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# Mariner 9 Ultraviolet Spectrometer Experiment: Structure of Mars' Upper Atmosphere

A. I. STEWART, C. A. BARTH, AND C. W. HORD

*Department of Astro-Geophysics and Laboratory for Atmospheric and Space Physics, University of Colorado, Boulder, Colorado 80302*

AND

A. L. LANE

*Jet Propulsion Laboratory, Pasadena, California, 91103*

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Analysis of 18 observations of the limb intensity profile of the CO Cameron bands in the Martian airglow shows that the equivalent subsolar zenith intensity, $I_{CAM}$, is related to the Ottawa 10.7cm radio flux index, $F_{10.7}$, by the expression

$$I_{CAM} = 0.062(74 + F_{10.7})\text{kR},$$

with a correlation coefficient of 0.80. Comparison of averaged limb intensities of the $CO_2^+$ doublet and the Cameron bands on four favorable occasions is consistent with the intensities being directly proportional, in the ratio 0.24:1. The mean of 18 Cameron band topside scale heights is 17.8km, corresponding to an exospheric temperature of 325°K, and the largest and smallest values observed differ by 9.5km. These observations are in accord with theoretical predictions within the uncertainties in the latter. However, the solar EUV flux used in these predictions is a factor of at least two too weak to produce the electron densities measured by the S-band occultation experiment.

## Introduction

A primary objective of the Mariner 9 ultraviolet spectrometer studies of the Martian airglow was to observe variations in the intensity and topside scale height of airglow emission features, and to examine the source or sources of these variations. A general survey of the ultraviolet airglow spectrum is given in an accompanying paper (Barth *et al.*, 1972a), and some early results showing significant variations in the scale height of the $CO(a\text{–}X)$ Cameron bands have been reported elsewhere (Barth *et al.*, 1972b). The present paper is concerned with measurements of the Cameron bands and of the $CO_2^+(\tilde{B}\text{–}\tilde{X})$ doublet, and their relationship to the solar extreme ultraviolet (EUV) flux and to the temperature in the Martian upper atmosphere.

The atmosphere of Mars is essentially pure $CO_2$ at all relevant altitudes. Because CO is very scarce (Kaplan *et al.*, 1969), the Cameron bands are produced by dissociative excitation of $CO_2$ (McConnell and McElroy, 1970; Barth *et al.*, 1971; Stewart, 1972). This may occur in photodissociation,

$$CO_2 + h\nu \rightarrow CO(a\,^3\Pi) + O, \quad \lambda < 1080\,\text{Å} \quad (1)$$

or, after photoionization,

$$CO_2 + h\nu \rightarrow CO_2^+ + e, \quad \lambda < 902\,\text{Å} \quad (2)$$

it may occur in photoelectron impact,

$$CO_2 + e \rightarrow CO(a\,^3\Pi) + O + e, \quad E > 11.5\,\text{eV} \quad (3)$$

or in dissociative recombination,

$$CO_2^+ + e \rightarrow CO(a\,^3\Pi) + O. \quad (4)$$

Although spectral variation in the EUV flux may affect one of these processes more than another, the total Cameron band intensity produced should depend more or less directly on the total EUV flux. (Only dissociative recombination, process (4), is subject to variations from another source, namely the extent to which $CO_2^+$ ions are converted to $O_2^+$ by reaction with O before recombining.) The emission scale height in the topside of the airglow layer (where the atmosphere is optically thin to the EUV radiation) should be equal to the neutral $CO_2$ scale height, and it is, therefore, a measure of the temperature at the top of the atmosphere. The $CO_2^+$ doublet is produced by photoionization of $CO_2$ (Dalgarno *et al.*, 1970):

$$CO_2 + h\nu \rightarrow CO_2^+(\tilde{B}\,^2\Sigma_u^+) + e, \quad \lambda < 687\,\text{Å}. \quad (5)$$

Because of the destruction of $CO_2^+$ ions by reaction with O, fluorescent scattering of sunlight contributes little to the intensity of the doublet; therefore, this intensity should be a direct measure of the total EUV flux below 687 Å.

The observations of the CO Cameron bands and of the $CO_2^+$ doublet described here were obtained on 18 occasions between November 28 and December 21, 1971, and on four occasions between December 15 and 21, 1971, respectively. They were generally made near local Martian noon, either near 50°S latitude with a solar zenith angle of 34° or in south equatorial latitudes with a solar zenith angle of between 7 and 23°. During the longer period the Ottawa solar 10.7 cm radio flux ($F_{10.7}$) varied from 109 to 145, in units of $10^{-22}$ W/m²/Hz.

