

Bernhard followed up this suggestion, using electron microscopy combined with cytochemistry and autoradiography to examine the effect of supranormal temperatures on baby hamster kidney and rat embryo cells in culture.

The nucleoli of these cells cultured normally at 37° C have the four usual components, 150–200 Å granules and a loose reticulum of 50–80 Å fibrils, the nucleolonema both containing RNA, a proteinaceous amorphous matrix and associated chromatin with intranucleolar ramifications. Incubation at temperatures between 37° C and 41° C does not affect the cells but at 42° C a critical point is reached and even 15 min exposure causes striking changes in the nucleolus. The granules and intranucleolar chromatin are lost. The nucleolus exclusively consists of closely packed fibrils 60–100 Å wide. Incubation at 43° and 44° C has the same effect but above this the cells begin to die. Apart from these nucleolar lesions the cells are remarkably resistant to the elevated temperatures. The nuclei appear normal and in the cytoplasm the only changes are slight swelling of the endoplasmic reticulum and mitochondria. Moreover, the nucleolar lesions are fully reversible. Cells returned to 37° C, after 1 h at 42° C, grow happily, regaining the lost nucleolar components. In fact there is an excess of granules in the nucleoli of recovering cells.

At 42° C the incorporation of tritiated uridine into nucleolar RNA is reduced by 90 per cent whereas

nuclear uptake is reduced by only 20 per cent. This selective inhibition of nucleolar RNA synthesis strongly suggests that supranormal temperatures do not inhibit RNA polymerase. If this were the case all nuclear RNA synthesis should be equally affected. One possible explanation is that the nucleolar-associated template DNA is particularly heat labile.

When cells were pre-labelled with uridine and then exposed to a temperature of 43° C, the overall pattern of labelling in the nucleus was like that in cells maintained at 37° C. Thus the pre-labelled nucleolar granules cannot simply move into the nucleoplasm in response to the higher temperature. Simard and Bernhard propose that at 42° C and above the granules unfold to form fibrils by a transformation involving only configurational changes in the ribonucleoprotein molecules and when returned to 37° C the reverse occurs. This is in keeping with the precursor product relationship between at least some of the nucleolar fibrils and the granules which has been claimed by several workers. Recently, however, Hay and Gurdon (*J. Cell Sci.*, 2, 151; 1967), who have studied the fine structure of the abnormal nucleoli in the so-called anucleolate mutant of *Xenopus laevis*, have questioned this relationship.

This point can be resolved by analysing isolated nucleoli, and Simard and Bernhard's temperature shock technique provides an interesting new approach for future studies of the various nucleolar components.

## Internal Structure and Energy Emission of Jupiter

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Jupiter emits much more energy than it absorbs. Explanations of the source of this heat depend upon our knowledge of its interior and of the behaviour of condensed matter at very high temperatures and pressures.

JUPITER emits more energy than it receives from the Sun. Gross and Rasool<sup>1</sup> in their theoretical study of the upper atmosphere of that planet concluded that the ratio of the emitted to the absorbed energy is about four, if the albedo is 0·47, while the more recent measurements of Low<sup>2</sup> indicate a ratio of about three. Thus an internal source of energy of nearly  $10^{33}$  ergs/year must exist. A concentration of radioactive elements characteristic of the Solar System would account only for  $5 \times 10^{-5}$  of the required energy. Similarly, the highest temperatures ever suggested for the inside of Jupiter are orders of magnitude too small to sustain exothermic nuclear reactions and so the gravitational field of the planet appears to be the most obvious source of energy<sup>1,2</sup>. The only other suggestion is that made by Dicke (personal communication), who has proposed that the energy release may be a consequence of a gradual decrease of the gravitational constant *G* which would lead to an increasing rate of rotation of the inner denser part of the planet with respect to the less dense outside mantle. This effect may result in generation of heat but so far the model has not been evaluated quantitatively.

