Reports

Petrology of Venus: Further Deductions

Abstract. *The carbon dioxide pressure of the atmosphere of Venus may be controlled by one or more of several decarbonation reactions. One of these is the formation of carbonate-rich liquids. The pressure-temperature equilibrium conditions of these reactions are in the range of those proposed for the surface of Venus.*

An analysis of the stability of mineralogic phases on the surface of Venus has recently been presented by Mueller (*1*). Such a priori considerations serve as a framework for formulating significant investigations to be carried out by planetary probes. The purpose of this report is to offer an extension of Mueller's ideas, to criticize several minor points in his paper, and to consider his suggestion that the high CO_2 content of the atmosphere is largely a result of the high temperature. The possible existence of pools of carbonate lava on the surface of Venus is discussed. The physicochemical condition assumed by Mueller is accepted as a basis for this discussion. The surface temperature is considered to be 425°C and the total pressure is considered to be equal to 10 atm with a relatively large amount of CO_2 and a small amount of H_2O.

Mueller indicates that the failure of the carbonation equilibria of $MgSiO_3$ cannot be invoked as an explanation for the supposed high CO_2 pressure in the lower atmosphere of Venus since formation of this phase by decarbonation at the temperatures assumed would result in CO_2 pressures of the order of hundreds of atmospheres. On the other hand, his statement that the CO_2 pressures over magnesite and dolomite are much greater than that supposed for the pressure of Venus cannot be interpreted rigidly since Weeks' (*2*) data indicate that a pressure of only 0.6 atm of CO_2 is required to maintain the stability of dolomite and 1.4 atm of CO_2 can maintain the stability of magnesite. Mueller's implicit suggestion, that the pressures required to maintain the stability of magnesium carbonates in the presence of silica is much greater than the assumed surface pressure of Venus, is, however, correct.

Bowen's decarbonation series (*3*), however, offers many carbonation equilibria, some of which may occur at temperatures and pressures similar to those proposed for Venus, taking the part of "buffer" reactions. For example, extrapolation of the high-temperature experimental data (*4*) to 425°C indicates that the reactions

$$\underset{\text{Diopside}}{CaMgSi_2O_6} + \underset{\text{Forsterite}}{Mg_2SiO_4} + \underset{\text{Calcite}}{2CaCO_3} \longrightarrow \underset{\text{Monticellite}}{3CaMgSiO_4} + 2\,CO_2$$

and

$$\underset{\text{Diopside}}{CaMgSi_2O_6} + \underset{\text{Calcite}}{2CaCO_3} \longrightarrow \underset{\text{Akermanite}}{Ca_2MgSi_2O_7} + CO_2$$

are, at this temperature, in equilibrium at approximately 10 atm. It may be that these reactions buffer the CO_2 pressure of the atmosphere of Venus.

It must be remembered that the inflections of many pressure-temperature curves are strongest precisely in the region of 425°C. Thus minor differences in the values assumed for surface temperature or for the composition of vapor or solid phases may be reflected by considerable changes in the carbonation equilibria. Thus the physicochemical parameters become increasingly significant and the precise location of the pressure-temperature curves by experimentation becomes more important.

The existence of carbonate melts on the surface of Venus must also be considered. Wyllie and Tuttle (*5*) have found that such a melt can be obtained in the system $CaCO_3$-$Ca(OH)_2$ at temperatures as low as 630°C at a eutectic which is at a pressure of less than 27 atm. Similarly, Gittins and Tuttle (*6*) have discovered that the eutectic in the system Na_2CO_3-$Ca(OH)_2$ is at 595°C and that in the system $Ca(OH)_2$-Na_2CO_3-$CaCO_3$ at 1000 atm with 20 percent H_2O is at 490°C. These minimum melting temperatures will be lowered, perhaps considerably, by the addition of other components such as K_2CO_3 and even $MgCO_3$. On the other hand, the temperature of melting and the amount of liquid formed is strongly dependent on the amount of water in the vapor phase so that a mixture of $CaCO_3$ and vapor with equal parts of water and CO_2 will, at 1000 atm, begin melting only at about 1000°C. The effect of vapor composition on more complex systems is yet to be determined.

