which CO radiation becomes effective.

Our results differ considerably from the temperature profile for Mars recently published by Johnson (*7*) in which the upper atmosphere is isothermal at 85°K. Johnson's value for the temperature is derived from the observation of Mariner IV's occultation experiment that the electron-density scale height above 125 km on Mars is 25 km. The neutral gas-density scale height will then be 12.5 km. If the principal ion is $O^+$, then for an isothermal atmosphere the temperature should be 85°K. However, if there is a positive temperature gradient, then the actual scale height in the atmosphere can be much larger than the isothermal scale height. For an atmosphere in hydrostatic equilibrium, the two scale heights, $H$ and $H'$ (actual and isothermal), are related by the following expression:

$$H = \frac{H'}{1 - \frac{H'}{T}\frac{dT}{dz}} \qquad (1)$$

Johnson assumes $dT/dz = 0$ and therefore infers that $H = H' = 25$ km. But, as seen from Eq. 1, depending on the temperature gradient and the actual temperature of that region, a number of solutions for $H$ are possible. If, for example, we assume that, in the atmospheric region explored by Mariner IV's occultation experiment (55°S, winter), $(dT/dz)_{125\ \text{km}} = 2°\text{K/km}$ (Fig. 1) and $T_{125\ \text{km}} = 150°\text{K}$, then for $H' = 25$ km, $H = 37.5$ km. This scale height will be consistent with an atomic oxygen atmosphere at $T \sim 150°\text{K}$.

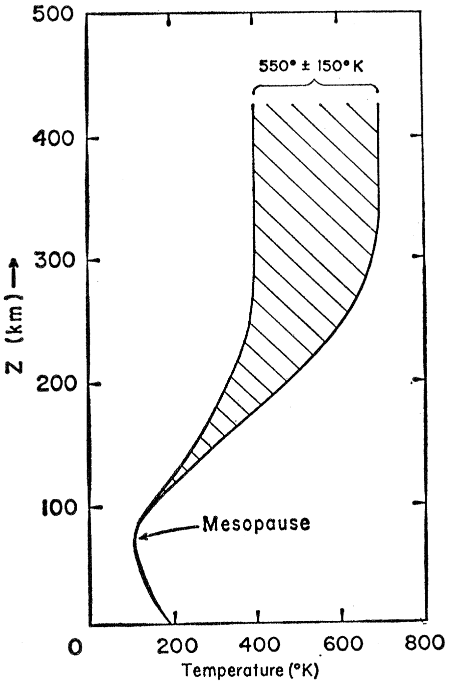

Fig. 1. Vertical distribution of temperature in the atmosphere of Mars. The range of uncertainty in the temperature of the upper atmosphere, ± 150°K, is shown as the hatched area. An atmosphere of pure $CO_2$ with a surface pressure of 8 mb was assumed.

The calculated temperature at 125 km altitude (Fig. 1) is slightly higher than 150°K, mainly because our model is an average for the whole planet, while the results of the occultation experiment concern the Martian atmosphere at 55°S, winter hemisphere, in the local afternoon.

It therefore seems clear that Johnson's model is based on only one of several ways in which measurements of electron-density scale height can be interpreted. It has the further disadvantage of putting stringent requirements on the energetics of the thermosphere. An isothermal thermosphere implies that, at each height, the amount of absorption of ultraviolet radiation *exactly equals* the emission by $CO_2$ and CO at that height. It is difficult to see how this condition will be met at all times and at all points on the planet.

Our result has some implications regarding the origin of the observed $CO_2$ on Mars.

At $T_{ex} = 550°\text{K}$, both $H_2$ and He will be lost rapidly, but O will not escape. The present atmosphere of Mars may therefore be a remnant of a heavier primitive atmosphere which once had a composition similar to that observed today on Jupiter—that is, with large quantities of $H_2$ and He and small amounts of $CH_4$, $NH_3$, and probably $H_2O$. Once $H_2$ and He have escaped, the residual atmosphere will be composed mainly of $CO_2$ with relatively small but substantial amounts of Ne and $N_2$ (*6*). If this is the process by which the atmosphere of Mars has evolved, then the exospheric temperature on Mars should be greater than the escape temperature for He, but less than the escape temperature for O—that is, $1100° > T_{ex} > 275°\text{K}$. Also, if the total amount of $CO_2$ in the Martian atmosphere is 5 mb, then from the cosmic abundance table it follows that there must also be at least 2 mb of Ne and 1 mb of $N_2$ in the atmosphere (*8*). Both these gases are difficult to observe from Earth, and their identification on Mars must therefore await *in situ* exploration.