Without going into the details of the radial density distribution in the planet, it is easily shown that a contraction of about 0·1 cm a year in the radius of the planet, which is  $7 \times 10^9$  cm, would yield the observed flux of energy<sup>2</sup>. In order to approach this problem in a more quantitative manner it appeared necessary to examine in some detail the existing models of Jupiter. What follows is the result of such an inquiry. This leads to a modification of the existing models, and also to an explanation of the observed energy flux; it appears at the same time to have a bearing on the origin of the large magnetic field of Jupiter and on the composition of its atmosphere.

### Models of Jupiter

Recent theories and discussions concerning the interior of Jupiter stem from the original work of De Marcus<sup>3</sup>, who assumed, in a first approximation, the existence of only hydrogen and helium on that planet. Using the best available equations of state, he arrived at a radial distribution of these elements which satisfied the known gravita-

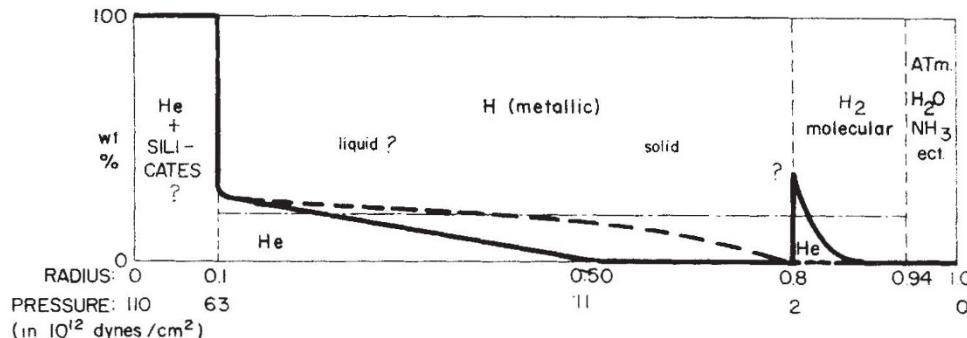


Fig. 1. Schematic radial distribution of elements in Jupiter according to various models. - - -, De Marcus; - · - ·, Peebles; —, modified.

tional multipole components, hydrostatic equilibrium, size and total mass. These results are roughly indicated in Fig. 1, which shows a small helium core surrounded by a thick layer of solid hydrogen in which the helium content decreases to nearly zero at the planet surface. At about 0.8 of the planet radius the solid hydrogen undergoes a transformation from a denser metallic phase to a less dense molecular phase.

Peebles<sup>4</sup> extended the De Marcus model by giving careful consideration to the atmosphere below the visible cloud layer and to the total helium abundance. He assumed that outside a small central core which may contain other elements besides hydrogen and helium the two elements are uniformly mixed—that is, that helium is sufficiently soluble in hydrogen and that convection currents effectively counteract any gravitational segregation. Peebles concluded that the atmosphere is most probably deep and adiabatic and that the mean atomic concentration of helium is 5 per cent, which corresponds to about 20 weight per cent. This model is also represented in Fig. 1. The low value of the critical temperature of hydrogen implies that there is probably a gradual change from a gaseous atmosphere to a liquid layer without there being a well defined surface.

The basic unavoidable weakness of these as well as of other models of planetary interiors has its roots in ignorance of the equation of state of condensed matter at very high pressure and at very high temperature. In particular, the melting points at high pressures are at best obtainable by extrapolation of low pressure experimental data by means of various semi-empirical relations such as, for instance, Simon's equation<sup>5</sup>. This is barely feasible even for the known molecular solid hydrogen; it is very difficult for the metallic form<sup>6</sup>, which has not been observed but the existence of which is almost certain. It is this gap in knowledge of the equations of state which leads to the coexistence of the De Marcus model, in which essentially all hydrogen is solid, and of the Peebles high temperature model, in which everything except perhaps a small inside core is assumed to be to some extent fluid so as to provide uniform mixing.

I now propose to show that a consideration of the hydrogen–helium equilibria leads to a model of Jupiter which is in a sense intermediate between the two described here.

