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New answer to the solar neutrino problem

MARC DIXMIER
15 rue Le Brun, 75013 Paris, France

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Abstract. We suggest a new answer to the problem of the solar neutrinos: a neutrino-photon interaction that would cause the neutrinos to disappear before they leave the sun or make them lose energy towards detection thresholds. We calculate the available energy in the system of the centre of mass, and show that the photons may be endowed with a pseudo-cross-section in the system of the sun. Under the assumption of an absorption, made to simplify the neutrino transport calculation, the chlorine experiment yields: $\sigma_a = 1{\cdot}8(^{+0\cdot7}_{-1\cdot0}) * 10^{-9}$ barn, which is close to $g_\beta/(\hbar c) = 4{\cdot}49 * 10^{-9}$ barn. The escape probability is substantially larger for the gallium neutrinos than for the chlorine neutrinos. Thermal radiation in the core of a supernova is suppressed by electrical conductivity, therefore the neutrinos from SN1987A could escape; they interacted with the photon piston in the outer layers of the supernova and the interaction has to be a scattering. The cosmological implications of a neutrino-photon interaction are discussed; Hubble's constant may have to be modified. The case of an elastic scattering between neutrino and photon is discussed in more detail.

Keywords. Solar neutrino; neutrino-photon interactions; supernova; cosmology.

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1. Introduction

The solar neutrino problem consists of the fact that the counting rate of the neutrinos detected on earth via the reaction $^{37}Cl(\nu_e,e^-)^{37}$ Ar is only about 28% of the rate predicted from the standard solar model [1]. More recently, experiments using the reaction $^{71}Ga(\nu_e,e^-)^{71}Ge$, which has a lower detection threshold, also indicate an important deficit in the counting rate of the solar neutrinos [2]. Various solutions have been proposed to this puzzle (see for instance [3]). This article intends to suggest a new solution: a *neutrino-photon interaction* that would cause the absorption of part of the neutrinos during their passage through the sun or, which amounts to the same from the viewpoint of measurements of earth, the simple or multiple scattering of those neutrinos, thereby transporting them to energies for which the detection cross-section is smaller or null; since the photon densities which exist outside the sun itself are very small the property according to which neutrinos propagate freely, as observed on earth, would not be modified.

The standard model of the electroweak interaction conserves the photon couplings of classical electromagnetism and therefore within this model the photon field is not coupled with the neutrino field ([4], chap. 5). This would not preclude a neutrino-photon interaction via a neutrino magnetic moment; however, a calculation by Aydin *et al* [5] indicates that the resulting scattering cross-section would be extremely small,

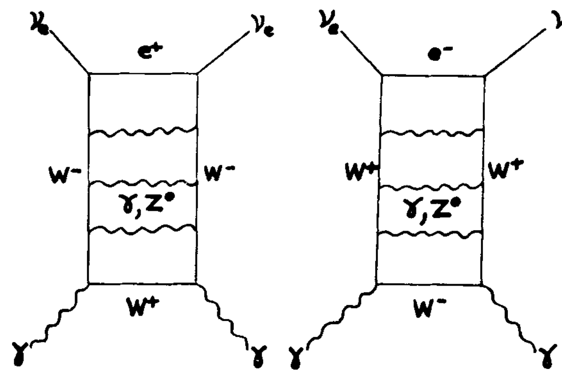

Figure 1. Possible Feynman diagrams of the neutrino-photon interaction.

considering the upper limits on the magnetic moment of the neutrino from astrophysics and from neutrino-electron scattering [6].

Cohen-Tannoudji suggested to us [7] that if the two W bosons exchanged between ν_e and γ in the diagrams of figure 1 were strongly coupled the $\nu_e - \gamma$ interaction would become a first-order process and could therefore give rise to a substantial cross-section (the existence of such strongly coupled pairs of W bosons has already been suggested by Chanowitz in his strong-coupling hypothesis to account for electroweak symmetry breaking, see [8], figure 2b). Das [9] has also shown that a spontaneous breaking of supersymmetry would lead to a neutrino-photon coupling.

