or into an outbred strain in the study by Dorin *et al.*[4]).

This new animal model of CF has several features that will greatly enhance its usefulness. The apparent absence of lethal bowel obstruction may allow survival until pathology in other organ systems such as lung, pancreas or liver can be further elicited. In addition, the marked variation of phenotype in animals with the same *cf* genotype provides an excellent opportunity to identify environmental and additional genetic factors that contribute to expression of disease. This heterogeneity in phenotypic expression, however, will need to be taken into account in studies of potential therapies that use clinical or pathological endpoints.

The apparent differences in the first two mouse models of CF underscore the complexities of modelling human diseases in animals. They are a timely reminder of the value of having important problems tackled by more than one research group, even if the differences in strategy seem minor. The challenge remains to use the full power of mouse genetics to understand the basis of the differences between these models in the context of the pathophysiology of CF in humans. □

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PALAEOCLIMATOLOGY

Avoiding a permanent ice age

William R. Kuhn

ALTHOUGH the Earth's climate is clement, on our neighbouring planets things are different. The greenhouse effect has run away on Venus, giving the planet a scorching atmosphere. And Mars is a frozen world. How lucky are we? Calculations by Caldeira and Kasting on page 226 of this issue[1] suggest that climate cooling when the Earth was young would have triggered the growth of carbon dioxide ice clouds high in the atmosphere, locking the Earth into a permanent ice age. The present warmth of our climate might be taken to indicate that previous notions of an early ice age are wrong.

One of the vexing problems of palaeoclimate is known as the faint young Sun paradox[2]. Models of solar evolution and observations of stars like our Sun in various stages of evolution indicate that solar luminosity was significantly less — by 25–30 per cent — than it is today — so much so that the Earth would have been a frozen world if all else remained the same. Yet there is geological evidence that there was liquid water on the planet up to 3.8 billion years ago[3]. Speculation has centred on increased concentrations of certain gases in the atmosphere that create a greenhouse effect, most notably carbon dioxide, and arguments have been put forth that the resulting warming could counteract the faint young Sun and save the planet from total glaciation.

Although the earlier studies of palaeoclimate recognized that carbon dioxide, in large enough amounts, could have counteracted the lower solar luminosity, they did not include the possibility that carbon dioxide ice crystals could have formed. Caldeira and Kasting speculate that air temperatures could have fallen enough for carbon dioxide ice clouds to have appeared in the young atmosphere. These clouds might have looked much as cirrus water ice clouds do today, which frequently appear as white, wispy or filamentary clouds above about 6 km. But there is a substantial difference: water ice clouds generally heat the Earth because of their substantial greenhouse effect[4], whereas carbon dioxide ice clouds would have more of a tendency to cool the surface because they are good scatterers of radiation, including solar radiation.

The possible existence of carbon dioxide clouds in the early atmosphere has implications for what are known as runaway effects. Could some transient change in the Earth or its atmosphere have made the early climate unstable, causing polar ice sheets to grow and cover the Earth? If so, then obviously the process was reversible.

Simple models have been developed that indicate the number and stability of climate states for different solar luminosities, and limit the ranges of those parameters that affect climate. For example, studies have shown that decreases of solar luminosity of perhaps only a few per cent could cause polar ice to spread over the whole planet[5,6]. In the light of Caldeira and Kasting's work, it seems unlikely that this happened even with a 25–30 per cent difference in solar luminosity. Carbon dioxide clouds may have formed that would have prevented the Earth from ever returning from its frozen state. (Even the build-up of gaseous carbon dioxide — cut off by ice from the Earth's rocky surface, a carbon dioxide sink — would not have negated this.) If Caldeira and Kasting are correct, then the Earth may have been warm from its birth and remained warm with an abundance of greenhouse gases such as carbon dioxide and water vapour.

