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Solar Neutrinos and Variations in the Solar Luminosity

The lack of detectable solar neutrinos has led to the proposal of solar models with variable luminosities.

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The theory of the evolution of stars which has been generally accepted predicts that the solar luminosity should change only on a time scale of thousands of millions of years. The stability of the solar luminosity arises because the nuclear reactions ultimately responsible for producing the energy emitted at the solar surface are assumed to proceed at a steady rate in the accepted theory. The large supply of energy available from the conversion of hydrogen to helium then permits the sun to survive roughly 10 billion years from the time it was formed until it must undergo a major internal readjustment. The accepted theory also predicts that neutrinos should be emitted by the nuclear reactions in the sun and that these neutrinos should be detectable at the earth.

Thus far, efforts by Davis and co-workers at Brookhaven National Laboratory to detect these solar neutrinos have failed. In fact, Davis and Evans (*1*) have set such a low limit on the number of neutrinos from the sun that the theory of stellar evolution is challenged in a very fundamental way. This discrepancy between the theory and observation raises the possibility that the theory is incorrect, so that our conclusions based on the theory can no longer be accorded complete confidence. Therefore we must now admit the possibility that the solar luminosity varies on a time scale of less than billions of years. Because the nuclear reactions and the core of the sun are involved with the production of neutrinos, the emphasis of the discussion in this article will be on the solar interior rather than the solar surface. A review of the effect of surface phenomena on the solar output has been given by Smith and Gottlieb (*2*).

Standard nuclear physics requires that two neutrinos be emitted for every helium nucleus formed by the fusion of four hydrogen nuclei. Because of the different ways the fusion can occur, the emitted neutrinos can have different energies. The most energetic neutrinos are those emitted by the decay of ^{8}B. These neutrinos are also most easily captured by the ^{37}Cl in Davis's detector. The branch of the proton-proton fusion process which produces ^{8}B occurs rarely, and the number of neutrinos produced in this way is sensitive to the details of the solar model. A model of the sun constructed in the accepted manner predicts (*3*) that 5.6×10^{-36} neutrinos should be captured per second per target atom in Davis's detector (the unit 10^{-36} capture per target atom per second is called a solar neutrino unit or SNU). Of this number, 4.3 SNU's are due to the ^{8}B neutrinos and 1.3 SNU's are due to other branches of the fusion process.

A crucial part of the calculation of a model of the sun is the knowledge of the values for a variety of physical parameters. The parameters whose values are most important are the nuclear reaction rates and the opacity of the matter to radiation. Because the most easily detected neutrinos are produced by a rare branch of the hydrogen fusion process, the specific values of the parameters used in the calculation influence the predicted result for Davis's experiment. The discrepancy between the predictions and observations would not be significant except for the fact that the nuclear parameters have been carefully measured at the Kellogg Laboratory of the California Institute of Technology and have been confirmed elsewhere (*4, 5*). The opacities used in the calculations were calculated at the Los Alamos Laboratory of the University of California (*3, 6*). Although the specific opacities used in the solar model calculations were not checked against experiments, the theoretical and numerical techniques have presumably been checked by comparison of calculated opacities to the observed opacity of air at high temperature.

The dependence of the ^{8}B neutrino flux on details of the solar model has suggested that the discrepancy between theory and observation is not serious. Recently, however, it has become clear that the discrepancy must be regarded as significant. Although the ^{8}B neutrinos are sensitive to the detailed structure of the solar models, the other neutrinos are not. As long as the solar models do not involve an instability, the energy from nuclear reactions must balance the energy emitted at the solar surface. This required rate of energy production leads to a very tight limit on the minimum rate of neutrino emission predicted by even nonstandard solar models. In fact, the smallest rate of neutrino production which has been achieved in a nonstandard solar model is 1.4 SNU's (*3*). The upper limit of about 1 SNU set by Davis and Evans (*1*) is very close to ruling out the assumption that nuclear reactions are currently producing the luminosity of the sun (*7*). Fowler (*8*) was the first to suggest that Davis's results might be explained by assuming the sun to be in a perturbed state at the present time. If correct, this suggestion leads to the almost certain conclusion that the solar luminosity is varying on a time scale of less than 30 million years.