### The Hydrogen–Helium Phase Equilibria

Schematically, the phase diagram of pure hydrogen at high pressures and at high temperatures, omitting the gaseous phase, consists of regions of solid molecular, solid metallic and liquid phases (see Fig. 2). The melting point  $T_M = 14^\circ\text{K}$  at low pressures is well known but the transition pressure  $P_t$  at  $0^\circ\text{K}$  is imperfectly known. Various extrapolations of the semi-empirical equation of state for the molecular solid and of the purely theoretical equation of state for the metallic solid yield values in the range

of  $1-3 \times 10^{12}$  dynes/cm<sup>2</sup> and a change of density of about 50 per cent<sup>4,5</sup>. Alder<sup>7</sup> questioned the validity of the extrapolated equation of state for the molecular form and, by means of entirely different considerations and in analogy to the known similar transition in solid iodine<sup>8,9</sup>, arrived at a transition pressure of  $20 \times 10^{12}$  dynes/cm<sup>2</sup>. Hitherto, all studies of the giant planets have been made using the lower values and I shall also assume a transition pressure of about  $2 \times 10^{12}$  dynes/cm<sup>2</sup>. It should be pointed out, however, that if the higher pressure turns out to be more correct, then drastic changes will have to be made in the variation with radius of both pressure and density for Jupiter and Saturn. Serious consequences for the temperature distribution will also follow because the normal and the radiative heat transfer rates must be expected to be quite different in the two phases. Some of these questions are discussed later on.

The location of the triple point  $S_1$  in Fig. 2 is rather uncertain. Simon's equation<sup>5</sup> can be used to extrapolate experimental points for  $P_t < 3.6 \times 10^9$  dynes/cm<sup>2</sup> or theoretical values for the constants of that equation can be used. It is also possible to calculate the melting temperature directly from the known fact that a solid melts when the root mean square amplitude of the atoms is about 0.2–0.25 of the mean radius of the unit cell<sup>10</sup>. Furthermore, the known Grüneisen constant and an approximate value of the Debye temperature which is obtainable for high pressures by various methods<sup>4,11</sup> can

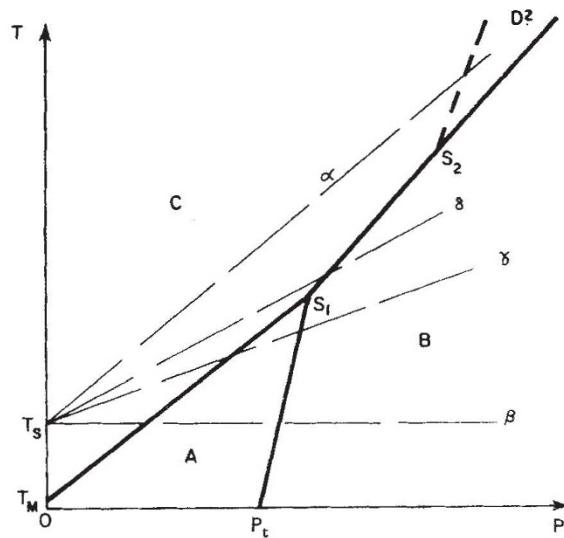


Fig. 2. Schematic  $T$ - $P$  phase diagram of hydrogen:  $C$ , liquid molecular;  $D_2$ , solid molecular;  $A$ , solid molecular;  $B$ , solid metallic (gaseous phase omitted). Lines  $\alpha$  and  $\beta$  illustrate the Peebles and the De Marcus models, lines  $\gamma$  and  $\delta$  the two modified models.  $P_t$  indicates the polymorphic transition pressure,  $T_M$  the normal melting temperature and  $T_S$  the surface temperature of the planet.

give information about the thermal expansion and vibration frequencies of solid molecular hydrogen near the transition pressure. While none of these methods is very reliable, most of the results lie in the range of 6,000–10,000° K. Because the transition pressure is probably not a steep function of temperature<sup>3</sup>, this temperature can be assumed also to apply to point  $S_1$ .