Recent descriptions of the active African volcano, Oldoinyo Lengai (*7*), state that it is ejecting carbonate lavas which are very rich in alkalies. Since the molten ejecta do not glow, a temperature less than 600°C is indicated. This occurrence also indicates that the pressure necessary to maintain a natural carbonate melt may be quite low.

It is not considered likely that the entire surface of Venus is covered by carbonate melt. The assumed temperature and low water content of the atmosphere would permit only the lowest-melting fraction of the rocks to form a liquid phase. In certain locations, where temperatures may be higher and the abundance of alkalies greater, the surface of Venus may have pools of carbonate liquid.

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References and Notes

1. R. F. Mueller, *Science* **141**, 1046 (1963).
2. W. F. Weeks, *J. Geol.* **64**, 245 (1956).
3. N. L. Bowen, *ibid.* **48**, 225 (1940).
4. L. S. Walter, *Am. J. Sci.* **261**, 488 (1963).
5. P. J. Wyllie and O. F. Tuttle, *J. Petrol.* **1**, 1 (1960).
6. J. Gittins, personal communication.
7. J. B. Dawson, *Bull. Volcanol.* **24**, 349 (1962).

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Xenon Tetroxide: Mass Spectrum

A new compound, xenon tetroxide, was formed by reaction of sodium perxenate (*1*) with concentrated sulfuric acid at room temperature. It was identified by mass analysis in a Bendix time-of-flight mass spectrometer with a modified source (*2*). The sample was prepared and introduced into the spectrometer by way of a pyrex system.

The spectrum of XeO_4 is shown in the oscilloscope display of Fig. 1. The typical isotopic pattern of xenon is repeated every 16 mass units up to XeO_4. The exact mass of the tetroxide is verified further by reference to the

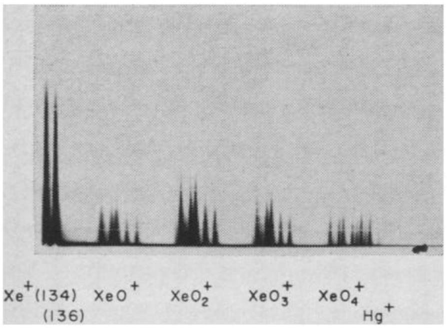

Fig. 1. Mass spectrum of xenon tetroxide.

spectrum of mercury. The fragmentation pattern varied very little with the energy of the ionizing beam of electrons.

The volatility of XeO_4 was demonstrated by its very rapid distillation when a liquid nitrogen bath was replaced by one of dry ice.

The same reaction conducted in a test tube yields a gas with a strong pungent odor which gives a test with potassium iodide-starch paper. These properties could be caused by ozone; however, only a small peak was observed at mass 48 in the mass spectrometer.

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References and Notes

1. J. G. Malm, R. W. Bane, B. D. Holt, in *Conference on Noble Gas Compounds, Proceedings*, H. H. Hyman, Ed. (Univ. of Chicago Press, Chicago, 1963), pp. 167–173.
2. M. H. Studier and E. N. Sloth, *ibid.*, pp. 47–49; M. Studier, *Rev. Sci. Instr.* **34**, No. 12, 1367 (1963).
3. Based on work performed under the auspices of the U.S. Atomic Energy Commission. We thank J. G. Malm for the sample of sodium perxenate and L. P. Moore for technical assistance.

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Computer Program for Printing Undeformed Fourier Maps

Abstract. *The program calculates the values of the function at those points where the computer can print them.*

A doubly periodic function that can be represented by a Fourier series with known coefficients is usually computed at m by n points in the mesh (two-dimensional period). The mesh, a parallelogram in the general case, has each of its sides subdivided into an integral number of parts, m or n. The machine prints the results in a rectangular array, which is a deformed map of the mesh. The deformation has two sources: (i) the map cannot be true to scale in both directions and (ii) the parallelogram is transformed into a rectangle.

The purpose of the program is to print an array of numbers that can be contoured directly into a map, on which true distances and angles can be measured. Two cases can be considered. In one the mesh is orthogonal (a rectangle) and in the other it is non-orthogonal (a parallelogram).

Orthogonal mesh. For example, ca in the orthorhombic system, with $c < a$.