Our recent awareness that we have the potential to alter global climate has accelerated the interest in and importance of climate modelling. Much of what we learn from those studies is applicable to our efforts to understand what Earth was like billions of years ago. However, we are finding that the Earth system is vastly complex, and it is not obvious whether the relative importance of a process in the geological past was the same as it is today.

For example, the biosphere plays a strong role in regulating climate today, but could hardly have done so a few billions of years ago. And what fraction of the Earth was covered by land? Rapid continental growth occurred 2.7–3 billion years ago[7], so that before then, there was probably little exposed land. How would this have affected the change in atmospheric carbon dioxide through rock weathering?

Solar radiation is clearly the most important determinant of the Earth's temperature. Last year, Graedel *et al.* called into question the magnitude of the solar flux early in Earth's history[8]. It is possible that the young Sun was not as faint as we thought. New solar models, albeit speculative, include an early solar mass loss that leads to luminosities larger than the 75–80 per cent generally assumed.

Another important uncertainty in modelling both palaeoclimate and present climate is the treatment of clouds. If it weren't for clouds in the present atmosphere, the temperature would be some 20 °C higher. Most clouds in our present-day atmosphere are more effective at reflecting solar radiation away from the surface than they are at trapping heat by the greenhouse effect. Cirrus clouds are the exception. It is not only cloud amount, thickness and droplet size that are important, but also

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height, which determines whether or not the temperature is low enough for ice clouds to form. The colder temperatures that would cause carbon dioxide ice crystals to form in the primitive Earth atmosphere might also cause water ice clouds to increase. If so, the cooling from carbon dioxide ice would have been counteracted. This is but one of the many unanswered questions that need to be explored.

In any case, as we improve our knowledge of the present Earth system we will gain further insight into the Earth's early climate. And while there is little for certain that we can say about that climate today, we should be able to narrow the bounds within which our climate evolved. ☐

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GEOPHYSICS

Earth's core not so hot

Al Duba

THE Earth's core is primarily iron, with a solid centre and a liquid outer region which is in contact with a solid mantle. The density and moment of inertia show that there is also a lighter element, sulphur or oxygen, alloyed with the iron. Calculating the temperature in this deep zone has been a time-honoured pastime in geophysics, because accurate knowledge of it is important for constraining both the Earth's radioactive heat budget and the physical conditions in which its magnetic dipole is generated. In a recent paper[1] fuel is added to the fires of controversy raging within the 'ironworker' community concerning temperatures in the Earth's core.

Using a laser-heated diamond-anvil cell (DAC), Boehler[1] and colleagues[2] from Mainz, Germany, measure melting points of Fe, FeO and FeS, the three most likely constituents of the Earth's core, to pressures of 114, 47.0 and 43.5 gigapascals (GPa), respectively. From these data a minimum temperature for the core–mantle boundary (CMB) is derived, ranging from 2,600 to 3,400 K. This result is in sharp contrast to the 3,600–5,300 K minimum temperature range proposed for the CMB based on Fe and FeO melting-point data reported earlier by Jeanloz and colleagues[3,4] from Berkeley, United States (see table). These differences become even larger at the inner-core/outer-core boundary where Earth's molten outer core contacts the solid inner core.

It is at this boundary that there is the possibility of setting a theoretical upper limit on the temperature if one makes the first-order assumption that Earth's core is pure iron and allows about 1,000 K for possible eutectic melting caused by the presence of the lighter element. Unfortunately, this theoretical calculation is subject to large uncertainties because it relies on the density dependence of thermodynamic properties which are difficult to obtain experimentally[5]. The inner-core/outer-core boundary temperature from theoretical consideration is intermediate to those extrapolated from the two experimental groups with a shading of a few hundred degrees in favour of the Berkeley results.

