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The Evolution of the Solar "Constant"

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ABSTRACT

The ultimate source of the energy utilized by life on Earth is the Sun, and the behavior of the Sun determines to a large extent the conditions under which life originated and continues to thrive. What can we say about the history of the Sun? Has the solar "constant", the rate at which energy is received by the Earth from the Sun per unit area per unit time, been constant at its present level since Archean times? Three mechanisms by which it has been suggested that the solar energy output can vary with time will be discussed, characterized by long (~ 10^9 years), intermediate (~ 10^8 years), and short (~ years to decades) time scales.

1. Introduction

Although the rate at which energy is supplied to the Earth by the Sun is generally regarded as being constant in time, there are sound astrophysical reasons for expecting a time variation in this important quantity beyond the well-known modulation of the solar "constant" due to changes in the details of the Earth's orbit. Three possible types of variation will be discussed:

1. The inexorable increase of the solar luminosity over geological timescales as the conversion of hydrogen into helium, which provides the thermonuclear power of the Sun, slowly increases the mean molecular weight in its interior. This luminosity increase, amounting to some 25% over the 4.7×10^9 year lifetime of the Sun, has been shown to be a nearly model-independent result not affected by the uncertainties arising from the difficulties concerning the interpretation of the solar neutrino experiment.
2. The infrequent temporary enhancement of the solar luminosity due to the gravitational energy release of material accreted onto the solar surface as the solar system traverses a dense interstellar cloud. This luminosity perturbation, which may have occurred half a dozen or more times during the Sun's history, is peaked in the short-wavelength region of the spectrum, and may constitute a serious hazard for life on Earth.
3. The small amplitude rapid fluctuations of the solar luminosity which may arise due to the finite efficiency and stochastic nature of convective energy transport.

The latter effect, while it should be less important for the evolution of life on our planet than the others, differs in being more accessible to direct experimental measurement than the long-timescale effects, and may have a significant impact on climatic change in the current epoch.

2. Accumulation of He ash

Most detailed numerical models of the structure and evolution of the Sun show a roughly 25% luminosity increase from the time of thermonuclear ignition to the present, and Newman and Rood (1977) have noted that this behavior is a direct consequence of energy generation by consumption of a light nuclear fuel (hydrogen) and accumulation of waste products (helium). It is therefore very difficult to avoid. A simple dimensional analysis of the differential equations of stellar structure (Cox and Giuli 1968) indicates that the luminosity should scale as roughly

$$L \propto \frac{ac}{\kappa_o} M^{5.5} R^{-0.5} \left(\frac{G m_p \mu}{k}\right)^{7.5} , \tag{1}$$

where M is the solar mass, R the solar radius, a is the radiation pressure constant $4\sigma/c$, κ_o is the opacity coefficient, G is the gravitational constant, m_p is the proton mass, k is Boltzman's constant, and μ is the mean molecular weight (Clayton 1968). If the solar mass and the fundamental constants remain constant then the logarithmic time derivative of the solar luminosity should be approximately

$$\frac{1}{L}\frac{dL}{dt} \approx -0.5 \frac{1}{R}\frac{dR}{dt} + 7.5 \frac{1}{\mu}\frac{d\mu}{dt} . \tag{2}$$

Thus if the source of solar energy is to a small extent gravitational contraction ($\frac{dR}{dt} < 0$) and principally the conversion of hydrogen into helium ($\frac{d\mu}{dt} > 0$), then the solar luminosity must be an increasing function of time. A quantitative estimate of the rate of change can even be made by this simple argument. If the solar luminosity is provided by the release of $\varepsilon = 6.4 \times 10^{18}$ ergs per gram of hydrogen converted into helium, then the average hydrogen mass fraction X in the solar interior must be changing at a rate

$$\frac{dX}{dt} \approx - \frac{L}{M\varepsilon}$$

$$\approx - 0.01/10^9 \text{ yrs.}, \tag{3}$$

and from

$$\mu \approx \frac{\frac{4}{3}}{1 + \frac{5}{3} X} \tag{4}$$

we have immediately from Eq. (2)

$$\frac{1}{L}\frac{dL}{dt} \approx \frac{L}{M\varepsilon} \frac{12.5}{1 + \frac{5}{3} X} \tag{5}$$

