The dynamic energy source of the Sun and the duplicity of the stellar energy production

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Received _______________; accepted _______________
Some possible ways of the energy production with fusion reactions in the Sun was explored theoretically in the first half of this century. Nowadays it is a standard view that the Sun produces its energy on a uniform level. I point out, that in the stellar and solar energy production a dynamic energy source is necessarily present behind the uniform one, and generates a direct connection between the core and the surface layers through tunnels.
1. Introduction

The standard solar model (SSM, [1,14]) states that the proton-proton cycle gives the 96.5% of the total solar energy production, the CNO cycle gives only 1.5% and the neutrinos make the remaining 2%. Nevertheless, the first experimental check of the SSM measured only the third of the predicted solar neutrino flux. One could think that the plausible cause could be that the energy production of the solar core is less than predicted. But it is hard to construct a solar model with a lower central temperature, which gives back the neutrino fluxes and the helioseismological tests as well, as the SSM can do. Moreover, the change of the standard solar model to a non-standard one would have consequences to the stellar evolution theories. Yet, the standard solar model seems to fit the best to the observational tests of the stellar evolution theories. So it seemed the best way to search the solution of the solar neutrino problem not in the astrophysics, but in the physics of the neutrinos, which would affect only the properties of the neutrinos on their way from the Sun to the Earth, without changing the physics in the Sun itself.

The fundamental characteristic of stellar energy production is the temperature-sensitivity [2,3]. The larger the mass of a star, the higher the temperature in its core, and therefore, the faster the nuclear reactions. That is the cause why the giant stars have much shorter lifetime than the dwarfs. The temperature-sensitivity can generate instabilities in the stellar cores. At higher temperatures the nuclear reactions proceed much faster, which produces much more heat, generating still higher temperature and so on. The whole star would explode in the absence of a stabilising agent. That stabilising agent is the gravitation for the star as a whole. The virial theorem shows that the heat energy is less than the gravitational, therefore the coefficient of the heat expansion of the star is negative. This means that when the stellar core becomes hotter, it expands, and the volume expansion against gravity cools down the star more effectively than the nuclear reactions heat it.
is the generally accepted argument for the idea that the stellar cores are thermally stable. But this statement is not valid for local heating, since in a local volume the gravity does not have such a significant effect, and, at the same time, the local heating time is much shorter, and so the thermo-nuclear instability is present. The calculations show that the time-scale of the thermonuclear expansion is $10^{-5}$s [2], much shorter than that of the volume expansion.

A principal theoretical difficulty arises at the origin of convection. We know that at most stars convection is present as a flow setting up by high temperature differences. But for the onset of convection it is also necessary that the initial perturbations has to be present. Since the convective cells has a characteristic size of some 1000 km, this would imply that initial perturbations should develop in a huge macroscopic volume. Nevertheless, atomic collisions can never generate macroscopic perturbations, since the collisions act to decay the fluctuations and since the convective zone before the convection sets up is in a radiative equilibrium and radiation also acts to smooth any occasionally developing fluctuation [4,5]. Therefore, a mechanism has to exist which is able to develop macroperturbations from below the convective zone. I was led to investigate the possible instabilities developing in the solar core in order to find a mechanism to generate the macroperturbations. It also seemed that the apparent fluctuations of the Homestake neutrino flux have significantly larger amplitude than the observational errors plus statistic fluctuations would allow it. This circumstance again pointed to the existence of an instability in the energy producing solar core.

