N-33561 (NAS 7-100)

# Limiting Model Atmospheres of Mars

*G.F. Schilling*

August 1962

R-402-JPL

A REPORT PREPARED FOR THE

JET PROPULSION LABORATORY

California Institute of Technology

*The* RAND *Corporation*

1700 MAIN ST. · SANTA MONICA · CALIFORNIA

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## SUMMARY

From factual observational knowledge, realistic upper and lower limits were calculated for the permissible ranges of temperature, pressure, and density of the Martian atmosphere. The results are presented here in the form of two model atmospheres. Model I is in convective equilibrium throughout; Model II, more realistically, assumes convective equilibrium to a tropopause level, then conductive equilibrium up to an altitude of 80 km.

These two numerical models show that Martian atmospheric parameters still range widely in possible extreme values. Therefore, with certain speculative assumptions, the author tried to form a new, more coherent picture. The result is a conjectural Model III, reaching to 200 km in altitude. It was based partly on the supposition that even a relatively small amount of oxygen would give rise to some ozone and, hence, to appreciable amounts of stratospheric heating. Though conjectural, this model atmosphere has some surprising and potentially important meteorological characteristics.

A combination of these three models allows us to predict with reasonable confidence ranges of Martian atmospheric conditions for specific heights up to 180 km over middle and low latitudes, regardless of season or time of day. The parameters of the Martian atmosphere are compared graphically, for practical use, with those of the Earth's.

# PREFACE

THE RESEARCH REPORTED here was supported by the Jet Propulsion Laboratory of the California Institute of Technology under Contract No. N-33561 (NASw-6 and NAS 7-100) for the National Aeronautics and Space Administration. The first stimulus was a request from Dr. G. Neugebauer of the Jet Propulsion Laboratory for reliable values of the Martian atmosphere, to be used in deriving engineering design criteria for scientific space missions to that planet.

Portions of the results were originally reported in the following technical documents:

"A Note on Atmospheric Entry: Mars versus Venus," in *Studies of the Physical Properties of the Moon and Planets*, Quarterly Technical Progress Report No. 2, The RAND Corporation, RM-2711-JPL, December 1960, pp. 22–23.

"Preliminary Remarks on a Permissible Model of the Lower Atmosphere of Mars," in *Studies of the Physical Properties of the Moon and Planets*, Quarterly Technical Progress Report No. 3, The RAND Corporation, RM-2769-JPL, April 1961, pp. 77–80.

*Extreme Model Atmospheres of Mars*, The RAND Corporation, RM-2782-JPL, June 1961.

"Parametric Comparison of the Atmospheres of Earth and Mars," in *Studies of the Physical Properties of the Moon and Planets*, Quarterly Technical Progress Report No. 4, The RAND Corporation, RM-2817-JPL, June 1961, pp. 27–45.

"On the Consequences of a Possible Ozonosphere on Mars," The RAND Corporation, P-2387, July 28, 1961; presented at the Symposium on Atmospheric Ozone, International Ozone Commission, Arosa, Switzerland, August 9, 1961.

"A Note on the Atmosphere of Mars," *Journal of Geophysical Research*, Vol. 67, March 1962, pp. 1170–1172.

# ACKNOWLEDGMENTS

MY THANKS to an unknown UCLA graduate student, who, during a recent lecture, asked why I had stated that the atmosphere of Mars contained no oxygen. Of course, I gave him the standard textbook answer, but afterwards I started to think . . . .

It is a pleasure to acknowledge the many helpful suggestions made by Bernhard Haurwitz, Yale Mintz, Diran Deirmendjian, L. E. Kaplan, Z. Sekera, and H. K. Paetzold, and the fruitful discussions with G. de Vaucouleurs, P. H. Abelson, and C. E. Sagan. Special appreciation must go to M. H. Davis, whose criticism helped to crystallize the ideas presented here and to shape the details of the conjectural construct. I am additionally indebted to W. W. Kellogg for his constructive editing and reshaping of the manuscript. Mrs. P. A. Walters performed the numerical calculations.

If ozone is indeed present on Mars, credit should be given to R. M. Goody, who, to my knowledge, was the first to suggest the potentially important role that ozone would play in thermal equilibrium conditions in the Martian atmosphere.

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# I. INTRODUCTION

EXAMINE CLOSELY our factual, observational knowledge of the Martian atmosphere and you will discover that the increased "accuracy" of data in more recent nonastronomical literature frequently derives from nothing more than continued quotation of "best" values without the warnings of the original investigators. In fact, our present reliable, quantitative knowledge can be stated—not just summarized—about as follows: (*a*) the mass of Martian atmosphere per unit surface area (i.e., the mass in a vertical column of 1 $cm^2$ cross section) is between one-third and one-ninth of the mass per unit surface area of the terrestrial atmosphere; and (*b*) the Martian atmosphere contains an unknown but small amount of $CO_2$, and appreciably less oxygen than the Earth's atmosphere. Also, radiometric observations of the ground temperature of Mars permit inferences about the range of air temperature near the surface.

Though much additional qualitative information exists, such as the presence and formation of polar caps, the motion of variously colored clouds, and the predominance of haze, it permits only indirect numerical inferences about the atmosphere. Excellent analyses can be found in the publications by Gerard de Vaucouleurs, Gerard P. Kuiper, Seymour L. Hess, and R. M. Goody.[1-4]

The present paper takes four steps toward a quantitative description of the principal physical parameters of the atmosphere of Mars:

First, on the basis of present factual knowledge and a minimum of speculative assumptions, we try to derive extreme limits for the ranges of temperature, pressure, and density which could prevail near the Martian surface. Originally, we considered these limits reliable enough for designing an atmospheric entry and landing capsule in a 1964–1965 space mission to Mars. We will show, however, that these limits bracket a very wide range.

Second, we compute the variations with altitude of temperature, pressure, and density in the Martian atmosphere, and determine limiting values for a troposphere in convective (adiabatic) as well as in conductive (isothermal) equilibrium. The results show still wider ranges in the possible values of atmospheric parameters, with no apparent possibility of narrowing them solely on the basis of current observational data.

Third, we consequently abandon these rigorous methods, and construct, by analogy with meteorological conditions on Earth, a model atmosphere of Mars which, though largely speculative, reveals some surprising and potentially rather important meteorological characteristics.

Finally, we combine all results in diagrams allowing us to determine the limiting values of Martian atmospheric parameters for any altitude up to 180 km, and to compare them with equivalent values in the Earth's atmosphere.

To permit interpolation and variation of the numerical results with different starting conditions, the appendices detail the analytical methods of computation used in this work.

For mathematical convenience, limiting values for altitude variations of the atmospheric parameters are tabulated to three significant figures. Obviously, in view of the concomitant uncertainties, they must not be taken as indicating the accuracy of any single value.

# II. INITIAL SET OF PARAMETERS

TABLE 1 LISTS the minimum and maximum values of Martian astronomical parameters used in the later computations. The data are based on a study by Kirby,[5] who took into account uncertainties in observations and showed the resultant permissible ranges.

Table 1

PERMISSIBLE RANGES OF OBSERVED AND COMPUTED ASTRONOMICAL PARAMETERS

| Parameter | Earth | Mars | |
|---|---|---|---|
| | | Minimum | Maximum |
| Equatorial radius (km) | 6378.388 | 3323 | 3438 |
| Polar radius (observed) (km) | 6356.912 | 3291 | 3359 |
| Planetary mass (from Martian satellite observations) (gm) | $5.977 \times 10^{27}$ | $0.6389 \times 10^{27}$ | $0.6455 \times 10^{27}$ |
| Mean surface gravity (computed) (cm $sec^{-2}$) | 981.44 | 360 | 390 |
| Solar constant (calculated) (cal $cm^{-2}$ $min^{-1}$) | $2.0 \pm 0.1$ | 0.7 (aphelion) | 1.1 (perihelion) |

Directly from observational data, the only "reliable" quantitative value for the Martian atmosphere is its *mass* per unit surface area.[6] Various authors have used a variety of methods, but all methods involve assumptions about the light-scattering properties of the Martian atmosphere. Nevertheless, we estimate with reasonable confidence that the columnar mass of the Martian atmosphere is somewhere between 114 gm/cm$^2$ and 340 gm/cm$^2$. From these limits, we will first derive or infer "rigorously" the probable limits of the other atmospheric parameters near the Martian surface.

Since misconceptions sometimes occur when basic physical formulas are applied to a description of another planet's atmosphere, the numerical calculations are explicitly shown in Appendix A. Merely note that all parameters are given in *absolute units.* And remember that though 1 gram-mass on Mars will exert a force, or have a "weight," of only about 375 dynes (as against approximately 980 dynes on Earth), an aneroid barometer calibrated on Earth will, on Mars, correctly register pressure values in dynes or millibars.

From the columnar mass of the Martian atmosphere we can readily calculate the probable limits of atmospheric pressure near the Martian surface, taking into account the accuracy to which we know the mean acceleration of gravity on Mars. In addition, pressure variation is likely in a real Martian atmosphere, but (by analogy with Earth) will probably amount to only 5 to 10 per cent from the mean.

Beyond estimates of the surface pressure, though, we can proceed only by assuming temperatures and mean molecular masses for the Martian atmosphere. For temperature estimates, we have to rely on inferences drawn from radiometric measurements of the Martian ground temperature.(7) For the mean molecular mass, our only datum is the presence of $CO_2$, although it is generally assumed that nitrogen may be the major constituent, with relatively small amounts of water vapor, argon, oxygen, and other gases in minute quantities.

Table 2 collects in logical sequence the computed limits for a variety of surface parameters and compares them with average conditions on Earth. It includes a "mean atmosphere," based not on "best" values, but on the arithmetical means of the maximum and minimum starting data (see Appendix B).

Table 2

PERMISSIBLE EXTREME RANGES OF MEAN VALUES OF ATMOSPHERIC PARAMETERS NEAR THE SURFACE OF MARS

| Parameter | Symbol (unit) | Earth's Atmosphere | Martian Atmosphere Minimum | Mean | Maximum |
|---|---|---|---|---|---|
| Mass per unit surface area | $M$ (gm cm$^{-2}$) | 1033 | 114 | 227 | 340 |
| Mean acceleration of gravity | $g_0$ (cm sec$^{-2}$) | 981 | 360 | 375 | 390 |
| Surface pressure | $p_0$ (mb) | 1013 | 41 | 85 | 133 |
| Mean molecular mass | $m$ | 28.97 | 28 | 29 | 30 |
| Atmospheric temperature near surface | $T_0$ (°K) | 288 | 200 | 250 | 300 |
| Atmospheric density near surface | $\rho_0$ (gm cm$^{-3}$) | $1.225 \times 10^{-3}$ | $4.6 \times 10^{-5}$ | $1.2 \times 10^{-4}$ | $2.4 \times 10^{-4}$ |
| Scale height near surface | $H_0$ (km) | 8.4 | 14 | 19.1 | 25 |
| Specific heat of air at constant pressure | $c_p$ ($10^7$ ergs gm$^{-1}$ °K$^{-1}$) | 1.0 | 0.95 | 1.0 | 1.05 |
| Adiabatic lapse rate | $\Gamma$ (°K km$^{-1}$) | −9.76 | −3.4 | −3.75 | −4.1 |
| Limit of convective atmosphere | $Z_\infty$ (km) | 29.5 | 53 | 67 | 79 |

# III. VARIATIONS WITH ALTITUDE

## MODEL I ATMOSPHERE

THE NEXT STEP, computing the probable extreme limits for values of pressure, temperature, and density at various heights in the Martian troposphere, we took in the following way. The limiting rate of temperature decrease for an atmosphere in convective equilibrium is given by the adiabatic lapse rate. Such an atmosphere, if in adiabatic equilibrium throughout, has a natural height limit readily calculated from the adiabatic relation. Up to this height, upper and lower limits for the atmospheric parameters at each altitude can be computed from the maximum and minimum values believed to prevail near the planetary surface (as listed in Table 2).