The neutrino-photon weak coupling theory of Bandyopadhyay, Chaudhuri *et al* (see for instance Bandyopadhyay [10, 11a]) could also lead logically to a neutrino-photon interaction; it is to be noted, though, that according to Stothers [12] this theory is excluded by the astrophysical evidence regarding the cooling rates of white dwarfs and red supergiants, but a neutrino-photon interaction such as we assume in this article might reduce the impact of Stothers' argument.

Finally it should be observed that, within (stellar) plasmas, photons become plasmons endowed with rest mass, thereby allowing processes such as $\gamma \rightarrow \nu + \bar{\nu}$ to take place [13].

In this article, we shall speculate no further on the possible causes of our postulated interaction but shall estimate the order of magnitude of the pseudo-cross-section that this interaction should have in order to account for the solar neutrino counting deficit, and shall speculate briefly on some other astrophysical implications of such an interaction.

2. Basics

2.1 *Black body radiation in vacuo*

Within an empty parallelepipedic box of volume V, the number of states for photons of energy comprised within the interval $(E_\gamma, E_\gamma + \mathrm{d}E_\gamma)$ amounts to

$$\mathrm{d}N_\gamma = \frac{8\pi}{(hc)^3} V E_\gamma^2 \mathrm{d}E_\gamma. \tag{1}$$

Let us write

$$x = \frac{E_\gamma}{kT} \tag{2}$$

where k is the Boltzmann constant and T is the absolute temperature. The spectrum of the number of photons in vacuo assumes the form

$$p(x) = \frac{1}{2\zeta(3)} \frac{x^2}{e^x - 1} \tag{3}$$

and the corresponding number density of photons is [14]

$$n_\gamma = \rho T^3 \tag{4}$$

$$\rho = 16\pi\zeta(3)\left(\frac{k}{hc}\right)^3 = 2{\cdot}0286(2)*10^7\,\gamma m^{-3}\,\mathrm{K}^{-3}. \tag{5}$$

The model of black body radiation in vacuo is currently in use, for instance in [16], to compute pressures and radiative heat transfer within stars. We shall use this model to evaluate the photon population within the sun; we shall see however in §4 that this model is no longer valid in the central regions of a supernova.

2.2 *Kinematics of the neutrino-photon interaction*

Since we are considering the interaction between two particles that propagate at limit velocity (we may neglect a possible rest mass of the neutrino within the energy domain considered [17]) we cannot as usual take for granted a reaction rate relative to the target density in the co-ordinate system of the centre of mass of the two particles.

Let $\mathbf{p}$ be the linear momentum of a particle and let E be its total energy, which boils down to its kinetic energy in the problem under discussion. Let us consider a neutrino and a photon with their directions of motion making an angle ψ in the non-primed co-ordinate system (co-ordinate system of the sun): see figure 2. The velocity of the centre of mass of the two particles is

$$\mathbf{v} = c\,\frac{\mathbf{p}_{\nu_e} + \mathbf{p}_\gamma}{p_{\nu_e} + p_\gamma}. \tag{6}$$

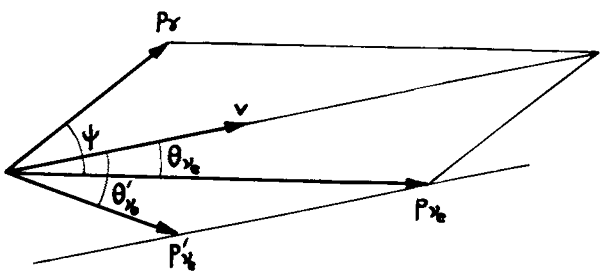

Figure 2. Kinematics of the neutrino-photon interaction: $\mathbf{p}_{\nu_e}$ = linear momentum of the neutrino in the co-ordinate system of the Sun; $\mathbf{p}_\gamma$ = linear momentum of the photon in the same system; $\mathbf{v}$ = velocity of the centre of mass (system); $\mathbf{p}'_{\nu_e}$ = linear momentum of the neutrino in that system.