$$\approx 0.05/10^9 \text{ yrs.}$$

if the Sun is composed primarily of hydrogen. As Newman and Rood showed, the luminosity enhancement predicted by (5) is shared by many classes of solar models, including exotic models constructed to be in agreement with the Brookhaven solar neutrino experiment (Davis 1978). Even these models share the basic assumption that the Sun is powered by thermonuclear reactions, and the increase in mean molecular weight resulting from fuel exhaustion and accumulation of nuclear "ashes" directly results in an increasing solar luminosity. As we see from Eq. (1), almost the only way to avoid the luminosity increase of some 5 to 7% per 10^9 years is to appeal to changes in the solar mass, radius, or one of the fundamental physical constants. The present solar wind is not sufficient to cause significant mass loss, and <u>increasing</u> the solar mass, as by accretion, only serves to further enhance the luminosity increase. Similarly the solar radius is thought to be very slowly decreasing under the influence of gravity, which contributes slightly to the luminosity increase, and it is difficult to increase the radius unless the rate of energy generation in the interior is increased - and we have seen that that is the major source of the luminosity enhancement. The predicted slow-but-steady increase of the solar luminosity over cosmic time scales would thus seem to be on very firm ground, unless the physical constants do not remain constant in time, as Professor Cameron has discussed at this conference.

3. Cosmic pollution

McCrea (1975) has recalled the suggestion of Hoyle and Lyttleton (1939) that the accretion of matter from the interstellar medium by the Sun acts as a trigger for the occurrence of Ice Ages on the Earth, through a complicated mechanism in which the luminosity perturbation resulting from the gravitational energy release of the matter falling onto the solar surface increases the rate of evaporation, which increases the cloud cover and the rate of precipitation, increasing the albedo of the planet and leading to glaciation. However, the climatic response of the Earth involves so many complex feedback links that it is not certain that even the algebraic sign of the global response to a perturbation of the solar luminosity is understood. Nonetheless, it seems clear that passage of the solar system through a dense interstellar cloud would have some impact on the terrestrial climate, whether or not we can state with confidence what the effect would be. Possible climatic consequences of such an encounter have been discussed by Begelman and Rees (1976) and Talbot, Butler, and Newman (1977). Encounters with clouds of sufficiently high density and low relative velocity to yield the high levels of accretion discussed by Hoyle and Lyttleton or McCrea would seem to be rare (less than one such encounter expected during the lifetime of the solar system) - which is just as well, since Talbot et al. have estimated that the resulting uv flux could be deadly for life on Earth. However, encounters with more modest clouds should occur many times during the lifetime of a star like our Sun, and encounters sufficient to cause significant climatic effects on Earth may occur at intervals averaging of order 10^8 years. Talbot and Newman would expect the occurrence of such events to be distributed randomly in time, reflecting the stochastic nature of collisions between randomly distributed objects, but McCrea has suggested that passage of the solar system through dense interstellar clouds occurs preferentially during the crossing of the spiral arms of our galaxy, which occurs at intervals of roughly 250 million years, and that there is a correlation between the time scales describing the motion of the solar system in the galaxy and the occurrence of epochs of glaciation in the paleoclimate of the Earth. Whether the occurrence is as regular as McCrea suggests, and whether the climatic impact is through the luminosity perturbation or through other mechanisms which have been suggested, such as compression of the solar wind cavity, dust loading of the Earth's atmosphere, or even the influence of supernova explosions which occur preferentially in or near dense clouds where massive young stars are thought to form, it seems clear that encounters between the solar system and dense interstellar clouds can have a significant impact on conditions for life on Earth. Whether or not they have actually done so in the past, and how often, is a matter of current controversy.

4. Stochastic convection

While the Sun's energy is thought to be carried outward from its site of production by thermonuclear reactions deep in its interior primarily by radiative transport processes throughout most of its mass, there is a relatively thin outer region where energy transport is primarily by convective motion. The quantitative understanding of energy transport by convection is poor, and most astrophysical calculations are done with the mixing length theory of convection, in which it is assumed that a typical fluid element moves on the average a distance equal to the mixing length ℓ before it mixes with its surroundings and gives up its excess heat energy. It is further assumed that the ratio $\alpha = \ell/H_p$ of the mixing length to the pressure scale height H_p (the distance over which the pressure changes by a factor of e, the base of natural logarithms), is a constant, usually taken to be about 1.5. Solar models, in particular, are "tuned" by adjusting the mixing length parameter α until the model radius is equal to the observed solar radius (the radius of a stellar model is a sensitive function of α). Dearborn and Newman (1978), however, have questioned how precisely we can characterize a complex stochastic process like convection by a single average quantity like α, and consider the consequences if the appropriate average value of α changes with time. If α is increased convection becomes more efficient and the same flux can be carried with a smaller temperature gradient; the convective envelope contracts slightly. If α is decreased convection becomes less efficient and a larger temperature gradient is required to produce the same net energy transport; the envelope expands slightly. In either case there is an interchange between the gravitational potential energy and internal energy of the material in the convection zone, and a luminosity perturbation results. The change in luminosity can be estimated as