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Solar Domains and Time Scales

In order to determine which region of the sun might be responsible for variations in the solar luminosity, let us examine the time scale for variations associated with these regions. We may divide the sun into several domains—the corona or solar wind, the chromosphere, the photosphere, the convective envelope, and the radiative interior. Most discussions of the sun-earth interaction center on the outer three regions of the sun. The outermost region is the solar wind, which has various types of inhomogeneities and irregularities. These irregularities have some direct influence on part of the earth's environment, but they are weakly coupled into the upper atmosphere. The next lower region is the chromosphere. Far more energy is emitted from this region than is involved in the solar wind. Typical phenomena in the chromosphere are plages, the chromospheric network, and flares. All these phenomena are closely associated with variations on a variety of time scales. In particular, the chromosphere is influenced by the solar cycle through the magnetic fields, and there are substantial changes in the chromosphere during the solar sunspot cycle. The next region is the photosphere, which emits most of the energy from the sun. The only evident cause of variation in this region is the occurrence of sunspots, which darken portions of the solar surface and reduce the rate at which energy is emitted from the affected portions. However, although some of the radiation is blocked by the sunspots, we do not know whether a small increase in the average temperature in regions around the sunspots completely compensates for the blocked radiation. A temperature rise of 2° or 3°K in a region much larger than the sunspots would enhance the rate of emission of energy and balance the losses in sunspot areas. Even though the radiation-blocking role of sunspots may have little direct influence on the solar luminosity, sunspots may be a symptom of a more deep-seated process which could alter the solar luminosity.

Below the photosphere lies most of the sun. The fact that light is emitted by the photosphere means that we cannot see below it. Consequently, very few properties of the subphotospheric layers can be obtained directly from observations. Velocity fields give us some information about the first region below the photosphere—the convective envelope. Unfortunately, knowledge of this first region is also complicated by the unsolved problem of convection, which involves complex nonlinear interactions. We have only very rough models of the convective envelope, and the structural details are uncertain. The convective motions in the envelope carry energy produced in the interior past a relatively opaque layer near the surface. Because of the relatively short time required for diffusion throughout the envelope, any energy coming into the base of the convective envelope will be distributed over the entire surface of the sun. Thus, the blocking effect associated with variations in sunspot number is not likely to change the solar luminosity, because if the energy is not emitted at one place it will diffuse to some other place. On the other hand, if the sunspot number is a measure of the overall average strength of the magnetic field, and if the magnetic field alters the efficiency of convection, then there could be an indirect coupling between sunspot number and the solar luminosity.

Below the convective envelope lies the bulk of the interior. Most models of the solar interior that I have calculated are stable against convection throughout the interior. This is the region where the nuclear energy is generated and through which the energy diffuses as radiation toward the solar surface.

Each of the domains described above has its characteristic time scale. The first three—the solar wind, the chromosphere, and the photosphere—can have very short time scales for changes if we include phenomena like solar flares. However, phenomena of this type are not likely to produce an average luminosity significantly different from that which has been measured in recent times. On the other hand, the convective envelope may be capable of modulating the average solar luminosity. There are three time scales involved with the convective envelope. The best known is the 11-year sunspot cycle which, according to the Babcock (*9*) dynamo theory, is involved with the global circulation in the convective envelope. In addition to this 11- or 22-year magnetic cycle, there is a convective turnover or circulation time of somewhere between 1 and 10 days. A less well known time scale in the convective envelope, which I will discuss more below, is the thermal cooling time of about 20,000 years. The convective envelope would respond to a sudden change in the flow of energy from the interior of the sun over a period comparable to the thermal cooling time. For example, if the flow of energy from below the convective envelope were to abruptly cease, the surface luminosity would decrease over a period of 20,000 years. Also, any change in the efficiency of convective energy transport on a time scale less than 20,000 years could alter the surface luminosity. Note that the time scales are progressively longer for each layer closer to the solar center, ranging from minutes or seconds for solar flares to days and then years and thousands of years for the convective envelope. In the deep interior the thermal diffusion time scale for the entire sun is just under 2 million years, and the diffusion time between the outer edge of the nuclear burning regions and the surface is 240,000 years. These time scales are summarized in Table 1. Finally, there is the nuclear time scale of 4×10^9 to 10×10^9 years. This nuclear time scale is roughly the lifetime of the sun on the main sequence and refers primarily to the destruction of hydrogen. In addition to hydrogen, several other nuclei could play a role in variability of the energy generation rate. Since the rates of nuclear reactions are very dependent on temperature, the lifetimes of the nuclei are far from constant throughout the sun. Table 2 gives the most important nuclear lifetimes for a current standard solar model (*3*). The lifetimes were calculated from rates given by Fowler *et al.* (*5*).