My calculations on the thermonuclear time-scales were strengthened by the arguments of Zel’dovich et al. [6] who has shown that the dissipative mechanism are too ineffective to stabilise against the local thermonuclear instability. Nevertheless, they did not attempt to find the way out of the dilemma of the local instability and global stability of the stellar
energy producing regions. My calculations led to the picture that the fundamental local thermonuclear instability of stellar cores generates "hot bubbles", plumes which has very different nature from the convective flows. In the case of the Earth, the plumes from the edge of the core have 50-100 larger speeds than the convective flows lithospheric plates. The diameter of the 'hot spots' of the Earth are around 200-300 meters and in this areas the heat upflow in the mantle is five times larger than elsewhere. This is why they are called 'hot spots', even when they do not seem to be related to any surface vulcano. These hot spots has a long lifetime of some ten or hundred millions of years, but they did not seem to participate in the plate-tectonic movements, which show their deep origin and rigid rotation. The solar 'hot spots' show as well anomalous activity, higher temperature, and rigid rotation. The parallel phenomena suggest that the flow in them also could be higher then elsewhere and that their material originates from significant depths. Beside the macro-instability producing the hot bubbles from the core, the local thermonuclear instability produces also microscopic effects. The stochastic atomic collisions can produce thermal instabilities, but since their size do not reach the critical threshold given by the actual Rayleigh number, which depends strongly on the size of the perturbation [5], they will decay. Nevertheless, they will be continuously re-generated and because of the temperature-sensitivity the effect of the microinstability will be that thermal inequilibrium will develop. Kaniadakis, Lavagno and Quarati [18,19] calculated some effects of the modified Maxwell-distribution to the solar structure and the neutrino spectrum. Their result is similar to that of the microinstabilities: they act to generate different temperatures of the ions and electrons, to increase the central temperature, and that they effect to change the neutrino spectrum towards the observed one. In this way, the effect of the micro-and macro-instabilities of the solar core seem to compensate each other in respect to the solar structure, and modify the neutrino production towards a better agreement with the observations. This compensating effect could be a reason why the standard solar model
seems still close to the helioseimological results.

In between 1994.10.12 - 1995.10.04 the GALLEX group [10] made 14 measurements. Their results, the GALLEX-III gives the lowest value yet measured, 41% of the SSM. This value is significantly lower than the 56% threshold which is compatible with the idea that the solar energy is supplied through proton-proton cycle. Since the error-bars sum up only to 10%, this result is the first measurement to show that there has to be an additional energy source of the Sun besides the proton-proton (and CNO) cycle, which produces a significant part of the solar energy supply. This result cannot be regarded as a mere fluctuation, since in the same time interval the KAMIOKANDE-III measurements also has shown the lowest measured rate, 34% of the SSM value [11]. The GALLEX rate $53.9 \pm 11$ SNU inevitably shows that it is not possible to produce all the solar luminosity with the proton-proton cycle, since in that case the minimum flux should be 87 SNU [7,8], which is above the $3\sigma$ threshold. These new neutrino measurements suggest an 8% decrease of temperature. But in this case an additional source of energy generation has to be present which has to produce the missing 28% of the solar luminosity. I suggest that this new type of energy production is produced in local thermonuclear runaways [2]. So we have to abandon the luminosity constraint in the context of a steady and hydrogen-burning solar core, since an additional new type of energy source is apparent.

Another fact is that the KAMIOKANDE is the only detector which is sensitive to neutral currents. Therefore, muon and tau neutrinos produced in the hot bubbles will be detected by the KAMIOKANDE and so one has to subtract their contribution from the observed rates. This circumstance offers another way to solve the apparent contradiction between the observations of the different neutrino detectors, and the beryllium neutrino problem.

These factors reveal the caveat in the argument of Castellani et al. [7] against all
astrophysical solution, and makes it possible to construct dynamic solar core models. The
attack of the paper is using all the data of the neutrino detectors, to present calculations
showing a new possibility for the solutions of the solar neutrino problems, and to accept the
new results GALLEX-III and KAMIKANDE-III by their face values, showing that it gives
another indication for a non-standard Sun. I use different effective temperatures for the
different neutrino productions. Haubold and Mathai [13] observed that the solar neutrino
problem may have an astrophysical solution when the deviations of the actual neutrino
temperatures from the SSM values are different for the different neutrino sources.