Excluding the physically impossible case in which the neutrino and the photon move exactly in the same direction,

$$\beta = \frac{|\mathbf{v}|}{c} < 1 \tag{7}$$

and the passage to the new co-ordinate system is allowed.
Calculating $|\mathbf{v}|^2$, we find:

$$\beta = \left[1 - \frac{2 p_{\nu_e} p_\gamma}{(p_{\nu_e} + p_\gamma)^2} (1 - \cos\psi) \right]^{1/2}, \tag{8}$$

$$(1 - \beta^2)^{1/2} = \frac{[2 p_{\nu_e} p_\gamma (1 - \cos\psi)]^{1/2}}{p_{\nu_e} + p_\gamma}. \tag{9}$$

Let θ_{ν_e} be the angle between $\mathbf{v}$ and the direction of motion of the neutrino, angle which is contained in the direction of planes defined by $\mathbf{p}_{\nu_e}$ and $\mathbf{p}_\gamma$; we have

$$\theta_{\nu_e} = \cos^{-1} \frac{p_{\nu_e} + p_\gamma \cos\psi}{[(p_{\nu_e})^2 + (p_\gamma)^2 + 2 p_{\nu_e} p_\gamma \cos\psi]^{1/2}} \tag{10}$$

The direction of $\mathbf{v}$ is completely defined by this formula and by the fact that $\mathbf{v}$ must be contained within the angle formed by $\mathbf{p}_{\nu_e}$ and $\mathbf{p}_\gamma$. Let us then define the **Ox** axis of the non-primed co-ordinate system as parallel to $\mathbf{v}$ and in the same sense, so that $v = |\mathbf{v}|$ in the adjunct Lorentz transform; then, E'_{ν_e} being the total energy of the neutrino in the co-ordinate system of the centre of mass (primed co-ordinate system), we find

$$E'_{\nu_e} = c \left[\frac{p_{\nu_e} p_\gamma (1 - \cos\psi)}{2} \right]^{1/2} \tag{11}$$

and

$$E'_\gamma = E'_{\nu_e} \tag{12}$$

as expected for particles with an equal rest mass, and the available energy is

$$E'_G = [2(1 - \cos\psi) E_{\nu_e} E_\gamma]^{1/2}. \tag{13}$$

For the component of $\mathbf{p}'_{\nu_e}$ along the axis **Ox′**, the adjunct Lorentz transform provides

$$p'_{\nu_e,x} = \frac{(1 - \beta^2)^{1/2}}{\beta} \frac{p_{\nu_e} - p_\gamma}{2} \tag{14}$$

and

$$p'_{\gamma,x} = -p'_{\nu_e,x}. \tag{15}$$

Let now θ'_{ν_e} be the angle between the axis **Ox′** and the direction of motion of the neutrino in the co-ordinate system of the centre of mass; we have

$$\theta'_{\nu_e} = \cos^{-1} \frac{p_{\nu_e} - p_\gamma}{[(p_{\nu_e})^2 + (p_\gamma)^2 + 2 p_{\nu_e} p_\gamma \cos\psi]^{1/2}}. \tag{16}$$

The direction of $\mathbf{p}'_{\nu_e}$ is completely defined by this formula and by the fact that $\mathbf{p}'_{\nu_e}$

Table 1. Estimate $(2kTE_{\nu_e})^{1/2}$ of the available energy in the system of the centre of mass of ν_e and γ, in KeV, as a function of the energy of the neutrino in MeV and of the temperature of the medium in million degree Kelvin.

$T \backslash E_{\nu_e}$	0·2	0·5	2	10
1	6	9	19	42
5	13	21	42	93
15	23	36	72	161

must be on the same side of $\mathbf{v}$ as $\mathbf{p}_{\nu_e}$; $\mathbf{p}'_{\nu_e}$ is located in the forward or backward hemisphere when $E_{\nu_e} > E_\gamma$ or $E_{\nu_e} < E_\gamma$.

For a crude estimate of the available energy let us take $\cos\psi = 0$ and $E_\gamma = kT$ in (13); we are thus led to table 1, which shows that E'_G usually is in the order of the tens of keV.

In the absence of data about the nature of a neutrino-photon interaction, we cannot undertake a computation of the angular distribution of the reaction products; however, the case of an elastic scattering has been investigated in the Appendix.

