Reports

Efficiency of Convection and Time Variation of the Solar Constant

Abstract. *Variations in the efficiency of convection resulting from its stochastic nature could be manifested as small (≲ 1 percent) fluctuations in the solar constant. This could result in changes in the earth's climate with time scales of decades to centuries.*

In most studies of stellar and solar evolution, the structure of the convective regions is determined by using a mixing length theory, with the assumption that the ratio of mixing length to pressure scale height is constant in space and time (*1*). Stellar convection is, however, recognized as being a largely chaotic phenomenon. In the work reported here we investigated the effects on solar models of a mixing length that varies with time because of the stochastic nature of convection. This is equivalent to varying the efficiency of convective energy transport. One expects the efficiency of convection to be influenced to some extent by the presence of magnetic fields, and the sun's surface magnetic field is observed to change markedly on a relatively short time scale. In fact, during the period known as the Maunder minimum, the surface magnetic field is thought to have been very weak for a period of ~70 years (*2*). Another possible cause of varying convective efficiency is the limited number of supergranules (~10^3) on the sun (*3*). Changing this number by 30 could cause a significant change in the energy carried by convection and result in variations of the solar convection zone on short time scales.

Because of the complicated feedback mechanisms involved, the effects of a varying solar constant on the climate are uncertain, but calculations have indicated that variations of 1 percent in the solar luminosity could lead to a change in the average temperature of the earth of 2°K (*4*). Also, observations by Lockwood (*5*) and Abbott (*6*) suggest some variation in the solar constant.

For perfectly efficient convection, the transport of energy through the convection zone is adiabatic, and the logarithmic temperature gradient with respect to pressure ($\nabla \equiv d\ln T/d\ln P$) is given by the adiabatic gradient, ∇_a. For completely inefficient convection, energy is transported by radiation (*7*) and the temperature gradient is the radiative gradient

$$\nabla_r = \frac{3\gamma LP}{16\pi acGMT^4}$$

where γ is the ratio of specific heats, L is luminosity, P is pressure, a is 4 times Stefan's constant divided by c, c is the speed of light, G is the gravitational constant, M is the mass of the star, and T is temperature. In actual convection, there is an intermediate case of finite efficiency where $\nabla_r > \nabla > \nabla_a$. Local mixing length theory (*8*) determines the gradient from the equation

$$\nabla = \nabla_a + \frac{\beta X}{\alpha^2} + X^2$$

$$= \nabla_r - \frac{3}{2\beta}\alpha^2 X^3$$

where X is determined from

$$\frac{3}{2\beta}\alpha^2 X^3 + X^2 + \frac{\beta X}{\alpha^2} = \nabla_r - \nabla_a$$

with

$$\beta = \frac{32\sqrt{2}\,\sigma T^3 GM}{\kappa\rho C_p P r^2}\left[\frac{\rho/P}{1-(d\ln\mu/d\ln T)_p}\right]^{1/2}$$

$$\alpha = l/H$$

where l/H is the ratio of the mixing length to the pressure scale height, σ is Stefan's constant, ρ is density, $\kappa\rho$ is the opacity (in square centimeters per gram), C_p is the specific heat at constant pressure, and μ is the mean molecular weight. The efficiency of convection is conveniently discussed in terms of α, and it is easy to show that the limit $\alpha \rightarrow \infty$ corresponds to $\nabla \rightarrow \nabla_a$ or completely efficient convection. Conversely, $\alpha \rightarrow 0$ leads to $\nabla \rightarrow \nabla_r$ and energy transport by radiation.

Our approach has been to represent the variation in convective efficiency by perturbing α. Varying α changes the temperature gradient ∇, and the structure of the convection zone must change in order to maintain hydrostatic equilibrium. Since the structure will adjust on a dynamic time scale (~10 minutes for the convection zone), the convection zone quickly reacts to any change in α. This structural readjustment causes an interchange between the gravitational potential energy and internal energy of the material in the convection zone. Increasing α makes the convection more efficient and causes a small collapse of the material in the convection zone. Decreasing α causes more energy to be transported by radiation. In this case the convection zone expands at the expense of internal energy. This change of the energy in the convection zone causes a change in luminosity of order

$$\delta L \cong \frac{GM\Delta m}{R^2}\;\frac{\delta l}{\tau}$$

where R is the radius of the star, Δm is the mass of the convection zone, and τ is the time scale on which the energy is released (or absorbed). If the time scale on which α (or the efficiency of convection) changes, τ_α, is longer than the thermal

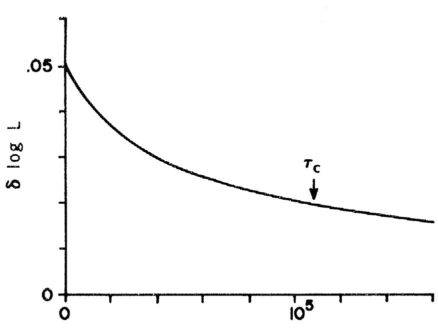

Fig. 1. Change in luminosity ($\delta\log L$) resulting from a particular change in mixing length ($\delta\alpha$). The slope of the relation gives $\delta\log L = 0.2\delta\alpha$ over the range $\alpha = 1.0$ to 1.5.