Evidence for Variations in Solar Luminosity

Next we need to consider the determination of the solar luminosity. Direct measurements of the solar constant are difficult. Labs and Neckel (*10*) recently reviewed solar luminosity measurements, and the values they discuss cluster around 1.95 cal cm^{-2} min^{-1} with a range of about 1 percent (*11*). Thus, variations in the solar luminosity of about 1 percent could not be ruled out. On the other hand, over the 2-year period represented by the measurements there does not seem to be any systematic trend in time. The formal standard deviation for all determinations is $0.003 L_{\odot}$. (I denote a standard, nonvariable solar luminosity by $L_{\odot}$ and use L for the actual value of the solar luminosity.)

A second set of data on the solar luminosity consists of the calorimetric measurements made over a period of 30 years by Abbot and co-workers at the Smithsonian Astrophysical Observatory (*12*). They were attempting to detect variations in the solar luminosity and felt that their measurements were indicative of true variations with an amplitude of 1 to 2 percent. The bulk of the amplitude of this variation is due to a large drop during the middle 1920's, while the remaining amplitude is about ½ percent. It is not clear what caused the 1924 drop in the measured value of L. It occurred in the space of a few months, simultaneously in both the Northern and the Southern Hemisphere. A change in the transparency of the atmosphere could probably not have caused this measured change, since the time scale for the change was short enough to rule out a global disturbance. Also, atmospheric transparency changes were at least partially corrected for by monitoring the sky brightness. Perhaps the change was caused by a variation in the experimental techniques of either collecting or reducing data. In any event, no other large change occurred during the period of the observations.

An indirect way of monitoring the solar luminosity is by measuring the average brightness of Uranus and Neptune. Some of the difficulties in measuring the solar constant arise because the sun is bright and its radiation is emitted from an extended disk which must be entirely included in the detecting aperture. Another problem is the lack of a convenient reference with which the sun can be compared. The outer planets, Uranus and Neptune, have small apparent diameters and are faint enough to be compared conveniently to stars. Brightness variations of 1 percent have been reported for these planets (*13*). These variations are correlated with each other and represent either the effect of variable solar luminosity or some effect of the solar wind.

The evidence for long-term variations in the solar luminosity is associated with the problem of the ice ages and climate variation. The evidence for climate variations has been reviewed recently by the U.S. Committee for the Global Atmosphere Research Program (*14, 15*). Ice ages involve changes in the earth's climate which can be translated into variations of the mean temperature. A variety of evidence indicates that the temperature of the earth is changing by roughly 5°K on a time scale of 30,000 to 100,000 years. Temperature variations on a time scale of 10^6 years are no larger than about 5°K. The problem of relating these temperature variations to possible solar luminosity changes raises an important question which I would like to see discussed further: If there is a variation in the amount of energy coming from the sun, what do global climate models suggest the change in the temperature will be? Some simplified climate models suggest that the temperature changes by 2°K for every 1 percent change in the solar luminosity (*16, 17*). These models assume constant cloud cover and may not yield reliable results. Because the ratio of temperature change to luminosity change relates the solar luminosity to the paleoclimatic data, it is important that this ratio be reliably known in order to interpret the solar neutrino experiment.

In addition to geophysical evidence on the earth, there is also geophysical evidence on Mars in the form of the ice shelf configurations that are seen near the poles (*18*). These ice shelves indicate that the Martian climate also varies. If there were a way of obtaining a time scale for the ice shelf configurations on Mars we would have two independent records of climate change, and if those records coincided there would be strong reason to conclude that the sun must be responsible for climate changes on both planets.

Much of the temperature variation on the earth and Mars may be due to variations in the earth's orbital parameters (*19*). The orbits undergo slow variations, and the rate of insolation probably changes enough to account for the amplitude of the temperature variation. However, the validity of the hypothesis that the paleoclimatic changes are due to orbit changes has not been conclusively established. This hypothesis for the ice ages involves a well-defined physical statement, which can be translated into a theoretical time scale for the temperature variations. Unfortunately, the geophysical time scale is hard to pin down precisely, so we cannot unambiguously compare the theory to the geophysical record.

