

Solar Spin-Down and Neutrino Fluxes

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GPO PRICE \$ _____

CFSTI PRICE(S) \$ _____

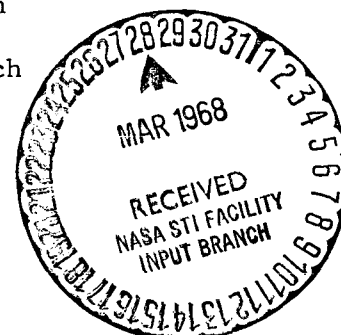
Hard copy (HC) 3.00Microfiche (MF) .65Abstract

FACILITY FORM 502	N68-19136	(THRU) _____
	(ACCESSION NUMBER)	
	<u>9</u>	(CODE) <u>29</u>
	(PAGES)	(CATEGORY) _____
	<u>TMX-60923</u>	
	(NASA CR OR TMX OR AD NUMBER)	

ff 653 July 65

We suggest that the failure of Davis to detect a flux of B^8 neutrinos from the sun may result from the maintainance of a high central hydrogen abundance. This could arise from the circulation currents associated with the spin-down of a fast rotating core. On this basis we predict a lower limit to the flux which is about the same as Davis' upper limit.

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One of the most significant experiments in astrophysics has been the attempt by R. Davis to detect the flux of B^8 neutrinos from the sun (Davis 1964, 1968). In order for his anticipated result to be meaningful in an astrophysical context, it has been important to make predictions of the expected flux based on stellar evolutionary theory as applied to the sun. Most of the older calculations have been rendered unreliable by recent revisions in the nuclear reaction cross sections for the reactions $Be^7(p,\gamma)B^8$ (Parker 1966) and $He^3(He^3,2p)He^4$ (Bacher and Tombrello 1968; Winkler and Dwarakanath 1967). It has been necessary to repeat these calculations using the revised nuclear data.

We have repeated our previous calculations of solar evolution with an assumed constant gravitational coupling coefficient (Ezer and Cameron 1965, 1966). In addition to the revised nuclear data, a number of other improvements were made in the code, details of which will not be given here. As a result of these changes we now take the mixing length in the convection theory to be 1.6 pressure scale heights.

The predicted B^8 neutrino flux at one astronomical unit throughout the history of the sun is shown in Figure 1. The value predicted for the present sun is $1.17 \times 10^7 \text{ cm.}^{-2} \text{ sec.}^{-1}$.

Meanwhile a much more extensive investigation of evolved solar models has been carried out by Bahcall and Shaviv (1968). After considering the effects introduced by variation of a number of parameters, they predicted a B^8 neutrino flux of $1.4(1 \pm 0.6) \times 10^7 \text{ cm.}^{-2} \text{ sec.}^{-1}$. Our prediction is quite consistent with this.

It has therefore come as a surprise that the preliminary results from Davis' experiment give an upper limit to the flux of $2 \times 10^6 \text{ cm.}^{-2} \text{ sec.}^{-1}$. This result poses a strong challenge to stellar evolutionary theory.

Of course the predicted flux is subject to various possible errors. These include, in particular, element abundances in the sun, and all of the various nuclear reaction data. However, the predicted flux is not changed by the necessary factor if one accepts the errors claimed for the abundance determinations and the nuclear data. It is the purpose of this note to point out that it may be possible to retain the accepted values for abundances and nuclear data by postulating that circulation currents exist in the solar core.

It may be seen in Figure 1 that the predicted B^8 neutrino flux rises by a factor 30 throughout solar history. This is primarily due to the increase in central temperature as the central hydrogen is depleted. It is evident that the flux would be strongly suppressed if the central hydrogen remained near its initial abundance. This would require that an extensive mixing process has been operative throughout solar history.

Such a mixing process may exist in connection with the solar spin-down process which has recently been discussed in connection with a possible solar oblateness (Howard, Moore, and Spiegel 1967; Dicke 1967; McDonald and Dicke 1967). Any reasonable model for the formation of the sun predicts that its initial spin is much greater than the presently observed value. The outer solar convection zone will be rapidly slowed

down through outward transport of angular momentum by the solar wind. The question which then arises is whether instabilities will occur which will lead to mixing between the convection zone and the radiative core with outward transport of angular momentum, leading to a spin-down of the core. Howard et al have claimed that the core will spin-down too rapidly to allow a mass quadrupole moment sufficient to account for the solar oblateness measured by Dicke and Goldenberg (1967). Dicke (1967) and McDonald and Dicke (1967) claim that solar stratification will sufficiently impede the spin-down process that a significant quadrupole moment is possible.

