

- Pearson, cited above; C. Bowman, cited above) at least as often as it yields CH_2 and H_2O .
20. For rate constants of reactions involved in CH_4 and C_2H_6 pyrolysis, see, for example, S. Bauer, *Symp. Int. Combust. Proc. 11th* (1967), p. 105; T. Asaba and N. Fujii, *Symp. Int. Combust. Proc. 13th* (1971), p. 155; S. Sorenson, P. Myers, O. Ueyehara, *ibid.*, p. 451; B. Bowman, D. Pratt, C. Crowe, *Symp. Int. Combust. Proc. 14th* (1972), p. 819.
 21. Our estimate of t_{chem} will be too small if partial reformation of CO by reactions such as the reverse of reaction 1 is appreciable. Since CH_3 and OH have very short lifetimes for conversion to CH_4 and H_2O , their concentrations should be close to their equilibrium values. Consequently, in an excess of CO the reformation of CO by the reverse of reaction 1 will be much slower than the forward reaction and can thus be ignored. On the other hand, our estimate of t_{chem} will be too large if other CO-to- CH_4 conversion mechanisms (such as heterogeneous reactions on Fe particles) exist. We are concerned here primarily with the order of magnitude of t_{chem} , which we expect to be less sensitive to the exact details of the kinetics.
 22. Because $Kt_{\text{chem}}(0) = H^2$ the influence of K in this expression is not immediately apparent. Its influence is, in fact, considerable since it determines the level $z = 0$ and thus the value for $f_{\text{CO}}(0)$.
 23. From its definition we compute $h_{\text{chem}} \approx 25$ km at the 1100°K level, where $H = 220$ km. Thus $h_{\text{chem}}^2/H^2 \approx 0.013 \ll 1$.
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 28. We thank J. Lewis, H. Larson, R. Beer, and F. Taylor for valuable discussions. The research was supported by NSF grant DES-74-14116 and NASA grant NGL-22-009-521. Part of this work was completed while R.G.P. was a summer visitor at the Jet Propulsion Laboratory, California Institute of Technology, which is supported by NASA contract 7-100.

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Minimum Size of Mammalian Homeotherms: Role of the Thermal Environment

Abstract. *The minimum size of a mammalian homeotherm appears to be related to the animal's maximum rate of endogenous heat production, the ambient thermal environment, and the animal's ability to be a facultative homeotherm.*

Pearson (1) analyzed data for metabolism of shrews and small mice and concluded that because metabolic rates per unit of body mass become increasingly large for smaller and smaller mammals, there exists a lower limit to mammalian size beyond which metabolic rates would become impossibly large. Indeed, his analysis predicted that the smallest mammal should be approximately the size of the smallest shrew (approximately 2.5 g). In this report I extend the work of Pearson to ask, Is the minimum size of mammalian homeotherms entirely a property of the animals, or is it, in part, determined by the thermal environment?

Many additional data now have been accumulated on the minimum metabolic rates of small mammals (Fig. 1). The relationship between minimum metabolic rate and body size in thermoneutrality is essentially linear ($r^2 = .42$), although a power function provides a slightly better fit ($r^2 = .48$; see Fig. 1 for regression). The smallest (about 7 g) adult mammals (excluding shrews and bats) have metabolic rates that are only one-third the rate reported (2) for the masked shrew.

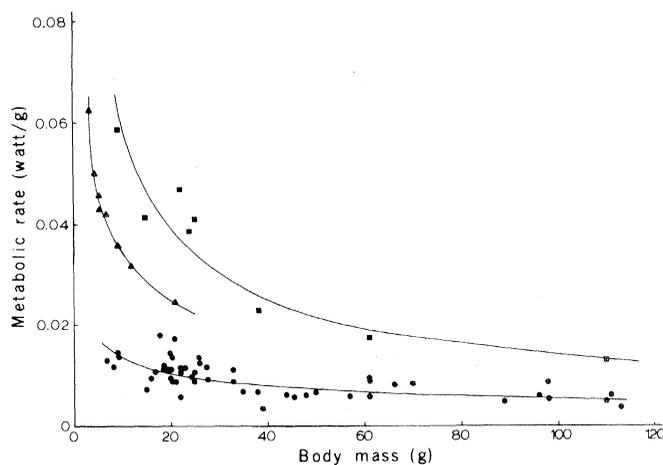
The metabolism-body mass relationships for most homeotherms do not show the dramatic increase in metabolism near

