

# Empirical Determination of Heating Efficiencies in the Mars and Venus Atmospheres

RICHARD W. STEWART AND JOSEPH S. HOGAN

*Institute for Space Studies, Goddard Space Flight Center, NASA, New York, N. Y.*

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In the course of a theoretical analysis of Mariner data on the Mars and Venus ionospheres, we have arrived at an empirical method for determining the heating efficiency  $\epsilon$  of extreme solar ultraviolet radiation interacting with a carbon dioxide atmosphere. The heating efficiency is defined as the fraction of absorbed solar ultraviolet radiation that is locally converted into heat. Although the heating efficiency can be calculated from existing estimates of molecular reaction rates and cross sections, the available knowledge of these parameters is incomplete, and a separate empirical confirmation of the theoretical values is of considerable interest.

The usefulness of this method for determining  $\epsilon$  rests upon the fact that the rate of decrease in electron density above the ionization peak is sensitive to variations in  $\epsilon$ . The temperature distribution at lower levels and the electron-ion recombination coefficient also affect the ionization profile, but their influence on the plasma densities well above the peak ionization is considerably smaller than the effect of changes in  $\epsilon$ .

The analysis of the ionospheric data in terms of heating efficiency has been carried out for both Mars and Venus. Our confidence in the empirically determined value is strengthened by the fact that similar results for  $\epsilon$  are obtained independently for the two planets. The best value for  $\epsilon$ , from combination of our analyses of Mars and Venus data, is  $0.31 \pm 0.10$ .

The present investigation makes use of a theoretical program which combines a method for calculating the thermal structure of the lower and middle atmosphere (Hogan, 1968), with a technique for determining the distribution of temperature, neutral density and ionization in the upper atmosphere (Stewart, 1968). The union of these programs determines atmospheric properties from the ground to the exosphere for any planet with a  $\text{CO}_2$  atmosphere, with allowance for changes in the solar flux, the acceleration of gravity, and the temperature and the pressure at the planetary surface. Profiles of temperature and neutral density are obtained from an iterative solution of the hydrostatic and energy balance equations, including energy transfer by radia-

tion, convection and conduction. Once the thermal structure of the atmosphere has been determined, the electron and ion densities are computed using a method described by Stewart (1968). A similar program for determining atmospheric structure has been developed by McElroy (1969). Differences in the results are discussed below.

Our radiative transfer calculation for the lower atmosphere employs an improved version of the  $15\mu$   $\text{CO}_2$  band model described earlier by Prabhakara and Hogan (1965). Frequency resolution in this model has been refined by an order of magnitude to obtain a more accurate representation of the  $\text{CO}_2$  absorption contour in the  $15\mu$  region, with integration now being performed using  $5 \text{ cm}^{-1}$  intervals. Both Lorentz and Doppler line-broadening mechanisms are included in the calculations,

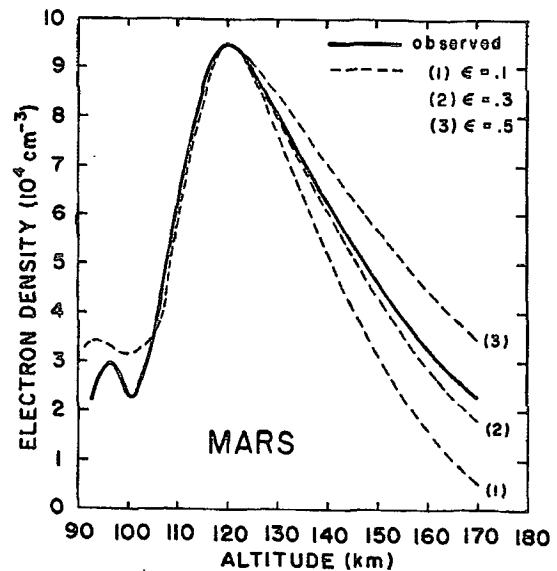


FIG. 1. Electron density profiles in the Martian atmosphere for several values of assumed photoionization heating efficiency. Below the level of peak ionization only one calculated electron density profile is shown, corresponding to  $\epsilon=0.3$ .

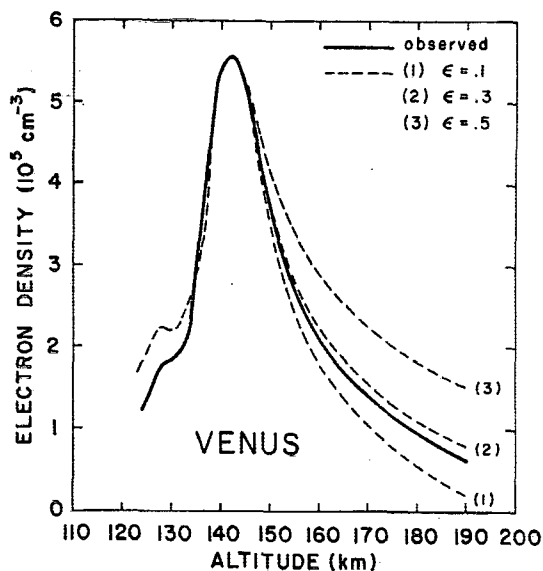


Fig. 2. Electron density profiles in the Venus atmosphere for several values of assumed photoionization heating efficiency. The altitude scale is based upon an assumed radius of 6052 km for Venus. Below the level of peak ionization only one calculated electron density profile is shown, corresponding to  $\epsilon=0.3$ .

as are departures from local thermodynamic equilibrium due to vibrational relaxation of  $\text{CO}_2$ .