Figure 1 presents the new melting data of Boehler[1] which are in good agreement with those reported for FeO as measured in a multi-anvil press[6] and in poor agreement with those obtained by the Berkeley group[3] in a laser-heated DAC. And Figure 2 compares the melting of Fe determined by the Mainz[2] and Berkeley[4] groups in the laser-heated DAC. The disparity between these two groups is astounding and reflects the difficulties of recreating core conditions in the laboratory. From the Figures and from the experimental procedures detailed by the authors, it seems unlikely that pressure measurement is responsible for the disagreement, as both groups use ruby fluorescence, a technique that has been tested and calibrated *ad nauseam*.

The rub probably lies in the melting-point measurement itself, which has two components — the observation of melting, and temperature determination concurrent with melting. The Figures reveal that the data scatter of Boehler and his colleagues is considerably less than that of the Berkeley group. Although it is not in itself an indication of the relative merits of two conflicting measurements, data scatter can emphasize the difficulties inherent in a particular measurement technique.

The Berkeley group uses four criteria to determine melting[7]. During the experiment, visual observations of textural changes on the surface of the sample following laser heating over the entire pressure range and of fluid motion within the sample during laser-heating at pressures up to 50 GPa were used. These observations are followed up, post-experiment, by optical examination of all samples and electron-microscopic examination of about half the samples. The temperature of the melt zone is calculated from average temperatures measured spectroradiometrically[8]. The melt zone is typically 2–4 μm in diameter, the laser beam doing the heating is 20–30 μm in diameter, and the field of view of the spectrometer is 90 μm in diameter. Average temperatures of the laser-heated sample area are determined from the spectrometer readings using Wien's approximation to Planck's law.

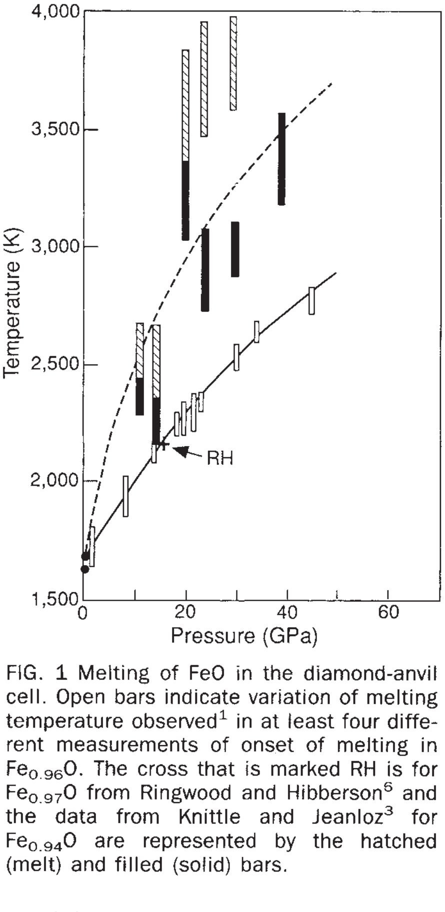

FIG. 1 Melting of FeO in the diamond-anvil cell. Open bars indicate variation of melting temperature observed[1] in at least four different measurements of onset of melting in $Fe_{0.96}O$. The cross that is marked RH is for $Fe_{0.97}O$ from Ringwood and Hibberson[6] and the data from Knittle and Jeanloz[3] for $Fe_{0.94}O$ are represented by the hatched (melt) and filled (solid) bars.

The temperature gradient across the laser-heated spot is then determined by scanning a 25-μm-wide sampling slit across a 250–300-μm-diameter image of

CORE TEMPERATURES DERIVED WITH SOLID-SOLUTION AND EUTECTIC MODELS FROM DAC DATA

Source	Core–mantle boundary		Outer-core/inner-core boundary	
	Solid-solution	Eutectic	Solid-solution	Eutectic
Mainz group[1,2]	3,200–3,400 K	2,600–2,800 K	4,200 K	3,500–3,800 K
Berkeley group[3,4]	4,800±500 K	3,800±200 K	7,600±500 K	6,600±500 K
Grover[5]	—	—	—	5,500 K