INTERSTELLAR NEUTRINO DENSITY AND COSMOGONY

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The cosmic neutrino density hitherto produced by the stars is estimated. Experimental determination of this quantity would be of great importance and any discrepancy between estimated and experimental value would be of great consequence for cosmogony. A brief review of the indirect (gravitational) and direct (atomphysical) possibilities of observation is given.

§ 1

Recently it has become evident that the neutrinos play an important role in certain periods of the evolution of the stars, and that they have to be considered as one of the most common constituents of the matter of the Universe.

In the stars heavy elements are being built up from hydrogen, this process being accompanied by the reaction

$$p^{+} \rightarrow n + e^{+} + \nu . \tag{1}$$

One can estimate easily, how many neutrinos have been produced by the stars up to now. According to data obtained by astronomical observations about $^2/_3$ of the known matter of the Universe is hydrogen, the rest is represented by the heavy elements. This means, that if formerly the baryonic charge of the Universe was carried exclusively by protons, up to now 10—20% of them have transmuted into neutrons. According to (1) the birth of every n is accompanied by the birth of a ν. The energy of the β neutrinos is greater than or equal to 1 MeV. Consequently, the mass concentration of the neutrinos of thermonuclear origin (as compared to the atomic mass density ϱ^*) is about 0.1‰ today. Since, according to the astronomical estimation, $\varrho^* \sim 2 \cdot 10^{-29}$ g cm^{-3}, the mass density of β neutrinos turns out to be $\varrho_\beta \sim 10^{-32}$ g cm^{-3}, and the intensity $I_\beta(\nu)$ of the overall neutrino radiation $I_\beta(\nu) \sim 10^6\ \nu\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ [1].

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The actual density is probably overestimated by having taken the mean energy of the neutrinos to be 1 MeV, because the energy of the neutrinos, the origin of which is far from here, may be considerably decreased by the DOPPLER shift. But it is not probable that this would cause a change in the order of magnitude.

Naturally, the β^+-decays accompanying the thermonuclear reactions are not the uniquely possible sources of the neutrinos. In the case of a direct $(e\nu)(e\nu)$ interaction a considerable part of the thermal radiation inside a celestial body of a temperature above 10^8 °K is carried by ν-$\bar{\nu}$ pairs, independently of the chemical composition [2, 3, 4, 5]. Let us estimate the neutrino contribution to this thermal radiation and the density of $\bar{\nu}$ of thermal origin. The calculation can be carried out on the basis of a special star model. Let us choose the model proposed by C. HAYASHI and R. C. CAMERON and worked out by them in detail for a giant star of mass $15.6\ M_\odot = 3.1 \cdot 10^{34}$ g [6]. On

Table

Period	Million years	$E(\gamma)$	$E_\beta(\nu)$	$E_\beta(\bar{\nu})$	$E_{th}(\nu\bar{\nu})$	ΣE
		in 10^{50} ergs units				
Contraction	1	—	—	—	—	—
H → He	156	410	28	—	—	440
He → C	12	69	3	—	10^{-3}	72
C → Ne	0.05	60	10	—	10	80
Ne → Fe	10^{-3}	0.3	—	—	24	24
Explosion	10^{-6}	0.1	0.1	10^{-3}	—	0.2

hand of this model, they describe the development in the course of time of the stellar material, from the initial state, containing 90% hydrogen, to the supernova explosion. The neutrino luminosity of the star is determined for β neutrinos by the thermonuclear reactions occurring in the stars and for the thermal ν-$\bar{\nu}$ pair radiation by the distribution of the density and temperature in the center of the star. In the supernova state also such elements are produced (and ejected) which show β^--decay, so they are $\bar{\nu}$-active (e.g. the natural radioactive elements on the Earth are of this kind).

The energies radiated during certain periods of the evolution of a giant star, calculated according to the HAYASHI—CAMERON model are summarized in the Table. It can be seen, that between the formation of the star and the supernova explosion altogether about 2‰ of the rest energy of the stellar matter has been liberated as radiation. The radiated energy is distributed in the following way: in the form of thermal optical radiation $540 \cdot 10^{50}$ erg (88%), in the form of β neutrinos $42 \cdot 10^{50}$ erg (7%), in the form of β antineutrinos $0.01 \cdot 10^{50}$ erg ($\ll 1\%$) and in the form of thermal neutrino pairs

$34 \cdot 10^{50}$ erg (5%). Our results mean that if all the stars obeyed the HAYASHI—CAMERON model exactly and if all the stars reached the final stage of their evolution, the mass density $\varrho(\nu)$ of the neutrino radiation being present in the Universe would be $^4/_3$ times as great as $\varrho_\beta(\nu)$, while the antineutrino density $\varrho(\bar{\nu})$ would be $^1/_3\ \varrho_\beta(\nu)$.

