NOTES AND CORRESPONDENCE

Temperature Distributions in the Lower Atmosphere of Mars from Mariner 6 and 7 Radio Occultation Data

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10 July 1970

1. Introduction

The Mariner occultation experiments (Kliore *et al.*, 1965, 1969) and ground-based spectroscopic observations (Gray, 1966; Belton and Hunten, 1966) have now established that the atmospheric pressure at the surface of Mars is close to 10 mb and that CO_2 is the major constituent of the atmosphere. Its thinness and composition suggest that the Martian atmosphere should approach radiative equilibrium close to the ground, with diurnal adjustments of the temperature in near-surface layers (Gierasch and Goody, 1968). Since several features of the preliminary temperature profiles deduced from the Mariner 6 and 7 occultation experiment by Kliore *et al.* (1969) were in sharp contradiction with theoretical predictions, we have carried out an independent re-analysis of the Doppler residual data, employing more refined estimates of the Mariner trajectories. Revised profiles of temperature have been obtained for the Mariner 6 and 7 entry and exit cases. Because certain aspects of these derived profiles bear important implications for theoretical studies of the lower atmosphere of Mars, we feel that their publication, prior to a complete discussion of the data reduction techniques (Hogan *et al.*, 1970), is warranted.

The revised temperature profiles shown in Fig. 1 differ from those published earlier in two important

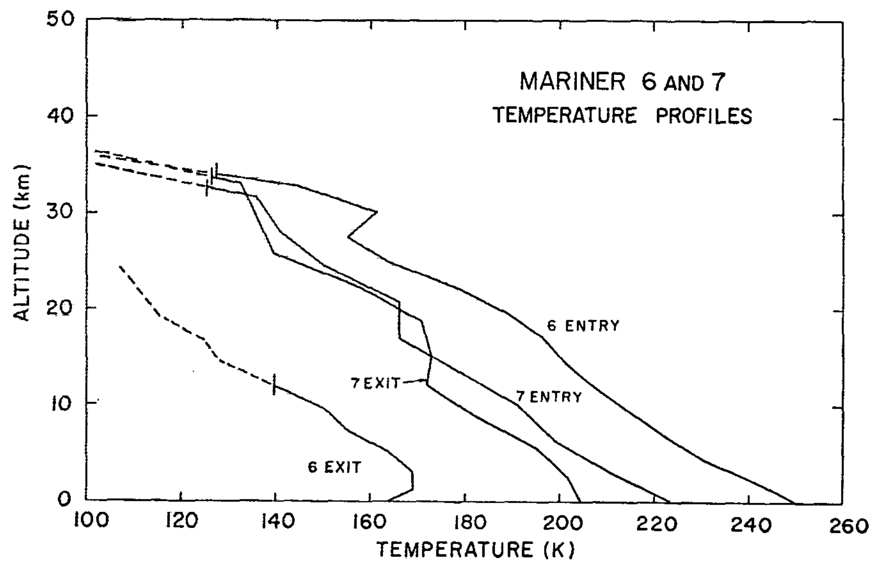

FIG. 1. Vertical temperature distributions in the atmosphere of Mars at the four occultation points of Mariners 6 and 7. Coordinates and local time of measurements are given in Table 1. The temperature near the ground should be accurate within 5K while near 30 km the estimated error is ±20K.

TABLE 1. Summary of results.*

	Latitude	Longitude	Local time	Surface pressure (100% CO_2)	Surface temperature (100% CO_2)
Mariner 6 Entry	3.7N	355.7E	15^h45^m	6.0 mb	250K
Mariner 6 Exit	79.3N	87.1E	22^h10^m	7.6 mb	164K
Mariner 7 Entry	58.2S	30.3E	14^h30^m	4.9 mb	224K
Mariner 7 Exit	38.1N	211.7E	3^h10^m	7.5 mb	205K

* A preliminary error analysis indicates formal errors no greater than 0.5 mb in surface pressure and no greater than 5K in surface temperature.

ways: 1) the Mariner 6 entry profile no longer exhibits a warm, isothermal stratosphere; and 2) the new air temperature at the surface, when compared with radiometric measurements of ground temperature (Munch, private communication; Neugebauer *et al.*, 1969), suggests a sizeable boundary discontinuity.

2. Data analysis

The Mariner 6 and 7 Doppler residual data (Station 12), which constitute the input to the present analysis, are characterized by unexpectedly large quasi-linear drifts, during the periods before and after occultation of the spacecraft by Mars. Superimposed on strong linear components are sinusoidal oscillations with periods ranging from 370 sec in the case of the Mariner 7 exit residuals to 1895 sec in the case of the Mariner 7 entry. Although these drifts can probably be explained as due to the combined effects of oscillator drifts and uncertainties in the Mariner 6 and 7 trajectories, their origin is not completely understood at the present time (Fjeldbo *et al.*, 1970). But because these effects extend far into pre-encounter and post-encounter periods, they cannot be related to atmospheric characteristics on Mars.

In order to deduce the properties of the Martian atmosphere from the Doppler residuals, these unwanted effects were removed by subtracting a least-squares fitted bias curve of the form $A+Bt+C\sin\omega t+D\cos\omega t$. Although visual inspection indicates a noise level of about 0.5 Hz in the residual data, a curve of the above type can be fitted to the data with a standard deviation of less than 0.1 Hz in all four cases.