Johnson has proposed the alternative hypothesis that the present atmosphere of Mars is a result of outgassing from the interior. This hypothesis implies that the atmospheric pressure on Mars was never greater than the present value of about 10 mb and that there must be large quantities of frozen water under the surface of Mars (*7*).

Only the future fly-bys and landers on Mars will be able to test these conjectures by measuring the exospheric temperature, searching for rare gases by mass spectrometer, and examining the surface properties of the planet. These questions regarding the origin and evolution of the Martian atmosphere are not only of profound scientific interest, but are also of the greatest general and philosophical importance because they relate to the primitive physical environment of the planets and the circumstances under which life may have developed on the earth and on other bodies in the solar system.

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#### References and Notes

1. M. J. S. Belton and D. M. Hunten, "The abundance and temperature of $CO_2$ in the Martian atmosphere," paper presented before American Astronomical Society, Berkeley, Calif., Dec. 1965; L. D. Gray, *AIAA (Amer. Inst. Aeron. Astronaut.) Bull.* **2**, 722 (1965).
2. A. Kliore, D. L. Cain, G. S. Levy, V. R. Eshleman, G. Fjeldbo, F. D. Drake, *Science* **149**, 1243 (1965).
3. C. Prabhakara and J. S. Hogan, Jr., *J. Atmos. Sci.* **22**, 97 (1965).
4. J. W. Chamberlain, *Astrophys. J.* **136**, 582 (1962).
5. M. B. McElroy, J. L'Ecuyer, J. W. Chamberlain, *ibid.* **141**, 1523 (1965).
6. S. I. Rasool, S. Gross, W. E. McGovern, "The atmosphere of Mercury," *Space Sci. Rev.*, in press.
7. F. S. Johnson, *Science* **150**, 1445 (1965).
8. For this composition the exospheric temperature of Mars is reduced by approximately 10 percent of that shown in Fig. 1, mainly because of the higher conductivity of neon.
9. One of us (W.E.M.) was supported by NASA grant N.S.G. 499.

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## Middle Devonian Lunar Month

Abstract. *Simple dynamical calculations regarding the number of lunar months in the Middle Devonian year differ slightly from results obtained from periodicities found in the breeding of corals.*

On the basis of counts of fine growth ridges on Middle Devonian corals, Scrutton has estimated that the Middle Devonian year contained 13 lunar months of 30½ days each (*1*). A check of the dynamical theory reveals slight disagreement with these figures. Jeffreys found that the loss of angular momentum by the earth varies as the sixth power of the moon's distance (*2*). This results in a relation between the length of the day and the geologic time scale given by the expression

$$T = 4.5\, a^{13/2} \qquad (1)$$

where $a$ is the distance of the moon relative to its present distance and $T$ is the time in $10^9$ years since $4.5 \times 10^9$ years ago. The dimensionless distance, $a$, during the Middle Devonian era ($T = 4.1$) was 0.986. This implies, if the masses of earth and moon have remained constant since the Middle Devonian, that the moon had a sidereal period equal to 0.981 of the period it has at present, or 26.803 present ephemeris days. Now, the length of the Middle Devonian day from Jeffreys' theory is estimated to be 0.998 of the present ephemeris day. The Middle Devonian sidereal month was, therefore, 26.856 Middle Devonian days long. The length $S$ of the synodic month (the month of the phases) with respect to which coral breeding periodicity has been suggested, is given by

$$S = ME/(E - M) \qquad (2)$$

where $M$ is the length of the lunar sidereal period and $E$ is the length of the year.

Wells, on the basis of astronomical data, finds approximately 339 days in the Middle Devonian year (*3*). Applying Eq. 2, one finds the length of the Middle Devonian synodic month to be 28.8 Middle Devonian days, 0.7 day shorter than the present synodic month. This result is approximately 1.7 days shorter than the length of the lunar cycle which Scrutton obtained from the palaeontological data (*1*). The dynamical treatment gives a Middle Devonian year of nearly 14 rather than 13 lunar months as the count of growth ridges seems to suggest. A difference of 6½ percent between the results of two completely different approaches to the problem, however, is not so serious. Runcorn's analysis (*4*), based upon Kepler's laws of motion applied to the earth-moon system, gives even better agreement.

