observations on 1995 March 13. The black line begins at UT 05:21, and the red line begins at UT 14:39. The separation of terrestrial and Cytherean emissions is clearly illustrated.

cannot be positively identified at the 30 Å resolution of that instrument. The *B–X* band is blended with emission from O I λ1152. At first sight, the relative intensities of these bands and the similarity with low-energy electron impact laboratory spectra (Kanik, James, & Ajello 1995) suggest that excitation of CO by photoelectrons is a major source of the emission. However, as is shown in § 3.2, it is possible to account for the observed brightness of the *C–X* (0, 0) band solely on the basis of resonance fluorescence of solar ultraviolet radiation. No other bands of either of these systems is detected, as expected from the strongly diagonal nature of both band systems and the high predissociation fractions for $v' \geq 1$ (Eidelsberg et al. 1991). There is also a weak indication of the $E\,^1\Pi$–$X\,^1\Sigma^+$ (0, 0) band at 1076 Å in the spectrum of Venus.

In addition to the principal C I multiplets at 1561 and 1657 Å, a number of other atomic carbon lines are identified in Figure 1. Some of these—the multiplets at 1329, 1280, 1277 and 1261 Å—were identified in the *Mariner 6* and *7* spectra of the upper atmosphere of Mars (Barth et al. 1971). In addition, we identify emission from C II λ1335 blended with the (9, 1) CO fourth positive band at 1339 Å, indicating the presence of C^+ in the ionospheres of Venus and Mars.

It is interesting to compare the ratio of these emissions

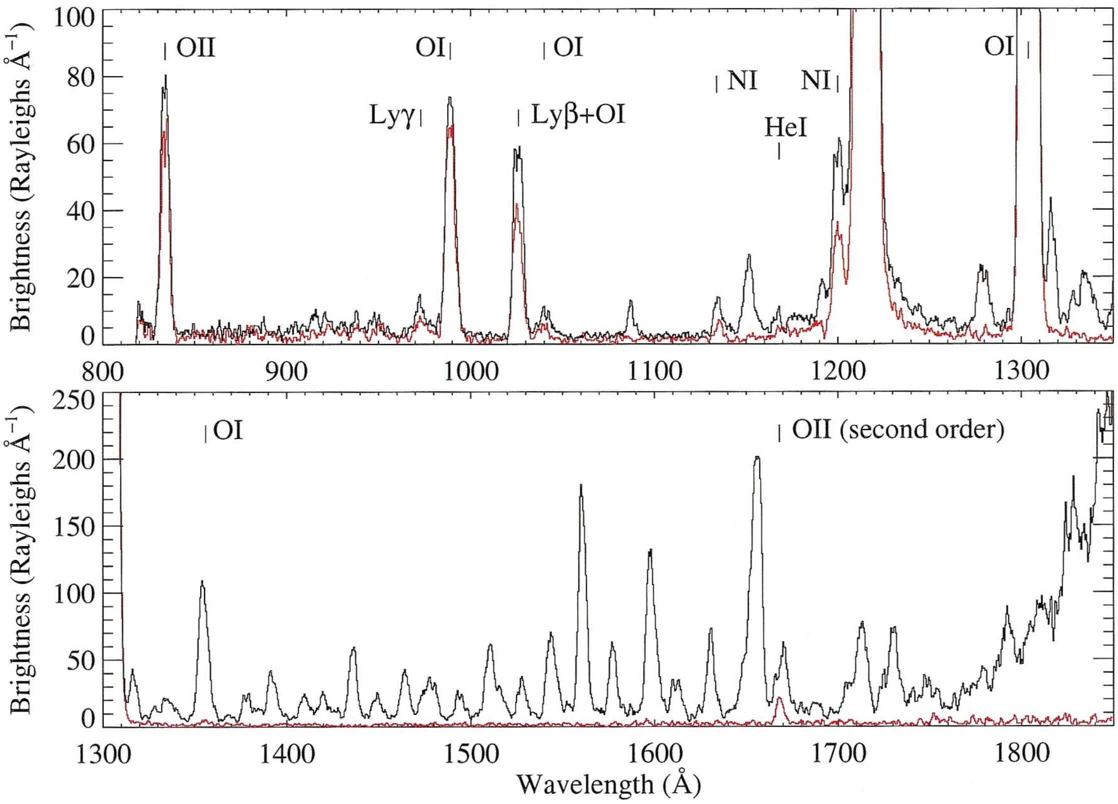

FIG. 3.—Spectra of Venus (with terrestrial background) and background alone (*red line*) corresponding to 516 s of data beginning at $\sim$700 s in Fig. 2. The data have been smoothed with a running mean over three 0.51 Å wide bins. Emissions common to both Venus and Earth are indicated.