The problem is one of scale only. In general, for any convenient scale, say 1 Å to 2 inches, c will be a nonintegral multiple M of the width of one machine-printed digit (or interval), and a will be another nonintegral multiple N of some interline spacing (single, double, . . .). The machine will be asked to calculate the values of the doubly periodic function precisely at the points where they can be printed. These points form a rectangular array, which we will call the "machine grid." Successive rows come at $x = pa/M$, where

$$p = 0, 1, 2, \ldots, m, m+1$$

and $m < M < m + 1$. Along each row, points come at $z = rc/N$, where

$$r = 0, 1, 2, \ldots, n, n+1$$

and $n < N < n + 1$.

The summation of the Fourier series at the points of the machine grid can be shortened thanks to a recurrence formula of H. Takahashi (*1*). To calculate either

$$C = \tfrac{1}{2}\, a_0 + \sum_{h=1}^{H} a_h \cos 2\pi hX$$

or

$$S = \sum_{h=1}^{H} a_h \sin 2\pi hX$$

(note that the coefficients a_h need not be the same in S as in C), compute the following sequence of u_n's:

$$\begin{aligned}
u_0 &= && a_H,\\
u_1 &= 2\,u_0 \cos 2\pi X && + a_{H-1},\\
u_2 &= 2\,u_1 \cos 2\pi X - u_0 && + a_{H-2},\\
&\cdots\cdots\cdots\cdots\cdots\cdots,\\
u_n &= 2\,u_{n-1} \cos 2\pi X - u_{n-2} && + a_{H-n},\\
&\cdots\cdots\cdots\cdots\cdots\cdots,\\
u_{H-2} &= 2\,u_{H-3} \cos 2\pi X - u_{H-4} && + a_2,\\
u_{H-1} &= 2\,u_{H-2} \cos 2\pi X - u_{H-3} && + a_1,\\
u_H &= 2\,u_{H-1} \cos 2\pi X - u_{H-2} && + a_0,
\end{aligned}$$

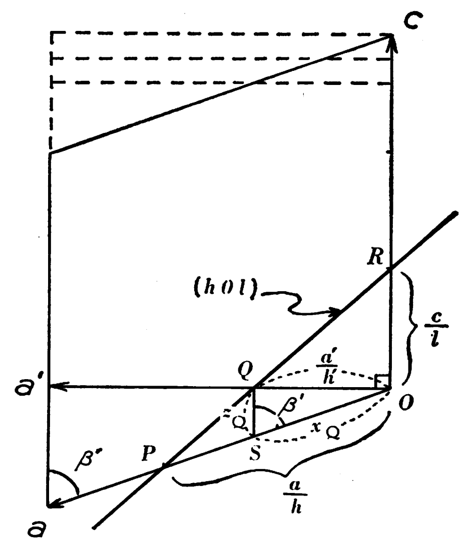

Fig. 1. Monoclinic mesh ca, with trace of $(h0l)$ plane and intercepts of the latter on a, a', and c, equal to OP, OQ, and OR, respectively.

but keep only the last three values. Then C or S, as the case may be, is given by

$$C = \tfrac{1}{2}\,(u_H - u_{H-2})$$

or by

$$S = u_{H-1} \sin 2\pi X.$$

Although the Takahashi formula was proposed for a small computer and for calculations that made use of an integral number of subdivisions in the period (for example, $M = m = 45, 60, 100, \ldots$; with $X = 1/M$), its main advantages are that it permits the use of a nonintegral number of subdivisions and that it eliminates the looking up of sine and cosine tables, which is usual in the Beevers-Lipson summation method.

Non-orthogonal mesh. For example, ca in the monoclinic system, with $a < c$.

The mesh is a parallelogram. In view of the fact that the translation repeat need not have the same shape as the mesh, we propose, for purposes of computation, that the repeat of the Fourier function be taken as a rectangle instead of a parallelogram. This result can be achieved by using nonintegral Miller indices $(h0l)$. For example, the parallelogram ca can be replaced by the rectangle ca' (Fig. 1), where

$$a' = a \sin \beta'$$

and

$$a'/h' = x_Q \sin \beta',$$