As for each of the reaction rates that the total reaction rate must comprise, we may write it down, in the center-of-mass co-ordinate system, under the form

$$\tau'_{\nu_e} = \sigma(E'_G)cn'_\gamma \tag{17}$$

where τ'_{ν_e} is the reaction rate, σ has the dimension of a cross-section, c is the velocity of light and n'_γ is the density, in the centre-of-mass co-ordinate system, of the photons having a typical energy E_γ and making a typical angle ψ with the neutrino motion in the co-ordinate system of the sun; σ must of course be averaged on the possible states of polarization of the photon and over the possible states of relative angular momentum.

When transposing the reaction rate from the centre-of-mass co-ordinate system to the co-ordinate system of the sun one has to apply a factor $(1-\beta^2)^{1/2}$ because of time dilation, but the target density has to be reduced by the same factor (it is higher in the c.m. co-ordinate system because of proper length contraction) so that the reaction rate relative to the target density, σc, is conserved. Since the neutrino always propagates at velocity c, we may compute its interaction probability in the co-ordinate system of the sun as if the photons encountered by the neutrino were endowed with the "cross-section" $\sigma(E'_G)$ in that co-ordinate system.

3. Application to solar neutrino attenuation

As for the standard solar model, we shall rely on the tables of values given in ([16], chap. 3, § 8) after a book by M. Schwarzschild. We need to know temperature as a function of radius, from which the number density of photons can be obtained through (4), and the relevant neutrino source as a function of radius. As for the total neutrino source, in a star such as the sun it is proportional to the fusion power density. The data of [16] only give the local power deposit, not taking into account the neutrinos, but the difference is negligible for the simplified calculation that we intend to achieve (let us however observe that following our hypothesis the neutrino interactions must

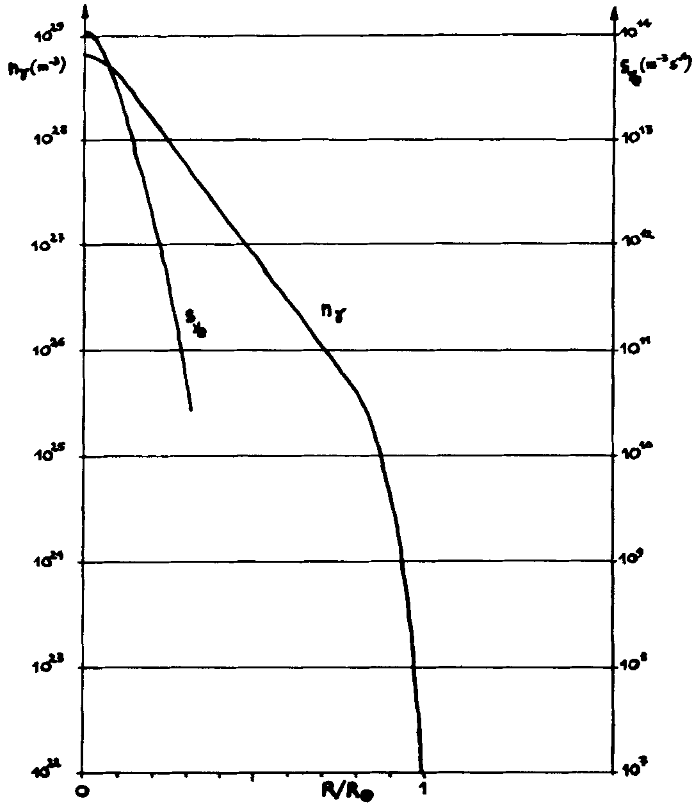

Figure 3. Photon number density and neutrino source density as functions of the distance from the centre of the Sun (standard model).

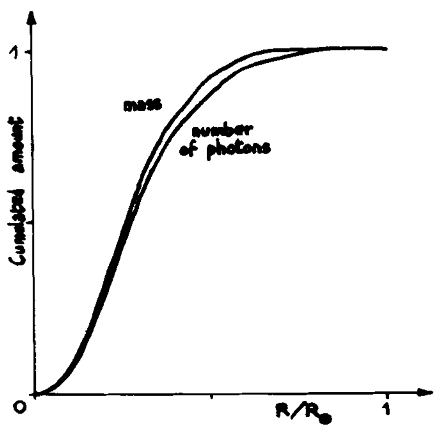

Figure 4. Integrated distributions of the mass and of the number of photons as functions of the distance from the centre of the sun (standard model; curve for mass is from [16], figure 3–3).

produce an additional energy deposit, noticeably in the peripheral layers of the star, that could somewhat modify the solar model; we shall return to this issue in § 4).