The Doppler residuals, corrected in the above manner, were integrated over time and combined with the trajectory data to obtain the change in phase path as a function of the planetocentric distance along the perpendicular to the line joining the centers of Earth and Mars. The phase data were then corrected for refractive bending of the signal by the Martian atmosphere, and were subsequently inverted using the technique described by Fjeldbo and Eshleman (1968). Thus, the distribution of refractivity as a function of the radial distance of the point of closest approach of a ray from the center of the planet was derived.

The radial distribution of refractivity was then used to derive radial distributions of temperature and pressure, assuming that the Martian atmosphere is composed entirely of CO_2, and that the hydrostatic law is applicable. The resulting profiles of temperature for the four occultation points on Mars are shown in Fig. 1. Table 1 shows the coordinates, the local time, and the most probable values of surface pressure and temperature corresponding to each point. Rather than indicating uncertainty boundaries, we have shown only individual curves in the figure. A discussion of the errors involved in the data reduction is presented elsewhere (Hogan *et al.*, 1970). For the assumed composition, the temperatures near the ground should be accurate within ± 5K, and the surface pressure accurate within ± 0.5 mb. However, the profiles should be viewed as less certain at higher levels with an estimated error of ± 20K near 30 km. The few sharp features in evidence in the figure are due to noise transferred from the residuals to the refractivity data. No data smoothing was performed in the course of the present analysis.

3. Discussion

It is interesting to compare the temperature profiles obtained here with those derived in the preliminary analysis of the occultation data. The greatest difference is found in the case of the Mariner 6 entry profile. This profile was the most controversial of those presented earlier, suggesting the presence of a warm, relatively isothermal region in the middle atmosphere. In the present analysis this feature does not appear (Rasool[1]). Therefore, we conclude that it was a consequence of unsatisfactory correction of the residual data in the preliminary reduction. In fact, we have been able to reproduce the earlier Mariner 6 entry profile by neglecting the sinusoidal component of the residual drift, and subtracting a purely linear fit to a reduced number of residual points. In general, the other three cases agree well with the results of Kliore *et al.* (1969).

The air temperature near the ground at the point of Mariner 6 entry is about 250K (Table 1) as opposed to the value of close to 280K derived in the first analysis. A ground temperature of 274±5K was obtained from the radiometer measurement at the same point

[1] Rasool, S. I., 1970: Interpretation of the S-band occultation experiment results. Paper presented at the First Annual Meeting, Planetary Division, AAAS, San Francisco, Calif., 19–21 January.

(Munch, private communication; Neugebauer *et al.*, 1969). Thus, an air-ground discontinuity of approximately 25K is indicated by the present results. A large discontinuity was predicted on theoretical grounds for analogous conditions by Gierasch and Goody (1968).

Several features in Fig. 1 are of considerable meteorological interest. In the case of Mariner 6 exit, for example, a temperature inversion appears near the ground. Such a feature might reasonably be expected at nighttime at high latitudes in the winter hemisphere. It is worth noting that a tendency toward a surface inversion is present in the Mariner 7 exit profile as well, which also corresponds to Martian night. There is also some evidence for an inversion or at least an isothermal region of several kilometers extent near the 15-km level in both the Mariner 7 entry and exit data.

Both the present analysis and the analysis of Kliore *et al.* (1969) have one important result in common. At all four occultation points, both the present and the previous results show an extremely cold region in the middle atmosphere, with the derived temperatures falling below the saturation curve of CO_2. The point at which each profile crosses the saturation curve is indicated in Fig. 1 by a vertical bar. The saturation curve may or may not offer a constraint on the temperature profile in the Martian atmosphere, depending on the degree to which CO_2 is supercooled. In any case, the derived temperature profile at lower altitudes is unaffected by the assumption that the temperature may not fall below the CO_2 saturation curve.

CO_2 saturation in the middle atmosphere of Mars is the most pervasive single feature of the temperature profiles deduced from the occultation data; in fact, the derived temperatures at all four occultation points have fallen below the CO_2 saturation curve in every reduction of the residual data to date. We believe that systematic errors in the data reduction cannot be responsible for these low temperatures. Two separate computer programs were developed independently by the authors as an internal means of cross-checking the results. These two techniques, when applied with the same assumptions to the raw residual and trajectory data, produce exactly the same temperature profiles. This result is of special interest because no thermal model of the Martian atmosphere has yet predicted temperatures low enough to permit condensation of CO_2 at these altitudes.

The alternative remains, however, that the raw data may have been affected by conditions in the Martian atmosphere in such a way that their inversion does not give a true representation of the temperature profile over the complete range of the data. For example, if 3×10^3 electrons cm^{-3} were present near the 0.1-mb level on Mars, analogous to the lower D region of the terrestrial ionosphere, this ionization would affect the inversion of the refractivity data, giving a spurious indication of low temperatures at that altitude (Stewart and Hogan[2]).

Although it is not possible at present to exclude either of these interpretations, we are convinced that the large vertical gradient of refractivity, measured by the Mariner 6 and 7 occultation experiments, is a real feature of the Martian middle atmosphere.

Acknowledgments. We wish to thank Dr. A. Kliore of JPL for his helpful advice during the course of the data reduction process. One of us (J.S.H.) is supported by a NAS-NRC Research Associateship.

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[2] Stewart, R. W., and J. S. Hogan, 1969: The atmosphere of Mars in light of the Mariner 6 and 7 observations. Paper presented at the National Fall Meeting of the American Geophysical Union, San Francisco, Calif., 15–18 December.