Let us look at another possible way to check on variations in the solar luminosity suggested by Sagan and Young (*20*). Suppose the sun is varying and the solar luminosity is going up and down by 5 percent, which is consistent with the geophysical record. We might ask, If the sun is varying, do stars similar to the sun also vary? One place in the sky to determine whether stars are varying slowly is a star cluster. Stars in a cluster are presumably all roughly of the same distance, age, and chemical composition. Consequently, their temperatures and apparent magnitudes should be very tightly correlated. The best example of this correlation is the color magnitude diagram of the Praesepe cluster given by Johnson (*21*). The main sequence line for the Praesepe cluster is very sharp. In the region where solar-type stars are found the width of the main sequence band is approximately 10 to 20 percent in luminosity. Thus, the spread in main sequence luminosities in the Praesepe cluster is consistent with 10 percent variations in the solar luminosity.

Faint Young Sun Problem

One aspect of the theoretical problem has not been addressed in the literature as much as it should be. Most evolutionary models of the sun require the solar luminosity to increase by about 30 percent from the time of formation of the sun to the present. Climate modeling should be done with earth models having a variety of geographic and atmospheric characteristics next to a sun having a luminosity

Table 1. Time scales of the sun.

Property	Time (years)	Reference
Granulation life	1.6×10^{-5}	(*29*)
Supergranulation life	2.3×10^{-3}	(*30*)
Convective envelope turnover time	1.5×10^{-2}	
Rotation period	7.2×10^{-2}	(*31*)*
Differential rotation shear period	2.5×10^{-1}	(*31*)*
Complete magnetic cycle period	2.2×10^{1}	
Convective envelope thermal cooling	2.0×10^{4}	
Thermal diffusion, center to surface	1.8×10^{6}	(*32*)†
Thermal diffusion, ^{3}He peak to surface	2.4×10^{5}	(*32*)†

*In the notation of Howard and Harvey (*31*) I have taken the shear period to be the rotation period times $a/(b + c)$. The quantities a, b, and c relate the rotational angular frequency ω to the heliographic latitude B by $\omega(B) = a + b\sin^2 B + C\sin^4 B$. †These diffusion times were calculated for the model of (*3*) using the theory of Henyey and L'Ecuyer (*32*).

Table 2. Lifetimes of nuclei at several values of $M_r/M_\odot$, where $M_\odot$ is the solar mass and M_r is the mass interior at radius r.

Nucleus	Lifetime (years) at $M_r/M_\odot$			
	0.0	0.2	0.4	0.6
^{1}H	6.3×10^{9}	4.3×10^{10}	2.3×10^{11}	1.7×10^{12}
^{3}He	1.6×10^{5}	1.2×10^{7}	3.2×10^{8}	1.5×10^{10}
^{3}He(^{4}He)*	5.6×10^{5}	1.6×10^{9}	3.8×10^{11}	1.5×10^{15}
^{7}Be	2.1×10^{-1}	3.7×10^{-1}	5.7×10^{-1}	1.02
^{7}Be(^{1}H)*	9.0×10^{1}	1.9×10^{4}	1.3×10^{6}	1.7×10^{8}
^{12}C	1.9×10^{6}	2.4×10^{9}	6.0×10^{11}	3.1×10^{14}
^{14}N	4.6×10^{8}	1.2×10^{12}	5.1×10^{14}	4.9×10^{17}

*These entries are lifetimes against capture by the species indicated in parentheses. All other entries are the lifetimes against capture by all species.

Table 3. Response of a solar model to variations in convective efficiency. Symbols are explained in the text.