Figure 1 and Table 3 show the limiting envelopes for the extremes of temperature, pressure, and density in Model I. We calculated a consistent set of parameters by maximizing and minimizing pressure extremes for adiabatic conditions, and by relating the maximum permissible air temperature near the surface[7] with the minimum probable adiabatic lapse rate (and, conversely, the minimum temperature with maximum lapse rate). How we computed the envelopes for density extremes is described in Appendix C. But Model I should be considered to be a purely theoretical construct, not a representation of likely conditions on Mars. It is included here to make our treatment more nearly complete; for it illustrates the characteristics of a purely convective regime in the troposphere, which in reality will extend only to the altitude of the tropopause (at present unknown). Of course, the minimum values for temperature above some 25 km altitude are of mathematical significance only, since $CO_2$ condenses at about 195°K at one atmosphere pressure, and nitrogen at about 77°K at one atmosphere pressure.

## MODEL II ATMOSPHERE

Envelopes for a more realistic, conventional Model II atmosphere are shown in Table 4 and Fig. 2. They are based on an assumed height of the Martian tropopause somewhere be-

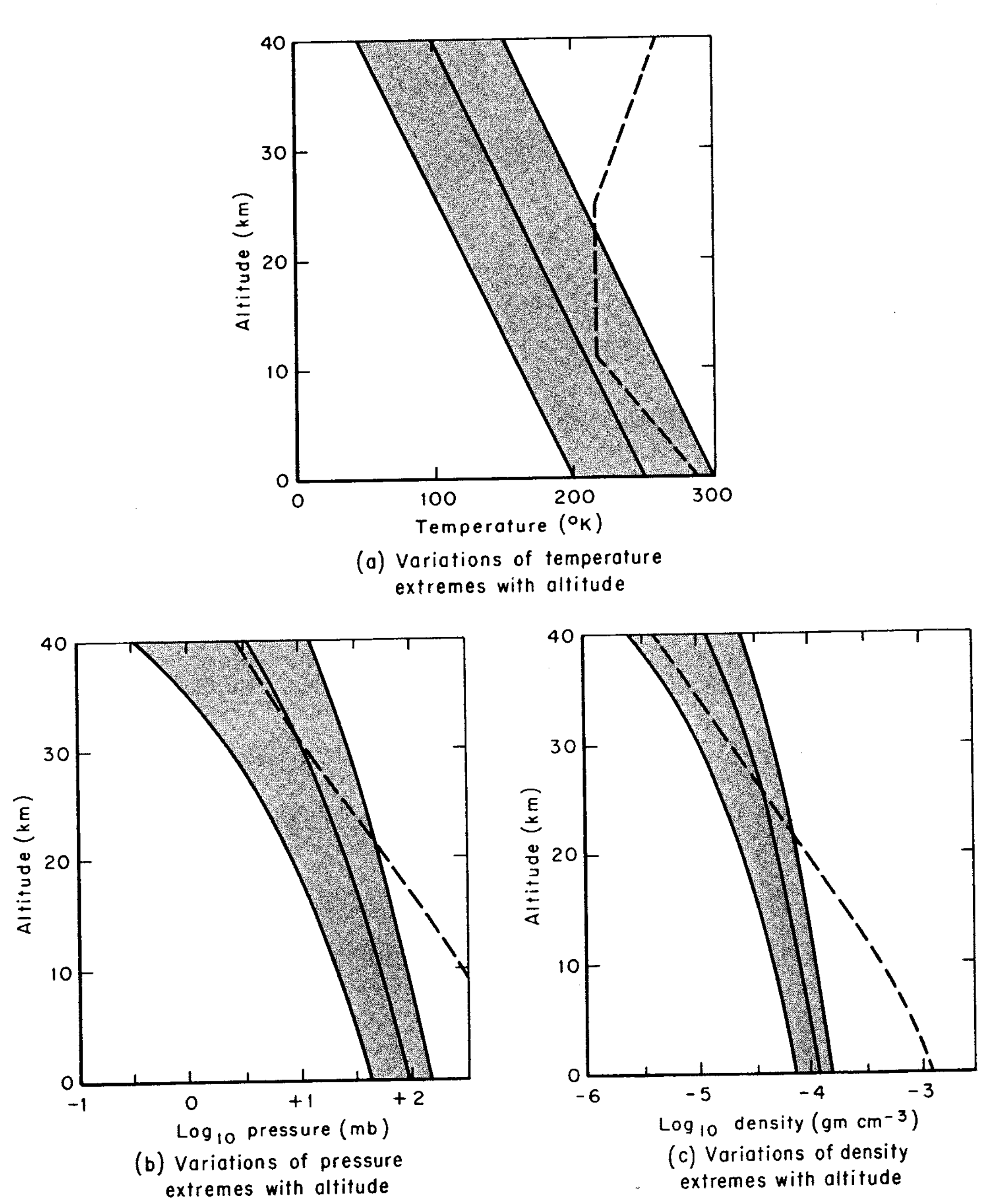


FIG. 1—Model I Mars Atmosphere in Convective Equilibrium Throughout (Earth ARDC 1959 model atmosphere shown as dashed lines)

Table 3

PROBABLE EXTREME RANGES OF PARAMETERS FOR MODEL I MARS ATMOSPHERE IN CONVECTIVE EQUILIBRIUM THROUGHOUT

| | Temperature (°K) | | | Pressure (mb) | | | Density (gm cm$^{-3}$) | | |
|---|---|---|---|---|---|---|---|---|---|
| Altitude (km) | Lower Limit | Mean | Upper Limit | Lower Limit | Mean | Upper Limit | Lower Limit | Mean | Upper Limit |
| 0 | 200.0 | 250.0 | 300.0 | 41.04 | 85.125 | 132.60 | $7.40 \times 10^{-5}$ | $1.19 \times 10^{-4}$ | $1.49 \times 10^{-4}$ |
| 2 | 192.4 | 242.5 | 292.6 | 36.0 | 76.5 | 121.4 | 6.74 | 1.10 | 1.40 |
| 4 | 184.8 | 235.0 | 285.1 | 31.3 | 68.6 | 110.8 | 6.12 | 1.02 | 1.31 |
| 6 | 177.3 | 227.5 | 277.7 | 27.1 | 61.3 | 100.9 | 5.52 | $9.39 \times 10^{-5}$ | 1.22 |
| 8 | 169.7 | 220.0 | 270.3 | 23.4 | 54.5 | 91.7 | 4.97 | 8.64 | 1.14 |
| 10 | 162.1 | 212.5 | 262.9 | 20.0 | 48.3 | 83.1 | 4.44 | 7.93 | 1.06 |
| 12 | 154.5 | 205.0 | 255.4 | 17.0 | 42.6 | 75.1 | 3.96 | 7.25 | $9.90 \times 10^{-5}$ |
| 14 | 147.0 | 197.5 | 248.0 | 14.3 | 37.4 | 67.6 | 3.50 | 6.61 | 8.92 |
| 16 | 139.4 | 190.0 | 240.6 | 11.9 | 32.7 | 61.3 | 3.08 | 6.00 | 8.58 |
| 18 | 131.8 | 182.5 | 233.1 | 9.82 | 28.4 | 54.4 | 2.69 | 5.43 | 7.86 |
| 20 | 124.2 | 175.0 | 225.7 | 8.02 | 24.5 | 48.5 | 2.33 | 4.89 | 7.24 |
| 22 | 116.6 | 167.5 | 218.3 | 6.46 | 21.1 | 43.1 | 2.00 | 4.39 | 6.65 |
| 24 | 109.1 | 160.0 | 210.9 | 5.13 | 18.0 | 38.1 | 1.70 | 3.91 | 6.08 |
| 26 | 101.5 | 152.5 | 203.4 | 4.01 | 15.2 | 33.6 | 1.42 | 3.47 | 5.56 |
| 28 | (93.9) | 145.0 | 196.0 | 3.07 | 12.7 | 29.4 | 1.18 | 3.06 | 5.06 |
| 30 | (86.3) | 137.5 | 188.6 | 2.30 | 10.6 | 25.7 | $9.63 \times 10^{-6}$ | 2.68 | 4.58 |
| 32 | (78.8) | 130.0 | 181.2 | 1.68 | 8.70 | 22.3 | 7.70 | 2.33 | 4.14 |
| 34 | (71.2) | 122.5 | 173.7 | 1.19 | 7.07 | 19.2 | 6.02 | 2.01 | 3.73 |
| 36 | (63.6) | 115.0 | 166.3 | .808 | 5.67 | 16.5 | 4.58 | 1.72 | 3.33 |
| 38 | (56.0) | 107.5 | 158.9 | .523 | 4.48 | 14.0 | 3.37 | 1.46 | 2.97 |
| 40 | (48.4) | 100.0 | 151.4 | .318 | 3.48 | 11.8 | $2.37 \times 10^{-6}$ | $1.22 \times 10^{-5}$ | $2.41 \times 10^{-5}$ |
| 52.78 | 0 | | | 0 | | | 0 | | |
| 66.67 | | 0 | | | 0 | | | 0 | |
| 80.77 | | | 0 | | | 0 | | | 0 |

tween 10 and 26 km.[3][8] Although we could have made the lower limits of temperature and pressure even smaller by placing the tropopause at a higher altitude, we adopted a temperature of about 100°K as probably the lowest that could exist in the Martian stratosphere. The upper limits for temperature and pressure were obtained somewhat arbitrarily by using the probable height ranges of the tropopause (as suggested by various authors), while remembering that the adiabatic lapse rate is a limiting value and that the equilibrium rate of temperature decrease in a convective atmosphere can be much smaller. This would lead either to a very high but cold tropopause level, or, conversely, to a relatively warm stratosphere. The given upper-limit temperature envelope should thus be a safe extreme limit for all altitudes, if the role played by the minor constituents of the Martian atmosphere is negligible (see Appendix D).