between Venus and Mars. From Table 1 we find that for all of the CO bands and the atomic carbon emissions this ratio is ≈ 15, whereas the ratio of solar flux is 5.3. This had been previously noted by Moos (1974) and reflects the lower CO/CO_2 mixing ratio on Mars compared to that on Venus.

3.2. *The* CO *Hopfield-Birge Bands*

Emissions from CO shortward of Lyα appear in the form of the Hopfield-Birge bands $C\,^1\Sigma^+ – X\,^1\Sigma^+$ (0, 0) at 1088 Å and $B\,^1\Sigma^+ – X\,^1\Sigma^+$ (0, 0) at 1151 Å. The *B*–*X* band is blended

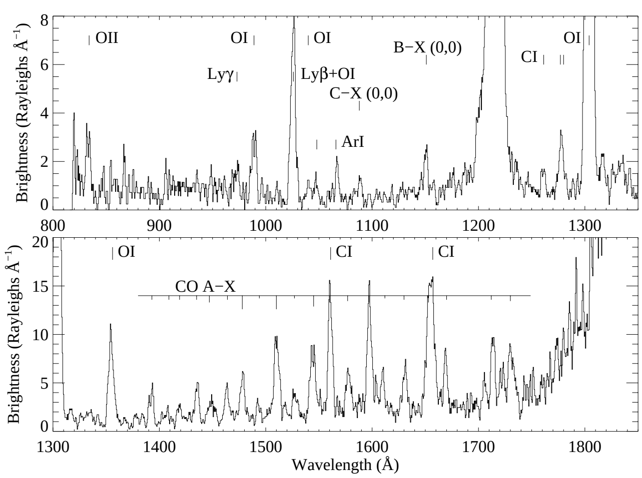

FIG. 4.—HUT spectrum of Mars obtained on 1995 March 12 beginning at UT 22:33. The integration time was 1444 s, and the data have been smoothed with a running mean over three 0.51 Å wide bins. This spectrum was obtained during orbit night and does not show the strong terrestrial emissions (with the exception of H I) seen in the Venus spectra.

with emission from O I λ1152. The intensities of these bands are not consistent with optically thin emission. Since no other bands of these systems were detected, a scenario of resonant scattering was assumed. The band is scattered from a column of CO defined by the optical thickness due to pure absorption by CO_2,

$$\mathscr{N}_{\rm CO} = \int_0^\infty N_{\rm CO}(z) e^{-\tau_{\rm CO_2}(z)}\, dz \;,$$

and computed using the number densities of the Venus International Reference Atmosphere (VIRA) model (Keating et al. 1985) and the model of Fox & Dalgarno (1979) for Mars, with CO_2 absorption coefficients taken from Nakata, Watanabe, & Matsunaga (1965).

To test the applicability of these atmospheric profiles to modeling the CO emission, we compared the column density derived from the (14, 3) band at 1316 Å of the fourth positive system ($A\,^1\Pi – X\,^1\Sigma^+$) and that derived using the above relationship. The brightness of the (14, 3) band (in rayleighs) in the optically thin limit is

$$B = g(14, 3)\mathscr{N}_{\rm CO} \times 10^{-6}$$

and measured to be 146 ± 25 R in the Venus spectrum. The *g*-factor for Lyα absorption in the (14, 0) band was evaluated using the oscillator strength recommended by Eidelsberg et al. (1999), 1.80×10^{-5}, based on their recent work and the work of Jolly et al. (1997) and Stark et al. (1998), together with the solar Lyα line profile from Lemaire et al. (1998) normalized to UARS/SOLSTICE measurements of the solar Lyα flux (Woods et al. 1996) made at the time of the Astro-2 mission. Branching ratios were taken from Kurucz (1976). We thus derive a CO column density of