## Data Processing

Figure 1 shows the average, after noise removal, of 120 of the most intense spectra obtained in the long wavelength (1900–3400 Å) channel of the instrument during November and December, 1971. The brightest emissions are the CO Cameron bands at 1900–2700 Å and the $CO_2^+$ doublet at 2890 Å, with maximum limb intensities typically in the ranges 200–300 amd 50–75 kR, respectively. Figure 2 shows a sample Cameron band limb profile,

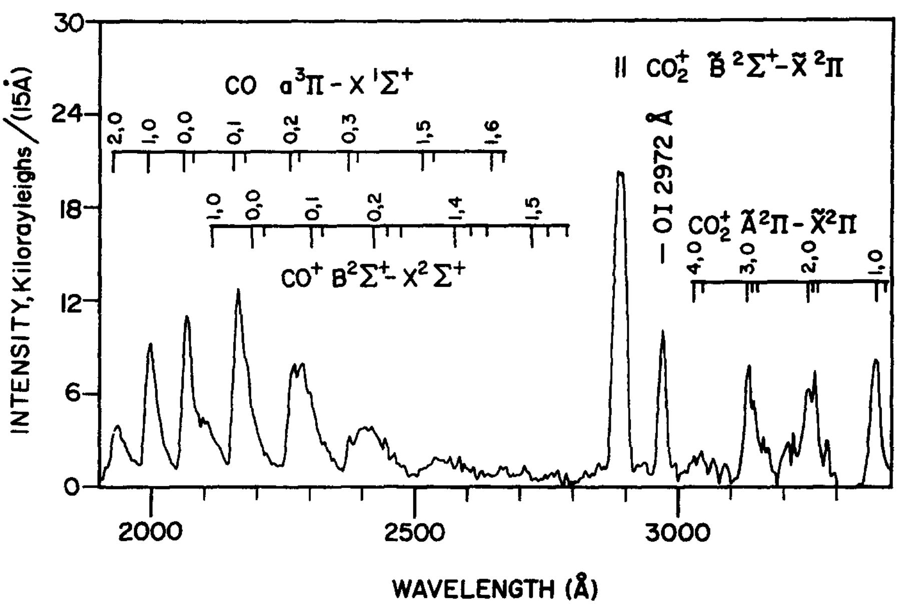


FIG. 1. Average of 120 spectra of the Martian airglow obtained during November and December, 1971. The Cameron ($a\,^3\Pi$–$X\,^1\Sigma$) bands of CO, the first negative ($B\,^2\Sigma^+$–$X^2\Sigma^+$) bands of $CO^+$, the $CO_2^+$ doublet ($\tilde{B}\,^2\Sigma^+$–$\tilde{X}\,^2\Pi$) and Fox–Duffendack–Barker ($\tilde{A}\,^2\Pi$–$\tilde{X}\,^2\Pi$) bands, and the OI($^3$P–$^1$S) transauroral line at 2972 Å are identified.

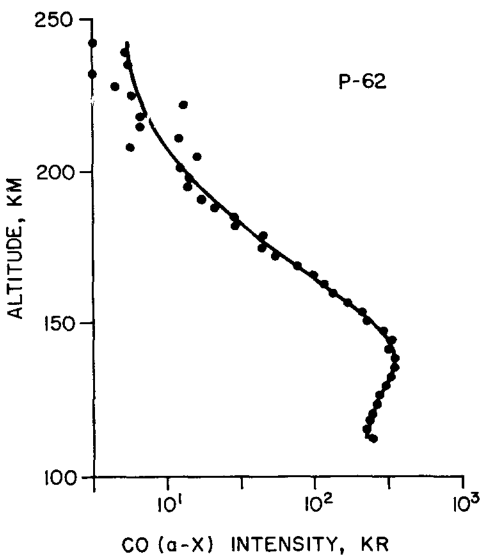


FIG. 2. Limb intensity profile of CO Cameron bands measured on orbit 62, December 15, 1971. The dots are the data points and the line is the best-fit synthetic profile described in the text.

obtained on the 62nd orbit, December 15, 1971. It exhibits the limb brightening and the exponential decrease of intensity in the topside which are expected for an optically thin emission. A small amount of residual noise is evident above 200km.