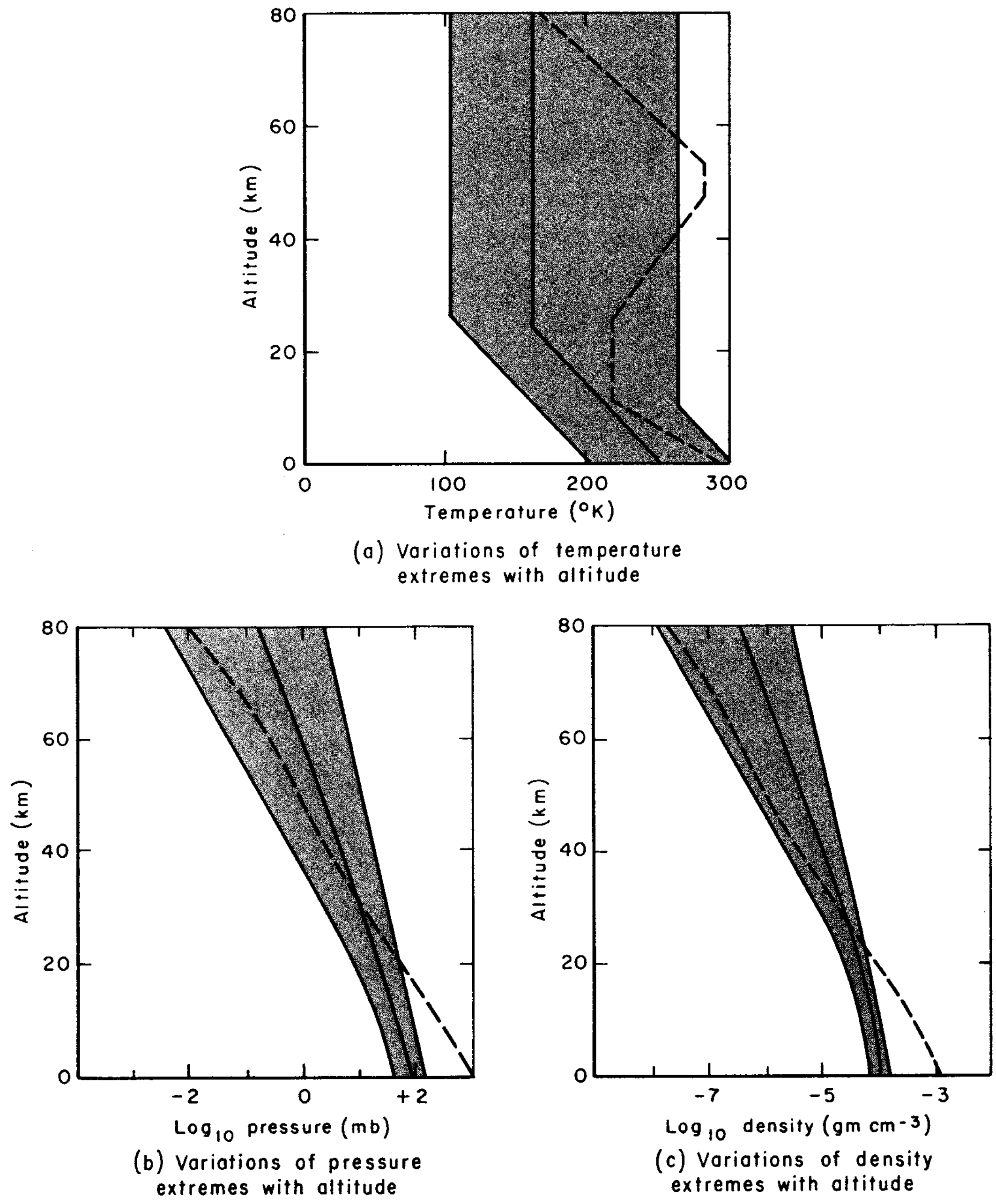


FIG. 2—Model II Mars Atmosphere in Convective Equilibrium to Assumed Tropopause Level, and in Conductive Equilibrium Above (Earth ARDC 1959 model atmosphere shown as dashed lines)

Table 4

PROBABLE EXTREME RANGES OF PARAMETERS FOR MODEL II MARS ATMOSPHERE IN CONVECTIVE EQUILIBRIUM TO ASSUMED TROPOPAUSE ALTITUDE AND IN CONDUCTIVE EQUILIBRIUM ABOVE

| Altitude (km) | Temperature (°K) Lower Limit | Temperature (°K) Mean | Temperature (°K) Upper Limit | Pressure (mb) Lower Limit | Pressure (mb) Mean | Pressure (mb) Upper Limit | Density (gm cm$^{-3}$) Lower Limit | Density (gm cm$^{-3}$) Mean | Density (gm cm$^{-3}$) Upper Limit |
|---|---|---|---|---|---|---|---|---|---|
| 0 | 200.0 | 250.0 | 300.0 | 41.04 | 85.125 | 132.60 | $7.40 \times 10^{-5}$ | $1.19 \times 10^{-4}$ | $1.49 \times 10^{-4}$ |
| 2 | 192.4 | 242.5 | 292.6 | 36.0 | 76.5 | 121.4 | 6.74 | 1.10 | 1.40 |
| 4 | 184.8 | 235.0 | 285.1 | 31.3 | 68.6 | 110.8 | 6.12 | 1.02 | 1.31 |
| 6 | 177.3 | 227.5 | 277.7 | 27.1 | 61.3 | 100.9 | 5.52 | $9.39 \times 10^{-5}$ | 1.22 |
| 8 | 169.7 | 220.0 | 270.3 | 23.4 | 54.5 | 91.7 | 4.97 | 8.64 | 1.14 |
| 10 | 162.1 | 212.5 | 262.9 | 20.0 | 48.3 | 83.1 | 4.44 | 7.93 | 1.06 |
| 12 | 154.5 | 205.0 | 262.9 | 17.0 | 42.6 | 75.2 | 3.96 | 7.25 | $9.63 \times 10^{-5}$ |
| 14 | 147.0 | 197.5 | 262.9 | 14.3 | 37.4 | 68.0 | 3.50 | 6.61 | 8.71 |
| 16 | 139.4 | 190.0 | 262.9 | 11.9 | 32.7 | 61.6 | 3.08 | 6.00 | 7.88 |
| 18 | 131.8 | 182.5 | 262.9 | 9.82 | 28.4 | 55.7 | 2.69 | 5.43 | 7.13 |
| 20 | 124.2 | 175.0 | 262.9 | 8.02 | 24.5 | 50.4 | 2.33 | 4.89 | 6.46 |
| 22 | 116.6 | 167.5 | 262.9 | 6.46 | 21.1 | 45.6 | 2.00 | 4.38 | 5.84 |
| 24 | 109.1 | 160.0 | 262.9 | 5.13 | 18.0 | 41.3 | 1.70 | 3.91 | 5.29 |
| 26 | 101.5 | 160.0 | 262.9 | 4.01 | 15.2 | 37.4 | 1.43 | 3.32 | 4.78 |
| 28 | 101.5 | 160.0 | 262.9 | 3.10 | 12.9 | 33.8 | 1.10 | 2.82 | 4.33 |
| 30 | 101.5 | 160.0 | 262.9 | 2.40 | 11.0 | 30.6 | $8.55 \times 10^{-6}$ | 2.40 | 3.92 |
| 32 | 101.5 | 160.0 | 262.9 | 1.86 | 9.33 | 27.7 | 6.62 | 2.04 | 3.54 |
| 34 | 101.5 | 160.0 | 262.9 | 1.44 | 7.92 | 25.0 | 5.12 | 1.73 | 3.21 |
| 36 | 101.5 | 160.0 | 262.9 | 1.12 | 6.73 | 22.7 | 3.97 | 1.47 | 2.90 |
| 38 | 101.5 | 160.0 | 262.9 | .863 | 5.72 | 20.5 | 3.07 | 1.25 | 2.63 |
| 40 | 101.5 | 160.0 | 262.9 | .668 | 4.82 | 18.6 | 2.38 | 1.06 | 2.38 |
| 45 | 101.5 | 160.0 | 262.9 | .352 | 3.22 | 14.5 | 1.25 | $7.03 \times 10^{-6}$ | 1.85 |
| 50 | 101.5 | 160.0 | 262.9 | .186 | 2.14 | 11.3 | $6.61 \times 10^{-7}$ | 4.67 | 1.44 |
| 55 | 101.5 | 160.0 | 262.9 | .0980 | 1.42 | 8.78 | 3.49 | 3.10 | 1.12 |
| 60 | 101.5 | 160.0 | 262.9 | .0517 | .946 | 6.84 | 1.84 | 2.06 | $8.75 \times 10^{-6}$ |
| 65 | 101.5 | 160.0 | 262.9 | .0273 | .622 | 5.33 | $9.70 \times 10^{-8}$ | 1.36 | 6.82 |
| 70 | 101.5 | 160.0 | 262.9 | .0144 | .418 | 4.15 | 5.11 | $9.11 \times 10^{-7}$ | 5.31 |
| 75 | 101.5 | 160.0 | 262.9 | .00758 | .278 | 3.23 | 2.70 | 6.05 | 4.14 |
| 80 | 101.5 | 160.0 | 262.9 | .00400 | .184 | 2.52 | $1.42 \times 10^{-8}$ | $4.02 \times 10^{-7}$ | $3.22 \times 10^{-6}$ |

We have tabulated all values to three significant figures for mathematical convenience only, not as an indication of real accuracy. The previously mentioned uncertainties also led us to neglect variation of the acceleration of gravity with altitude. We believe that the extreme envelopes given by the Model II atmosphere are realistic upper and lower limits of atmospheric conditions that could prevail in middle and low latitudes on Mars. Actual conditions should fall between these envelopes independent of season or time of day, assuming that our present ideas about the physical nature of the Martian atmosphere are not too far from reality. In fact, at the present moment, any single datum, whether obtained by a space probe or by a high-altitude balloon observation of Mars, will probably suffice to indicate where within these limits the actual conditions prevail.

But until this datum is available, speculation about minor constituents leads us to construct a generally warmer atmosphere, outside the upper limit for the temperature envelopes of Model II. This will be attempted in the next section.

# IV. CONJECTURAL ATMOSPHERIC STRUCTURE

WE FIRST HOPED for enough data to allow fairly firm conclusions about the physical nature and state of the Martian atmosphere. Certainly, this was a prerequisite for any attempt to carry the calculations of extreme limits above the altitudes of Model II. Although this turned out to be impossible, we were tempted to try combining available information about Mars into some sort of coherent picture,[9] basing it on the few facts already cited, and taking advantage of the suggestions and insights of other authors who have attempted something similar.

It should be emphasized that the model presented in this section is based on far too few quantitative data to be more than a conjecture. Yet, it does include many of the important qualitative as well as quantitative features we know to date; it is the simplest conceivable model, based on the premise that the atmospheres of Earth and Mars had similar histories, and now differ principally because the two planets, themselves, differ physically.

The following paragraphs discuss only the principal considerations. Included in the references are contributing observational data, inferences, and suppositions that would be superfluous to list here.

## EQUILIBRIUM

The most important uncertainty, in many respects, concerns the height of the tropopause and the temperature structure of the upper atmosphere. Since on Earth the temperature of the upper stratosphere is largely determined by the absorption of solar ultraviolet, a major question for Mars is: Has its upper atmosphere an appreciable amount of ozone? We think it likely that it has, from the following general or qualitative arguments.

- It is probable that the meteorological conditions near the Martian surface correspond in certain respects to the conditions that would exist on Earth at a fictitious high plateau at about 11 km elevation. At this altitude on Earth the columnar mass of air above is equal to the total columnar mass of the atmosphere above the surface of Mars. This analogy affects considerations about atmospheric transmission characteristics and absorption path lengths of solar radiation.

- The atmospheric surface pressure on Mars is reached only at an altitude of about 15 to 18 km on Earth, and conditions in the Martian troposphere and upper atmosphere may correspond in certain instances to conditions in the Earth's atmosphere at those altitudes where the same atmospheric pressure and density values are found. A number of authors, in describing the Martian atmosphere, have simply related these levels on the supposition that the same chemical reactions should occur where the same pressure and density conditions exist. While this is true for certain processes, especially those of production and recombination, we shall prefer to relate levels above which the total columnar masses are equal. This difference in procedure will be important when considering the probable equilibrium conditions resulting from absorption and recombination over large depth intervals.

- The upper limit for the concentration of oxygen in the Martian atmosphere is frequently cited as 0.0015 of the oxygen concentration in the Earth's atmosphere.[1] This amounts to a total depth in a vertical column of about 250 cm NTP. Based on this upper limit, it is generally believed that only a negligible amount of ozone could be present on Mars.

- On Earth, the maximum absolute concentration of ozone is found at about 20 to 25 km altitude, with some 0.15 to 0.45 cm NTP ozone found above this level. But at approximately 50 km altitude on Earth, where the maximum heating occurs, and even up to 70 km where heating still occurs, only a very small amount of ozone is present, perhaps between 0.0001 cm/km and 0.000001 cm/km NTP. Even if we accept the 0.15 per cent upper limit for the amount of oxygen in the Martian atmosphere, it may be that such a small amount would have interesting implications with regard to the absorption of solar energy and resultant heating. In addition, H. K. Paetzold has stated (private communication) that a theoretical study indicates that the $O_3$ concentration appears to be approximately proportional to the logarithm of the $O_2$ concentration. This means that amounts of $O_2$ even as slight as suggested for Mars could give rise to appreciable amounts of ozone, sufficient to permit the existence of a Martian ozonosphere and consequent radiative heating.

