# PRELIMINARY RESULTS OF THE *MARINER IV* RADIO OCCULTATION MEASUREMENTS OF THE UPPER ATMOSPHERE OF MARS*

G. Fjeldbo and V. R. Eshleman

*Stanford University*
*Stanford, California*

A. J. Kliore, D. L. Cain, and G. S. Levy

*Jet Propulsion Laboratory*
*Pasadena, California*

F. D. Drake

*Cornell University*
*Ithaca, New York*

The radio occultation experiment conducted with the tracking and telemetry system of the *Mariner IV* spacecraft has provided new and precise information on the physical properties of the Martian atmosphere (Ref. 1).

The purpose of this paper is mainly to discuss that part of the occultation data analysis that is related to the upper atmosphere of Mars. This portion of the study is important because:

1. It helps us form a more complete picture of how the Martian atmosphere changes with the altitude (that is, the temperature profile, number density profiles, etc., together with the controlling physical and chemical processes).

2. The precision with which one can determine the refractive index, and therefore the number density, in the lower neutral atmosphere depends on how well one can separate the refractive effects caused by the ionized and the neutral regions of the atmosphere.

When an electromagnetic wave propagates through an ionized medium, its wavelength is longer than it would be in free space. Figure 38 illustrates how this effect caused a decrease in the two-way phase path as *Mariner IV* moved in behind the Martian ionosphere.

---

*Presented by G. Fjeldbo. The principal investigator for the *Mariner IV* radio occultation experiment was A. J. Kliore.
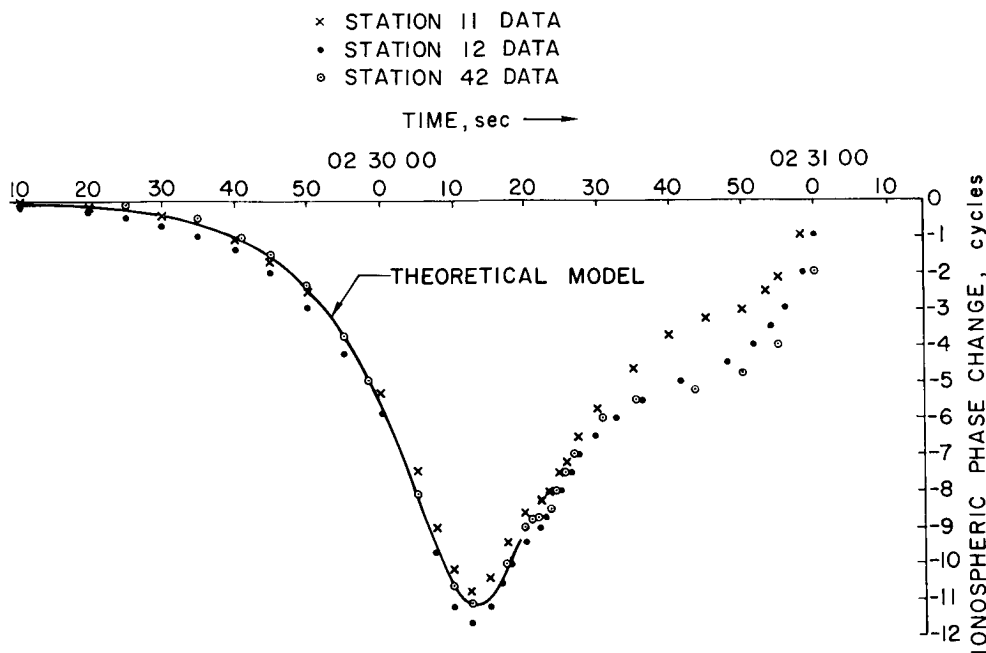
Fig. 38. Ionospheric phase change vs time, during immersion

Data from three different JPL tracking stations are shown in this figure.