Figure 3 represents the total neutrino source density and the photon number density as functions of the radius. In figure 4, one can see that the radial distribution of photons within the sun is roughly proportional to the radial distribution of mass and that nearly all the photons, as well as nearly all the mass, are contained within a sphere of radius $0{\cdot}7 * R_\odot$; we find that the total number of photons within the sun is $1{\cdot}10 * 10^{54}$ whereas the total number of matter particles (electrons and nuclei) is $1{\cdot}94 * 10^{57}$, or 1 photon per 1760 matter particles.

Figure 3 shows than the total neutrino source is much more concentrated near the centre of the sun than the photon distribution is, and J N Bahcall *et al* ([1], table 7) have shown that this is even truer of the high-energy neutrino sources. Since the escape probability P_0 of a neutrino must have a minimum at the centre of the sun, it is therefore stationary around this point and a good approximation for computing the average value of P_0 will be to assume that all high-energy neutrinos are being emitted at the very centre of the sun. In the absence of data about the neutrino-photon interaction we shall assume it to be an absorption in order to simplify the neutrino transport calculation, which then boils down to an integration (although we shall see in § 4 that the real interaction has to be a scattering), and, since (13) shows that the available energy E'_G is not extremely variable, we shall attribute to the photons an average pseudo-cross-section independent of the temperature of the medium as well as of the energy of the neutrinos; this will at least provide us with an order of magnitude of the total pseudo-cross-section to account for solar neutrino attenuation. The escape probability of the high-energy neutrinos is therefore

$$\bar{P}_0 \cong \exp\left(- \sigma_a \int_0^{R_\odot} n_\gamma(R) \mathrm{d}R \right) \tag{18}$$

According to Bahcall *et al* [1], the neutrino source of the sun without attenuation, as detected by ^{37}Cl nuclei, is worth $(7{\cdot}6 \pm 3{\cdot}3)$ SNU [20], whereas the experiment on earth detects $(2{\cdot}1 \pm 0{\cdot}3)$ SNU [21]; therefore

$$\bar{P}_0 = 0{\cdot}28^{+0{\cdot}28}_{-0{\cdot}11} \tag{19}$$

Since

$$\int_0^{R_\odot} n_\gamma(R) \mathrm{d}R = 7{\cdot}18 * 10^{36} \gamma m^{-2} \tag{20}$$

there comes {20}:

$$\sigma_a \cong 1{\cdot}8(^{+0{\cdot}7}_{-1{\cdot}0}) * 10^{-9} \mathrm{barn}. \tag{21}$$

As for the attenuation of the total neutrino source, a finite-difference computer calculation enabled us to find the corresponding $\bar{P}_0$ as a function of σ_a. This curve is shown in figure 5; with the above range of values for σ_a, there comes

$$\bar{P}_0 = 0{\cdot}41^{+0{\cdot}25}_{-0{\cdot}21} \tag{22}$$

This could account for the apparently higher rate of capture of neutrinos by ^{71}Ga in the preliminary results of the gallium experiments [2].

If we consider the physical coefficient g_β in the Hamiltonian of β disintegration