- The upper "limit" of 0.15 per cent for the amount of oxygen in the Martian atmosphere is known to be doubtful, and may be too low. L. D. Kaplan has suggested (private communication) that this upper limit may be too low by as much as an order of magnitude because of failure to allow properly for pressure broadening of the $O_2$

rotational lines in the Earth's atmosphere. Thus, while $O_2$ has never been identified in the Mars atmosphere, we will assume for our model that it is present on Mars and has not escaped totally from the Martian exosphere.

- On Earth, according to Mitra,[10] ozone is found at high altitudes primarily because of the absorption of solar radiation by oxygen in the region of the *Runge-Schumann bands* (1760 A–1925 A) in the reaction:

$$O_2 + h\nu \longrightarrow O_2^*$$
$$O_2^* + O_2 \longrightarrow O_3 + O$$

It is carried downward to some extent to levels below 40 km by turbulent mixing. On Mars, even with a smaller relative concentration of oxygen, this reaction should be present, but spread over a much larger interval of depth.

- On Mars, the *Runge-Schumann continuum* (1250 A–1760 A) may also play a role in the formation of ozone through

$$O_2 + h\nu \longrightarrow O + O$$
$$O + O_2 + M \longrightarrow O_3 + M$$

This continuum radiation has a large absorption coefficient and on Earth is probably entirely used up at low ionosphere altitudes (above 80 km). But with a relatively small total amount of oxygen present on Mars, spread over a large depth interval, this radiation should be able to penetrate deeper. In addition, the minimum pressure for three-body collision processes (about $10^{-2}$ mb) is reached at about 80 km altitude on Earth, but considerably higher on Mars because of the lower gravity. This would indicate an ability of ozone to be formed from oxygen atoms at all altitudes up to $10^{-2}$ mb.

- At lower levels on Earth, ozone may also be formed when oxygen is dissociated by solar radiation in the *Herzberg continuum* between 2000 A and 2400 A[11] and in the *Herzberg bands* between 2400 A and 2600 A. Again, this continuum radiation should be able to penetrate deep into the Martian atmosphere.

- On the basis of these arguments, one can deduce that on Mars the highest altitude at which ozone is formed (the "top" of the ozonosphere) will be higher than on Earth. (On Earth, it is about 70 km.) The level of maximum ozone concentration, on the other hand, may be at an altitude similar to that found on Earth (some 20 km). The maximum amount of heating, however, will be found near the top of the ozonosphere on Mars, as on Earth, and will therefore take place at higher altitudes on Mars. This also implies that the altitude range over which heating due to ozone absorption could occur is much larger on Mars than on Earth.

- In other words, the slower decrease of pressure with altitude on Mars will cause heating from ozone to start at higher levels than on Earth. On the other hand, the smaller relative concentration of oxygen (and ozone) will cause heating to occur at lower levels than on Earth.
- In the absence of any heating from ozone, radiative equilibrium considerations[3] lead to certain inferences about the probable temperature of the Martian tropopause and, hence, its probable altitude. Based on such considerations, it is generally believed that the base of the Martian stratosphere is higher than on Earth, perhaps as high as 40 km. If sufficient ozone is present on Mars to absorb appreciable solar energy and produce radiative heating, the situation is drastically changed. On this basis we must expect that higher equilibrium temperatures exist in the Martian atmosphere over a wide range of altitudes.

Although these speculative arguments alone will not yet permit the construction of a model atmosphere, without additional assumptions, we can now proceed with our attempt at synthesis.

## PHYSICAL ANALOGIES

Let us imagine ourselves on an 11-km-high plateau, on an Earth about one-tenth as large in mass, and about one-half as large in diameter. To simplify, let us ignore the atmosphere below our level and consider the altitude variation as being governed by one-third the acceleration of gravity that exists on our real planet. Since the altitude variation of temperature is primarily governed by the selective absorption of solar radiation, our primary mathematical tool will be the amount of columnar mass above any altitude (see Appendix E). Thus, we equate the characteristic heights above our imaginary plateau (such as stratosphere and ozonosphere) to the corresponding altitudes on Earth under equal atmospheric mass, where changes in the temperature lapse rate occur (as given by the ARDC 1959 model atmosphere[12]). This is far from being a realistic argument; it would be applicable as a *first-order approach* only if the composition of the Martian atmosphere were identical with that of the Earth's.

In accord with conclusions by Mintz,[7] let us start at ground level with a mean air temperature of 250°K, based on a maximum ground temperature of 300°K, and assume that temperature variations of the actual Martian surface (as determined from infrared observations) affect the atmospheric temperature in only a very shallow layer near the ground. Furthermore, we speculate for two reasons that the height of the Martian tropopause is, at most, between 2 and 5 km:

First, the average height of Earth's tropopause is between 8 and 17 km, depending on the geographical latitude. The columnar mass above these heights is about the same as we can expect for the total columnar mass above ground level on Mars. At this height on our imaginary plateau, we would find ourselves almost in a stratosphere in conductive equilibrium, especially if a relatively high amount of $CO_2$ causes a concentration of infrared absorption and emission processes very near the planetary surface, and if ozone is formed down to low levels. Second, while this argument would suggest that the Martian atmosphere may be isothermal from only a few hundred meters above ground level, we must recall the large temperature variations of the ground, as discussed by Mintz.[7] In consequence, let us arbitrarily place the *mean* height of the tropopause at 4 km, approximately the pressure level on Earth of maximum ozone concentration.

Some of these arguments lend themselves to critical numerical analysis, and we hope other authors will perform the suggested calculations of radiative processes.

## MODEL III ATMOSPHERE

Better than words, Fig. 3 and Table 5 illustrate the resultant variations of atmospheric parameters with altitude and describe the developed Model III atmosphere. Oversimplified and conjectural as it is, it has some interesting features. Briefly, the numerical results are as follows:

The mean atmospheric temperature on Mars decreases upwards from 250°K near the ground with a mean adiabatic lapse rate of 3.75°K/km to a height of 4 km. Above this, the temperature remains constant up to an altitude of 40 km, where it increases again to a value of about 300°K at 100 km. It remains constant at this value up to 130 km, and then decreases again with an almost adiabatic lapse rate to a height of 200 km, or less. We assume that at this altitude, or at one even lower, heating may begin from absorption of far-ultraviolet radiation, which would also produce ionization and dissociation. Therefore, we calculated no values above 200 km, and refer the reader to Yanow[13] for a recent discussion of the Martian ionosphere.

If Model III indeed resembles conditions in the upper atmosphere of Mars, we may then a priori venture the following conjectural conclusions:

1. If the general circulation above the low tropopause in the Martian stratosphere is governed to some extent by ozone, the predominant dynamic regime may consist of

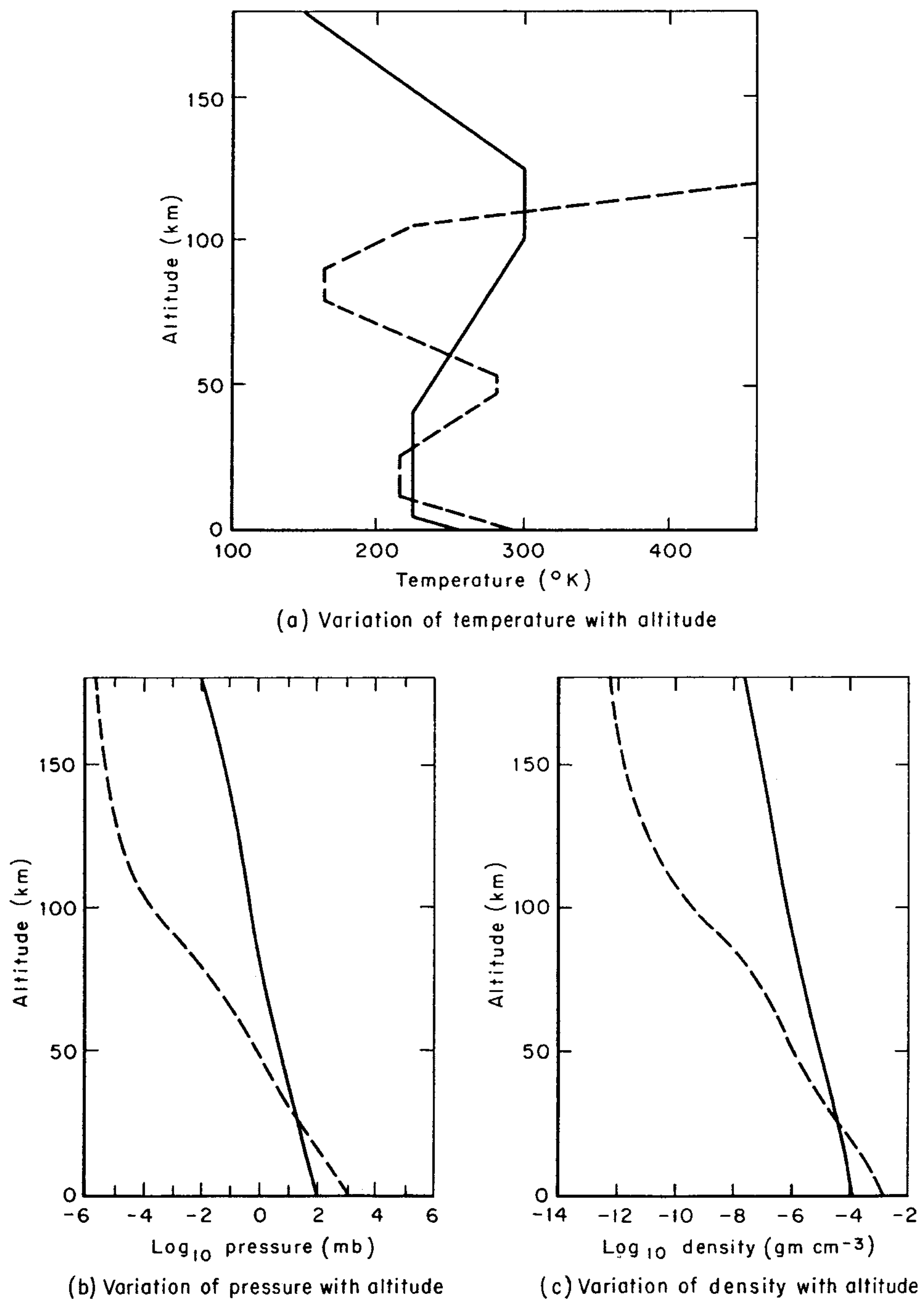


**Fig. 3—Conjectural Model III Mars Atmosphere** (Earth ARDC 1959 model atmosphere shown as dashed lines)

Table 5

CONJECTURAL MODEL III MARS ATMOSPHERE

| Altitude (km) | Temperature (°K) | Pressure (mb) | Density (gm cm$^{-3}$) |
|---|---|---|---|
| 0 | 250.0 | 85.125 | $1.19 \times 10^{-4}$ |
| 1 | 246.3 | 80.7 | 1.14 |
| 2 | 242.5 | 76.6 | 1.10 |
| 3 | 238.8 | 72.4 | 1.06 |
| 4 | 235.0 | 68.6 | 1.02 |
| 6 | 235.0 | 61.5 | $9.12 \times 10^{-5}$ |
| 8 | 235.0 | 55.1 | 8.17 |
| 10 | 235.0 | 49.3 | 7.32 |
| 15 | 235.0 | 37.5 | 5.56 |
| 20 | 235.0 | 28.5 | 4.23 |
| 25 | 235.0 | 21.6 | 3.21 |
| 30 | 235.0 | 16.4 | 2.44 |
| 35 | 235.0 | 12.5 | 1.86 |
| 40 | 235.0 | 9.50 | 1.41 |
| 50 | 246.0 | 5.63 | $7.98 \times 10^{-6}$ |
| 60 | 257.0 | 3.42 | 4.64 |
| 70 | 268.0 | 2.12 | 2.76 |
| 80 | 279.0 | 1.34 | 1.68 |
| 90 | 290.0 | $8.60 \times 10^{-1}$ | 1.03 |
| 100 | 301.0 | 5.62 | $6.52 \times 10^{-7}$ |
| 110 | 301.0 | 3.74 | 4.33 |
| 120 | 301.0 | 2.49 | 2.89 |
| 130 | 301.0 | 1.66 | 1.92 |
| 140 | 271.0 | 1.10 | 1.41 |
| 150 | 241.0 | $6.88 \times 10^{-2}$ | $9.95 \times 10^{-8}$ |
| 160 | 211.0 | 4.06 | 6.71 |
| 170 | 181.0 | 2.21 | 4.26 |
| 180 | 151.0 | 1.08 | 2.49 |
| 190 | (121.0) | $4.48 \times 10^{-3}$ | 1.29 |
| 200 | (91.0) | $1.45 \times 10^{-3}$ | $5.54 \times 10^{-9}$ |

