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 3.5 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*).

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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 luminosity 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

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

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 $\alpha \simeq 1$, $\beta \simeq 3.5$, and

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

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

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

Table 1. Some classes of solar models sharing the problem of the faint young sun. One SNU = 10^{-36} neutrino capture per target atom per second. The last column gives the total predicted neutrino capture rate. Abbreviation: T-D, time-dependent.

Model	Reference	$\frac{1}{L}\frac{dL}{dt}$ (10^9 years)$^{-1}$	X_0	$\Sigma\sigma\phi$ (SNU)
Standard	*(25)*	0.053	0.77	5.6
	(26)	0.066	0.75	5.9
	(27)	0.063	0.74	4.7
Extensive mixing in bursts	*(26)*	0.052*	0.72	T-D
Central black hole	*(28)*	0.053*	0.72	1.0†
Enhanced proton-proton reaction rate	*(29)*	0.062	0.70	0.1
Nonradiative energy transport	*(27)*	0.053	0.90	0.8
Depleted Maxwell tail	*(30)*	0.072	0.74	0.9
Low interior Z plus accretion	*(25, 31)*	0.053*	0.88	1.4
Rapidly rotating core with spinup	*(19)*	0.013*	0.69	13.0

*Denotes models with luminosity excursions. †This neglects the contribution to the counting rate of neutrinos produced by processes in the vicinity of the black hole itself, which may be large.

For the solar photospheric heavy element abundance $Z/X \approx 0.02$ and $\mu \simeq 1.33/(1 + 1.66\,X)$, where Z is the mass fraction of material heavier than helium, X is the mean hydrogen mass fraction ($\simeq 0.75$ initially for standard models), and X is related to L through energy conservation by

$$\frac{dX}{dt} \simeq -\frac{L}{\epsilon M} \approx -0.01/10^9 \text{ years} \quad (4)$$

where ϵ ($\simeq 6.4 \times 10^{18}$ erg/g) is the energy released by the conversion of hydrogen to helium. Thus we can conclude from these elementary considerations that

$$\frac{1}{L}\frac{dL}{dt} \simeq \frac{12.5\,L}{M\epsilon(1 + 1.66\,X)} \quad (5)$$

which for present standard values is about $0.05/10^9$ years. This result is in reasonable agreement with detailed numerical solar models and is shared by models as disparate as those listed in Table 1, although in some models brief luminosity excursions are superimposed on the slow but steady luminosity enhancement due to fuel consumption. Intercomparison of the numbers in Table 1 is not meaningful because of the different detailed input physics used and approximations made for some models. Note, however, that the few models with neutrino fluxes less than the current experimental upper limit of 1.8 solar neutrino units (SNU) *(11)* share with the others the characteristic that the luminosity increases by some tens of percent over the life of the sun, as one would expect from Eq. 5.

Examination of Eq. 2 shows that apparently the only hope for slowing the increase in L, other than abandoning nuclear energy production (even the central black hole model with its auxiliary energy source relies on nuclear energy for most of its life), is a variation in some physical constant or the mass of the sun. Variation of G is predicted by some cosmologies, and early analyses of the sun with the Brans-Dicke cosmology found a large decrease in solar luminosity *(12, 13)*. [The more detailed models of Pochoda and Schwarzschild *(13)*, sometimes cited as evidence against the Brans-Dicke theory, use parameter values which greatly exaggerate the decrease.] Roxburgh *(14)* recently used similar arguments against the variations in G predicted by Dirac's large-number hypothesis. However, we can see from Eq. 2, coupled with the fact that the earth was closer to the sun with higher G, that the solar "constant" would remain roughly constant if $(dG/dt)/G \simeq -3 \times 10^{-12}$ year^{-1}. This is a smaller variation than is considered in *(12–14)*, and is consistent with the upper limit of Shapiro and Reasenberg *(15)*; it is an order of magnitude less than that reported by van Flandern *(16)*. For a flat Brans-Dicke cosmology such a change would require $\omega \simeq 12$, which is ruled out by recent observations of light bending *(17)* that require $\omega > 23$.

Models in which G on the solar distance scale is smaller than the laboratory value, so that the mass of the sun $>> 2 \times 10^{33}$ g, can produce small changes in L, but encounter difficulties with the required helium abundance *(18)*. Some models with rapidly rotating cores with spinup *(19)* have intervals in which L decreases, but are much too oblate. In general, the predictions of Eq. 2 are borne out in all but the most exotic cases.

Having seen that a faint young sun is one of the most unavoidable consequences of stellar structure considerations, we turn to its climatic consequences. The temperature variations one derives by considering the earth to behave as it would without an atmosphere are in strong conflict with the observations. More complicated, but still highly simplified, models exist for the present earth *(3, 4)*. While somewhat different, they have the same general behavior. A good example is given in figure 1 of North *(4)*, which shows the dependence of the latitude of the edge of the ice sheet on the solar constant. He finds a solution with three branches (one unstable) which has the present earth on a very steep part of the curve. (The only slowly varying stable solution is the completely frozen earth.) As the solar constant decreases, the ice sheet advances rapidly until we drop off our present branch to complete glaciation. This occurs with a solar constant only a few percent less than its present value. To recover our present climatic state requires that the solar constant be increased to ~1.3 its present value.