In the upper atmosphere, we solve the heat conduction equation with a solar ultraviolet ( $\lambda < 1700 \text{ \AA}$ ) heat source, taking into account cooling by radiative de-excitation of the atmospheric constituents at high levels.

For these calculations we have assumed pure  $\text{CO}_2$  atmospheres at all altitudes for both Mars and Venus, choosing boundary conditions appropriate to the occultation points (Kliore *et al.*, 1965, 1967). On Mars these conditions are a ground temperature of 160K, a ground pressure of 5 mb and a solar zenith angle of  $67^\circ$ . On Venus, boundary temperature, pressure and solar zenith angle were assumed to be 237K, 30 mb and  $33^\circ$ , respectively.

For these conditions, the distributions of temperature, neutral density and electron density on Mars and Venus were computed for values of the heating efficiency  $\epsilon$  ranging from 0.1–0.5. In Figs. 1 and 2 we compare electron density profiles calculated for Mars and Venus, respectively, with the actual distributions of ionization observed by Mariners 4 and 5. Both figures illustrate the sensitive connection between the electron density above the peak and the photoionization heating efficiency. In these calculations, the electron density distribution for each  $\epsilon$  was normalized to the observed peak electron density by a minor adjustment of  $\alpha_{\text{CO}_2^+}$ , the dissociative recombination coefficient for  $\text{CO}_2^+$  ions with electrons.

The separate values of heating efficiency for Mars and Venus which provide best agreement with the iono-

spheric observations are  $0.35 \pm 0.1$  and  $0.27 \pm 0.08$ , respectively. The probable error in the result for Mars is based upon the uncertainties in the electron distribution derived from Mariner 4 (Fjeldbo and Eshleman, 1968). Since no error estimates are available for the Mariner 5 data on the Venus ionosphere, we have assumed that the percentage probable error in the Venus data is the same as in the case of Mars.

These values for  $\epsilon$  may be compared with the values calculated on theoretical grounds by Henry and McElroy (1968). Their results are wavelength-dependent, and range in magnitude from 0.43 to 0.71 at different wavelengths. We have investigated the effects of a wavelength-dependent heating efficiency on the calculation, and find no significant variation in the results as a consequence of wavelength-dependence. Therefore, for comparison with Henry and McElroy, we have simply weighted their values by the incident solar ultraviolet flux in the appropriate wavelength band. The weighted average of the Henry and McElroy results for  $\epsilon$  is 0.59, in comparison with our empirically determined value of 0.31. In a separate paper (Hogan and Stewart, 1969) we discuss the effects of these values of  $\epsilon$  on the exospheric temperatures of Mars and Venus.

This analysis also yields a value for  $\alpha_{\text{CO}_2^+}$  in the Mars and Venus ionospheres. A determination of  $\alpha_{\text{CO}_2^+}$  is possible since the magnitude of the peak ionization density is principally dependent of the values of  $\alpha_{\text{CO}_2^+}$  and the solar EUV flux. The probable error in the EUV solar flux determination is quoted by Hinteregger *et al.* (1965) at  $\pm 30\%$ , while the error margin in the observed peak ionization density on both Mars and Venus is approximately  $\pm 20\%$  (Kliore *et al.* 1965, 1967). The uncertainty in our determination of  $\alpha_{\text{CO}_2^+}$  is thus  $\pm 50\%$ . This error estimate does not allow for additional uncertainties in the correlation between the solar EUV and the decimeter fluxes, which was the basis for extrapolating the Hinteregger data to the times of the Mariner 4 and 5 occultations. With this qualification, we find that the observed peak electron densities in both Venus and Mars ionospheres are reproduced within the limits of uncertainty reported by the Mariner experimenters (Kliore *et al.*, 1965, 1967) if  $\alpha_{\text{CO}_2^+} = 1.7 \pm 0.9 \times 10^{-7} \text{ cm}^3 \text{ sec}^{-1}$ . This result for  $\alpha_{\text{CO}_2^+}$  may be compared with the value of  $3.8 \pm 0.5 \times 10^{-7} \text{ cm}^3 \text{ sec}^{-1}$  measured in the laboratory by Weller and Biondi (1967).

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