simple large-scale circulation patterns with a great seasonal interchange between hemispheres.[14] Of immediate interest will be the potential rapid transport of water vapor from one hemisphere to the other twice each year. In other words, as soon as the winter pole and the atmosphere above it is heated by solar radiation in early spring, the polar ice cap will melt or sublime, and the water in crystalline or vapor form has only to reach the stratosphere above a low-lying tropopause in order to be transported around the whole planet toward the summer pole. Another result could be an apparent day-to-day progression of water near the surface in a direction away from the winter pole.

2. M. H. Davis (private communication) has pointed out that the model, by suggesting a mechanism for heating the middle atmosphere, explains why the $CO_2$ bands re-

ported by Sinton and Strong[15] at $9.4\mu$ and $10.4\mu$ are seen as absorption bands in infrared spectra of Mars. (Though the temperature of this $CO_2$ must be high enough for the lower rotational energy state to be sufficiently populated, it must be lower than the temperature of the ground, or the band would appear in emission rather than in absorption.)

3. The level of nacreous or mother-of-pearl clouds, found on Earth near 20 km, could be as high as 40 km on Mars, as a result of the very slow decrease of pressure and density in Model III. Noctilucent clouds, occurring on Earth near the temperature minimum at 70–90 km, would be expected to occur near 200 km on Mars, if at all. These conclusions follow directly, if the relevant processes on Mars are analogous to those on Earth. Further, the relatively high pressure and density values of the Martian upper atmosphere (a pressure level of 55 km on Earth corresponds to some 100 km on Mars in Model III) coupled with the potential presence of haze or dust particles even at levels of some 200 km may partially contribute to the planet's increase in apparent diameter when viewed in blue light.

Based on our *present factual knowledge*, the most probable conditions fall within the extremes given by Model II. Nevertheless, as an alternative to an artificial "Mean Atmosphere" within these limits, the author prefers Model III, which represents an upper extreme condition for a warm atmosphere where ozone plays a maximum role.

## TROPOSPHERIC METEOROLOGY

An earlier study[16] concluded that there is one area on Earth where certain climatological conditions may, in basic principle, approximate those of Mars. This is the Chang Tang, a wide plateau in Tibet, about the size of California but with a minimum elevation of 15,000 ft, surrounded by still higher mountain ranges. Unfortunately, most of what little we know about the meteorology of this desolate area comes from occasional travelers,[17][18] who seldom go beyond descriptions of violent dust storms. But meteorological data are available for a number of more southern stations in Tibet, and some reasonable extrapolations can be made from these and other observations.[19-21]

Much of the surface of the Chang Tang is bare rock or soil; grass and plants are deep-rooted but rarely more than 3 in. high. Its climate is reportedly unique among deserts. As expected, the daily change in air temperature near the surface is extreme, being hottest within one hour after local noon and coldest just before sunrise. Strong winds usually spring up around 2 or 3 p.m., when there is enormous convection. Most of the year there is no precipitation; the low water-vapor content permits only occasional high clouds. While the temperature lapse rate is super-adiabatic near the surface and nearly dry-adiabatic above, some 1.5 to 2 km above the surface the temperature appears to remain constant. It is there, according to Flohn,[19] that we find the free-air regime; thus, surprisingly, the jet stream occurs rather near the surface, but is unaffected by the plateau.[22] Also interesting is the singular phenomenon of "Staubnebel" (dust fog), observed and discussed by Ficker.[21]

A detailed study of the peculiarities in flora of the Chang Tang may help predict climate and, therefore, meteorological phenomena on Mars. Even a rough picture of probable conditions may help in the selection and design of initial space probe instrumentation.

Presently, we can advance only a few speculative arguments, based essentially on the Model III Atmosphere.

1. It is probable that on Mars a strong convective regime, caused by a large daily variation of surface temperatures, extends up to about 5 km. During the day, a super-adiabatic lapse rate prevails in a shallow layer near the surface, with a nearly adiabatic lapse rate above. At this time we can infer, from preliminary, qualitative energy calculations, that the tropopause may disappear during the night while the atmosphere above remains unaffected (Fig. 4). If so, a landing capsule operation

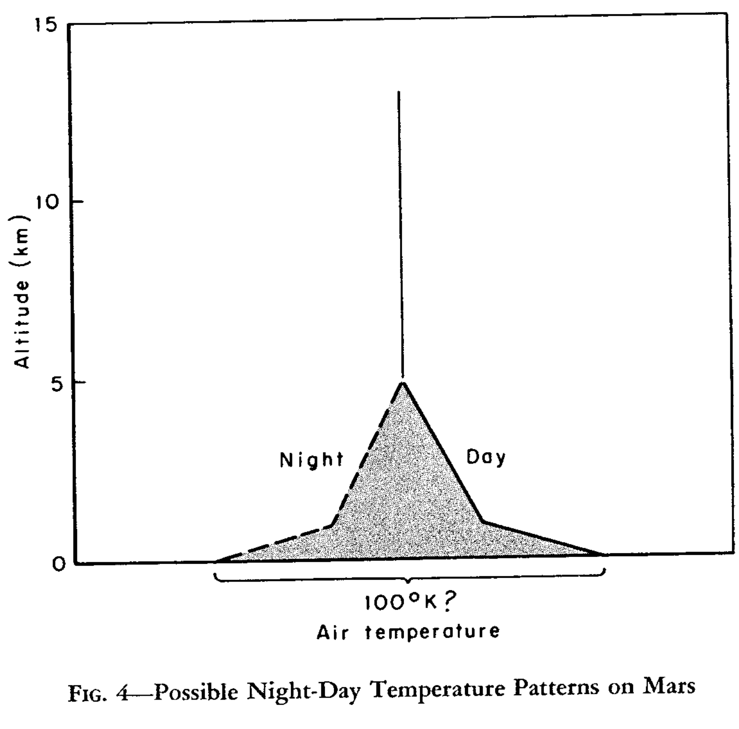


FIG. 4—Possible Night-Day Temperature Patterns on Mars

would have to be ready to encounter strong convection in the lowest few kilometers during daytime. In addition, strong horizontal winds may be expected in the local afternoon areas. A fuller, quantitative calculation is already in progress.

2. We would not expect to find many water clouds in a troposphere that is rather shallow, cold, rarefied, and dry. Rather, we would be prepared for considerable amounts of fog or haze, infrequent low-lying clouds, and, perhaps in the rarefied stratosphere, high clouds in thin layers of ice crystals, frozen $CO_2$, or dust. As mentioned before, large daily air-temperature changes would be likely only very near the ground. Since we can reasonably assume that the moist and dry adiabatic lapse rates are nearly identical, clouds might form only under special daytime conditions, over highly absorbing and heated surface areas.
3. The tropopause may disappear almost completely in the winter. This would further inhibit water-cloud formation, but permit thin $CO_2$ clouds to be formed at higher levels. It would also lend support to the arguments made previously in favor of a seasonal exchange of water between hemispheres.
4. Finally, if the Martian atmosphere is relatively dry and the surface eroded, we can readily infer that dust governs the predominant meteorological characteristics in the Martian troposphere—phenomena ranging from violent dust storms, wandering dunes, and selective light transmission, to perhaps such singular features as extensive "dust fog" and abrasive decomposition.

# V. PARAMETRIC COMPARISON WITH EARTH

## EQUIVALENT ALTITUDE LEVELS

THE COMPARISON of a Martian altitude level with one on Earth where atmospheric parameters reach the same mean values is useful for a number of engineering problems as well as scientific problems. For instance, the design of landing capsules will demand reliable limits for the altitude distributions of pressure, density, and density gradient. Determining these to a great extent, the altitude variation of atmospheric temperature will also be influenced by the altitude variation of columnar mass (atmospheric mass in a vertical column of 1 $cm^2$ cross section). To illustrate, we compared probable conditions on Mars (as given by the provisional model atmospheres) with mean conditions on Earth.

By using Model Atmospheres II and III as limiting conditions, and taking into account the variation of gravitational acceleration with altitude, we calculated the probable extreme ranges of the altitude levels of pressure, density, and columnar mass (see Appendix F). Table 6 summarizes the resulting "pressure altitudes." For easy application, Figs. 5, 6, and 7 graphically compare the pressure, density, and columnar mass for the two planets. The

Table 6

EXTREME RANGES OF EQUAL "PRESSURE ALTITUDES" FOR EARTH AND MARS

| Altitude on Earth (km) | Pressure (mb) | Altitude on Mars (km) ("Pressure Altitude") | | |
|---|---|---|---|---|
| | | Model II Lower Limit | Model III | Model II Upper Limit |
| 10 | 265 | $<0$ | $<0$ | $<0$ |
| 20 | 55.3 | $<0$ | 8 | 18 |
| 30 | 11.85 | 16 | 36 | 49 |
| 40 | 3.0 | 28.3 | 62.8 | 76.5 |
| 50 | 0.879 | 37.8 | 89.4 | 101 |
| 60 | 0.256 | 47.4 | 119 | 126 |
| 70 | 0.0602 | 58.8 | 152.4 | 154.6 |
| 80 | 0.0101 | 72.6 | 181 | 190 |