It can be seen from Fig. 38 that the main ionospheric layer on Mars caused an 11-cycle phase decrease—or an apparent position change of the spacecraft of about 75 cm in the direction of the Earth ($\lambda \approx 13.6$ cm). Starting at about $02^h\ 30^m\ 20^s$, another change of only about 4 cm was observed at each of the tracking stations, and it is believed that this was caused by a minor layer in the lower ionosphere.

From the ionospheric phase path data one can determine the electron density profile of the Martian ionosphere (Ref. 2). The preliminary electron density profile shown in Fig. 39 was computed from the data taken as the propagation paths probed through the ionosphere above the bright area Electris. The solar zenith angle was about 70°, and the Martian local time was early afternoon. Electris is in the southern hemisphere of Mars at latitude 50°, and it was winter there at the time of the measurement.

The peak electron density is seen to be of the order of $10^5$ cm$^{-3}$ at a height of 120 km. The plasma scale height at the top side is about 24 km. Both the small scale height and the low altitude of the main layer show that the Martian atmosphere is considerably colder than previously anticipated.
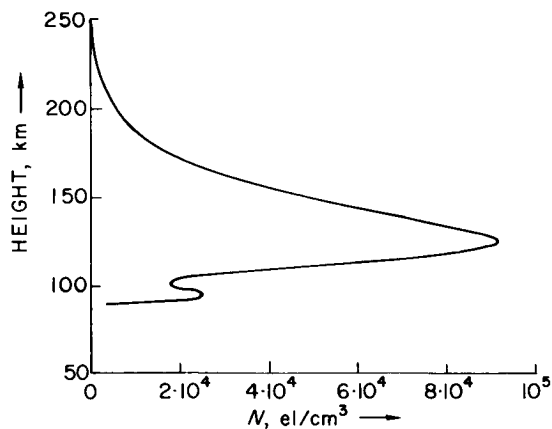


Fig. 39. Electron number density vs altitude above Electris. Martian local time, 1 p.m.

Measurements were also made during occultation exit. In that case the radio energy probed through the night-time ionosphere above Mare Acidalium in the northern hemisphere of Mars. The signature of the night-side ionosphere appears to be very weak, however, and about all we can say at present is that the measurements suggest that the electron density on the night side was down by at least a factor of 20 from the peak density measured on the day side.

The problem is of course that sensitivity to these low electron densities is not very great at S-band frequencies.

However, this low sensitivity is by no means inherent in the radio occultation method when this technique is seen from a broader point of view. Thus, a somewhat different scheme has been suggested—in which two or more harmonically related frequencies may be used to probe the atmosphere of Mars (Refs. 3 and 4). Choosing the lowest frequency at a few hundred Mc/sec would provide a more sensitive measurement of ionospheric electron densities. In addition, the two-frequency technique has the advantage that one can separate the effects of the electrons and the neutral molecules because of their different dispersive properties.

Next, a brief discussion will be given of the temperature and some of the reactions thought to be important in the upper atmosphere of Mars.

Carbon dioxide is apparently the main constituent in the lower atmosphere of Mars (Ref. 1). In addition, there may be some nitrogen and argon. At a higher altitude, $CO_2$ is dissociated into CO and O by the solar ultraviolet flux shortward of about 1700 A (Ref. 5).

Atomic oxygen is lighter than CO, $N_2$, A, and $CO_2$; thus the number density of O is not expected to decrease as rapidly with altitude as do the number densities for the other constituents. Hence, above some altitude one might expect atomic oxygen to become the main constituent.

Some of the preliminary models we have made for the Martian atmosphere have $O^+$ as the main ion at and above the electron density peak. These models have a temperature at the top side of the ionosphere of about 90°K—which corresponds to an electron scale height of 24 km.