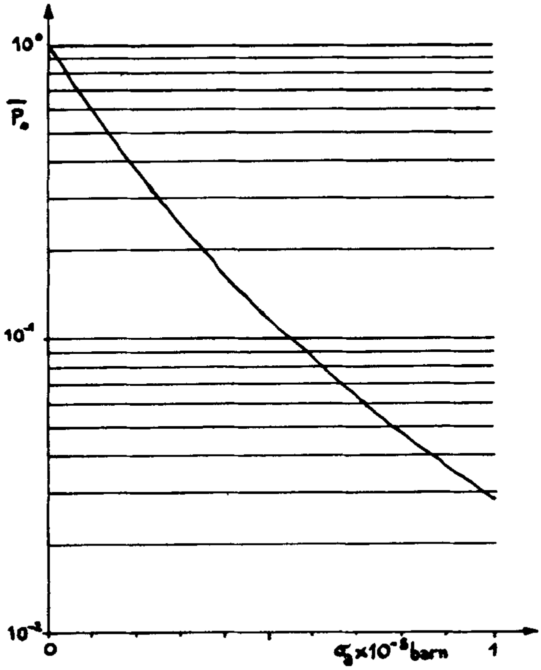

Figure 5. Average probability for a neutrino to leave the sun as function of the pseudo-cross-section of the photon, in the case of an absorption.

([22], chap. 15, § 6) we may deduce a quantity σ' having the dimension of a cross-section

$$\sigma' = \frac{g_\beta}{\hbar c} = 4{\cdot}485(13) * 10^{-9}\,\text{barn} \tag{23}$$

which is very close to σ_a; we believe that this unlikely coincidence is a strong argument in favour of our hypothesis.

The idea of a neutrino-photon interaction is reminiscent of the Compton effect and suggests the idea of a neutrino that would only be a neutral electron [23]; the Thomson cross-section is of course much larger than σ'.

4. Application to supernova SN1987A

In a star such as the sun, the inferior cut-off energy of the plasma for electromagnetic waves

$$E_p = \hbar e \left(\frac{n_e}{\varepsilon_0 m_e} \right)^{1/2} \tag{24}$$

(ε_0 being the vacuum permittivity, n_e the electron density and m_e the electron mass) is always small when compared to kT: using the data of Kourganoff [16] we find that, at the centre of the sun, $E_p = 0{\cdot}29\,\text{keV}$ and $kT = 1{\cdot}26\,\text{keV}$; at $R/R_\odot = 0{\cdot}3$, $E_p = 0{\cdot}097\,\text{keV}$ and $kT = 0{\cdot}59\,\text{keV}$; at $R/R_\odot = 0{\cdot}7$, $E_p = 0{\cdot}0093\,\text{keV}$ and $kT = 0{\cdot}16$

keV. But such is not the case inside a supernova, where the cut-off energy becomes much larger than kT. Consider first the centre of a pre-supernova of 15 solar masses ([24], figure 1): for temperature $T = 7{\cdot}62*10^9$ K and density $d = 9{\cdot}95*10^{12}$ kg m^{-3}, assuming for the sake of simplicity totally ionized ^{56}Fe, there comes :$E_p = 1{\cdot}96$ MeV and $kT = 0{\cdot}66$ MeV. Away from the centre E_p decreases with respect to kT. Both become equal to 0·56 MeV at a radius of 560 km enclosing 0·85 solar mass; after that E_p fast becomes much smaller than kT. Consider next, after the implosion has occurred, a neutron star at the density of nuclear matter, or $3*10^{17}$ kg m^{-3}, but with still 25% of protons ([25]; the assumption on the relative concentration of protons, which falls to 5% in a star that has cooled off, is not essential), there comes:$E_p =$ 250 MeV, whereas kT may be of the order of 10 MeV.

These are about the conditions that exist in the core of a supernova after collapse [24]; therefore the density of photons even at thermal equilibrium must be very small. However the conditions at the so-called neutrinosphere, about 40 km from the centre, are relatively softer: $kT \sim 5$ MeV and $d \sim 10^{14}$ kg m^{-3} [24] which with the very crude approximation of totally ionized ^{56}Fe gives $E_p = 6{\cdot}2$ MeV; therefore the photon density, although smaller than that of black body radiation in vacuo, can be up to the same order of magnitude.

Let us assume that the absorption pseudo-cross-section that we have already found to account for the solar neutrino deficit still holds although we are now dealing with hard photons and hard neutrinos and anti-neutrinos (what follows would not necessarily apply to other neutrino flavours than that of the electron). From (4) and (21), assuming black-body radiation in vacuo and neglecting the flow velocity of stellar matter, the locally defined mean-free-path of the neutrinos, considering only their interaction with the photons, is

$$\Lambda = (\sigma_a \rho T^3)^{-1} \sim (6{\cdot}5 \times 10^9/T)^3. \qquad (25)$$

At the centre of the sun we would have $\Lambda = 88{,}000$ km. For $kT = 5$ MeV we have $\Lambda = 1{\cdot}4$ mm; for $kT = 1$ MeV, $\Lambda = 176$ mm; for $kT = 100$ keV, $\Lambda = 176$ m; for $kT = 10$ keV, $\Lambda = 176$ km and for $kT = 1$ keV, $\Lambda = 176{,}000$ km.