Two aeronomically important quantities, the equivalent zenith intensity and the topside emission scale height, were extracted from the observed limb profiles by comparing them with simple synthetic profiles. An analytic representation of a theoretical Cameron band volume emission rate profile was found which contained, as parameters, the altitude, maximum emission rate, and topside scale height. The synthetic limb profiles were then generated by integrating along the instrument's line of sight, making allowance for the range and for the size and alignment of the field of view. A constant residual noise level was introduced as a fourth parameter, and a best fit to the observed profile was then obtained by a least-squares method. This process yielded the topside scale height directly, and the equivalent zenith intensity was found by integrating the best-fit emission rate profile over altitude. Figure 2 includes the best-fit synthetic limb profile.

In the case of the $CO_2^+$ doublet, the signal-to-noise ratio was less favorable and the model emission profiles less reliable. However, on each of four occasions, the geometry of the experiment was such that between 15 and 25 spectra of large and nearly equal intensity were obtained, and reliable doublet-to-Cameron-band intensity ratios were found by spectral averaging. These ratios form the basis of the discussion of the $CO_2^+$ doublet in this paper.

## RESULTS AND DISCUSSION

Because the excitation of the Cameron bands results directly from the absorption of solar EUV photons by an essentially pure $CO_2$ atmosphere, the zenith intensity should be proportional to the total EUV flux and to the cosine of the solar zenith angle. In the absence of direct measurements of the EUV, the airglow intensity may be compared with $F_{10.7}$, since there is a large body of direct and circumstantial evidence that the EUV and $F_{10.7}$ are correlated. In Fig. 3, 18 equivalent zenith Cameron band intensities ($I_{CAM}$) are plotted against $F_{10.7}$ after removal

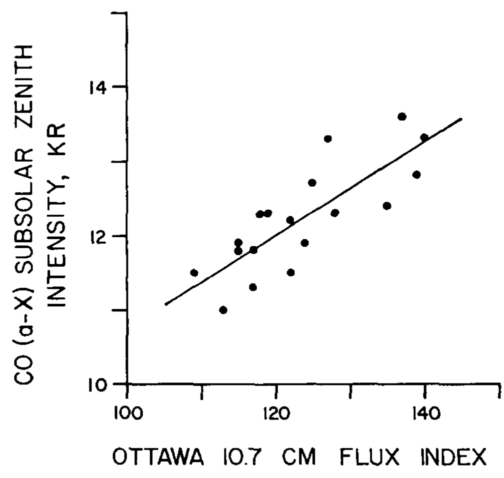


FIG. 3. Equivalent Cameron band subsolar zenith intensities obtained from 18 limb intensity profiles obtained between November 28 and December 21, 1971, plotted against $F_{10.7}$.

of the dependence on solar zenith angle. A linear regression yields the expression

$$I_{CAM} = 0.062(74 + F_{10.7})\text{kR}, \quad (6)$$

with a correlation coefficient of 0.80. For comparison, application of a linear regression to 15 measurements of the summed intensities of five strong solar EUV lines (Hall *et al.*, 1969) yields:

$$\Sigma\Phi_{EUV} = 6.5 \times 10^7(115 + F_{10.7}) \text{ photons cm}^{-2}\text{sec}^{-1}, \quad (7)$$

with a correlation coefficient of 0.62. The similarity of these two expressions circumstantially confirms the postulated dependence of $I_{CAM}$ on the EUV flux. The difference in the constant terms in (6) and (7) may be qualitatively understood in terms of the contribution to $I_{CAM}$ of other strong solar lines, which Hall *et al.* did not include in their sum but which appear to have a stronger, nonlinear dependence on $F_{10.7}$. It may be noted here that Prinz and Meier (1971) find that the terrestrial $N_2$ Lyman–Birge–Hopfield band airglow, which is excited by photoelectron impact and, therefore, depends on the EUV flux, also appears to be well correlated with $F_{10.7}$.

The sun does not, in general, present the same face to the Earth and Mars; and allowance for this should be made when comparing airglow measurements on Mars with solar indices measured from the Earth. For the present observations, the Earth "lagged" 2.7 days behind Mars, but the maximum correlation between $I_{CAM}$ and $F_{10.7}$ is obtained if a lag of 1.4 days is assumed (the value used in Figs. 3 and 5 and Eq. 6). The difference may indicate that temporal variations in solar active regions are of comparable importance to the heliographic variations which give rise to the well-known 27-day cycle.

Figure 4 is a plot of the $CO_2^+$ doublet intensity against the CO Cameron band intensity on four favorable occasions. The best-fit straight line is not significantly different from a straight line through the origin, as would be expected since the emissions are in large part excited by the same solar photons. The mean ratio is 0.24:1, and the implied mean subsolar zenith intensity of the doublet is 3.0kR, in good accord with the prediction of 3.5kR due to photoionization by Dalgarno *et al.* (1970).