A much more difficult problem is the question of the existence or absence of a phase change between a molecular and a metallic liquid. So far, no such drastic polymorphic changes have been observed in any liquid. As mentioned here, melting occurs when the amplitude of atomic vibrations reaches a critical value such that the initial density is decreased by more than 30 per cent. This change is comparable with the change of density between metallic and molecular solid hydrogen, so that the chances of the existence of a liquid metal seem remote. On the other hand, a constant density curve starting in the  $P-T$  diagram in the solid metallic phase would probably enter a metallic liquid phase given a sufficiently high  $T$  and  $P$ . Actually, the calculated slope of such constant density curves is not much higher than the slope of the theoretical melting curve of the metallic phase so that the point  $S_2$ , if it exists at all, must be expected to occur at an extremely high temperature.

Next, it is necessary to consider the influence of helium on the phase diagram of hydrogen. It is known that helium is very soluble in liquid molecular hydrogen<sup>12</sup> and this might apply also to the solid form. Theoretical estimates based on the known  $H_2-H_2$ ,  $H_2-He$ , and  $He-He$  interactions<sup>13,14</sup> indicate a solubility not less than 50 atomic per cent. One would expect the melting point of this solution to be lower than that of pure molecular hydrogen. The situation with the metallic phase of hydrogen is quite different because noble gases are essentially insoluble in metals<sup>15</sup>. This can also be inferred from the known highly repulsive interaction between H and He (ref. 16). The problem changes considerably when a helium atom is embedded in metallic hydrogen which is being further compressed (J. J. Hopfield, personal communication). Such a compression increases the Fermi energy of the electrons in the metal while at the same time it lowers and narrows the potential barrier between the outside electrons of helium and the metal. Eventually an electron of the helium atom may tunnel into the metal and the positive helium ion will enter the metallic lattice to form an alloy. This is somewhat analogous to the formation of the known stable  $HeH^+$  molecule<sup>17</sup>. An exact solution of the problem is complicated, but an estimate of the required pressure can be made by calculating the density of the metallic hydrogen at which its known Fermi energy  $E_F$  or its crystalline potential  $E_s$  is comparable to the first ionization potential of helium. The value of  $E_s$  can be obtained from its relation to other quantities<sup>18</sup> or from the empirical form  $E_s = 2.5 (E_F)^{3/4}$  (C. Bocciarelli and R. F. Schwartz, personal communication). The result is a minimum pressure in the range of  $7-11 \times 10^{12}$  dynes/cm<sup>2</sup>. It follows that at higher pressures there is a metallic hydrogen–helium alloy which, in accord with the usual behaviour of similar alloy systems, will have a lower melting temperature than pure metallic hydrogen.

### The Modified Model and the Contraction of a Solid Hydrogen Planet

This discussion of the hydrogen–helium system leads to the following conclusions concerning the interior of Jupiter. The transition from molecular to metallic hydrogen occurs at a temperature which lies either below or above  $S_1$  in Fig. 2. In the first case, there is a solid–solid interface. In the second, there is a solid–liquid interface. In either case the molecular hydrogen contains dissolved helium. The metallic layer is essentially pure hydrogen above that depth at which an alloy with helium

can exist. Presumably this helium reached the central regions of the planet at an early stage of the gravitational segregation of the planet when the central pressures were too low to produce metallic hydrogen. The central core is presumably mostly solid helium, but it may contain other heavier elements<sup>3,4</sup>. In the layer of liquid molecular hydrogen there are undoubtedly strong convective currents which lead to mixing and to a rather small temperature gradient. At the interface with the solid metallic form or with the solid molecular form, there has to be the usual boundary layer of essentially motionless liquid which, depending on the value of the assumed non-convective heat transfer rates, can be of the order of 100 m thick.