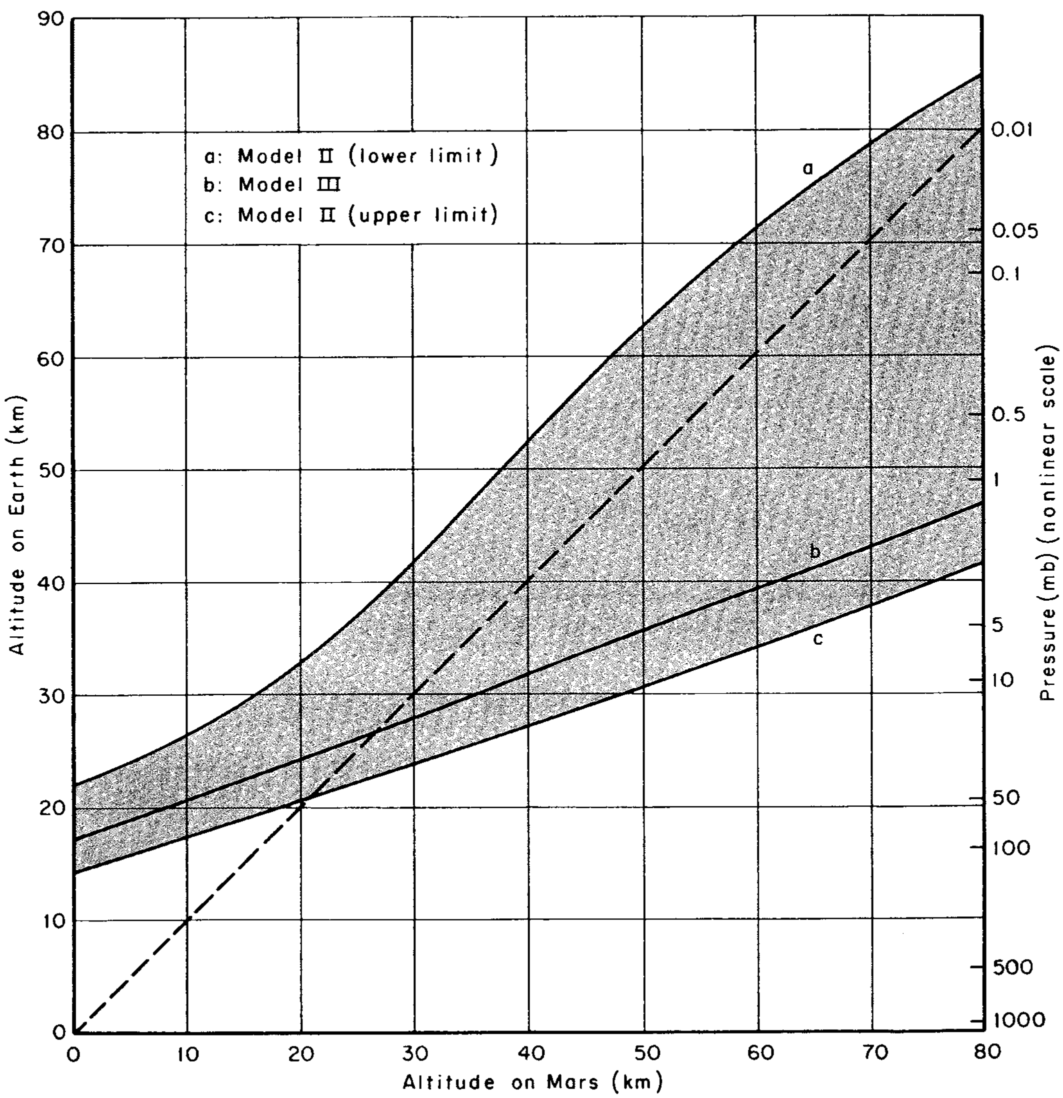


FIG. 5—Extreme Ranges of Equal Pressure Altitudes for Earth and Mars

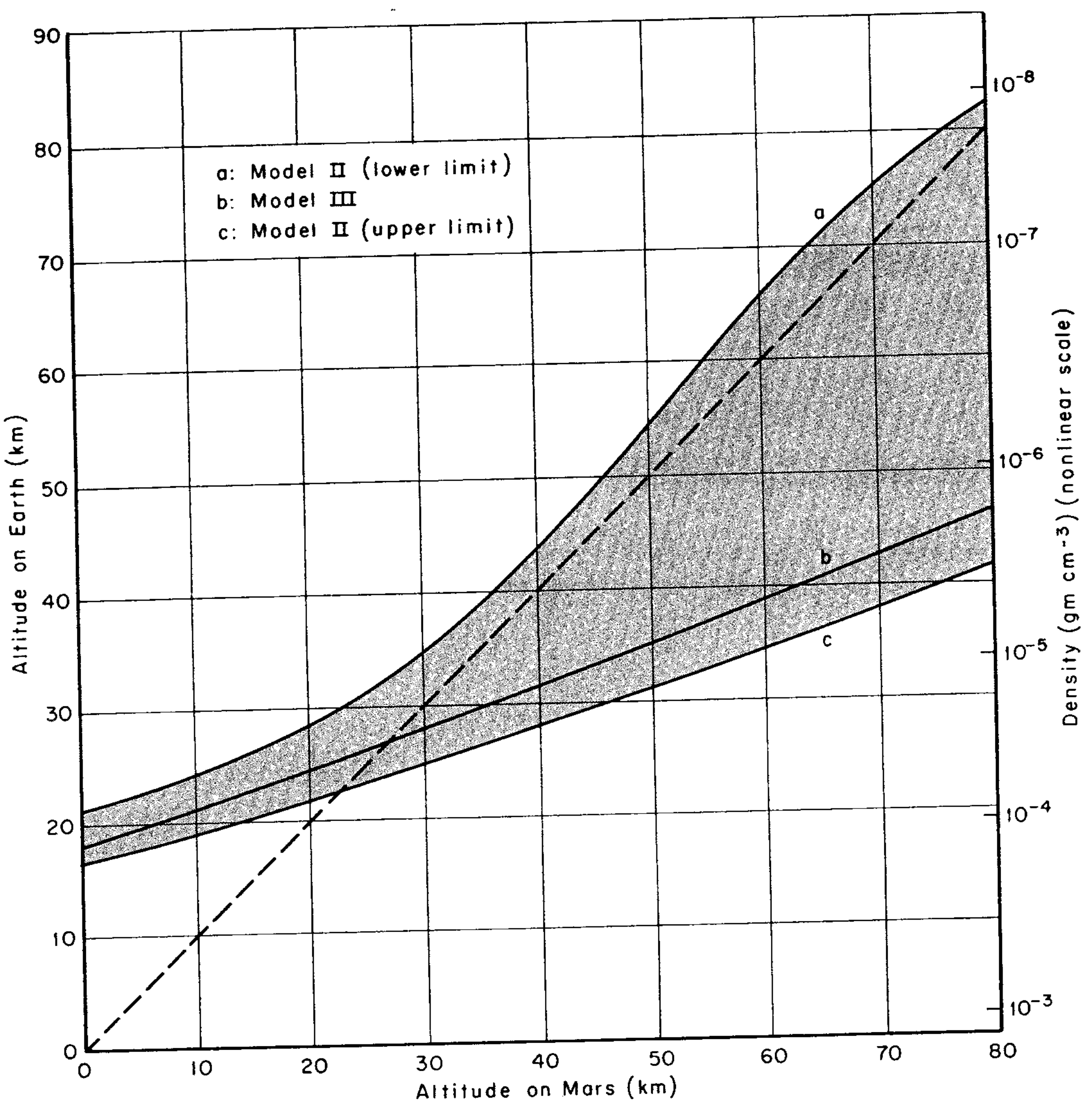


FIG. 6—Extreme Ranges of Equal Density Altitudes for Earth and Mars

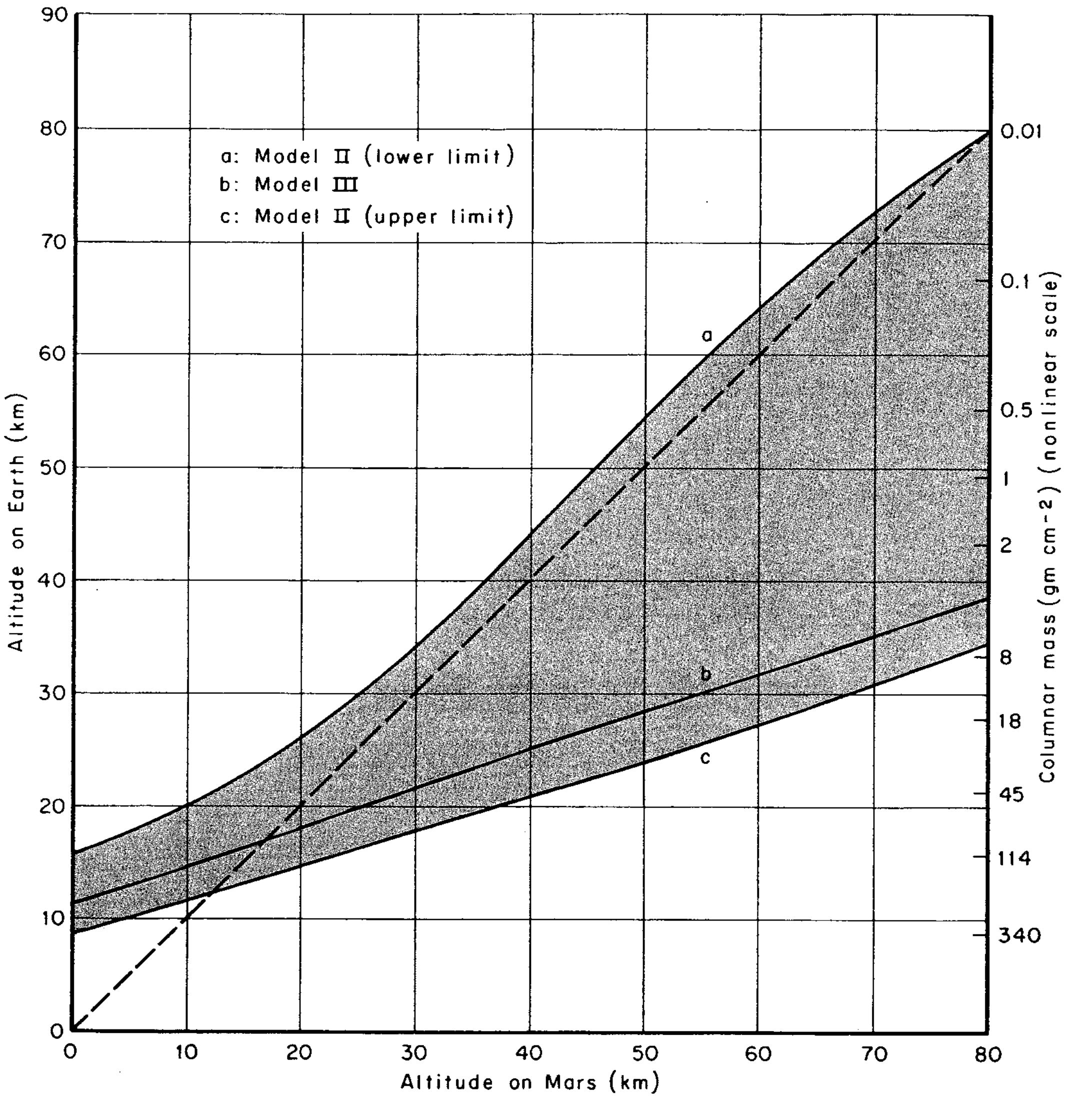


FIG. 7—Extreme Ranges of the Altitude Levels of Equal Columnar Mass on Earth and Mars

abscissa in each figure represents altitude on Mars; the ordinate represents both the altitude on Earth and the absolute values (on a nonlinear scale) of one atmospheric parameter applicable to both Earth and Mars. For practical use, the shaded area in each figure spans the probable conditions on Mars in low and middle latitudes up to an altitude of 80 km, with full allowance for variations due to time of day or season. The broken line is that of equal altitudes on Mars and Earth; any point below it represents a higher altitude on Mars than on Earth for a given parameter value, any point above it a lower altitude.

From Fig. 5, for example, we see that at an altitude of 40 km on Mars the atmospheric pressure will be between 18.6 mb and 0.7 mb—the pressures found on Earth between 27 km and 52 km altitude. Similarly, a pressure of 10 mb, which is found on Earth at about 31 km altitude, may be found on Mars somewhere between 18 km and 52 km above the surface.

Obviously, these ranges of uncertainty are extremely wide. Indeed, they demonstrate just how "reliable" is our present knowledge.

## CONCLUSIONS

The actual conditions of the Martian atmosphere over middle and low latitudes—regardless of time of day or season—should fall within the limits shown in Table 7.