Most stars have not yet reached the final stage of their evolution, and the most common stars are dwarfs, the evolution of which is not yet understood in enough detail to allow a comprehensive calculation. It is probable, however, that in the case of a dwarf star the temperature is lower and the degeneracy is stronger than in the case of a giant star. Therefore the ratio $E_{\text{th}}(\nu\bar{\nu})/E_\beta(\nu)$ is smaller in the case of the dwarf stars than it would be according to the HAYASHI—CAMERON model. (The processes of high ν-$\bar{\nu}$ productivity are slowed down and other processes of small productivity become dominating [7, 8, 9].) It seems to be certain that

$$\varrho(\nu) \lesssim 10^{-32}\,\text{g cm}^{-3}, \quad \varrho(\bar{\nu}) \leq \frac{1}{3}\,\varrho(\nu) \tag{2}$$

is a good estimation of the density of the neutrinos occurring in the Universe. The average energy of a neutrino is not greater than 1 MeV, only a small fraction of them has energies of 2—3 MeV. (We should like to give a more accurate estimation in another paper [10].)

§ 2

One may ask whether there is another possible source which may make an essential contribution to the present neutrino density? It is not probable that another reaction does exist, which has escaped notice and which could produce a thermal ν-$\bar{\nu}$ pair radiation of an intensity greater than 1 erg $\text{g}^{-1}\,\text{s}^{-1}$ in the circumstances that reign in the interior of the dwarf stars (degenerated gas of 10^7—10^8 °K temperature). One can rather imagine that besides the short-lived pre-supernovae, there is a considerable amount of matter in the Universe which is in the ideal gas state and is of about 10^9 °K temperature. Here one may think of certain types of variable stars in a certain interval of the period of their variation; or rather of the central parts of our Galaxy or other galaxies. Since the centers of the galaxies make up a considerable part of the matter of the Universe, their contribution to $\varrho(\nu)$ may be important.

According to some hypotheses, the state of the matter in the central regions of the galaxies is yet more singular than that of supernovae. In the centers of the galaxies the density may be higher than that of nuclear matter and the Fermi energy of the nucleons may be greater than the mass of the pion or the mass difference between the hyperon and the nucleon. (State of degenerate hyperon gas [11].) According to AMBARTSUMIAN [12] the evolution of the galactic centers leads to the decay of this state, while in HOYLE's opinion [13] it leads to the catastrophic formation of such a state. The occurrence of such catastrophic transitions seems to be verified by astronomical observations (ejection of matter out of the central regions of galaxies, the strange properties of the radio source 3C273B, etc.). If temperatures occur which are characterized by the relation $kT \gg m_\pi \cdot c^2$ a considerable part of the matter can go over into mesons, the decay of which produces high energy neutrinos.

According to some other theories all the matter of the Universe was in such a hot state about 10^{10} years ago and the decay of this state could produce a high neutrino intensity [14, 2].

To procure direct observational evidence for the occurrence of such a hot state of the cosmic matter seems to be hopeless at first sight. But the cosmic neutrino background may offer a check for the existence of this state: if $\varrho(\nu)$ turns out to be larger than the value given by [2], this fact could scarcely be explained without supposing the existence of "hot matter". A more straightforward proof of its existence would be the observation of cosmic muon-neutrinos, as these are produced only by processes, where the energy involved is greater than 100 MeV. These neutrinos mostly arise from the pion decay:

$$\begin{aligned} &\pi^+ \to \mu^+ + \nu_\mu, \quad \pi^- \to \mu^- + \bar{\nu}_\mu, \\ &\mu^+ \to e^+ + \bar{\nu} + \bar{\nu}_\mu, \quad \mu^- \to e^- + \bar{\nu} + \nu_\mu. \end{aligned} \tag{3}$$

The hot matter therefore produces β neutrinos and μ antineutrinos in numbers of equal order of magnitude. One cannot imagine an exception from this rule. In matter of high atomic number Z and in which the electron gas is degenerated, the capture processes

$$\mu^- + Z \to (Z - 1) + \nu$$

may become predominant and may diminish the $\bar{\nu}$ radiation. The ν radiation, however, survives always besides the ν_μ-$\bar{\nu}_\mu$ radiation. It could be diminished only by the reactions

$$\mu^- + \mu^+ \to 2\,\gamma$$

but this would need an unimaginably large muon density ($n > 10^{24}\ \mu^\pm\ \mathrm{cm}^{-3}$). (The γ radiation would be converted into ν-$\bar{\nu}$ pairs even in this case [8].)