The melting temperature of a metallic solid solution depends on composition and thus it is not possible to specify the radius at which the  $He-H$  alloy becomes liquid. Assuming a required minimum pressure of  $11 \times 10^{12}$  dynes/cm<sup>2</sup>, the maximum radius of this layer is about one-half of the radius of the planet. There will be strong convective currents in this layer.

A schematic comparison of the three models here discussed is indicated in Figs. 1 and 2.

As a first approximation to the problem of the contraction of Jupiter, let us to begin with consider briefly a pure hydrogen planet of a uniform density  $\bar{\rho}$ , radius  $R$  and modulus of compressibility  $K$ . The total free energy of the system, which includes its gravitational energy  $\Omega$ , is lowered if  $\delta E$ , given by

$$\delta E = \delta\Omega - \delta W = -2\pi R \left( \frac{8}{15} \pi G R^3 \bar{\rho}^2 - 3K \Delta R \right) \delta R \quad (1)$$

is positive. Here  $\delta\Omega$  is the change in the total gravitational energy resulting from a decrease  $\delta R$  of the radius and  $\delta W$  is the simultaneous increase in the stored elastic energy produced by a previous strain  $\Delta R/R$ . Thus there is a maximum value  $\Delta R_{\max}$  for which  $\delta E > 0$  and a maximum value of energy which can be released ( $8/45$ )  $\pi G^2 R (\bar{\rho}^2) M^2 K^{-1}$ , where  $M$  is the mass of the planet. Because  $\Delta R_{\max}$  is proportional to  $\bar{\rho} M$ , it follows that  $\delta E$  is always positive for  $R$  greater than a certain critical value  $R_c \sim K^4 (\bar{\rho})^{-1}$ . For most solids at high pressures  $K \sim \rho^2$  and thus  $R_c$  is a constant characteristic of the solid. For hydrogen, the appropriate values give  $R_c \sim 10^{10}$  cm which is close to Russell's upper limit for cold bodies as obtained by De Marcus from detailed calculations<sup>3</sup>. This assumes, of course, that the pressures are sufficiently low so that the planet can be treated as a solid rather than as a degenerate gas.

Clearly the assumption of a uniform density is not correct for a large body. Fortunately, both for the molecular and for the metallic phase of solid hydrogen, the relationship  $P = A(\rho^2 - \rho_0^2)$  is reasonably well obeyed in the range of the pressures which exist in more than 90 per cent of the volume of the planet. This leads to  $K = 2A \rho^2$  and to the well known Laplace radial distribution  $\rho(r) = \rho_c(L/r) \sin(r/L)$  where  $\rho_c$  is the central density and  $L^2 = A(2\pi G)^{-1}$  with  $L = 3.18$  and  $2.8 \times 10^9$  cm for the molecular and the metallic phase respectively. For  $R < 10^9$  cm, the radial gradient of pressure and of density is negligible for the effects discussed here. The Laplace distribution is not applicable near the surface of the planet, but its use is entirely satisfactory for the purposes of this study which deals primarily with the interior. Expressions for the change in the total gravitational energy  $\delta\Omega$  and for the change in the elastic strain energy  $\delta W$  can be obtained but are quite cumbersome. A good approximate value for  $\delta E$  can be, however, obtained using equation (1) and an average density in a sphere of radius  $R$ :  $\bar{\rho} = 3\rho_R L^2 R^{-2} [1 - RL^{-1} \operatorname{ctg}(RL^{-1})]$  where  $\rho_R$  is density at the surface of the sphere. It is interesting that for a 10 per cent prestrain  $\Delta R/R$  in a hypothetical solid molecular hydrogen planet of the size of Jupiter, nearly 40 per cent of the evolved gravitational energy would be used for compressing the solid and the net rate of energy

emission would be  $\delta E/\delta R = 5 \times 10^{31}$  ergs/cm. The emission rate would be about four times greater for a hypothetical solid metallic planet of the same size.