Bates has shown that radiative recombination of $O^+$ with electrons takes place somewhat faster at low than at high temperatures (Ref. 6). In spite of this temperature effect, it does not seem possible to explain the loss rate in the Martian ionosphere on the basis of radiative recombination of $O^+$. It is therefore necessary to assume that molecules of minor constituents take part in the loss processes. One can, for instance, consider the following possibilities:

$$O^+ + N_2 \rightarrow NO^+ + N \qquad (1)$$

$$O^+ + O_2 \rightarrow O_2^+ + O \qquad (2)$$

$$O^+ + CO_2 \rightarrow O_2^+ + CO \qquad (3)$$
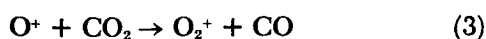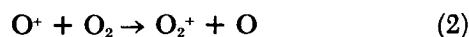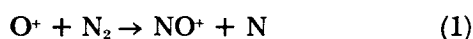
where the molecular ions may lose their charge quite easily through dissociative recombination with electrons.

The two first reactions are relatively well known and are thought to play an important role in the Earth's ionosphere (Refs. 7 and 8). The last reaction, brought to our attention by E. E. Ferguson, should also be considered because the lower atmosphere of Mars contains large amounts of $CO_2$.

In models where $O^+$ is the principal ion and where one of Reactions (1)–(3) is the main loss process, there is a Bradbury-type layer (such as the Earth's F2 layer) at 120 km altitude. The number density of atomic oxygen is of the order of $10^9$ $cm^{-3}$ at the peak of this layer. If Reaction (1) is assumed to be the main loss process ($k \approx 10^{-12}$ $cm^3$/sec), one finds that there would have to be large amounts of $N_2$ present in order to account for the loss rate, which is of the order of $10^2$ $cm^{-3}$ $sec^{-1}$. In fact, a rate coefficient of $10^{-12}$ $cm^3$/sec requires that $N_2$ should have a higher abundance than $CO_2$ in the lower atmosphere of Mars, at least if it is assumed that the lower atmosphere is mixed. However, $CO_2$ must be the main constituent in the lower atmosphere in order to explain the occultation data and the spectroscopic measurements (Ref. 1). Therefore, it is tempting to look for other alternatives.

If Reaction (2) is assumed to be responsible for the loss of $O^+$, one finds that with $k \approx 10^{-11}$ $cm^3$/sec it would be necessary to have on the order of 20% $O_2$ at the peak of the main ionospheric layer in order to account for the loss rate. The spectroscopic observations indicate that there is less than 0.1% $O_2$ in the lower atmosphere of Mars (Ref. 9). However, the $O_2$ distribution in the Martian atmosphere is complicated by the fact that atomic oxygen, produced by photodissociation of carbon dioxide, associates to form $O_2$. Molecular oxygen might, therefore, still be of some importance for the loss of $O^+$, at least in the lower portion of the Martian ionosphere.

At present, the most promising model appears to be one in which $O^+$ mainly loses its charge through Reaction (3). With a reaction rate coefficient of the order of $10^{-9}$ $cm^3$/sec (Ref. 10), one finds that it is necessary to have on the order of $10^6$ $CO_2$ molecules/$cm^3$ at 120 km altitude. This appears to be within reach of what can be supplied through upward diffusion.

Another approach one might take in constructing models for the Martian atmosphere is to assume that a considerable portion of the oxygen formed through the

dissociation of carbon dioxide has been lost. (If this could take place to such an extent that $CO^+$ became the principal ion, then the main ionospheric layer would be of a Chapman type. The temperature on the top side, corresponding to a molecular weight of 28, would be about $150°$ K. The ion $CO^+$ could lose its charge through dissociative recombination with electrons.)

There are two ways that O could conceivably be lost: escape into space or loss of $O_2$ through oxidation processes involving the surface crust. The first process is not expected to be important because the temperature is too low (Refs. 11 and 12). The second process would require diffusive and convective transport of oxygen from the dissociation region down to the surface. However, such a transport would probably not have too important an effect on the CO/O ratio in the upper atmosphere of Mars, since both constituents probably would be transported downwards at approximately the same rate. Therefore, it appears that we are left with atomic oxygen as the principal constituent in the Martian ionosphere.