It is easy to be suspicious of such a simplified model. Yet there are strong correlations between the glacial advances of the past million years and the variation in mean insolation due to changes in the earth's orbit, obliquity, and precession *(20)*. The changes in energy input are quite small; the relatively large glacial advances argue for an extreme sensitivity such as that found by North.

Of course, these models are for the present earth. A billion or more years before present, the continents were in entirely different positions, and the atmosphere might have been quite different, with substantial contributions to the greenhouse effect from components not present in large amounts in the current atmosphere *(6)*. [Even the possibility that the moon was captured after the earth was formed could substantially change the early climate *(21)*.] Living organisms could play an important part in determining the atmospheric composition; it has been suggested *(22)* that the biosphere adjusts itself in such a way that the surface temperature of the earth remains nearly constant. The increased heating due to radioactivity might lead to different rates of tectonic activity, volcanism, and input of material into the atmosphere. Hart *(23)* has included many possibilities in his detailed computer simulation of the evolution of the earth's atmosphere, and finds a higher global temperature before the appearance of free O_2, due primarily to a strong greenhouse effect.

Thus it is possible to compensate for the faint young sun. However, the uncertainties entering into such a calculation are great, and many of the processes involved are only poorly understood quantitatively. The transition to an oxidizing atmosphere began 1 to 2 $\times$ 10^9 years ago

(24), and this places strong restrictions on the greenhouse components required by (6, 22, 23). Continued progress in our understanding of the history of the terrestrial atmosphere and the paleoclimate over time scales exceeding 10^9 years will indicate whether these complex models are correct and dramatic atmospheric evolution has fortuitously offset the reduced solar power input to the planet in the past [or perhaps that the Gaian or biological thermostat (22) has been operative]. Regarding the astrophysical aspects of the problem, if compensating effects such as those found by Hart (23) are ruled out, then the general nature of the predicted increase of the solar luminosity suggests that the study of stellar structure will be presented with a problem even more fundamental than is the solar neutrino dilemma.

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High Pressures on Small Areas

Abstract. *Small diamond indentors with spherical tips were pressed against a polished diamond flat. Pressures were calculated from Hertz contact theory. Very high pressures were achieved on small areas.*

As Hertz first showed, high pressures can be generated when a sphere is pressed against a flat (1). In our experiments single crystals of diamond were used for both the spherical tip and the flat anvil (Fig. 1).

The contact pressure that develops when an indentor with a spherical tip is pressed against a flat plate is given by

$$P_0 = \left(\frac{3}{2}\right)^{1/3} \pi^{-1} \left(\frac{E}{1-\nu^2}\right)^{2/3} R^{-2/3} F^{1/3} \quad (1)$$

where P_0 is the contact pressure at the center, F is the applied force, E is Young's modulus, ν is Poisson's ratio, and R is the radius of the indentor (2). In this relation it is assumed that the contact radius is small as compared to R and that linear elasticity is valid.

Several small diamond indentors with spherical tips ranging in radius from 2 to 20 μm were pressed against a highly polished diamond flat [E = 11.41 Mbar and ν = 0.07 (3)]. On the basis of Eq. 1, pressures as summarized in Table 1 were obtained. After a given load was removed, both the anvil and the indentor were examined carefully. High-magnification photographs were made of the indentor profile at different known rotations and these were carefully compared with the profiles for the same rotations prior to loading. Also direct photographs of the tip end obtained by viewing along the axis were made. By these techniques the onset of permanent deformation could be observed.

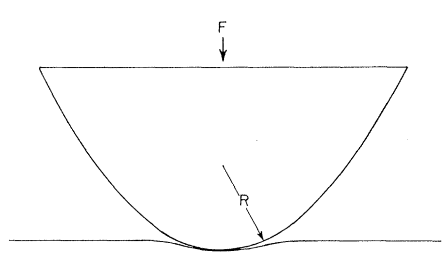

Fig. 1. Diagram of a spherically tipped diamond indentor of radius R pressed against an initially flat diamond anvil with a force F. Typically the indentor is a single crystal diamond 1/500 to 1/1000 carat with a tip radius of 2 to 20 μm, and it is mounted in a steel shank. The flat is single crystal diamond (about ½ carat) with parallel faces, also mounted in a steel shank. Because of the small size of the indentor, the damage to the flat is quite local and many tests can be made on the same flat if different areas are used.

There are three possible modes of failure. The diamond may fracture, plastically deform, or undergo a phase transformation. Usually failure occurred by a definite ring crack on the flat diamond. Observations were made with a Reichert optical microscope equipped with Nomarski interference contrast. As the indentor radius decreased, higher pressures were obtainable before fracture. We have found (for a radius range of 400 to 20 μm) that the pressure at which fracture occurs on a (100) face follows the equation

$$P_0^{f} = \left(\frac{2.4}{R}\right)^{1/3} \quad (2)$$

where P_0^f is the peak pressure (in megabars) at which fracture occurs and R is in micrometers. This type of behavior is in keeping with the general trend of Auerbach's law (4). For R = 2 μm, the pre-

Table 1. Results of pressure measurements.

Radius of tip (μm)	Highest P_0 without failure (Mbar)	P_0 with failure (Mbar)	Comment
20	0.9	1.0	Ring crack
8	1.0	1.2	Ring crack
6.5	1.2	1.3	Ring crack
2.5	1.2	1.4	Tip and flat fractured
2	1.4	1.6	Failure mode not determined*

*Possible failure modes include (i) fracture or ring crack, (ii) plastic deformation, and (iii) phase transformation.