In reality, however, Jupiter does have a metallic and a molecular phase and thus the gravitational contraction of a two phase model has to be considered<sup>19</sup>. The pertinent equations are

$$\frac{\delta\Omega}{\delta R_2} = -\frac{3}{5} \frac{GM_c^2}{R_1^2} \left( R_1 \frac{\delta Q}{\delta R_2} - Q \frac{\delta R_1}{\delta R_2} \right) \frac{\delta R_2}{\delta R_1}$$

where

$$Q = 1 - \frac{5}{2\gamma} + \frac{3}{2\gamma^2} + \frac{1}{\gamma^2} \left[ \frac{5(\gamma-1)}{2\beta^2} + \frac{1}{\beta^5} \right]$$

with  $\beta = R_1/R_2$ ,  $\gamma = \rho_1/\rho_2$ , subscripts 1 and 2 referring to the metallic core and the molecular mantle respectively and  $M_c$  being the mass of the core; further,  $\delta W = \delta W_1 + \delta W_2$  with  $\delta W_1 = 6\pi R_1 K_1 \Delta R_1 \delta R_1$  and  $\delta W_2 = 6\pi K_2 (R_2^3 - R_1^3)^{-1} (R_2^2 \Delta R_2 - R_1^2 \Delta R_1)$ ,  $(R_2^2 \delta R_2 - R_1^2 \delta R_1)$ . The requirement that the pressure should be the same on both sides of the boundary between the two phases leads to  $(\Delta R_1/R_1) [K_1 + \beta^3 K_2 (1 - \beta^3)^{-1}] = (\Delta R_2/R_2) K_2 (1 - \beta^3)^{-1}$ . There is a similar relation for  $\delta R_1$  and  $\delta R_2$ . For  $R_1 = 5.6$  and  $R_2 = 7 \times 10^9$  cm, these equations give  $\delta E/\delta R_2 = 3 \times 10^{33}$  ergs/cm for a 10 per cent prestrain.

If it is now assumed that the radius of the metallic core  $R_1$  increases by  $\delta R_1$  at the expense of the molecular mantle without adjustment of the gravitational shrinkage, then  $\delta R_2 = (1 - \rho_1/\rho_2) R_2^2 R_1^{-2} \delta R_1 = (1 - \gamma) \beta^2 \delta R_1$  and

$$\frac{\delta\Omega}{\delta R_1} = \frac{3}{5} \frac{GM_c^2}{R_1^2} \left( 5Q + R_1 \frac{dQ}{dR_1} \right)$$

For the numerical values appropriate for Jupiter, this gives  $\delta E/\delta R_1 \sim 7.5 \times 10^{33}$  ergs/cm. There is also an additional term  $PdV$  caused by the change of density which is orders of magnitude smaller.

If the enlarged metallic sphere shrinks so as to reach the proper Laplace density distribution, additional gravitational energy will be released and a part will be used for increasing the stored elastic energy. The shrinkage is given by  $-(1-f^{-1})\delta R_1$  where  $f = x^{-2}[1 - 2xtg x + x^2(\sin x)^{-2}]$  with  $x = R_1/L$ . The effect is an increase of  $\delta\Omega$  by about 30 per cent. Thus the net available energy is about  $10^{34}$  ergs/cm with less than 5 per cent of it going into strain assuming, as before, a prestrain of 10 per cent. It should be emphasized that the magnitude of the assumed prestrain is such that its effect on the calculated energy release caused by phase change is less than that due to other approximations. As the phase change progresses, the requirement of hydrostatic equilibrium alters the density and pressure distribution in such a manner that the transition pressure occurs at progressively greater radii.

Thus it appears that a gradual increase of the metallic core at the expense of the molecular mantle of about 1 mm/yr would yield the required amount of energy for the presently observed rate of Jupiter's emission. It remains to explain this rate.

