N76 14542

Solar Models in Relation to Terrestrial Climatic Variations

A. G. W. CAMERON
Harvard College Observatory and Smithsonian Astrophysical Observatory

One of the suggested possibilities to explain the lack of observation of solar neutrinos is that the Sun may have undergone a thermal expansion at the center, lasting a few million years, with an accompanying decrease in luminosity, producing an ice age. A critical examination is given of this hypothesis.

Most of the papers at this meeting have dealt with relatively small changes in the state of the Sun that may or may not be accompanied by relatively small changes in the state of Earth's atmosphere. The present paper deals with the possibility of occasional larger changes in the state of the Sun, lasting for some millions of years, that might be responsible for producing more drastic changes in Earth's climate, called ice ages. I have recently given a more complete summary of this situation, and the reader interested in more details and references is referred to this (Cameron, 1973).

For some years, Raymond Davis, Jr., of the Brookhaven National Laboratory has been attempting to detect neutrinos emitted from the Sun. He has been utilizing a large tank underground in a mine in South Dakota that contains some 100 000 gallons of commercial cleaning fluid, C_2Cl_4. The expected action of the more energetic solar neutrinos is to convert some atoms of ^{37}Cl into atoms of ^{37}Ar, which is a radioactive nuclide. Periodically, every month or two, the tank is purged of rare-gas atoms, which are collected. The argon is separated and any radioactive argon atoms are detected by a carefully shielded counter. The great sensitivity of this experiment may be judged from the fact that Davis is looking for the production of only a few radioactive argon atoms per month in this large tank.

Davis's experimental results are usually quoted in terms of a unit depending in part on the expected neutrino interaction cross section with ^{37}Cl atoms. This unit is called the solar neutrino unit (SNU). When the experiment was first designed, model calculations had predicted that Davis should obtain a signal equivalent to about 30 or 40 SNU. However, he did not detect any signal, and with added effort, which has involved increasing his detector sensitivity greatly, he has pushed down the limit to the point where the solar neutrino flux is not greater than about 1 SNU. Meanwhile, there have been some revisions in nuclear reaction cross sections, whose redetermination has been motivated by these experimental results, and current solar models predict that he should detect a signal of about 7 SNU. It is this discrepancy that has led to an intense search for aspects of nuclear astrophysics, stellar physics, or neutrino physics that might be an error. Here I shall deal with only one of these suggested methods for evading the solar neutrino difficulty, that involving a temporary thermal expansion of the center of the Sun. This idea was originally suggested by W. A. Fowler.

Suppose that a considerable amount of thermal energy is suddenly dumped into the center of the Sun. This heats up the gas, increasing the pressure, and causing the center of the Sun to expand. This expansion, in turn, adiabatically cools the gas to a temperature lower than that which the center of the Sun would normally have. This cuts down the rate of the thermonuclear reactions occurring there, and hence it will also greatly cut down the emission of neutrinos from the central regions of the Sun. This excess energy will diffuse out of the center of the Sun, over the course of a few million years, allowing the central region to relax toward the normal condition.

There have been a number of discussions in the last 2 yr of a possible way in which such a sudden energy release might take place. To show schematically how this happens, it is necessary to consider the basic energy-producing reactions in the Sun and their temperature sensitivities. I shall give here only the first of the so-called "proton-proton reaction chains" that is probably responsible for most of the energy generation in the Sun, but which is not responsible for producing neutrinos to which the Davis detector is sensitive.

The first step is the proton-proton reaction: $^{1}H(p, \beta^{+} \nu)^{2}D$. This reaction, involving a β decay, is a rare one and has a relatively low temperature sensitivity in the center of the Sun, about the fourth power of the temperature at the center of the Sun. This reaction is immediately followed by another: $^{2}D(p, \gamma)^{3}He$. The deuterium formed in the first reaction is almost instantaneously removed and converted to ^{3}He by this reaction. The ^{3}He builds up until there is enough of it present for it to react with itself: $^{3}He\ (^{3}He, 2p)^{4}He$. This reaction has a much higher temperature sensitivity, something like the 20th power of the temperature near the center of the Sun.

As a result of the different temperature sensitivities of these reactions, the amount of ^{3}He which will be present under steady-state conditions will increase as one goes away from the center of the Sun. This results from the fact that much larger amounts of it are needed to compensate the relatively smaller reaction rate at lower temperatures in the Sun.

Therefore it is evident that if some mechanism could produce a large-scale and sudden mixing of the central regions of the Sun, the amount of ^{3}He at the center would be greatly increased. The amount would then be much in excess of that needed to produce ^{4}He at the steady-state rate established by the basic proton-proton reaction. Hence the excess ^{3}He would more rapidly be destroyed in the central region of the Sun, releasing energy at higher than the normal rate and providing the source for the relatively sudden release of energy that has been postulated.