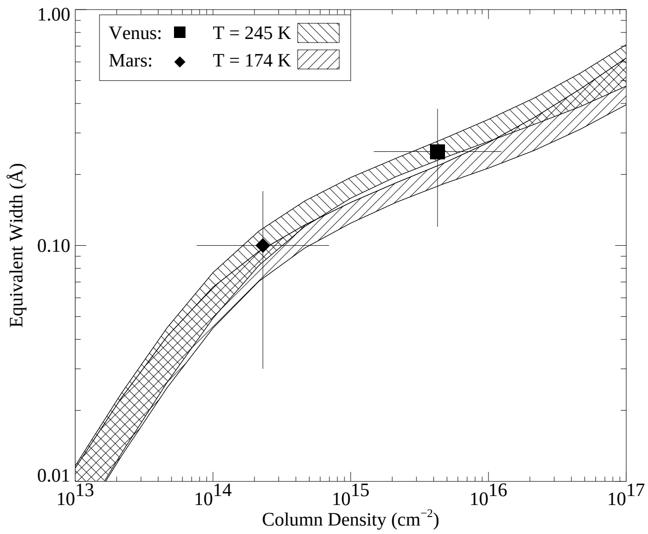

FIG. 5.—Theoretical curves of growth for the $C\,^1\Sigma^+ - X\,^1\Sigma^+$ (0, 0) transition of CO. The cross-hatched areas represent the bounds of experimental values for the absorption oscillator strength. Data points for Venus and Mars are shown as determined from the HUT data and atmospheric models from Keating et al. (1985) and Fox & Dalgarno (1979).

3.4×10^{16} cm^{-2}, whereas the VIRA model predicts a column of 5.2×10^{16} cm^{-2}. The close agreement, considering the uncertainty in all of the parameters involved in the g-factor calculation, supports our use of these model atmospheres.

Following the treatment of Liu & Dalgarno (1996), a theoretical curve of growth was calculated using the rates of emission from the excited electronic state of each rovibrational transition to determine the expected omnidirectional brightness, $4\pi\mathscr{I}$, in rayleighs. The equivalent width of the band is then defined as $EW = 4\pi\mathscr{I}/\pi\mathscr{F}_{\odot}$, where $\pi\mathscr{F}_{\odot}$ is the incident solar flux determined from HUT observations of the Moon and the lunar albedo as given by Henry et al. (1995). To compute the curve of growth, we used a density-weighted temperature average to characterize both the kinetic and rotational temperatures. Including transitions through rotational quantum number $J = 30$, we produced curves of growth for both Venusian and Martian C–X (0, 0) emissions as shown in Figure 5. The curves appear as bands with the upper edge corresponding to an oscillator strength of 1.177×10^{-1} (Chan, Cooper, & Brion 1993) as recommended by Morton & Noreau (1994), and the lower corresponding to 6.19×10^{-2} (Eidelsberg et al. 1991).

The emissions appear to be consistent with resonant scattering from the upper atmospheres of both planets. As with the A–X bands, the observed ratio of the emissions between Venus and Mars is ≈ 15, whereas the ratio of the solar flux is 5.3. This difference reflects the lower CO mixing ratio on Mars as well as a reduced thermospheric temperature at $\tau_{CO_2} = 1$. Curves of growth for B–X (0, 0) ($f = 6.5 \times 10^{-3}$; Stark et al. 1999) were determined in the same manner as for C–X (0, 0), and the equivalent width corresponding to the appropriate column density was used to calculate an expected 28 ± 10 R and 1.8 ± 0.8 R of emission from Venus and Mars, respectively. Subtracting these from the total observed emission results in O I λ1152 emission of about 100 ± 14 R for Venus and 4.5 ± 2.0 R for Mars, most likely due to direct electron impact excitation of atomic oxygen.