### The Rate of Energy Emission

Because metallic solid hydrogen does not dissolve helium, the phase change discussed here requires that helium dissolved in the molecular phase should diffuse away from the interface towards larger radii. The driving force for this diffusion is, of course, the consequential decrease of the total free energy of the system. The situation is relatively easy to evaluate if the diffusion occurs in solid molecular hydrogen for which the diffusion coefficient and its activation energy are known<sup>20,21</sup>. Unfortunately, there is no experimental information about the corresponding activation volume. In most metals, however, the activation volume is between 0.6 and 0.9 of the atomic volume<sup>22</sup>. For a pressure of  $2 \times 10^{12}$

dynes/cm<sup>2</sup> and a temperature around 3,500° K one obtains  $D = 3 \times 10^{-(10 \pm 1)}$  cm<sup>2</sup> per sec. The corresponding mean diffusion distance of 0.03–0.3 cm/yr is in the right range to account for the observed rate of energy emission. Peebles<sup>4</sup> has also estimated this diffusion coefficient using other approximations.

If at the molecular-metallic interface the molecular phase is liquid the situation is much more difficult to evaluate because experimental and theoretical knowledge of diffusion in liquids is not satisfactory<sup>23</sup>. Although diffusion in liquids near the melting temperature is in general appreciably faster than in solids, it increases more slowly with temperature than in solids because of the much lower activation energy<sup>23,24</sup>. Almost nothing is known about the influence of pressure on this diffusion. Nevertheless, on the basis of extrapolations based on estimated viscosities of liquid hydrogen at high pressures and temperatures, the expected diffusion rate of helium in liquid hydrogen is not in contradiction with the rates calculated here for the solid phase. It should be stressed that the convective currents in the liquid phase have little if any effect on the helium removal process because the critical diffusion occurs over distances several orders of magnitude smaller than the thickness of the stationary boundary layer.

The Elsasser<sup>25</sup> mechanism for generating magnetic fields in planets is based on the principle of a hydro-magnetic dynamo, which entails rapid rotation of the planet and strong convective currents in an electrically conducting liquid. Clearly these conditions cannot be satisfied on Jupiter if only the molecular liquid is present because that must be strongly insulating. On the other hand, a liquid metallic hydrogen-helium alloy of the kind discussed here could explain the huge magnetic field, and the proposed size of this liquid layer is just about the same fraction of the total volume of the planet as of the Earth. The central location of the liquid core suggests a centrally located magnetic dipole and contradicts Warwick's earlier interpretation<sup>26</sup> of the decameter radio emission. It is supported, however, by the recent studies of decimeter radio emission<sup>27</sup> and by the studies of decameter radiation, if coexistence of axisymmetric dipole and quadrupole moments is assumed<sup>28</sup>. Such a situation could result from an uneven distribution of the solid phase; this would suitably perturb the roughly centrosymmetric pattern of the convective currents in the liquid. A similar mechanism could account for a local magnetic anomaly suggested by Ellis and McCulloch<sup>29</sup>.

An interesting consequence of the progressive enrichment of helium in the layer of molecular hydrogen is that it implies a higher helium to hydrogen ratio in the atmosphere proper. This enrichment would help to account for the mean molecular weight deduced by Öpik<sup>30</sup> of 4.3, or by Baum and Code<sup>31</sup> of 3.3, without invoking rather complicated mechanisms. It is also suggested by some recent studies of the Jovian atmosphere<sup>32,33</sup>.

Finally, what if the higher rather than the lower transition pressure from the molecular to the metallic form of hydrogen turns out to be more correct? The main consequence would be the presence of a small metallic core made of a presumably helium rich hydrogen-helium alloy. This core would be liquid and would be surrounded by a thick solid molecular hydrogen mantle. It is not certain whether this liquid metallic core would be sufficiently conductive or sufficiently large to account for the huge magnetic field.

### Conclusions

The modified "intermediate" model of the interior of Jupiter described here has certain physico-chemical advantages compared with the earlier models and several interesting consequences as well. Unfortunately, present quantitative uncertainties about the hydrogen-helium

system and the heat conduction and convection in that system make detailed calculations premature. Careful comparison with the known multipole gravitational moments is needed to confirm the presence of higher helium content in the outer layers of the planet. The fair degree of agreement between the calculated and the observed rate of energy emission, although not conclusive, suggests that the proposed mechanism may indeed be operative.