$t - 4.7 \times 10^9$ years (10^5 years)	l/H	L ($L_\odot$)	R ($R_\odot$)	ΔM_e ($0.001 M_\odot$)	$\Delta r_e/R$	T_e (°K)	$\sigma\phi$ (10^6 cm^{-2} sec^{-1})
0.0	1.50	1.208	1.121	4.42	0.211	5714	4.78
1.0	1.50	1.210	1.122	4.41	0.211	5714	4.78
2.0	1.61	1.241	1.107	5.06	0.216	5789	4.78
2.5	1.77	1.294	1.088	6.07	0.222	5903	4.79
3.0	2.32	1.505	1.034	9.81	0.241	6288	4.82
3.5	1.77	1.166	1.054	7.84	0.230	5844	4.80
4.0	1.23	0.994	1.124	4.04	0.205	5436	4.76
4.5	0.96	1.059	1.205	2.11	0.187	5334	4.73
5.0	1.23	1.216	1.186	2.73	0.197	5567	4.72
5.5	1.77	1.379	1.111	5.23	0.218	5934	4.76
6.0	2.05	1.424	1.068	7.57	0.231	6102	4.78

0.75 times the present luminosity. What happens to the oceans—do they freeze?

The only discussion of this question is that by Sagan and Mullen (*22*). Global average models based on atmospheric and geographic parameters appropriate for the present-day earth, primarily due to Sellers (*17*) and Budyko (*16*), indicate that the answer is yes, the earth does freeze over. Once the earth is frozen it is unlikely to melt because the albedo for ice is greater than that for water. If the earth ever did become frozen over, it might not be able to melt. There is evidence of liquid water as long ago as 3 billion years (*23*). On the other hand, the climate models used thus far to study this question are much less sophisticated than those being developed as part of the Global Atmospheric Research Program. If a really good model of the earth with a solar luminosity 25 percent lower than the present luminosity shows that there is no way to keep the earth from freezing over, then the prediction of a low luminosity for the young sun probably points up another serious discrepancy between stellar model theories and observation. If so, we may have two clues that are pointing us toward a new type of solar model. However, not all the models that have been proposed to solve the solar neutrino problem are also capable of solving the low luminosity problem.

Variable Solar Models

The idea that the sun could undergo luminosity variations has been suggested in the past. In particular, Öpik (*24*) started work on this question about 1940 and continued it through the early 1950's. He pushed vigorously the idea that the sun is undergoing large luminosity variations. However, the model Öpik proposed to cause the sun to have variable luminosity is physically untenable. He proposed that the heavy elements diffuse into the center of the sun. Eventually these elements would increase the opacity in the center of the sun until the temperature gradient became superadiabatic. There would then be a mixing episode in the middle of the sun, causing this heavy material to be thrown out of the core and the core opacity to drop. This process could be cyclic. The problem is that the diffusion time for the heavy elements to settle into the interior is quite long. Calculations by D. Elliott and myself, based on the diffusion theory of Aller and Chapman (*25*), show that an element like iron diffuses into the center of the sun at velocity of 7×10^{-10} cm/sec—too slowly for it to produce any significant changes in chemical composition during the life of the sun.

Another idea, which is a little harder to dispose of, was suggested by Dilke and Gough (*26, 27*). Their model involves a transient instability in the sun triggered by the distribution of ^{3}He. The ^{3}He causes a pulsational instability which, according to the model, grows to a point where nonlinear effects come into play and mix the interior of the sun. The ^{3}He nucleus that drives the instability is produced by the proton-proton chain as an intermediate product of hydrogen fusion. At low temperatures, the fusion process does not go to completion and a high abundance of ^{3}He is built up. When the ^{3}He mixes into the center of the sun it can burn to completion and generate a large amount of energy. The release of this large amount of energy in the core of the sun causes the overlying layers to expand and the temperature in the center of the sun to decrease. The decrease in temperature turns off the nuclear reactions and the production of neutrinos. It also causes the luminosity of the sun to decrease. Presumably these mixing episodes occur periodically during the life of the sun, with the most recent one, about 10^6 years ago, causing both the ice ages and the lack of neutrinos.

I have carried out calculations based on the Dilke-Gough model and some results are shown in Fig. 1. As long as the mixing episodes occur intermittently throughout the sun's lifetime, no substantial chemical gradients can be built up. In order to simulate the evolution of the sun during the interval before the most recent mixing cycle, I artificially mixed the inner 0.75 solar mass ($M_\odot$) of a solar model continuously until the model reached an age of 4.45×10^9 years. The time when artificial mixing terminated is denoted by the arrow A in Fig. 1. The model then evolved through a phase of the present cycle without artificial mixing. During this interval the model brightened substantially and became 40 percent overluminous. This high luminosity represents the normal state of the sun in the Dilke-Gough model. At time B in Fig. 1, when the model had reached an age of 4.7×10^9 years, it was once again artificially mixed. The mixing was done by homogenizing successively larger regions of the solar core until 0.75 $M_\odot$ was homogenized. The simulated interval during which this artificial mixing occurred was 10^6 years and ended at time C. The calculated luminosity during the interval from time B to time C is unreliable because of numerical difficulties associated with artificial mixing.