the minimum size of mammalian homeotherms that has been reported for shrews (1). This is partly because the metabolic data for shrews were all determined for animals held at 24°C , which is lower than thermal neutrality for all shrews (3). Thus, the experimental conditions were cold enough that the animals responded with elevated metabolic rates to maintain homeothermy. Because the amount of cold stress to the shrews is related inversely to body size, smaller and smaller shrews had higher and higher metabolic rates. However, it is not so clear that very small shrews would necessarily have extraordinarily high metabolic rates if subjected to conditions of thermal neutrality, and, indeed, there are some data showing that British shrews have metabolic rates (at rest and during activity) that are not different from those of similarly sized mice (4).

For several reasons related to heat transfer from organisms (namely, that the surface area/body mass ratio of homeotherms is greater in smaller animals, and that the convective boundary layer of still air around any animal is thinner for smaller animals), smaller body size (with all other things held constant) is usually related to greater heat losses from animals. That the minimum metabolic rates (heat production) relative to body size for small mammals do not show a dramatic increase as body size becomes smaller (5) indicates that very small mammals need not have extraordinarily high rates of metabolic heat production to remain homeothermic. However, the range of thermal environments in which an animal can maintain a minimum metabolic rate and a constant body temperature becomes smaller for smaller animals, such that an infinitely small animal can maintain a constant body temperature only in a perfectly constant thermal environment. Thus, a very small animal can be homeothermic if (i) it has the capacity for extraordinarily high heat production (6), or (ii) it has the capacity for precise body temperature regulation through nanoclimate selection and possibly the ability to be facultatively homeothermic. The former seems to describe endothermic mammals and birds, and the latter tends to describe numerous reptiles and insects.

How, then, can one predict the minimum size of endothermic homeotherms? The answer is that it is not possible to predict the smallest size of endothermic homeotherms without also specifying the environment in which the animal exists. Homeotherms theoretically can be infinitely small (in thermoneutral environ-

Fig. 1. Metabolic rates (M) of homeotherms as a function of body mass (m). Minimum metabolic rates of (●) small mammals at thermoneutrality (12), (▲) shrews held at 24°C (1), and (■) small mammals held at 0°C (2). The best-fit equation for mammals at thermoneutrality is $M = 0.033m^{-0.39}$ ($r^2 = .48$); the best fit for shrews at 24°C , $M = 0.103m^{0.475}$ ($r^2 = .96$); and the best fit for mammals at 0°C , $M = 0.27m^{-0.64}$ ($r^2 = .92$).



ments). However, in cold environments small endothermic homeotherms generally must produce a larger amount of heat to maintain a constant body temperature which is higher than the ambient effective environmental temperature (7). Thus, if there is a limit to the maximum heat production (metabolic rate) of a homeotherm (8), then the lower limit to size for homeotherms is also determined for particular ambient thermal environments. For example, assume that the maximum attainable metabolic rate for mammals is 0.065 watt/g. Then a mammal in a thermoneutral environment apparently could be infinitely small and also be homeothermic (Fig. 1). On the other hand, a mammal held in an ambient thermal environment of 24°C could be no smaller than about 8 g (Fig. 1) and remain homeothermic (9). Moreover, a mammal kept at 0°C could not be smaller than about 8 g (Fig. 1) and be homeothermic (10).

In summary, a species need only evolve a capacity for endothermic heat production if the ability (or the cost of the ability) to precisely regulate body temperature behaviorally is prohibitive. If an endothermic strategy is adopted, a minimum body size is imposed that appears to be determined primarily as a function of (i) the animal's maximum rate of endogenous heat production (6), (ii) the ambient thermal environment, and (iii) the animal's ability to be a daily or seasonally facultative homeotherm (11).