One of the main difficulties in identifying the ion loss processes in the Martian ionosphere is the uncertainty in the reaction rate coefficients, particularly with respect to temperature dependence. Thus, further studies of these effects might require revision of the preliminary conclusions in this paper.

The low temperatures obtained from the occultation data appear to be in reasonable agreement with atmospheric models where $CO_2$ is the main constituent at ground level. This conclusion is based on calculations utilizing the work of Bates, Chamberlain, and others, which shows that $CO_2$, CO, and O are more effective in radiatively cooling the upper atmosphere than is molecular nitrogen, which was previously believed to be the main constituent (Refs. 12, 13, 14, and 15).

Most of the clouds and hazes in the Martian atmosphere are observed at altitudes below 30 km (Ref. 16). However, there is also some evidence of violet haze layers around 100 km altitude. Urey and Brewer (Ref 17) have suggested that this might be caused in part by ●, which absorbs in the ultraviolet and blue. The occultation experiment strengthens this suggestion, since $CO^+$ is quite certainly one of the important ions in the upper atmosphere of Mars.

Figure 40 illustrates how the atmospheric mass density varies with altitude. With a Bradbury-type ionospheric layer where the principal ion $O^+$ is losing its charge through one of Reactions (1)–(3), we find that the mass density at 120 km altitude should be of the order of $2.10^{-14}$ g/cm$^3$. However, the mass density could be two orders of magnitude higher if the main ionospheric layer were a Chapman layer with $CO^+$ as the principal ion.
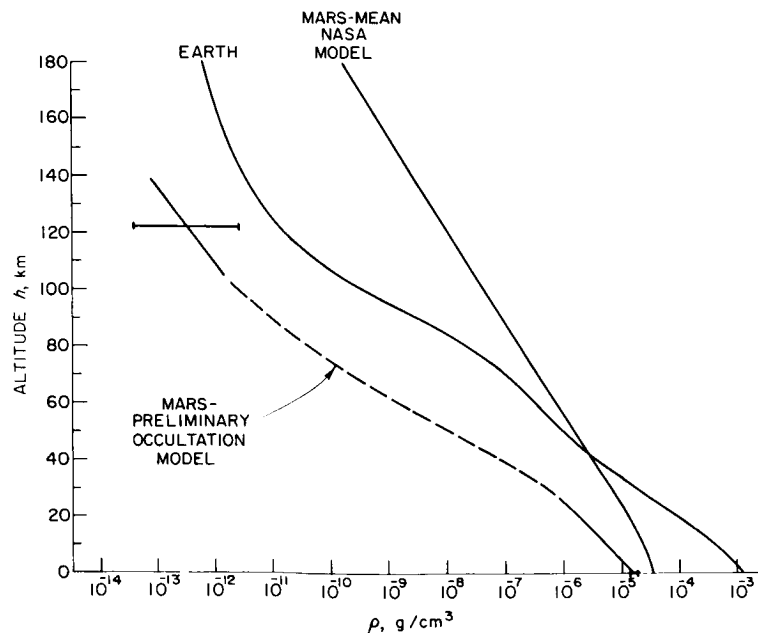
**Fig. 40. Atmospheric mass density vs altitude**

This difference in interpretation results in the uncertainty indicated by the error bar shown at 120 km altitude.

The most interesting point illustrated in Fig. 40 is that the mass density distribution shown for Mars and for the Earth do not cross each other at higher altitude. Previously the opposite was believed to be true, and the argument was that since the gravity is less on Mars than on the Earth, the scale height has to be larger.

The question of how the mass density varies with altitude in the Martian atmosphere has also some practical implications. If one wants to put a satellite in orbit around Mars, one needs to know how the atmospheric density varies with altitude. Most previous models required an orbit altitude of several thousand kilometers for a satellite with 50 years lifetime, but the occultation results suggest that a few hundred kilometers may be sufficient.