It is necessary to emphasize that we do not know of a suitable mixing mechanism that would be needed to produce this effect. The only detailed mechanism suggested is an oscillatory overstability of the central regions of the Sun, leading to mixing, proposed by Dilke and Gough. However, this mechanism has come under severe criticism by Ulrich and others. Thus at the present time we have nothing to suggest for a driving mechanism that would cause the mixing, and this is the fundamental weak point in this whole approach. All we can do is suppose that the mixing happens, and inquire as to the consequences. This simply recognizes that there is a considerable amount of strange behavior associated with the dynamics of rotating fluids that we do not yet understand, so that perhaps it may be possible in the future to find a driving mechanism for the mixing if the consequences should look interesting.

Let me cite a specific numerical example, calculated by Ezer and Cameron (1972). In this experiment, 56 percent of the central mass of the Sun was suddenly mixed, which meant that its composition was rendered uniform. This led to an increase of ^{3}He near the center, and the additional energy released by destruction of this nuclide caused the center of the Sun to expand over a period of about 2 million years. Following an initial neutrino flash immediately after the mixing, the neutrino production fell off markedly throughout the Sun, and the expected detection by Davis dropped to about 0.5 SNU. The photons then gradually diffused out of the center of the Sun, allowing the solar core to relax back toward normal conditions over the following 4 million years. The total time involved in the core expansion was thus 6 million years, and during this period of time the solar luminosity dropped to a minimum of about two-thirds of normal. There was a small overshoot in luminosity at the end of the recovery period, which would gradually die out over a somewhat longer period.

It is reasonable to expect that the large decrease in luminosity of the Sun would produce an ice age. We are presently involved in an ice age, which has lasted for a few million years. As long as the poles of Earth are covered by ice, this is to be regarded as an ice age, and we are not concerned with the motion of the ice sheet back and forth between high and low latitudes. It appears that Earth was free of polar icecaps throughout most of geologic history. Thus the numerical example that I have just cited cannot be expected to be truly representative of the situation. If something like this were to happen, we would identify the present as a period of reduced solar luminosity so that the normal solar luminosity would be considerably higher than at the present time, perhaps 50 percent greater. This would have burnt more hydrogen in the central region of the Sun, leading to a rising level of the normal solar neutrino flux, and the current dip in this neutrino flux would not be as great as indicated in the example. A more realistic calculation would probably bring the minimum down only comparable with Davis's upper limit on the neutrino flux.

To judge from the geologic record, this sort of mixing would have to occur about four times per billion years throughout the history of the Sun. If this should prove to be an explanation for the terrestrial ice ages, then I wish to emphasize the restrictions imposed on the process by these calculated time scales. These calculations seem to pin down the total duration involved in the luminosity excursion quite well; I would not expect this duration to be much affected by any details of the mixing mechanism that might be determined in the future, with one exception that will be discussed.

Therefore, it is important that the geologic record does not seem to give clearcut determinations of the general duration of ice ages, nor does it seem to give very precise evidence for the time at which the present ice age began. I, at least, have been unable to find any precise determinations of these quantities in my somewhat cursory examination of the literature. Thus, this picture for the production of ice ages would certainly be in trouble if it were found that the present ice age had extended for much longer than 3 or 4 million years. I have seen a report in the popular press that recent drilling in the Antarctic ice sheet has indicated an age much greater than this, perhaps of the order of 20 million years; until details of this should appear in the scientific literature, it is not possible to judge the validity of such reports.

If it should be decided that one wishes to preserve this mechanism for accounting for Earth's ice ages and also to accommodate longer durations of these ice ages, then there is one possible way in which this might be done. If the hypothetical mixing mechanism has a longer time period associated with it than 6 million years, so that the excess ^3He is driven toward the center of the Sun on this longer time scale, then the duration of the luminosity dip in the Sun could be extended. However, the amplitude of the luminosity dip would be correspondingly decreased. Under these circumstances, it would no longer be possible to reduce the solar neutrino flux down to the limit indicated by Davis's experiment, and the entire motivation for this suggestion would disappear.

At the present time, I am rather pessimistic about the possibility that this suggested mechanism will solve the solar neutrino problem and provide an explanation of the ice ages. The lack of a suitable mixing mechanism despite the interest generated by this suggestion is one cause for such pessimism. The sharply limited duration possible for such ice ages is another. Nevertheless, I think it is well worthwhile to carry out additional work on this suggestion, particularly with regard to calculations of general worldwide climatic conditions under conditions of a higher than normal solar luminosity and additional investigations of the dynamics of rotating fluids. Unfortunately, astronomical evidence for such major luminosity variations is unlikely to be found, because the temperature and luminosity of the Sun change in such a way as to drive the Sun straight down the main sequence, so that other stars undergoing these changes would simply now appear to be of lower than normal mass but otherwise normal in all respects. Meanwhile, if some other explanation of the solar neutrino puzzle should prove to be successful, then we would no longer have a motivation for belief in the present suggested mechanism.

REFERENCES

Cameron, A. G. W., 1973, "Major Variations in Solar Luminosity," *Rev. Geophys. Space Phys.*, **11,** p. 505.

Ezer, D., and A. G. W. Cameron, 1972, "Effects of Sudden Mixing in the Solar Core on Solar Neutrinos and Ice Ages," *Nature,* **240,** p. 180.

DISCUSSION

RASOOL: The luminosity of the Sun has changed over billions of years. Can you give the present thinking of how this evolution has taken place?