The neutrinos can actually leave the star since they have been observed in the case of SN1987A [26, 27] therefore their interaction with the photons must be a scattering. This would not preclude $\bar{\nu}_e$ detection on earth since we are dealing with hard neutrinos, of the order of tens of MeV on arrival.

What will therefore happen is that the ν_e emitted through electronic capture on nuclei in the core matter and the $\nu, \bar{\nu}$ (or at least the $\nu_e, \bar{\nu}_e$) emitted during the cooling-off of the core will push on the stellar matter, via the photon distribution within that matter, at a radius of the order of but smaller than that of the so-called neutrinosphere, and expel the outer layers of the star with tremendous energy. These neutrinos as well as those trapped inside the ejecta will finally be released when the ejecta cool off or are dispersed, and will rejoin in outer space those which have already been able to diffuse through the outer layers of the star (thus contributing in their own way to the ejection process). All these must have contributed to the time spread of about 10 s of the neutrino burst detected on earth. Here is a new answer to the puzzle of how the explosion of type II supernovae is at all possible [28].

One should observe that the introduction of a cut-off energy for the photons tends to reduce radiation pressure and, which is more important, radiative heat transfer; a complete study of this problem would also take into account the presence of a general magnetic field and the role of the polarons.

5. Other implications of a neutrino-photon interaction

It suffices to look at the value of the optical thickness in (20) to understand that a neutrino-photon interaction cannot be directly observed on earth, even using a powerful focussed laser beam. One should rather count on the discovery of a sub-nuclear reaction in which that interaction would be an intermediate step or hope for a theoretical prediction that would also account for the agreement between σ_a and σ'. One should also look at the consequences of such an interaction for stellar balance and stellar evolution in general.

On the other hand, a neutrino-photon interaction may have important consequences in cosmology. For instance, let us consider a photon from the big bang which has been travelling through space since the origin of our universe; let us assume that this photon encounters along its way the current density of primordial ν_e and $\bar{\nu}_e$, estimated at $1{\cdot}1*10^8\ \nu\,\mathrm{m}^{-3}$ [29]. The optical thickness of the neutrinos encountered by this photon will then be about

$$\frac{2\,cn_\nu}{3\,H_0} = 9*10^{33}\ \nu\,\mathrm{m}^{-2} \tag{26}$$

where H_0 is Hubble's constant, taken by us to be $\cong 75\,\mathrm{km/(s\,Mpc)}$. Since the kinematics before the interaction are symmetrical between photon and neutrino—still assuming the rest masses to be negligible—if we apply bluntly the cross-section found in § 3 to $\bar{\nu}_e$ as well as ν_e, we find that the photon has 0·16% chances to interact with a neutrino before reaching us. The probability of interaction is, in fact, much higher and even infinite, since the density of primordial neutrinos in the aged universe decreases as $[\mathscr{R}(t)]^{-3}$, $\mathscr{R}(t)$ being the radius of the universe at age t. Of course, one should also take into account the other neutrino flavours.

It is to be noted that if the photon-neutrino interaction is an elastic scattering the neutrino population of the universe will stay in thermal equilibrium with its photon population well after it has ceased to be coupled with nuclei.

It general, there would be an attenuation of the photons coming from far-remote sources which should lead to a reassessment of Hubble's constant, leading to an increase in its value since the distance of the sources would currently be overestimated.

On the other hand, it has been observed that, if the rest mass of the neutrinos is larger than $1\,\mathrm{eV}/c^2$, they may be captured by the gravitational field of galaxies [29]. Karoji *et al* have discovered an excess redshift for the light sources that are visible through galactic clusters [30]. To explain this effect, these authors rule out summarily the idea of a neutrino-photon interaction; however, as they themselves notice, the type of interaction required to explain this excess redshift without suppressing the punctual appearance of the sources is a scattering with a very large cross-section and a very small exchange of transverse momentum. If this was by any chance the case, Hubble's constant would have to be strongly reduced with respect to the currently accepted values.