Table 10 summarizes the more striking features of the upper atmosphere of Mars.

### Acknowledgment

**Table 10. Summary of preliminary results for the upper atmosphere of Mars**

| Property | Value |
|---|---|
| | **Immersion**[a] |
| Maximum electron density, el/cm³ | $9.0 \pm 1.0 \times 10^4$ |
| Altitude of maximum, km | $120 \pm 5$ |
| Electron scale height above maximum, km | $24 \pm 3$ |
| Temperature at the top side, °K<br>O principal ion<br>CO principal ion | $90 \pm 12$<br>$150 \pm 20$ |
| Preliminary estimate of the atmospheric mass density at 120 km, g/cm³ | $2 \times 10^{-14}$ to $2 \times 10^{-12}$ |
| | **Emersion**[b] |
| Maximum electron density, el/cm³ | $<5 \times 10^3$ |

[a] Over Electris at 50° S latitude, 177° E longitude, early afternoon, winter, solar zenith angle 70°.

[b] Over Mare Acidalium at 60° N latitude, 36° W longitude, night, summer, solar zenith angle 106°.

## REFERENCES

1. Kliore, A. J., Cain, D. L., Levy, G. S., Eshleman, V. R., Fjeldbo, G., and Drake, F. D., 1965, *Science*, Vol. 149.

2. Fjeldbo, G., and Eshleman, V. R., 1965, *J. Geophys. Res.*, Vol. 70, pp. 3217–3227.

3. Eshleman, V. R., 1965, Chapter 14 in *Solar System Radio Astronomy*, ed. J. Aarons, Plenum Press, New York, p. 267.

4. Fjeldbo, G., Eshleman, V. R., Garriott, O. K., and Smith, F. L., III, 1965, *J. Geophys. Res.*, Vol. 70, p. 3701.

5. Herzberg, G., 1961, *Molecular Spectra and Molecular Structure: I. Spectra of Diatomic Molecules*, D. Van Nostrand Co., Inc., New York.

6. Nawrocki, P. J., and Papa, R., 1963, *Atmospheric Processes*, Prentice-Hall, Inc., New Jersey.

# REFERENCES (Cont'd)

7. Rishbeth, H., and Garriott, O. K., 1964, *Introduction to the Ionosphere and Geomagnetism*, Tech. Rpt. No. 8, NsG-30-60, SU-SEL-64-111, Stanford Electronics Laboratories, Stanford University, Stanford, California.

8. Nicolet, M., and Swider, W., 1963, *Planetary Space Sci.*, Vol. 11, pp. 1459–1482.

9. Owen, T. C., and Kuiper, G. P., 1964, *Communications of the Lunar and Planetary Laboratory*, No. 32.

10. Fehsenfeld, F. C., Schmetlekopf, A. L., and Ferguson, E. E., *J. Chem. Phys.*, to be published, private communication.

11. Kuiper, G. P., 1947, Chapter 12 in *The Atmospheres of the Earth and Planets*, ed. G. P. Kuiper, University of Chicago Press, Chicago, Illinois.

12. Chamberlain, J. W., 1962, *Astrophys. J.*, Vol. 136, pp. 582–593.

13. Bates, D. R., 1951, *Proc. Phys. Soc.*, Vol. B64, pp. 805–821.

14. Norton, R. B., 1964, *A Theoretical Study of the Martian and the Cytherean Ionospheres*, NASA Tech. Note TN D-2333, National Aeronautics and Space Administration, Washington, D. C.

15. McElroy, M. B., L'Ecuyer, J., Chamberlain, J. W., 1965, *Astrophys. J.*, Vol. 141, pp. 1523–1535.

16. de Vaucouleurs, G., 1954, *Physics of the Planet Mars*, Faber and Faber, Ltd., London.

17. Urey, H. C., Brewer, A. W., 1957, *Proc. Royal Soc. of London*, Vol. A241, pp. 37–43.