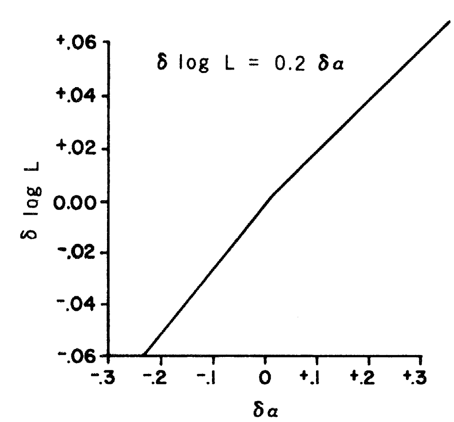

Fig. 2. Change in luminosity after a sudden change in α of 0.25. There is an immediate increase in the luminosity of 10 percent ($\delta\log L = 0.05$), and the luminosity decays to the initial value on a time scale of ~ 1.1×10^5 years.

time scale of the convection zone, τ_c ($\sim 10^5$ years), then $\tau = \tau_\infty$ and the change in luminosity will depend on the rate of change of α ($\delta L \propto d\alpha/dt$). Since α has little effect on the structure of the central regions of the sun, the luminosity returns to its original value on the time scale τ_c if the efficiency of convection stops changing.

Faster changes in α ($\tau_\alpha < \tau_c$) lead to different behavior. The internal energy lost (or gained) because of a change of α cannot be replaced (or leak out) on time scales shorter than τ_c. In this case $\tau = \tau_c$ and $\delta L \propto \delta\alpha$ or

$$\delta \log L \cong 0.43 \frac{GM\Delta m}{LR^2} \frac{H}{\tau_c} \delta\alpha \cong 0.2\delta\alpha$$

for a standard solar model, where $H = 10^{10}$ cm is the pressure scale height; M is the mass of the sun, $M_\odot$; Δm is $0.008\ M_\odot$; $R = 6 \times 10^{10}$ cm is the radius at the base of the convection zone; L is the solar luminosity, $L_\odot$; and τ_c is 10^5 years. This behavior has been observed in detailed numerical models with reasonable quantitative agreement (see Fig. 1). If there is a single rapid change in α, the luminosity will quickly change by an amount $\sim 0.2\ \delta\alpha$, and then decay to the original luminosity on a time scale as shown in Fig. 2. However, if α continuously changes on a short time scale, the luminosity will accurately track the change in α. Our model yields a relation $dL = 4 \times 10^4\ d\alpha/dt$ in the case where the convective efficiency changes on a long time scale ($\gtrsim 10^5$ years). This is a slightly larger change than that suggested by Ulrich (*8*), but the difference can be accounted for by uncertainties in the actual structure of the convection zone (differences in solar models).

Thus it is seen that changes in the solar constant of 1 percent can result from varying α by as little as 0.02. One wonders then whether it is reasonable for solar convection to be so precisely characterized by an average quantity like α, or whether small changes in the effective mixing length (efficiency of convection) might naturally occur (*9*).

The present understanding of convection is inadequate to prove the existence of time-varying convective efficiency, but such variation is not out of the question. Abbott's belief that he had detected a time variation of the solar constant has been widely doubted, but modern observations cannot exclude variations in the solar constant of 0.1 to 1 percent on a time scale of years to decades. In view of the extreme sensitivity of global climate models to changes in the solar constant (*10–15*) and the results of our analysis, which indicate that variations in the solar constant can occur on short time scales, it would seem that an observational program to monitor the solar constant over a period of years to 0.1 percent or better is in order.

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Investigation of Electron Tunneling Between Cytochrome c Peroxidase and Cytochrome c

Abstract. *The nature of electron transfer between the bound complex cytochrome c and cytochrome c peroxidase has been investigated. Experimental verification of the predicted charge-transfer band provides evidence of electron tunneling as the mechanism of transfer between these molecules in solution at room temperature. The measured transfer distance is ≃7 angstroms between heme edges, which results in a distance of ≃15 to 20 angstroms between iron atoms.*

We report photoinduced electron transfer between cytochrome c (C) and cytochrome c peroxidase (CP) at room temperature, which has been predicted by the theory of nonadiabatic electron tunneling in biological molecules (*1*). This model predicts a new charge-transfer band (*2*) whose intensity and width provide a definitive verification of electron tunneling, yield information about the transfer distance, and characterize the properties of the electron tunneling process. Previous experiments by Potasek and Hopfield (*3–5*) have verified this process in a model system consisting of cytochrome c–iron hexocyanide [C-Fe$(CN)_6$]. In this report, nonadiabatic electron tunneling is verified between CP and C, a biological donor-acceptor pair found in mitochondria.

Cytochrome c peroxidase catalyzes the oxidation of ferrocytochrome c (C^{II}) to ferricytochrome c (C^{III}) in the presence of hydroperoxide. The binding between CP and C is electrostatic, with two binding sites for C on CP (*6*), and depends on ionic strength and pH.

Electronic wave function overlap enables electron tunneling to occur between CP and C and also allows for the direct optical excitation of an electron from one molecule to the other without first exciting the electron on one molecule. The molar extinction coefficient for this charge-transfer band is given by (*2*)

$$\epsilon(E) = 1.22 \times 10^{19} \frac{T^2 a^2}{E\sigma} \exp\left[-\frac{(E - E_{\mathrm{peak}})^2}{2\sigma^2}\right] \quad (1)$$

in which E is energy, E_{peak} is the peak position of the Gaussian charge-transfer band, σ is the standard deviation, T is the tunneling matrix element and is related to the distance transferred, and a is the distance between the centers of gravity of the donor and the acceptor.

However, the magnitude of the charge-transfer band is on the order of 10^6 times smaller than other sample absorbances, which renders static spectroscopy unfeasible. A method of excitation spectroscopy was used to detect the band. The experimental apparatus has been described previously (*4*). It includes an excitation source, a filtered tungsten lamp, the light from which is chopped by a variable-speed chopper and then focused on the sample. The change in sample absorbance is monitored by light from a xenon arc lamp that is passed through a monochromator.