3.3. *Argon and Helium*

Argon emission at 1048 and 1066 Å is detected only in the spectrum of Mars (Fig. 4). The upper limits for Venus are consistent with the known argon mixing ratio of less than 100 parts per million. Note that Ar I λ1066 appears brighter than Ar I λ1048, even though the fluorescence efficiency of the 1048 Å line is 3.5 times higher than that of the 1066 Å line.[2] This is the result of the higher CO_2 absorption cross section at 1048 Å. Using the approach of Bertaux et al. (1981), we find an argon mixing ratio of 0.016 and 0.021 from the brightness of the 1048 and 1066 Å lines, respectively. Considering the uncertainties in both the data and the fluorescence efficiencies, this result is in good agreement with the known value of 0.016 for Mars (Barth 1985). The Ar I multiplets near 867 Å are not detected on either Mars or Venus.

Figure 3 also shows the presence of He I λ584 in second order at 1168 Å in the spectrum of Venus. The second-order effective area of HUT was only ~ 1 cm^2, compared to the peak first-order effective area of 25 cm^2 near 1150 Å (Kruk et al. 1999), so that the derived brightness has a large statistical uncertainty, 300 ± 200 R. Nevertheless, this result is

[2] The Ar I g-factors are evaluated using solar fluxes inferred from the HUT observations of sunlight reflected from the Moon (Henry et al. 1995).

TABLE 2

COMPARISON OF HUT OBSERVATIONS OF VENUS WITH *Venera 11/12* AND *Galileo*

Species	Wavelength (Å)	HUT (R)	*Venera 11/12*[a] (R)	*Galileo*[b] (R)
He I	584	300 ± 200	275	200 ± 60
O II..................	834	91 ± 41	156	180 ± 60
Ar I..................	867	<4.0[c]	<55	
O I	989	45 ± 33		130 ± 30
H I Lyβ + O I......	1026	115 ± 23		270 ± 60
Ar I..................	1048	<1.9[c]	<130	
O I	1304	2800 ± 110	6200	
CO A–X	1500[d]	965 ± 110	2400	
C I...................	1657	1500 ± 50	12500	

[a] Bertaux et al. 1981. Average of both missions.
[b] Hord et al. 1991.
[c] 1 σ statistical limit.
[d] 45 Å wide band centered at 1500 Å includes (1, 0) and (2, 0) bands.

consistent with prior measurements of He I emission from *Venera* and *Galileo*.

3.4. *Other Emissions*

Shortward of Lyα, other emission features detected include O II λ834, O I λ989, H I Lyβ, and N I λλ1134 and 1200. The atomic nitrogen features are identified for the first time, although, as above, N I λ1134 appears to be present in the *Galileo* EUV spectrum of Venus. The disk brightnesses for both Venus and Mars are listed in Table 1. While there are many weak features present in the spectrum of Venus between 840 and 1000 Å, most of these are of terrestrial origin, primarily of atomic and singly ionized nitrogen, and the contributions from Venus are at least an order of magnitude lower than those reported by Stern et al. (1996) from a sounding rocket observation.

3.5. *Comparison with Venera 11/12 and Galileo*

Table 2 gives a comparison of the HUT measurements of the disk of Venus with those reported from *Venera 11* and *12* (Bertaux et al. 1981) and, more recently, *Galileo* (Hord et al. 1991). The *Galileo* flyby of Venus was in 1990 February, during solar maximum, while the HUT observations in 1995 March were at a time approaching solar minimum. This is reflected in the roughly factor of 2 difference between the two sets of data, which must be considered excellent agreement. The *Venera 11/12* measurements were made in 1978 December, also approaching solar maximum. Thus, a similar argument accounts for the difference in O I and O II brightnesses between HUT and *Venera*. However, it appears that the *Venera* channels at wavelengths longward of 1500 Å were severely contaminated by scattered light.

4. CONCLUSION

We have obtained far-ultraviolet spectra of Venus and Mars in the range 820–1840 Å at ∼4 Å resolution with the HUT during the Astro-2 mission in 1995 March. The spectra of both planets are rich in CO band emission, some of the systems being identified for the first time, together with strong O I and C I multiplets. Resonance fluorescence is identified as the dominant source of the CO emission. Atomic nitrogen emissions are also identified in the spectrum of Venus, while the Ar I doublet is seen only in the spectrum of Mars. These spectra, obtained at higher spectral resolution than was possible from earlier flyby and orbiting missions to these planets, elucidates and extends the earlier spectroscopic measurements and should provide guidance in the interpretation of the far-ultraviolet spectra obtained during the recent *Cassini* flyby of Venus (Stewart et al. 1999).

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