2. General equations of the individual neutrino fluxes

The basic equations describing the neutrino production of the quiet solar core in terms
of the individual neutrino fluxes $\Phi_p$, $\Phi_{Be}$, $\Phi_{CNO}$ and $\Phi_B$, and the observed rates with the
gallium-detector $S_G$ and the chlorine-detector $S_C$ are

$$ S_G = S_G(B) + G_p\Phi_p + G_{Be}\Phi_{Be} + G_{CNO}\Phi_{CNO} $$

(1)

$$ S_C = \Phi_{Be} + C_{CNO}\Phi_{CNO} + C_B\Phi_B + C_{pep}\Phi_{pep}, $$

(2)

where $C_i$ and $G_i$ are the detector sensitivities of the chlorine and gallium detectors, given
by Table I. in [8]. Solving these equations for $\Phi_{Be}$ and $\Phi_p$,

$$ \Phi_{Be} = (S_C - C_B\Phi_B - C_{CNO}\Phi_{CNO} - C_{pep}\Phi_{pep})/C_{Be} $$

(3)

$$ \Phi_p = (S_G - G_{Be}S_C/C_{Be} + \alpha_B\Phi_B + \alpha_{CNO}\Phi_{CNO})/G_p $$

(4)

$$ \alpha_i = G_{Be}/C_{Be}C_i - G_i. $$

(5)

For the individual fluxes their time dependence may be approximated as

$$ \Phi_B = R(K)\Phi_B(SSM) = T_B^{24.5}\Phi_B(SSM), $$

(6)
where $T_B$ (and later on all the $T_i$ temperatures) are dimensionless temperatures, normalised to the standard value, $T_B = T_B(\text{average, actual})/T_B(\text{average, SSM})$.

\[
\Phi_{Be} = R_{Be}\Phi_{Be}(SSM) = T_{Be}^{11.5}\Phi_{Be}(SSM) \tag{7}
\]

\[
\Phi_{CNO} = R_{CNO}\Phi_{CNO}(SSM) = T_{CNO}^{20}\Phi_{CNO}(SSM) \tag{8}
\]

\[
\Phi_p = R_p\Phi_p(SSM) = T_p^4\Phi_p(SSM) \tag{9}
\]

Now inserting these temperature-dependent equations into the basic equations of the neutrino fluxes (3), (4), I obtain the two basic temperature-dependent equations for the neutrino fluxes (neglecting the pep fluxes):

\[
T_{Be}^{24.5}C_B/C_{Be}\Phi_B(SSM) + T_{CNO}^{20}C_{CNO}/C_{Be}\Phi_{CNO}(SSM) + T_{Be}^{11.5}\Phi_{Be} = S_C/C_{Be} \tag{10}
\]

\[
T_{Be}^{24.5}\alpha_B\Phi_B(SSM) + T_{CNO}^{20}\alpha_{CNO}\Phi_{CNO}(SSM) - T_p^4G_P\Phi(SSM) = S_G - G_{Be}/C_{Be}S_C \tag{11}
\]

Now I regarded $T_B$, $T_{Be}$ and $T_{CNO}$ as being equal with $T_c$, since they are all characteristic to temperatures of the different maximum neutrino productions, at $r = 0.04, 0.06$ and $0.05R_{Sun}$, i.e. relatively close sites. Nevertheless, I allowed $T_p$ to be different, because $T_p$ is characteristic for a region around $r = 0.10R_{Sun}$, which may be regarded as being a site not too close to the above three. In this way I have only two unknowns to be determined, $T_c$ and $T_p$, and I have two equations for them.

Using the observed time-averaged values of the neutrino fluxes, $S_G = 69.7SNU$ [10], $S_C = 2.56SNU$ [13], the standard neutrino fluxes from [14] are $\Phi_B(SSM) = 5.71 \times 10^6 cm^{-2}s^{-1}$, $\Phi_{CNO}(SSM) = 1.1 \times 10^9 cm^{-2}s^{-1}$, $\Phi_{Be}(SSM) = 0.47 \times 10^{10} cm^{-2}s^{-1}$, $\Phi_p(SSM) = 5.71 \times 10^{10} cm^{-2}s^{-1}$, $C_{Be} = 0.24 \times 10^{-9}$, $C_B = 1.09 \times 10^{-6}$, $G_{Be} = 7.32 \times 10^{-9}$, $G_B = 2.43 \times 10^{-6}$, $C_{CNO} = 0.40 \times 10^{-9}$, $G_{CNO} = 8.67 \times 10^{-9}$, $G_p = 1.67 \times 10^{-9}$, the
solutions are $T_c = 0.95$ and $T_p = 0.96$. The obtained results show that no beryllium-neutrino problem arise, and the temperatures are remarkably close to the most recent seismological solar models [9]. The determination of the temperatures in the solar core with the above equations present a very sensitive method for the temperatures of the different layers of the solar core, as their one percent variation already leads to values incompatible with equations (10) and (11). In this way the presented general calculation of the solar core temperatures remarkably do not lead to any solar neutrino problem, as it contains the basic physics and so it has definite consequences for the other neutrino fluxes which are not included directly. For example, in the case of a constant solar core a boron neutrino flux from the quiet solar core $\Phi_B = 0.28$ (or $0.37$) $\Phi_B(\text{SSM})$ is required with $T_B = 0.95$ (or $T_B = 0.96$). This means that the remaining part of the neutrinos, as observed by the KAMIOKANDE, do not originate from the quiet core, but from the hot bubbles. The KAMIOKANDE is the only detector, which is sensitive to neutral currents. Therefore, heavy neutrinos produced outside of the proton-proton cycle may be detected by the KAMIOKANDE and so we should subtract their contribution from the observed rates. There is no such a problem as the problem of beryllium neutrinos; instead, the basic equations of the neutrino fluxes state clearly that the Kamiokande observes neutrinos besides the boron neutrinos of the quiet solar core.