A number of hypotheses can be advanced to reconcile the differences. Possibly the similarity which exists between the number of diurnal ridges per band on the old corals and the length of the lunar cycle is fortuitous. One species of modern coral has 28 diurnal ridges per band, one and one half less than the number of days per synodic month (Scrutton, *1*); this would make it a highly inaccurate astronomical timepiece. There also exists the possibility that our understanding of the recent history of the earth-moon system is incomplete. For example, excellent agreement is obtained between the observations of Devonian corals and the astronomical calculations if one assumes that the present observed rate of retardation of the earth's rotational period applied during the Middle Devonian era. But since the tide-raising force, which plays a large role in increasing the earth's period of rotation, varies as $a^{-3}$, the moon was certain to have had a far greater effect upon slowing down the earth's rotation in the past when it was nearer the earth.

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### References

1. C. T. Scrutton, *Palaeontology* **7**, 522 (1965).
2. H. Jeffreys, *The Earth* (Cambridge Univ. Press, London, 1924).
3. J. W. Wells, *Nature* **197**, 948 (1963).
4. S. K. Runcorn, *ibid*, **204**, 823 (1964).

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## Kyanite-Sillimanite Equilibrium at 750°C

Abstract. *Reversal of the kyanite-sillimanite inversion has been accomplished hydrothermally at 750°C. The inversion pressure at 750°C is 8.1 ± 0.4 kilobars. The calculated pressure-temperature slope at this point is 17.7± 1.0 bars per degree celsius. Geologically, this result seems more plausible than previous estimates of the location of the boundary. When combined with other work on the relative stability of andalusite, the data indicate that andalusite cannot be stable at a pressure greater than 4.2 kilobars.*

The polymorphism of $Al_2SiO_5$ is one of the most significant features which characterize metamorphic rocks. The andalusite polymorph, of density 3.14 gm/cm$^3$, is restricted to hornfelses, pelitic schists of the lower grades, and some pegmatites. The sillimanite polymorph (density 3.24 gm/cm$^3$) is very characteristic of high-grade schists, gneisses, and granulites. Kyanite (density 3.66 gm/cm$^3$) is found chiefly in medium-grade schists, hydrothermal veins, eclogites, and a few pegmatites and is probably the most widely distributed of the three polymorphs. Because of its high density it is considered to be a product of the most deep-seated kind of metamorphism. The passage of kyanite to sillimanite as the aluminum silicate in rocks of a metamorphic terrane has become established as one of the prime indicators of progressive metamorphism (*1*). The transition is believed to represent increasing temperature of metamorphism at more or less constant pressure.

Petrologists have long hoped that experimental determination of the $Al_2SiO_5$ pressure-temperature diagram would elucidate the pressure and temperature conditions which prevailed during different kinds of rock metamorphism. These hopes have been somewhat fulfilled in the last 10-year period by a series of studies which, although they did not define the aluminum silicate equilibrium relations as well as it is now possible to do so, nevertheless demonstrated that kyanite requires quite high pressures for its stability at elevated temperatures and indicated that these pressures are in the range encountered in the earth's crust, though near the upper limit. The findings of Clark *et al.* (*2*) and of Clark (*3*) were the result of experiments made with dry materials at the very high temperatures which were necessary to produce reaction in the sluggish aluminum silicate system. Reversals of the kyanite-sillimanite equilibrium were accomplished above 1300°C in a solid-pressure-medium piston-cylinder apparatus. A long extrapolation to the temperature range of interest (300° to 700°C) was necessary.

A direct determination with dry materials in the crustal temperature range was performed by Bell (*4*) using a rotating-piston Bridgman anvil device. The accelerative effect of high shear stress made it possible to produce reactions in crystalline starting materials in a few hours even at temperatures as low as 300°C. The results for the kyanite-sillimanite equilibrium fell very close to the extrapolation of the Clark data (*3*), which might be considered surprising in view of the pressure variation and uncertainty existing under the flat anvils (*5*) and of the unknown effects of high shear stress as a thermodynamic parameter in influencing the apparent pressure-temperature locations of the equilibrium lines. Bell found a