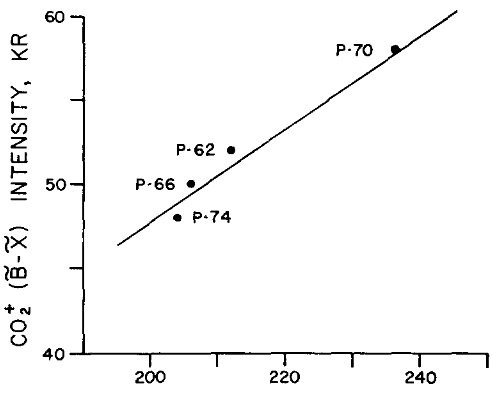


FIG. 4. Averaged $CO_2^+$ doublet limb intensities plotted against averaged CO Cameron band limb intensities for four favorable observations between December 15, 1971 (Orbit 62) amd December 21, 1971 (Orbit 74).

Figure 5 shows the measured Cameron band topside scale height plotted against $F_{10.7}$. The quantities are clearly uncorrelated. Atmospheric thermal structure calculations of the type described by Stewart (1972) predict that this scale height should

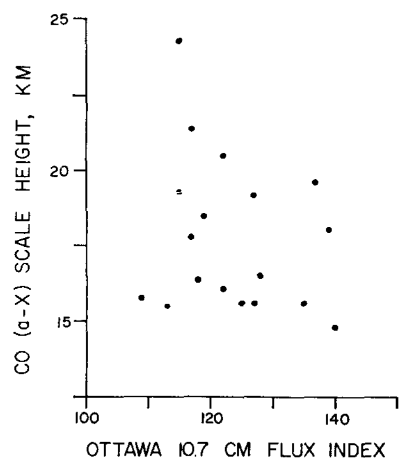


FIG. 5. Topside Cameron band scale heights, obtained from limb intensity profiles as described in the text, plotted against $F_{10.7}$.

vary by no more than about 2 km as $F_{10.7}$ varies between 109 and 145. The observed variations are much larger than this, and it seems likely that the temperature in the upper atmosphere of Mars is strongly affected by processes not directly related to solar activity. Heating by dissipation of atmospheric gravity waves and cooling by turbulent heat transport are obvious possibilities, as is the case on Earth (Hines, 1965; Johnson, 1966). The great Martian dust storm of 1971 was in progress throughout the period covered by the present observations, and the activity in the lower atmosphere may well have affected the upper atmosphere. The average scale height from Fig. 5 is 17.8 km, and the largest and smallest are 24.3 and 14.8 km; the corresponding exospheric temperatures are 325, 445 and 270 K, respectively.

The most striking difference between the present results from Mariner 9 and the corresponding results from Mariner 6 and 7 in 1969 is the apparent reduction in the Cameron band intensities by a factor of about 2.5. Changes in the level of solar activity, and in ionospheric composition (which might eliminate dissociative recombination, process (4), as an excitation mechanism), might account for a 40% reduction. It is believed that the remaining discrepancy may be ascribed to the superior calibration of the Mariner 9 instrument in the 1900–2500 Å region. The Mariner 9 intensities are readily accounted for by theoretical calculations (similar to those of Stewart, 1972) which employ the EUV flux reported by Hinteregger (1970), together with the laboratory results of Lawrence (1972) on process (1), of Ajello (1971) and Wells *et al.* (1972) on process (3), and of Wauchop and Broida (1972) on process (4). The Mariner 9 $CO_2^+$ doublet intensities are very similar to those measured by Mariner 6 and 7; this similarity is consistent with the small reduction expected theoretically on the grounds of lower solar activity and implied by the slight decrease in the observed electron densities (Fjeldbo *et al.*, 1970; Kliore *et al.*, 1972).

The theoretical picture with regard to the temperatures in the Martian upper atmosphere is less satisfactory than with regard to the airglow intensities. Stewart (1972) was able to account for the Mariner 6 and 7 exospheric temperature of 350°K by allowing for the large amounts of energy apparently being radiated away in the ultraviolet airglow. The Mariner 9 results suggest that this energy loss was overestimated by a factor of about two, and the appearance of this excess energy as heat increases the theoretical exospheric temperature by about 70°K. This problem might be resolved if the electronic energy of $O(^1D)$, which is abundantly produced by photodissociation of $CO_2$ and by dissociative recombination of $O_2^+$ and perhaps $CO_2^+$, is not converted to kinetic energy upon quenching, as has been generally assumed. If a substantial fraction is instead converted to vibrational energy in $CO_2$ and subsequently radiated away in infrared transitions, the theoretical temperatures can be brought back into agreement with the observations.