The results obtained for a static solar core present solid evidence for a solar core being cooler than standard and, at the same time, it is also indicated that there are selective deviations from the standard solar model in the different depths of the solar core. These results have a high relevance in the study of the solar neutrino problem and in constructing realistic solar models. Having found such a sensitive tool for the study of the solar core as the equations presented above, I applied these equations to a solar core varying in time as well.
In case of solar activity minimum, I can use $S_C(\text{min}) = 4.1\text{SNU}$ [17] and $S_G(\text{min}) = 53.9\text{SNU}$ [10]. With these values (10) gives $T_c = 0.973$ and substituting this value to (11) an unphysical value of $T_p = 2.17$ arises. The cause of this discrepancy could be i.) observational errors in $S_C$ and $S_G$, or ii.) an unidentified flux contributes to the Homestake detection rates, for which the GALLEX is less sensitive. Regarding ii.), it is known that in the Homestake the contribution of the intermediate energy neutrino fluxes are around 30\% while they constitute only around 2\% in the gallium detectors. Therefore, the time-dependence of the solar energy and neutrino production indicates that in the solar activity minimum the yet unidentified flux is supplied by intermediate energy neutrinos, produced by the hot bubbles.

In case of solar activity maximum, $S_C(\text{min}) = 2.3\text{SNU}$ [13]. With $S_G(\text{max}) = 79\text{SNU}$ [10] the derived values are $T_c = 0.945$ and so $T_p = 0.77$. Regarding such a large deviation as unphysical points to the presence of a yet unnoticed neutrino flux present around solar activity maximums. This additional neutrino flux $\Phi_b(\text{max})$ has to give a term besides the boron neutrino fluxes in (10) and (11) if we want a physically consistent description of the solar core using the observed neutrino fluxes. In this way I identified another yet unrecognised physical process present in the solar core, being active around solar activity maximums, producing high-energy neutrinos.

It is interesting, that a puzzling difference is observed between the frequency shifts of the even $l = 0, 2$ and odd $l = 1, 3$ modes [15]. These significant differences indicate a "sandwich" structure of the Sun, a coupling between the different depths at the very neighbourhood of the centre. A similar phenomenon may occur if there is a direct transfer from a central region to an outer layer.

Another interesting point, that the flares at the solar surface do show central 'tunnels' between their footpoints to the loop-tops [16], indicating that they set up as the consequence
of subphotospheric mass outflows. This "unexpected" phenomenon was predicted ten years ago on a purely theoretical basis of the convective flare theory [17] declaring a direct connection of the solar core with the surface through isolated "channels" or "volcanic funnels".

3. Conclusions

The main result of the presented calculations is that all the neutrino measurements are indicative and quite compatible with the theoretical result that a new type of energy production mechanism is active in the solar core. Our calculations outline its physical nature and suggest that at solar minimum it produces intermediate energy CNO neutrinos and at solar maximum it possibly contributes to the flare effect in the high energy neutrino fluxes. These predictions can be proven with future measurements of the solar neutrino spectra.