C. RICHARD TRACY

Department of Zoology and
Entomology, Colorado State University,
Fort Collins 80523

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- Very small animals do not have the option of greatly increasing their insulation against heat loss by increasing the length of their fur or feathers. The pile of a shrew's coat could not become more than a small fraction of a centimeter in length before it would impede locomotion [see also B. K. McNab, *J. Exp. Biol.* **53**, 329 (1970)].
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- Pearson (1) pointed out that there has to be a limit to how much food can be gathered and processed to produce heat.
- This assumes that all mammals conform to the pattern reported for shrews at 24°C (1, 5).
- This assumes that all mammals conform to the

- pattern reported for small mammals at 0°C (4).
- That is, the animals are not homeothermic at all times of the day or year.
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Implications of Solar Evolution for the Earth's Early Atmosphere

Abstract. *The roughly 25 percent increase in luminosity over the life of the sun shared by many different solar models is shown to be a very general result, independent of the uncertainties suggested by the solar neutrino experiment. Superficially, this leads to a conflict with the climatic history of the earth, and if basic concepts of stellar evolution are not fundamentally in error, compensating effects must have occurred, as first pointed out by Sagan and Mullen. One possible interpretation supported by recent detailed models of the earth's atmosphere is that the greenhouse effect was substantially more important than at present even as recently as 1 billion to 2 billion years ago.*

Almost all solar models predict an increase in the solar luminosity on the order of 25 percent during the life of the sun. However, excluding brief excursions, there is no observational or experimental evidence that the solar constant has been significantly smaller in the past (1). In fact, recent evidence indicates that over cosmic time scales the temperature of the earth has actually decreased (2). Yet simple models (3, 4) of terrestrial climate indicate that a decrease of even a few percent in the solar constant produces a completely glaciated earth, which, because of the high albedo of ice, requires a solar constant higher than the present value to thaw the planet. At least superficially, we have a glaring conflict between solar models and the biological and isotopic temperature history of the earth.

While individuals among climatologists and stellar evolution theorists have been aware of this problem for some time (5), it has been ignored by the communities as a whole. Sagan and Mullen (6) and Katz (7) point out that the predicted solar luminosity increase is not likely to be substantially in error and thus leads to a conflict with the temperature history of the earth. They suggest modifications to the earth's early atmosphere as a solution. However, most interest in terrestrial effects of solar evolution has been in the well-established oscillatory temperatures (8) of the past million years or so and their possible relation to a temporary excursion in the solar luminosity (9). The fact that some suggested solutions to the solar neutrino problem had associated luminosity excursions seemed attractive.

In this report we would like to emphasize the magnitude of the conflict. First we will show that an increasing solar lu-

minosity is a basic feature shared by even quite exotic solar neutrino-oriented models. Then we will examine the conflict with climate models and possible solutions in more detail.

The complexity of stellar evolution calculations often gives rise to the suspicion that they might be inaccurate. In some details such as the flux of high-energy neutrinos this may be the case, but the luminosity increase discussed here depends in a fundamental way on the difficult to avoid assumption that the sun's energy source is the fusion of hydrogen into helium. This can be shown quite simply.

Dimensional analysis of the equations of stellar structure as in (10), for example, shows that the luminosity scales as

$$L \sim \frac{ac}{\kappa_0} M^{3+\beta} R^{-\alpha} R^{3\alpha-\beta} \left(\frac{G\mu M_H}{k} \right)^{4+\beta} \quad (1)$$

where the opacity law has been taken to be $\kappa = \kappa_0 \rho^\alpha T^{-\beta}$, in which ρ is density and T is temperature; M and R are the stellar mass and radius; M_H is the mass of the hydrogen atom; μ is the mean molecular weight; a is the radiation density constant; c is the velocity of light; G is the gravitational constant; and k is Boltzmann's constant. For the sun $\alpha \approx 1$, $\beta \approx 3.5$, and

$$L \sim \frac{ac}{\kappa_0} M^{5.5} R^{-0.5} \left(\frac{G\mu M_H}{k} \right)^{7.5} \quad (2)$$

The dependence on radius is weak (and the solar radius does not change rapidly), so as μ increases because of hydrogen burning, L increases approximately as

$$\frac{1}{L} \frac{dL}{dt} \sim \frac{7.5}{\mu} \frac{d\mu}{dt} \quad (3)$$