Table 7

INFERRED LIMITS OF ATMOSPHERIC CHARACTERISTICS

| Altitude Range (km) | Suggested Source | |
|---|---|---|
| | Lower Extreme | Upper Extreme |
| 0 to 60 | Model II Lower Limit | Model II Upper Limit |
| 60 to 130[a] | Model II Lower Limit | Model III |

[a] Model II must be extrapolated for values above 80 km.

Obviously, these estimated limits are reliable partly because they are so broad. And though they may prove useful as criteria for initial engineering design, they will have to be refined for more demanding uses.

APPENDIX A

# BASIC FORMULAS AND NOTATIONS

## Atmospheric Equations

$$p = Mg$$

where $p$ = atmospheric pressure in $10^3$ dynes $cm^{-2}$ or mb
$M$ = columnar mass (mass of atmosphere per unit surface area) in gm $cm^{-2}$
$g$ = acceleration of gravity in cm $sec^{-2}$

$$p = \rho R(T/m)$$

where $\rho$ = atmospheric density in gm $cm^{-3}$
$R$ = universal gas constant (chemical) = $8.31439 \times 10^7$ ergs $(°K)^{-1}$(gm-mole)$^{-1}$
$T$ = temperature in °K
$m$ = mean molecular mass (dimensionless)

$$H = (RT/mg) \times 10^{-5}$$

where $H$ = scale height (equal to height of homogeneous atmosphere) in km

$$L = (\partial T/\partial z)$$

where $L$ = rate of temperature change with altitude in °K $km^{-1}$

$$\Gamma = (\partial T/\partial z)_{ad} = -(g/c_p)$$

where $\Gamma$ = adiabatic lapse rate in °K $km^{-1}$

$$g_z = g_0 [r/(r+z)]^2$$

where $r$ = planetary radius in km
$z$ = geometric altitude above planetary surface in km

## Subscripts

| | |
|---|---|
| 0 | surface value |
| $z$ | altitude on Mars |
| $h$ | altitude on Earth |

| | |
|---|---|
| max | maximum permissible value |
| min | minimum permissible value |
| mean | mean value |

Superscripts

| | |
|---|---|
| $''$ | probable upper limit |
| $'$ | probable lower limit |
| $\oplus$ | Earth |
| ♂ | Mars |

**Atmosphere in Conductive (Isothermal) Equilibrium**

$$L = 0$$

$$T = \text{constant}$$

$$\left.\begin{aligned} p_z &= p_0 e^{-z/H} \\ \rho_z &= \rho_0 e^{-z/H} \end{aligned}\right\} \text{neglecting variations of gravity with altitude}$$

**Atmosphere of Constant Lapse Rate**

$$T_z = T_0 + L(z - z_0)$$

$$p_z = p_0 \left( \frac{T_0}{T_0 + L(z - z_0)} \right)^{mg/RL}$$

$$\rho_z = \rho_0 \left( \frac{T_0}{T_0 + L(z - z_0)} \right)^{1+(mg/RL)}$$

**Atmosphere in Convective (Adiabatic) Equilibrium**

$$L = \Gamma = -\frac{g}{c_p}$$

$$T_z = T_0 + \Gamma(z - z_0)$$

$$p_z = M_0 g \left( 1 - \frac{g}{T_0 c_p} \Delta z \right)^{mc_p/R}$$

$$\rho_z = \frac{m}{T_0 R} M_0 g \left( 1 - \frac{g}{T_0 c_p} \Delta z \right)^{(mc_p/R)-1}$$

**Adiabatic Relation**

$p/\rho^{\gamma} = \text{constant}$, where $\gamma$ is the ratio of specific heat of the gas at constant pressure $(c_p)$ to that at constant volume $(c_v)$, and $c_p - c_v = R/m$. The natural height limit of an atmosphere in convective equilibrium, where the density becomes zero, is given by

$$Z_\infty = \frac{p_0 \gamma}{\rho_0 g (\gamma - 1)} = T_0 \frac{c_p}{g}$$

APPENDIX B

# ATMOSPHERIC PARAMETERS NEAR SURFACE*

$$M_{max} = 0.33 \times M^{\oplus} = 340 \text{ gm cm}^{-2} \text{ (adopted)}$$
$$M_{min} = 0.11 \times M^{\oplus} = 114 \text{ gm cm}^{-2} \text{ (adopted)}$$
$$M_{mean} = \frac{M_{max} + M_{min}}{2} = 227 \text{ gm cm}^{-2}$$

where $M^{\oplus} = 1033$ gm cm$^{-2}$ is the mean columnar mass on Earth.

$$p_{0\,max} = M_{max} \times g_{max} = 132.6 \text{ mb}$$
$$p_{0\,min} = M_{min} \times g_{min} = 41.04 \text{ mb}$$
$$p_{0\,mean} = \frac{1}{4}(M_{max} + M_{min})(g_{max} + g_{min}) = 85.125 \text{ mb } (1 \text{ mb} = 1 \times 10^{3} \text{ dynes cm}^{-2})$$

Possible extreme limits for surface density, based on the given temperature and surface pressure only (see Table 2), could be calculated from

$$\rho_{0\,max} = \frac{p_{0\,max} \times m_{max}}{T_{0\,min} \times R} = 2.392 \times 10^{-4} \text{ gm cm}^{-3}$$
$$\rho_{0\,min} = \frac{p_{0\,min} \times m_{min}}{T_{0\,max} \times R} = 4.607 \times 10^{-5} \text{ gm cm}^{-3}$$

and extreme values of the scale height at adiabatic temperature near the surface from

$$H_{max} = \frac{R \times T_{0\,max}}{m_{min} \times g_{min}} = 24.75 \text{ km}$$
$$H_{min} = \frac{R \times T_{0\,min}}{m_{max} \times g_{max}} = 14.21 \text{ km}$$
$$\Gamma_{max} = -\frac{g_{max}}{c_{p\,min}} = -4.105^{\circ}\text{K km}^{-1}$$
$$\Gamma_{min} = -\frac{g_{min}}{c_{p\,max}} = -3.249^{\circ}\text{K km}^{-1}$$

However, these extreme limits have validity only for permissible conditions near the surface. When considering realistic extreme examples for a model atmosphere involving variations with altitude, the equations in Appendix C were applied.

*See Tables 1 and 2.

## APPENDIX C

# MODEL I ATMOSPHERE*

THE EXTREME PERMISSIBLE temperature-altitude envelopes, representing upper and lower limits, could be obtained by relating the minimum permissible air temperature near the surface with the maximum permissible lapse rate, and vice versa, from the following relation:

$$T_{z\,\max} = T_{0\,\max} + \Delta z \Gamma_{\min} = T_{0\,\max} - \frac{g_{\min}}{c_{p\,\max}} \Delta z$$

$$T_{z\,\min} = T_{0\,\min} + \Delta z \Gamma_{\max} = T_{0\,\min} - \frac{g_{\max}}{c_{p\,\min}} \Delta z$$

These temperature values are tabulated in Table 8 as functions of height.

Table 8

EXTREME PERMISSIBLE TEMPERATURE-ALTITUDE ENVELOPES FOR ADIABATIC ATMOSPHERE (NEGLECTING LAPSE-RATE RESTRICTIONS)

| Altitude (km) | Temperature (°K) | | | Altitude (km) | Temperature (°K) | | |
|---|---|---|---|---|---|---|---|
| | Minimum | Mean | Maximum | | Minimum | Mean | Maximum |
| 0 | 200 | 250 | 300 | 22 | 109.7 | 167.5 | 224.6 |
| 2 | 191.8 | 242.5 | 293.1 | 24 | 101.5 | 160.0 | 217.7 |
| 4 | 183.6 | 235.0 | 286.3 | 26 | 93.3 | 152.5 | 210.8 |
| 6 | 175.4 | 227.5 | 279.4 | 28 | 85.1 | 145.0 | 204.0 |
| 8 | 167.2 | 220.0 | 272.6 | 30 | 76.8 | 137.5 | 197.1 |
| 10 | 159.0 | 212.5 | 265.7 | 32 | 68.6 | 130.0 | 190.3 |
| 12 | 150.7 | 205.0 | 258.8 | 34 | 60.4 | 122.5 | 183.4 |
| 14 | 142.5 | 197.5 | 252.0 | 36 | 52.2 | 115.0 | 176.6 |
| 16 | 134.3 | 190.0 | 245.1 | 38 | 44.0 | 107.5 | 169.7 |
| 18 | 126.1 | 182.5 | 238.3 | 40 | 35.8 | 100.0 | 162.8 |
| 20 | 117.9 | 175.0 | 231.4 | | | | |

However, to arrive at a consistent set of atmospheric parameters for a model atmosphere, the probable extreme values of pressure at any altitude were calculated from

*In convective equilibrium throughout.

$$\text{Upper Limit:}\quad p''_z = M_{\max}\, g_{\max}\left(1 - \frac{g_{\max}}{T_{0\,\max}\, c_{p\,\max}}\,\Delta z\right)^{m_{\min} c_{p\,\max}/R}$$

$$\text{Lower Limit:}\quad p'_z = M_{\min}\, g_{\min}\left(1 - \frac{g_{\min}}{T_{0\,\min}\, c_{p\,\min}}\,\Delta z\right)^{m_{\max} c_{p\,\min}/R}$$

which required that

$$\text{Upper Limit:}\quad T''_z = T_{0\,\max} - \frac{g_{\max}}{c_{p\,\max}}\,\Delta z$$

$$\text{Lower Limit:}\quad T'_z = T_{0\,\min} - \frac{g_{\min}}{c_{p\,\min}}\,\Delta z$$

and the corresponding values of density must then be obtained from

$$\text{Upper Limit:}\quad \rho''_z = \frac{p''_z m_{\min}}{R \times T''_z}$$

$$\text{Lower Limit:}\quad \rho'_z = \frac{p'_z\, m_{\max}}{R \times T'_z}$$

While independent extreme limits for temperature, pressure, and density could have been maximized and minimized, this was done only for the permissible surface ranges given in Table 2. For Model I the above relations were used to derive an internally consistent set of parameters. Apart from the requirement that the maximum molecular mass $m_{\max}$ has to be used with $c_{p\,\min}$, a considerable number of envelopes could be calculated, dependent on the basic parameter to be optimized at a given altitude. It is felt that the relations chosen for Model I come numerically closest to this objective. The results are shown in Table 3.

## APPENDIX D

# MODEL II ATMOSPHERE*

ADIABATIC EQUILIBRIUM was assumed to exist only up to the level of the tropopause, and an isothermal condition was assumed to predominate above.

### Minimum Envelopes

Model I values were used up to an altitude of $z = 26$ km, where the lower limit of temperature $T' = 101.5°$K. Above this, isothermal conditions at this temperature were adopted, on the basis that $CO_2$ would freeze at about 130°K at these altitudes and much lower stratospheric temperatures were considered unrealistic, although, by analogy with water-vapor cloud formation on Earth, some supercooling may be possible.

Above $z = 26$ km, the following relations were used

$$p'_z = p'_{26} \exp\left[-\frac{g_{\min} m_{\max}}{R \times T'_{26}} (z - z_{26})\right]$$

$$\rho'_z = \rho'_{26} \exp\left[-\frac{g_{\min} m_{\max}}{R \times T'_{26}} (z - z_{26})\right]$$

### Maximum Envelope

Model I values were used up to $z = 10$ km, where $T'' = 262.9°$K, and isothermal conditions were adopted above this level on the assumption that a higher stratospheric temperature is unlikely in view of a low water-vapor concentration.

$p''_z$ and $\rho''_z$ were computed, therefore, from

$$p''_z = p''_{10} \exp\left[-\frac{g_{\max} m_{\min}}{R \times T''_{10}} (z - z_{10})\right]$$

$$\rho''_z = \rho''_{10} \exp\left[-\frac{g_{\max} m_{\min}}{R \times T''_{10}} (z - z_{10})\right]$$

---

*See Table 4.