I wish to thank my colleagues Professors Daniels, Deutsch, Dicke, Hopfield, Keil, Peebles and Wigner for many interesting discussions and for advice.

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## Pre-Columbian Maize in Southern Africa

by

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Maize is indigenous to America and can only be propagated by man. Its presence in Southern Africa in the fourteenth century is therefore particularly intriguing.

MAIZE is an American plant which does not propagate itself, so that its presence is due to human agency. There is, however, evidence for the presence of maize in southern Africa, south of a line from the mouth of the Zambezi in the east to the mouth of the Cunene in the west, which raises several questions about the human agency responsible.

This article comments on observations made in the early sixteenth century which indicate that there was maize in southern Africa when the Portuguese arrived. The same evidence also suggests that people responsible for introducing maize to the coastal regions of eastern Africa were Arabs; that migrating African tribes which had obtained maize from the Arabs introduced it to the interior; and that this introduction of maize occurred before Columbus discovered America. I am not here concerned with the agency initially responsible for bringing maize from America to the Old World.

### European Evidence

The first European to reach Mozambique around the Cape was Vasco da Gama, who recorded *milho* there in March 1498; in an account of the capture of two boats in the Mozambique channel, da Gama wrote: "In the one we took, we found seventeen men, besides gold, silver and an abundance of maize (*milho*) and other provisions". This record, however, was not published until 1512.

The word *milho* is of interest because it is the standard Portuguese name for maize and was used for maize in the early records of Portuguese administration on the east African coast. As early as 1506 at Sofala<sup>2</sup> the following entry occurs in the King's Treasury: "... merchandise and items were spent in buying one hundred and seventy-seven bags of maize with fifteen heads of maize to each bag for the maintenance of the people of this fortress". An entry

on September 1, 1511<sup>3</sup>, which includes reference to sorghum and rice, further clarified the meaning of *milho*: "Ber-tolomeu Perestrello, factor of this fortress of Sofala . . . order you Troylos Bramdam . . . to give . . . to these forty-nine people . . . four hundred *alqueires* of unhusked rice and fifty four *alqueires* of maize (*milho*) and nine *alqueires* of kaffir corn (*mexoreira*) . . . ". On *mexoreira*, Junod<sup>4</sup> noted: "The word . . . nowadays designates the small grey kaffir corn in Lourenço Marques". Kaffir corn is a South African name for *Sorghum vulgare*.

The account of an introduction of maize by the administrator of the Dutch East India Company to the Cape will be found in Van Riebeeck's journal. He expected to find maize in Angola and finally obtained it from West Africa. His Guinea slaves understood its cultivation, which was unknown by his Dutch farmers. To describe this cereal Van Riebeeck used variants of the word *milho*, namely *mily* and *milie*. Such terms for maize are found in use only in South Africa.

In January 1658 Van Riebeeck<sup>5</sup> sent a vessel to Angola to search, among other things, for "maize". Van Riebeeck in his journal<sup>6</sup> had written *milie*, not "maize". In July 1658<sup>5</sup> Van Riebeeck encouraged the planting of maize or "Turkish wheat obtained from Guinea" as the "right time for planting maize is now approaching and the slaves know well how to do it". Van Riebeeck's words were "*mily ofte Turcxe taruw*"<sup>6</sup>. Burtt-Davy<sup>7</sup> held that *milie* "is derived from the Portuguese word *milho*, from the Latin *milium*, the name for millet".

Van Riebeeck, who joined the Dutch East India Co. in 1639, was brought into contact with Portuguese trading to Africa and the East in the course of his employment. His use of the terms *mily* and *milie* reflect the Portuguese usage of *milho* for maize in the seventeenth century.

The term used today by the Portuguese for maize is still *milho*, and it has been in continuous use. Indeed Santa