6. Conclusion

In this article, we propose a new answer to the problem of the sub-detection of the solar neutrinos: a neutrino-photon interaction which would cause the neutrinos to disappear before they leave the sun or which would make them lose energy. The assumption of an absorption, made to simplify the transport calculation, leads to: $\sigma_a \cong 1{\cdot}8{*}10^{-9}$ barn, in striking agreement with the quantity of the same dimension deduced from the Hamiltonian of β disintegration. The detection probability is substantially larger for the gallium than for the chlorine neutrinos. The observation of the neutrinos from SN1987A does not contradict our hypothesis since thermal radiation is strongly suppressed in the core of a supernova by the electrical conductivity of the medium; the neutrinos interact with the photon piston present in the outer layers of the supernova, thus contributing to their ejection, and the interaction must definitely be a scattering. Our interaction is difficult to observe on earth but it has important implications in astrophysics and cosmology. Word is now to the theoreticians.

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Appendix

Elastic scattering between a neutrino and a photon

As announced in § 2·2 we are going to investigate the case of an elastic scattering, analogous with the Compton effect. Let $\mathbf{q}'_{\nu_e}$ be the kinetic momentum of the neutrino in the c.m. system after the interaction has taken place ($\mathbf{q}'_{\nu_e}$ need not be contained within the plane of figure 2) and let F'_{ν_e} be the corresponding energy, which must be equal to E'_{ν_e} in this case; finally, let ι'_{ν_e} be the angle between $\mathbf{q}'_{\nu_e}$ and $\mathbf{v}$. Let $\mathbf{q}_{\nu_e}$, F_{ν_e} and ι'_{ν_e} be the corresponding elements in the system of the sun. The adjunct Lorentz transform yields

$$\cos \iota_{\nu_e} = \frac{\cos \iota'_{\nu_e} + \beta}{1 + \beta \cos \iota'_{\nu_e}} \tag{A1}$$

If all the domain of values of ι'_{ν_e} is covered the same is true for ι_{ν_e}; of course, for ι_{ν_e}, the forward domain of directions with respect to $\mathbf{v}$ is favoured.

Table 2. Energy of the neutrino after an elastic scattering with a photon.

$\cos \iota'_{\nu_e}$	$\cos \iota_{\nu_e}$	F_{ν_e}
-1	-1	$E'_{\nu_e}[(1-\beta)/(1+\beta)]^{1/2}$
$-\beta$	0	$E'_{\nu_e}(1-\beta^2)^{1/2} = E_{\nu_e}E_\gamma(1-\cos\psi)/(E_{\nu_e}+E_\gamma)$
0	β	$E'_{\nu_e}/(1-\beta^2)^{1/2} = (E_{\nu_e}+E_\gamma)/2$
1	1	$E'_{\nu_e}[(1+\beta)/(1-\beta)]^{1/2}$
$-\cos\theta'_{\nu_e}$	$\cos(\psi-\theta_{\nu_e})$	E_γ
$\cos\theta'_{\nu_e}$	$\cos\theta_{\nu_e}$	E_{ν_e}

The adjunct Lorentz transform also yields

$$F_{\nu_e} = E'_{\nu_e} \frac{(1-\beta^2)^{1/2}}{1-\beta\cos\iota_{\nu_e}} \tag{A2}$$

and we may draw up table 2. If the domain of values of ι'_{ν_e} is homogeneously covered the interaction is a powerful slowing-down in the co-ordinate system of the sun, since the neutrino and the photon may even exchange their energies. On the other hand, it may also happen that the neutrino gain energy through its interaction with the photon: such is the case when $\iota'_{\nu_e} < \theta'_{\nu_e}$; that is logical since the interaction might be part of a thermalization process. Of course, in any eventuality we have

$$0 \leqslant F_{\nu_e} \leqslant E_{\nu_e} + E_\gamma \tag{A3}$$

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