Table 9 gives the numerical values of the set of basic and derived quantities which were used for Models I and II. Comparison with Table 2 will illustrate the differences between maximum and minimum permissible values near the planetary surface, and upper and lower limit values as starting points for a self-consistent model atmosphere. A partial justification for the choice and adoption of some of the specific extreme values can be found in detailed discussions by M. H. Davis.[(23)(24)]

Table 9

CONSTRUCTION PARAMETERS FOR MODELS I AND II

| Parameter | Lower Limit | Mean | Upper Limit |
|---|---|---|---|
| $M_0$ | 114 gm cm$^{-2}$ | 227 | 340 |
| $T_0$ | 200°K | 250 | 300 |
| $g_0$ | 360 cm sec$^{-2}$ | 375 | 390 |
| $c_p$ | $0.95 \times 10^7$ | $1.0 \times 10^7$ | $1.05 \times 10^7$ |
| $m$ | 30 | 29 | 28 |
| $\Gamma$ | $-3.790$°K km$^{-1}$ | $-3.75$ | $-3.714$ |
| $p_0$ | 41.04 mb | 85.125 | 132.6 |
| $\rho_0$ | $7.404 \times 10^{-5}$ gm cm$^{-3}$ | $1.188 \times 10^{-4}$ | $1.488 \times 10^{-4}$ |
| $H_0$ | 15.4 km | 19.1 | 22.8 |
| $z_{\text{stratosphere}}$ | 26 km | 24 | 10 |
| $H_{\text{stratosphere}}$ | 7.8 | 12.2 | 20 |

## APPENDIX E

# CONJECTURAL MODEL III ATMOSPHERE

ADIABATIC EQUILIBRIUM was assumed to extend from $z_0$ (0 km) to $z_{I}$ (4 km), approximately the pressure level where the maximum ozone concentration is found on Earth.

Isothermal equilibrium was assumed to prevail from $z_{I}$ (4 km) to $z_{II}$ (the altitude on Mars equivalent in overlying air mass to an altitude on Earth of 25 km—mean height of lower part of Earth ozonosphere where temperature begins to increase with height).

A constant temperature lapse rate was assumed between $z_{II}$ and $z_{III}$, with $z_{III}$ defined as the altitude on Mars where the overlying air mass equals that found on Earth at 45 km (lower level of maximum ozonosphere temperature). A temperature of about 300°K was assumed for the mean temperature of the Martian ozonosphere, approximately equal to the maximum daytime temperatures likely to occur in the Martian ground surface and in the air near the ground at midday. Such an ozonosphere temperature would not be inconsistent with $CO_2$ band observations, assuming that they are seen in absorption spectra against a warmer surface.* Any quantitative value would depend on an arbitrary assumption about the relative numerical concentrations of these substances and, of course, free oxygen in the Martian atmosphere. With such assumptions a realistic value of the probable ozonosphere temperature could probably be determined by downward integration. This approach was felt to be too speculative at this time.

Between $z_{III}$ and $z_{IV}$, the mean temperature was approximated to remain constant at 301°K; $z_{IV}$ was taken to be equivalent to an Earth altitude of 55 km, in a way analogous to that used for $z_{II}$ and $z_{III}$.

Above $z_{IV}$, the temperature was assumed to decrease nearly adiabatically to an unspecified altitude $z_V$, where heating due to dissociation and ionization by far ultraviolet, and consequent ionospheric heating, may begin to occur. This probably does not occur below some 150 to 200 km.

*The above is also qualitatively compatible with consideration of Plass[25] with regard to radiative heating of the Earth's atmosphere in the presence of ozone, water vapor, and carbon dioxide.

If, on Earth, a pressure $p_h^{\oplus}$ is found at an altitude $h$, then the columnar mass of air $M_h^{\oplus}$ remaining above this altitude is given by

$$M_h^{\oplus} = \frac{p_h^{\oplus}}{g_h^{\oplus}}$$

On Mars, the same amount of columnar mass $M_z^{♂}$ will be found at an altitude $z$, exerting a pressure $p_z^{♂}$, so that

$$p_z^{♂} = M_z^{♂}\, g_z^{♂}$$

Since $M_z^{♂} = M_h^{♂}$ by definition in our method of construction, where $h$ is known, and $z$ is the unknown,

$$p_z^{♂} = p_h^{\oplus} \frac{\bar{g}_z^{♂}}{g_h^{\oplus}}$$

To obtain these altitudes $z$ on Mars in accord with the assumptions detailed earlier, the numerical calculations employed an iteration technique as follows: With

$$z_{\mathrm{I}} = 4 \text{ km}, \qquad p_0 = 85.125 \text{ mb}, \qquad T_0 = 250°\text{K}, \qquad \frac{\partial T}{\partial z} = \Gamma = -\frac{g}{c_p},$$

$p_{\mathrm{I}}$ is obtained from the adiabatic relation, as in Model II.

The altitude $z_{\mathrm{II}}$ was calculated in successive approximations from

$$p_{\mathrm{II}} = p_{25}^{\oplus} \frac{g_{\mathrm{II}}^{♂}}{g_{25}^{\oplus}} = p_{\mathrm{I}} \exp\left[-\frac{m g^{♂}}{R T_{\mathrm{I}}}(z_{\mathrm{II}} - z_{\mathrm{I}})\right]$$

where $M = 29$ throughout, $T_{\mathrm{I}} = 235°\text{K}$, $\partial T/\partial z = 0$ between $z_{\mathrm{I}}$ and $z_{\mathrm{II}}$, $p_{25}^{\oplus}$ is the atmospheric pressure on Earth at 25 km altitude, $g_{25}^{\oplus}$ is the Earth's gravitational acceleration at 25 km altitude, $g_{\mathrm{II}}^{♂}$ is the initially unknown Mars gravitational acceleration at the initially unknown altitude $z_{\mathrm{II}}$, and $\bar{g}^{♂}$ the Mars mean gravitational acceleration in the interval $z_{\mathrm{I}}$ to $z_{\mathrm{II}}$. The iteration gave a $z_{\mathrm{II}} = 39.9$ km, which was approximated as 40 km.*

The altitude $z_{\mathrm{III}}$ was obtained, again by numerical iteration, from the relations

$$p_{\mathrm{III}} = p_{45}^{\oplus} \frac{g_{\mathrm{III}}^{♂}}{g_{45}^{\oplus}} = p_{\mathrm{II}} \left[\frac{T_{\mathrm{II}}}{T_{\mathrm{II}} + (z_{\mathrm{III}} - z_{\mathrm{II}}) \dfrac{\partial T}{\partial z}}\right]^{m\bar{g}^{♂}/R(\partial T/\partial z)}$$

$$T_{\mathrm{III}} = T_{\mathrm{II}} + (z_{\mathrm{III}} - z_{\mathrm{II}}) \frac{\partial T}{\partial z}$$

*Note that the gravitational acceleration appears in the exponent, and its variation with altitude cannot be neglected in solving for heights $z_i$.

For an assumed temperature maximum of $T_{III} \approx 300°K$ at height $z_{III}$, and $z_{II} = 40$ km, this resulted in a constant rate of temperature increase of $\partial T/\partial z = 1.1013°K\ km^{-1}$, between $z_{II}$ and $z_{III}$, and a height of 99.1 km for $z_{III}$. In view of the large uncertainties, this was approximated as $z_{III} = 100$ km.

The altitude $z_{IV}$ was then calculated from

$$p_{IV} = p_{55}^{\oplus} \frac{g_{IV}^{\male}}{g_{55}^{\oplus}} = p_{III} \exp\left[-\frac{m\bar{g}^{\male}}{RT_{III}}(z_{IV} - z_{III})\right]$$

as before, for $\partial T/\partial z = 0$ between $z_{III}$ and $z_{IV}$. The resultant $z_{IV}$ of 128.8 km was approximated as 130 km.

Finally, the temperature was assumed to decrease with a slightly less than adiabatic lapse rate of $\partial T/\partial z = -3°K\ km^{-1}$ above the altitude $z_{IV}$.

The numerical values thus adopted are tabulated in Table 10 at levels of temperature discontinuity. The variations with altitude for the resulting Model III atmosphere are shown in Table 5 and Fig. 3. It is felt that the conjectural model represents extreme conditions on Mars for an atmosphere heated efficiently by solar radiation.

Table 10

CONSTRUCTION PARAMETERS FOR MODEL III

| Level | Altitude (km) | Temperature $T$ (°K) | Temperature Change $L$ (°K km$^{-1}$) | Scale Height $H$ (km) | Pressure $p$ (mb) | Gravity $g$ (cm sec$^{-2}$) |
|---|---|---|---|---|---|---|
| $z_0$ | 0 | 250[a] | | 19.1 | 85.125[a] | 375[a] |
| | | | −3.75[a] | | | |
| $z_I$ | 4[a] | 235 | | 18 | 68.6 | 374.1 |
| | | | 0[a] | (18.21) | | (370) |
| $z_{II}$ | 40 | 235 | | 18.4 | 9.5 | 366 |
| | | | 1.1 | (21.4) | | (360) |
| $z_{III}$ | 100 | 301[a] | | 24.4 | 0.56 | 354 |
| | | | 0[a] | (24.59) | | (351) |
| $z_{IV}$ | 130 | 301 | | 24.8 | 0.17 | 348 |
| | | | −3[a] | | | (341) |
| $z_V$ | 200 | 91 | | | 0.0015 | 334 |

NOTE: Values for pressure and gravitational acceleration at Earth altitudes entering the calculation were taken from the ARDC 1959 model atmosphere.[12]

[a] Assumed or adopted values; see text. Mean values for height intervals are in parentheses.

The value used for surface acceleration of gravity on Mars approximates the most probable values in middle and low latitudes for an idealized rotating planet. The astronomical characteristics for such an idealized planet Mars were as follows:

| | |
|---|---|
| Planetary mass | $0.6422 \times 10^{27}$ gm |
| Equatorial radius | 3380.5 km |
| Dynamical flattening | 0.0052 |
| Polar radius | 3362.9 km |
| Radius at latitude 45° | 3371.7 km |
| Surface acceleration (non-rotating) | |
| Equator | 374.8 cm $sec^{-2}$ |
| 45° latitude | 376.8 cm $sec^{-2}$ |
| Pole | 378.8 cm $sec^{-2}$ |
| Gravitational constant | $6.67 \times 10^{-8}$ $cm^3$ $gm^{-1}$ $sec^{-2}$ |
| Rate of rotation | $24^h\ 37^m\ 23^s$ |

## APPENDIX F

# PARAMETRIC COMPARISON

THE EXTREME RANGES of equivalent altitude levels were calculated by taking into account probable extremes of the variation of gravitational acceleration with altitude. In accord with the permissible ranges of radius given in Table 1, the values of surface gravity listed in Table 11 were used.

Table 11

ASTRONOMICAL CONFIGURATIONS OF EXTREME CHARACTERISTICS

| Item | Model II Lower Limit | Model III | Model II Upper Limit |
|---|---|---|---|
| Mars radius (km) | 3438 | 3380 | 3323 |
| Surface gravity (cm $sec^{-2}$) | 360 | 375 | 390 |

Thus the lower limit is for a planet Mars which, because it has the maximum observed equatorial radius, has the lowest values of surface gravity but therefore the smallest rate of decrease of gravitational acceleration with altitude. Conversely, the upper limit is for a planet Mars (or a high or middle latitude on Mars) with a smaller radius, and hence a sharper rate of decrease of gravitational acceleration with altitude. A rotational relief, however, has not been numerically considered.

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