After time C in Fig. 1 normal evolution resumed, although a large perturbation had been introduced by the artificial homogenization. The ^{3}He nuclei, introduced into the solar core by the mixing, were converted into ^{4}He in a time much less than 10^6 years. The energy released during this conversion caused the solar core to expand and cool in accordance with the virial theorem. Both the luminosity of the model and the rate of neutrino production decreased as a result of the cooling, until at 4.70165×10^9 and 4.70301×10^9 years the luminosity of the model was equal to the present solar luminosity. The exact time when the correct luminosity is achieved depends on the choice of the initial abundance of ^{4}He in the model. Changes in the initial ^{4}He abundance shift the entire luminosity and neutrino capture rate curves up or down more or less uniformly. In general, the flux of neutrinos is lower on the rising branch of the luminosity curve than on the falling branch.

If we are to identify this model as representing the evolution of the sun, then it seems likely that we should choose the later of the two possible times for the present time. This choice is also advantageous for comparison with the paleoclimatic data because it places a period of relatively slow solar luminosity change in the immediate past. Nonetheless, the model presented here involves a 10 percent luminosity decrease and increase within the span of the last 10^6 years. Using the ratio of a 2°K terrestrial temperature change for every 1 percent luminosity change, this model requires a 20°K terrestrial temperature decrease and increase during this same time span. Such a large temperature change is clearly at variance with the paleoclimatic data, which suggest that there have been temperature changes of 5°K during intervals of 100,000 years and do not suggest that there has been a long-term trend of similar amplitude. Rood (*28*) has calculated a model with assumptions very similar to those made here and obtained results much like mine. I conclude that rapid intermittent mixing of the solar core is unlikely to be the reason for the failure to detect solar neutrinos.

Finally, there is a possibility that magnetic field interactions could alter the efficiency of convection in the solar envelope. We know that the magnetic field of the sun undergoes an 11-year cycle. It is possible that this 11-year cycle is superimposed on a long-term trend. Perhaps some of the magnetic field is diffusing backward toward the solar core and is gradually building up the strength of the solar cycle to a point where it could modify the efficiency of convection. Some calculations I have done to check this possibility are summarized in Table 3. After a normal solar model had evolved to the correct age, I began changing the mixing length parameter, l/H, on a time scale of 2×10^5 years. As l/H was changed from its initial value of 1.5, the rate of energy flow through the convective zone alternately increased and decreased. Since the rate of energy flow into the convection zone from below was unaltered by the change in l/H, the energy content of the matter in this zone was altered, causing the model to expand and contract. Table 3 gives the instantaneous surface luminosity of each model as well as the total radius R and effective temperature T_e. The columns labeled ΔM_e and $\Delta r_e/R$ give the mass contained in the convective envelope and the depth of the convective envelope Δr_e relative to the total radius R. The final column gives the neutrino capture rate $\sigma\phi$. Although the surface luminosity is changed considerably by the variations in convective efficiency, the rate of neutrino emission is nearly constant. If the present time is identified as a period of relatively high solar luminosity, as in the fifth and last rows of Table 3, the average solar luminosity can be depressed below the present luminosity. Because the rate of neutrino emission is determined by the average luminosity rather than the present luminosity, the neutrino emission rate will also be depressed.