CAMERON: The standard kind of solar models would make the solar luminosity increase from the time when the Sun was on the zero edge main sequence to now by, I think, it is something like 35 or 50 percent, of that order, a gradual increase. If you believe in time variation of *G,* you can actually make the solar luminosity gradually decrease over all of that period of time. If you believe in the Brans-Dicke theory, you can do anything you want. If not, then the solar luminosity has increased by an order of 40 or 50 percent since the time the Sun was formed.

BOOK: Is it possible that there are neutrino absorbers somewhere in the Sun that are far more effective because there is far more mass in the Sun than in Davis' experiment? How does one know that there is not a lot of chlorine or some other neutrino absorber somewhere in the Sun, since not very much is known about its constitution?

CAMERON: There is nothing special about chlorine except that it happened to lead to a convenient rare-gas radioactivity at the detector. The neutrino cross sections are pretty well calculated and they are known in some cases experimentally, at least at the higher energies. The standard calculations say that the mean free path for absorption of typical solar neutrinos is something like 80 light years of ordinary lead. That is a measure of how transparent matter ordinarily is to the passage of such neutrino fluxes. This is why Ray Davis can have 100,000 gallons of cleaning fluid down in the mine and only detect a few atoms per month. The stuff is really terribly transparent.

It would be far more upsetting to physics to say that there was some sort of neutrino absorber in the Sun than to assume that the Sun behaves in the way I suggested. So it is a matter of choosing which field you want to do drastic things in.

I should have mentioned that the idea that we are now in an ice age on Earth has been picked up by Carl Sagan and some of his colleagues who say that Mars is also in an ice age. One of the other things that he suggested, however, I would like to lay to rest: that is that when the sun changes in this way, the distribution of stars (which are also doing this) on the main sequence that one can measure for a cluster or something like that is broadened.

When we look at, in fact, how the temperature and radius of the Sun change together, it turns out that the Sun, when it decreased in luminosity, moved exactly down the main sequence. Therefore, this does not produce any broadening of the main sequence, so this is not an effect that one can look for astronomically.

QUESTION: How fast do you think the solar luminosity changes?

CAMERON: The time scale for a luminosity decrease occurred in just a little less than 1 million years, and most of the recovery occurred in about a 2-million year period.

QUESTION: Yes, but that would be the rate of change for this particular process. How fast do you think it could change if you just perturbed it in some way? What would be the lower limit for changing solar luminosity due to maybe other forces? How fast can a big thing like that change?

CAMERON: If you make any major perturbation in the structure, the relaxation time is basically the Kelvin-Helmholtz relaxation time. When one is dealing with the core, it is just like 5 or 6 million years. If one is dealing with the outer envelope of the Sun, it is rather longer, maybe 50 million years; so you can get the fastest response if you just deal with the core. In terms of the neutrino problem, just doing something to the envelope is not going to help you.

ARKING: Can we have an explanation of why you have to have such a drastic change in luminosity if you were to, say, alter the rate at which you are producing energy in the center of the Sun? Or another way of looking at it, if you suddenly turn off the energy-producing reactions in the center of the Sun, would not the Sun continue to be luminous at approximately the same solar constant for millions of years before the effect would be seen on the surface?

CAMERON: That is correct. If you turned off all the nuclear reactions in the Sun, the Sun would keep shining, it would keep contracting, and the luminosity would, in fact, follow pretty much the horizontal branch; that is, it would stay level as the Sun shrunk and as the surface temperature increased.

ARKING: So why do you need a 30-percent change in luminosity?

CAMERON: The whole question is what do you have to do to the Sun to shut off the neutrinos enough not to violate the Davis experiment. The argument is that you have to cause the center to expand, and, therefore, you have to dump energy into it, and it is a natural consequence of the response of the Sun to dumping that energy into the core that decreases the luminosity.

QUESTION: Would a strong magnetic field of the order of millions of gauss, in the interior of the Sun have any effect?

CAMERON: Such a field would help a little bit. It would not help nearly as much as you need if you wanted to try to cure the neutrino problem strictly with such a field.

DAVIS: I am curious as to where you got your 20 million year figure for the Antarctic Icecap because, as

I recall, the ice at the bottom of the core at Byrd Station has a radiocarbon date of about 40 000 to 50 000 yr, which would probably fit your theory better.

CAMERON: It would be fitted very much better. All I remember is that sometime this summer I read an interview with somebody who had done a measurement, and it was quoted as 20 million years. I have not seen it in the literature, all I have seen it in is a popular report; therefore, I don't know how good that number is. Other people have tried to look at ocean temperatures and have said that they seem to have been steadily decreasing over the last 50 million years, for example, and I do not know how good those numbers are. If one can say that the duration is longer than about 6 million years, the basic point I am trying to make is that one is in trouble with this explanation no matter what you do because, even if you make the Sun behave this way, it will not cure the neutrino problem. Maybe there is some other explanation for the neutrino problem, and the Sun still behaves this way, but we still do not know of a driving mechanism that would make it behave this way, another very fundamental weakness of this theory.