$$\delta L \approx \frac{GM\Delta m}{R^2} \frac{H_p \delta\alpha}{\tau} , \tag{6}$$

where we have expressed the change in gravitational energy in terms of the change in the mixing length parameter, Δm is the mass of the convection zone, and τ is the timescale on which the energy is released or absorbed. If the timescale τ_α on which α is changing is longer than the thermal response time of the envelope $\tau_c \sim 10^5$ yrs. then $\tau = \tau_\alpha$ and the luminosity perturbation depends on the rate of change of the mixing length parameter as found by Ulrich (1975). However, if α is changing on time scales short compared to the thermal timescale of the envelope ($\tau_\alpha << \tau_c$) then, although the structure of the envelope can adjust on the dynamic timescale ~ 10 m, the excess energy can be radiated away or absorbed only on the timescale $\tau = \tau_c$, and the luminosity perturbation depends only on the amplitude $\delta\alpha$. Evaluating Eq. (6) numerically for a standard solar model yields

$$\delta \log L \approx 0.2 \, \delta\alpha , \tag{7}$$

which has been confirmed to good accuracy with detailed numerical models. The luminosity perturbation given by (7) would decay away on the timescale τ_c if no new perturbation $\delta\alpha$ is introduced; if changes in α are frequent the luminosity will track with the response function (7). The fine structure of the solar luminosity could thus be quite jagged, depending on the behavior of α. The solar constant is not monitored to much better than 1%, and 1% changes in L would result from fluctuations as small as $\delta\alpha \approx 0.02$. Since significant climatic effects could result from luminosity excursions at this level, it is a matter of concern that our current understanding of convection cannot rule them out. Dearborn and Newman mentioned the influence of magnetic fields on convection, the limited number of supergranules (which may be directly related to the convective cells themselves) observed on the surface of the Sun, and the inherently random nature of convective motion as reasons for suspecting fluctuations in the efficiency of convection may exist. Whether such effects are responsible for the apparent solar variations reported by Livingston et al. (1977) and White and Livingston (1978) is not yet known. The luminosity fluctuations discussed here would be manifested on the time scale on which the efficiency of convection is changing, which is most likely month, years, or decades depending on the mechanism involved, although longer time scales have also been discussed. They may thus be responsible for climatic effects in the present epoch, although it is not yet certain whether they occur.

5. Conclusions

Three mechanisms have been discussed by which the solar luminosity may change in time. The slow steady increase in solar luminosity of some 5% per 10^9 years is a fundamental consequence of energy generation by thermonuclear reactions, and is difficult to avoid unless fundamental physical constants do not remain constant over cosmic timescales. Very large ($\gtrsim$ 10%) luminosity excursions due to encounters between the solar system and interstellar clouds of high density are unlikely to have occurred, but cannot be ruled out. Their effect on conditions for life would be profound. More modest ($\lesssim$ 1%) luminosity enhancements due to encounters with clouds of lower density or larger relative velocity may have occurred half a dozen or more times during the history of the solar system, and could have devastating effects on life, since the luminosity perturbation due to solar accretion of interstellar matter is peaked at short wavelengths. Encounters with clouds of modest density producing small ($\lesssim$ 0.1%) luminosity enhancements may have occurred 50 or more times since the formation of the solar system, and could produce significant climatic effects through a variety of mechanisms, not all of them connected with the resulting distortion of the solar spectrum. These effects are on less certain ground than the long-time-scale enhancement due to fuel consumption, but encounters between the solar system and dense interstellar clouds should have had some impact on the conditions under which life has developed on Earth. Finally, it has been suggested that fluctuations of the efficiency of convection result in small amplitude variations of the solar luminosity on relatively short time scales. These have not been shown to occur, but may be important for the fine structure of the paleotemperature curves if they are real.

It is not likely that the solar "constant" has remained strictly constant, and time variation of this important quantity may have had significant impact on the development of life on our planet.

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