The response of the model to variations in convective efficiency is roughly proportional to the change in l/H divided by the time period over which this change occurs. A rough quantitative statement of this relation is $L - L_{av} \approx 3 \times 10^4 d(l/H)/dt$ where the luminosity L and the average luminosity L_{av} are relative to $L_\odot$ and t is in years. If the magnetic field of the sun were to change the convective efficiency by 0.5 percent in 3000 years, a change in solar luminosity of about 5 percent would occur. For this same rate of change of l/H, the solar radius would change at a rate of about 10^{-5} $R_\odot$ per year, where $R_\odot$ is the present solar radius. Although this rate of change is small, the fact that the solar radius is a different variable from the solar luminosity might make such a radius variation worth searching for. It is important to note that this suggestion has no bearing on the neutrino problem because the luminosity variations are limited to 5 percent by the geophysical record. For the rate of neutrino emission to be lowered by the luminosity variations imposed by the solar envelope, we must assume that the luminosity flowing into the envelope from below is less than the present surface luminosity. Presumably the average of the surface luminosity over a long period of time is equal to the core luminosity. In order to meet the observational limit imposed by Davis's measurements, the average solar luminosity would have to be reduced to 0.80 times the present solar luminosity. The present sun would then be 20 percent brighter than average. This is clearly incompatible with paleoclimatic data. Nonetheless, small luminosity variations could be occurring as a result of the hypothesized interaction of the magnetic field and convection. These small variations in the solar luminosity could be a contributing cause for the more or less regular variations in the earth's temperature.

Conclusions

The recent study of solar models has suggested that the solar luminosity could vary on a time scale shorter than the age of the earth. Until now, the assumption that the solar luminosity is a constant has been questioned only on rare occasions. There are two possible processes that could cause luminosity variations. Any change in the solar luminosity due to the suggested processes could profoundly affect the climate of the earth by altering the average temperature. The existence of short-term luminosity variations that might be climatically significant could be confirmed by a modern revival of the efforts to monitor the flux of solar energy. The theory of the solar interior which predicts the behavior of the solar luminosity remains in a confused state. None of the explanations for the lack of detectable neutrinos have yet proved satisfactory. Until such time as we understand the results of Davis's experiment, we cannot have confidence in any predictions based on the theory of the solar interior.