The obtained results show that for the time-averaged values of the solar core the Sun shows a temperature $0.96T(SSM)$ around $r = 0.10R_{Sun}$ while at the deeper layers around $r = 0.05R_{Sun}$ the temperature has a different value of $0.95T(SSM)$. This result can not be regarded as marginal since the equations describing the production of the individual neutrino fluxes are highly sensitive to the temperatures and $T_c = T_p = 0.96$ would lead to larger than three $\sigma$ deviations from the observed values, to $S_C = 3.19SNU$ and $S_G = 104.8SNU$.

A scheme of the solar structure is derived, which has a definite suggestion that below 0.10 solar radius the standard solar model is to be replaced by a significantly cooler and varying core. Nevertheless, it is indicated that the compensating effect of the thermonuclear micro-instabilities effectuating an increase in the central temperatures and a parallel
decrease in the neutrino fluxes [18, 19] balances the cooling effect.

Another prediction of the dynamic solar core model is that the chemical composition of the solar wind varies significantly with the phase of the activity cycle, more enhanced in heavy elements near to maximum. SOHO can test this prophecy. Crooker published results showing this effect: "the proton temperature and velocity closely anti-correlates with the electron density and temperature in the solar wind" [20].

The discovery of the dynamic energy source of the stars has a significance in relation to the world-view of science as well. The dynamic energy production is very sensitive to the effects of the environment, to the week tidal effects, and so it is able to couple such far branches of science as the celestial mechanics, the nuclear astrophysics and the stellar activity phenomena. The conclusion that the planets participate in the regulation of the solar energy production show that the Sun cannot be regarded as a closed system but an open one in its most fundamental nature.

4. Acknowledgement

The work is supported by the Hungarian Scientific Research Foundation OTKA under No. T 014224.
REFERENCES

1Bahcall, J. N. 1996, Astrophys. J. 467, 475

2Grandpierre, A. 1990, Sol. Phys. 128, 3

3Grandpierre, A. 1996, Astron. Astrophys. 308, 199

4Grandpierre, A. 1977, University Doctoral Thesis

5Grandpierre, A. 1984, in "Theoretical Problems in Stellar Stability and Oscillations", eds. M. Gabriel, A. Noels, Liege, 48

6Zeldovics, Ya. B., Blinikov, S. I., and Sakura, N. I. 1981, Physical Basis of Structure and Evolution of Stars (in Russian), Izd. Moskovskovo Univ., Moskva, Sect. 3.

7Castellani, V., Degl’Innocenti, S., Fiorentini, G., Lissia, M. and Ricci, B. 1996, astro-ph/9606180, Physics Reports

8Castellani, V., Degl’Innocenti, S., Fiorentini, G., Lissia, M. and Ricci, B. 1994, Phys. Lett. B324, 425

9Shibahashi, H. and Takata, M. 1996, Publ. Astron. Soc. Japan 48, 377

10GALLEX Collaboration, 1996, submitted to Phys. Lett. B

11Fukuda, Y. et al., 1996, Phys. Rev. Lett. 77, 1683

12Haubold, H. J. and Mathai, A. M. 1995, Astrophys. Space Sci. 228, 113

13Davis, R., Jr. 1996, Nucl. Phys. B (Proc. Suppl.) 48, 284

14Bahcall, J. N. 1988, Neutrino Astrophysics, Cambridge University Press, Cambridge
15Regulo, C., Jimenez, A., Palle, P. L., Perez Hernandez, F., Roca Cortes, T. et al., 1994, Astrophys. J. 434, 384

16Uchida, Y. 1996, Adv. Space Res. 17, 19

17Grandpierre, A. 1986, in "Flare Stars and Related Objects", Proc. Symp. Byurakan Astrophys. Obs., ed. L. V. Mirzoyan, 176 bibitem 18Kaniadakis, G., Lavagno, A. and Quarati, P. 1996, Phys. Lett. B369, 308

19Quarati, P. 1996, talk given at the United Nations/European Space Agency Workshop on Basic Space Science, 9-13 September, 1996, Bonn, Germany; E-mail address: Quarati@polito.it

20Crooker, N. U. 1983, in NASA Conf. Publ. No. 2280, "Solar Wind Five", ed. M. Neugebauer, p. 303