For the purposes of our present analysis we assume that the solar spin-down process keeps the composition of the sun fairly homogeneous throughout a large part of its interior. Since there is much dispute over the fluid dynamics of the spin-down process, it is not clear whether our present assumption favors one side or the other of the above discussion. However, it is evident from the relatively high abundance of beryllium in the solar photosphere that the outer convection zone has not been diluted by a large factor. This need not rule out extensive mixing in the core if, as Spiegel (1967) has suggested, the convection zone acts as a "rigid" boundary giving rise to an Ekman layer in the outer layer of the core. Meridional circulation may also exist in the core.

Solar evolution with an unmixed core leads to an increase in the luminosity by a factor 1.35 during the evolutionary age of 4.5×10^9 years. This results primarily from the conversion of hydrogen into

helium, which reduces the number of electrons in the interior and hence decreases the opacity. It is likely that solar evolution with a mixed core would have much the same luminosity history, since the overall reduction in opacity would be about the same with the hydrogen-burning products redistributed throughout the interior. Under these circumstances the mean mass fraction of hydrogen in the sun would be reduced from 0.74 (assumed in our initial models) to 0.70, and the mean helium mass fraction would rise from 0.24 to 0.28. For simplicity we assume a uniform evolved composition with these altered abundances. We assume the central density would rise by three per cent to compensate for the smaller number of particles per gram of matter with a consequent reduction of pressure.

In this extreme model the B^8 neutrino flux is not that indicated in the lower left hand corner of Figure 1. The proton-proton chain has an energy generation rate which varies as $T^{4.06}$ under central solar conditions, where T is the temperature (see for example Reeves 1965). Hence the temperature rises by a factor $(1.35)^{1/4.06} = 1.0765$. The B^8 flux is correspondingly increased.

The abundance of B^8 in the solar interior will increase over that in our initial main sequence models by a factor depending on the product of the temperature sensitivities of the $He^3(\alpha, \gamma)Be^7$ and $Be^7(p, \gamma)B^8$ reactions, since the $He^3(He^3, 2p)He^4$ reaction is the dominant energy-generating reaction at the center of the sun. From Reeves (1965) we can write approximately for the number density of Be^7

$$N_7 \approx \frac{\langle \sigma v \rangle_{34} N_3 N_4}{p_{7e}}$$

where $\langle \sigma v \rangle_{34}$ is a measure of the rate of the $\text{He}^3(\alpha, \gamma)\text{Be}^7$ reaction, p_{7e} is the rate of electron capture of Be^7 , and N_3 and N_4 are the number densities of He^3 and He^4 . The abundance of N_3 , in turn, is approximately

$$N_3 \approx N_1 \left(\frac{\langle \sigma v \rangle_{11}}{2 \langle \sigma v \rangle_{33}} \right)^{\frac{1}{2}}$$

where $\langle \sigma v \rangle_{11}$ measures the rate of the p-p reaction, $\langle \sigma v \rangle_{33}$ that of the $\text{He}^3(\text{He}^3, 2p)\text{He}^4$ reaction, and N_1 is the abundance of hydrogen. At 1.4×10^7 °K, the quantities $\langle \sigma v \rangle_{11}$, $\langle \sigma v \rangle_{33}$, $\langle \sigma v \rangle_{34}$, and p_{7e} vary as the temperature raised to the powers 4.06, 16.30, 17.08, and -0.5. The $\text{Be}^7(p, \gamma)\text{B}^8$ reaction varies as $T^{13.50}$.

Putting together the abundance, density, and temperature variations, we thus estimate that the B^8 neutrino flux will increase by at least a factor $1.14 \times (1.0767)^{24.96} = 6.7$ over that in the initial model. This gives a lower limit to the predicted flux of $2.5 \times 10^6 \text{ cm}^{-2} \text{ sec}^{-1}$. This is about the same as Davis' upper limit.

It is evident that element abundances and nuclear data can readily be adjusted within the claimed errors to reduce our lower limit below Davis' upper limit. Hence we believe that the solar spin-down circulation problem deserves much more careful examination, since it is possible that it may have a major effect on solar evolution.