A final problem persists through all discussion of the Martian upper atmosphere. The solar EUV flux of Hinteregger (1970), which adequately accounts for the airglow intensities and exospheric temperatures, is too weak to account for the electron densities observed by Mariner 6 and 7 (and 9) by a factor of between 2 and 3, according to whether the major ion is $O_2^+$ or $CO_2^+$ (Stewart, 1972). No satisfactory resolution of this inconsistency is in sight.

## Acknowledgments

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## References

Ajello, J. M., (1971). Emission cross sections of $CO_2$ by electron impact in the interval 1260–4500 Å. II. *J. Chem. Phys.* **55**, 3169–3177.

Barth, C. A., Hord, C. W., Pearce, J. B., Kelly, K. K., Anderson, G. P., and Stewart, A. I. (1971). Mariner 6 and 7 ultraviolet spectrometer experiment: Upper atmosphere data. *J. Geophys. Res.* **76**, 2213–2227.

BARTH, C. A., STEWART, A. I., HORD, C. W., AND LANE, A. L. (1972*a*). Mariner 9 ultraviolet spectrometer experiment: Mars airglow spectroscopy and variations in Lyman alpha. *Icarus* **17**, 457–468.

BARTH, C. A., HORD, C. W., STEWART, A. I., AND LANE, A. L. (1972*b*). Mariner 9 ultraviolet spectrometer experiment: Initial results. *Science* **175**, 309–312.

DALGARNO, A., DEGGES, T. C., AND STEWART, A. I. (1970). Mariner 6: Origin of Mars ionized carbon dioxide ultraviolet spectrum. *Science* **167**, 1490–1491.

FJELDBO, G., KLIORE, A. J., AND SEIDEL, B. (1970). The Mariner 1969 occultation measurements of the upper atmosphere of Mars. *Radio Sci.* **5**, 381–386.

HALL, L. A., HIGGINS, J. E., CHAGNON, C. W., AND HINTEREGGER, H. E. (1969). Solar-cycle variation of extreme ultraviolet radiation. *J. Geophys. Res.* **74**, 4181–4183.

HINES, C. O. (1965). Dynamical heating of the upper atmosphere. *J. Geophys. Res.* **70**, 177–184.

HINTEREGGER, H. E. (1970). The extreme ultraviolet solar spectrum and its variations during a solar cycle. *Ann. Geophys.* **26**, 547–554.

JOHNSON, F. S. (1966). The atmosphere of Mars. Paper presented at the 7th meeting of COSPAR, Vienna, May 10–19, 1966.

KAPLAN, L. D., CONNES, J., AND CONNES, P. (1969). Carbon monoxide in the Martian atmosphere. *Astrophys. J.* **157**, L187–192.

KLIORE, A. J., CAIN, D. L., FJELDBO, G., SEIDEL, B. L., AND RASOOL, S. I. (1972). Mariner 9 S-band occultation experiment: Initial results on the atmosphere and topography of Mars. *Science* **175**, 313—317.

LAWRENCE, G. M. (1972). Photodissociation of $CO_2$ to produce $CO(a^3\Pi)$. *J. Chem. Phys.* **56**, 3435–3441.

MCCONNELL, J. C., AND MCELROY, M. B. (1970). Excitation processes for Martian dayglow. *J. Geophys. Res.* **75**, 7290–7293.

PRINZ, D. K., AND MEIER, R. R. (1971). OGO-4 observations of the Lyman–Birge–Hopfield emission in the day airglow. *J. Geophys. Res.* **76**, 6146–6158.

STEWART, A. I. (1972). Mariner 6 and 7 ultraviolet spectrometer experiment: Implications of the $CO_2^+$, CO and O airglow. *J. Geophys. Res.* **77**, 54–68.

WAUCHOP, T. S., AND BROIDA, H. P. (1972). Lifetime and quenching of $CO(a^3\Pi)$ produced by recombination of $CO_2$ ions in a helium afterglow. *J. Chem. Phys.* **56**, 330–332.

WELLS, W. C., BORST, W. L., AND ZIPF, E. C. (1972). Production of $CO(a^3\Pi)$ and other metastable fragments by electron impact dissociation of $CO_2$. *J. Geophys. Res.* **77**, 69–75.

## DISCUSSION

MAROV: The correlation you find between the ultraviolet intensity and the solar 10.7-cm flux is interesting, but the heating is done by solar radiation shorter than 300 Å, so your correlation is not necessarily indicative of the true heating efficiency.

T. DONAHUE: Is the 1304-Å emission variation correlated?

STEWART: No, we believe that it is independent.