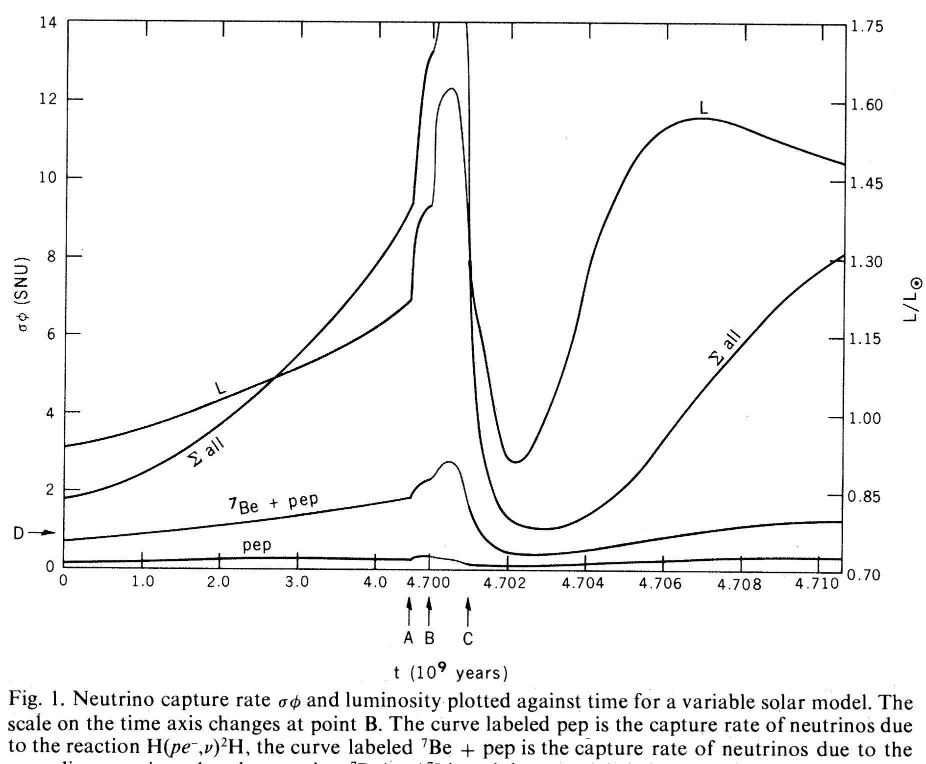

Fig. 1. Neutrino capture rate $\sigma\phi$ and luminosity plotted against time for a variable solar model. The scale on the time axis changes at point B. The curve labeled pep is the capture rate of neutrinos due to the reaction $H(pe^-,\nu)^2H$, the curve labeled ^7Be + pep is the capture rate of neutrinos due to the preceding reaction plus the reaction $^7Be(e^-,\nu)^7Li$, and the curve labeled Σ all is the capture rate due to all reactions, including most importantly the reaction $^8B(e^+\nu)^8Be^+$. The model was continuously mixed from time $t = 0$ until point A. It then evolved normally until point B, where artificial mixing was initiated gradually. By point C mixing out to 0.75 $M_\odot$ was complete and normal evolution was again allowed. The arrow D marks the upper limit on Σ all imposed by Davis's experiment.

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Molecular Biology of Bacteriophage Mu

Genetic and biochemical analysis reveals many unusual characteristics of this novel bacteriophage.

M. M. Howe and E. G. Bade

When sensitive strains of *Escherichia coli* K12 are infected with the temperate bacteriophage Mu, approximately 2 percent of the resulting lysogens are found to have acquired a new nutritional requirement (*1*). The unusual mutagenic capability of this bacteriophage stimulated much interest and prompted the name Mu (for *mu*tator). Since then, the original hypothesis that the mutagenesis occurs by insertion of the Mu prophage into the inactivated gene (*1*) has been confirmed by both genetic and physical means (*2–7*).

Since most temperate bacteriophages integrate into one or a small number of specific sites in the host chromosome, Mu is unusual in its ability to integrate in many sites. Much of the current work on Mu is directed toward understanding the mechanism by which this integration occurs.

Recent analysis has revealed that Mu is unusual in other ways as well. For example, Mu DNA contains host DNA sequences (*8–10*) and is found associated with host DNA during lytic development (*11–13*). It is interesting that in these aspects Mu seems to be more similar to the oncogenic animal viruses SV40 (simian virus 40) and polyoma (*14*) than to other bacteriophages.

This article includes a discussion of Mu integration, the properties of Mu-induced mutations, the genetics and physiology of Mu, and the structure and replication of the phage DNA.

General Properties of Mu

Mature Mu virions are similar in appearance to those of bacteriophage P2 (*15, 16*). The Mu virion is composed of a head 540 Å in diameter, a contractile tail sheath 1000 Å long and 180 Å wide, a base plate and tail spikes (*16*). The density of the mature particles was found to be 1.454 g/ml (*17*) and 1.468 g/ml (*16*) in independent measurements. As yet, nothing is known about the proteins of the virion. Information about the size and structure of the double-stranded DNA is presented below.

The host range of Mu is rather limited. It grows on *E. coli* K12 (*1*), on *Citrobacter freundii* (*18*), and on some strains of *Shigella dysenteriae* (*1*), but not on *Salmonella typhimurium* or on *E. coli* C, B, S, or W (*1*). Host range mutants of Mu able to grow on *E. coli* C and on *Shigella* have been isolated (*19*). Within *E. coli* K12 strains, some mutants resistant to Mu are also resistant to bacteriophages P1 and P2, and many show increased sensitivity to phages T3, T7, and C21 (*20*). The rate at which Mu adsorbs to sensitive cells varies depending on the conditions. In medium containing $5 \times 10^{-3} M$ to $1 \times 10^{-2} M$ Ca^{2+} and Mg^{2+} adsorption is 80 to 95 percent complete within 15 minutes at 37°C (*9, 19*).

The titers of Mu lysates often decrease with time. Part of this decrease is due to phage adsorption to cell debris remaining after brief centrifugation and can be prevented by more extensive centrifugation (*9*).

Upon infecting a sensitive bacterium, Mu may develop lytically to produce more phage or it may form a lysogen. In the lysogenic state the phage DNA is integrated into the host chromosome, and most functions of the prophage or of a superinfecting Mu are not expressed (*21, 22*). The formation of stable lysogens of Mu is not a very efficient process. In a single cycle of infection the majority of the cells are killed, and only 5 to 10 percent of the survivors are lysogens (*20*). The remainder, which are all sensitive to subsequent infection by the phage (*20*), may have been abortively lysogenized or simply not infected. The proportion of lysogens in a culture infected with Mu can be increased to 100 percent by prolonged incubation (for example, overnight) of the phage-cell mix-

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