We wish to point out that the evolution of other stars may be similarly affected by a core spin-down process. Since the age of our galaxy is based on the stellar evolution ages of star clusters, this age must now be regarded as unreliably determined.

We are grateful to R. Davis for communicating his results to us in advance of publication. This research has been supported in part by grants from the National Science Foundation and the National Aeronautics and Space Administration.

Figure Caption

Figure 1. The B^8 neutrino flux at one astronomical unit during the evolution of the sun. Also shown are Davis' experimental upper limit and the lower limit calculated in this paper for a continually mixed solar core.

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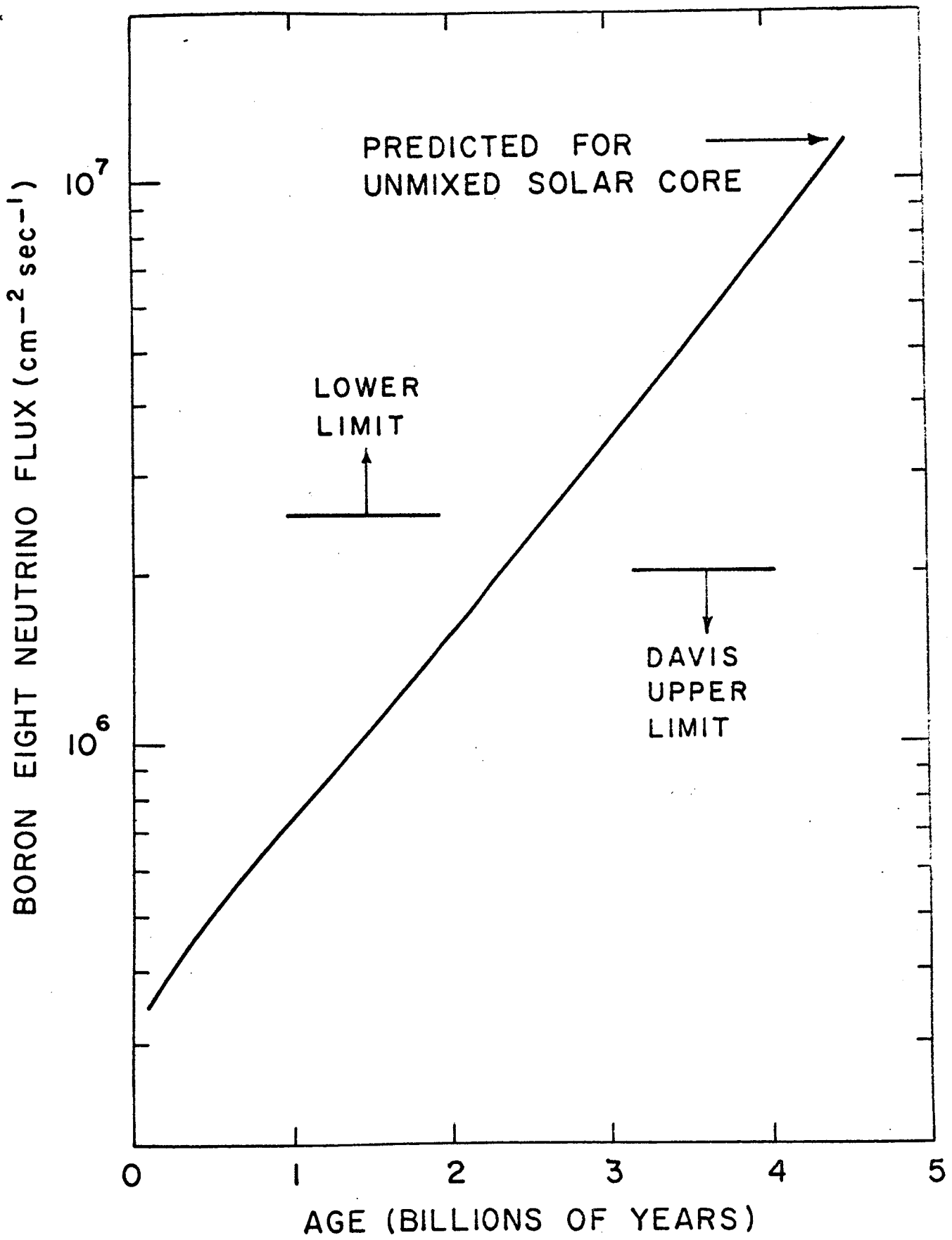


Figure 1