§ 3

If the density of neutrinos is comparable to that of the stellar matter, the gravitational effect of the neutrinos may play an important role in the formation of the cosmologic structure of the Universe. On the other hand, once this structure is established, it offers a new possibility for the estimation of the value of the astronomically unobservable mass density of the neutrinos. Accepting the cosmological model of general relativity, and taking into account the HUBBLE constant and the lowest limit of the age of star systems, we are led to the value [2]

$$\bar{\varrho}(\nu) < 10^{-28}\,\mathrm{gcm}^{-3}.$$

Independent of the uncertain validity of the homogeneous model the neutrino density may appear in connection with the stability of cluster of galaxies. A cluster of galaxies of mass M, by means of its gravitational field, may give rise to an inhomogeneity in the otherwise homogeneous neutrino sea. In a region of the space with gravitational potential $\Phi(r)$ a neutrino with momentum p has the energy

$$\varepsilon = cp\left[1 + \frac{\Phi(r) - \Phi(\infty)}{c^2}\right].$$

Therefore the density of completely degenerate neutrino gas (this assumption is made for the sake of simplicity) is modified by the gravitational potential to

$$\varrho_\nu(r) = \varrho_\nu(\infty)\left[1 + \frac{\Phi(r) - \Phi(\infty)}{c^2}\right]^{-3}.$$

Since the gravitational potential of the cluster with mass M at a large distance varies according to

$$\Phi_*(r) - \Phi_*(\infty) \sim -\frac{kM}{r} \ll c^2,$$

(where k is the gravitational constant) we obtain

$$\varrho_\nu(r) - \varrho_\nu(\infty) \sim \frac{3kM}{c^2}\frac{\varrho_\nu(\infty)}{r}. \tag{4}$$

Therefore the inhomogeneity contributes to the gravitational potential at the center of the cluster by

$$\delta\Phi(0) \sim -k\int_0^{D/2} \frac{\varrho_\nu(r) - \varrho_\nu(\infty)}{r}\,dV \sim \frac{6\pi k^2}{c^2} MD\,\varrho_\nu(\infty).$$

If therefore there is only one cluster with mass M in the space and the diameter D of the region occupied by the neutrinos tends to infinity, $\delta\Phi(0)$ diverges. We may use, however, the mean distance of the clusters of galaxies instead of D. On doing this we conclude that the contribution of the neutrino inhomogeneity to the potential becomes comparable to the potential of the cluster itself, if

$$\varrho_\nu(\infty) \sim \frac{c^2}{4\pi k D R} \sim 10^{-24}\,\mathrm{g\,cm^{-3}}\,.$$

According to stellar statistical observations some clusters are stable in spite of the fact that an instability would follow from their dynamical data (density and velocity values) [15]. Supposing $\delta\Phi(0) \sim 10\,\Phi_*(0)$, the induced inhomogeneity of the neutrino sea can explain the stabilization. One has to stress, however, that this requires a neutrino density which is a million times as high as the observed density of astronomical matter. According to the opinion of some researchers such a high density cannot be excluded in principle. The accelerating role of the inhomogeneity in the neutrino sea at a gravitational collapse would be also worth investigating.

§ 4

From what has been said in the foregoing paragraphs, it is evident that the empirical determination of the value and the character of the astronomical neutrino density would be very important.

Pontecorvo and Smorodinsky [2] were the first to call the attention to the fact that the background values of the experiments of Reines and Cowan, and of Davis give an upper limit for the density of ν and $\bar{\nu}$ in the region between 1 and 10 MeV. They state that this is smaller than $10^{-24}\,\mathrm{g\,cm^{-3}}$. One cannot, however, expect the energy of the neutrinos of astronomical origin to be so high. The mentioned data do not give any information as to the soft component of the neutrino radiation. (E.g. provided the energy spectrum is a thermal one, the measurements referred to above would allow a neutrino temperature of $20 \cdot 10^6$ °K, which leads to an integral neutrino density $\varrho(\nu) \sim 91\,\mathrm{g\,cm^{-3}}$.) For the observation of the soft component Weinberg [17] proposed the investigation of the β-spectrum of H^3; the occupied $\bar{\nu}$ states (because of the Pauli principle) slow down, whereas the occupied ν states (via the forced $\nu + H^3 \to He^3 + e^-$ decay) precipitate the β-decay and deform its spectrum:

$$f(E) = CF_Z(E)\,E\sqrt{E^2-1}\,(E_0-E)^2\,[1-N_{\bar{\nu}}(E_0-E)],\ \text{if}\ E < E_0\,,$$

$$f(E) = CF_Z(E)\,E\sqrt{E^2-1}\,(E_0-E)^2\,N_\nu(E-E),\ \text{if}\ E > E_0\,.$$

(Here E is the energy of the electron, E_0 its maximal energy in m_0c^2 units, N_ν and $N_{\bar{\nu}}$ represent the occupation probability of the ν and $\bar{\nu}$ states, and

F_Z is the Coulomb factor.) Comparison with the observed β-spectrum of tritium leads to a neutrino temperature of $T < 10^6$ °K and a density of the soft component (in the KeV region) of $\varrho(\nu) + \varrho(\bar{\nu}) < 10^{-9}$ g cm^{-3}. Though this value lies very far from the astronomically interesting region, the measurement of the β-spectrum offers the best possibility for the detection of the interstellar neutrinos and antineutrinos in the region under 1 MeV (Fig. 1).

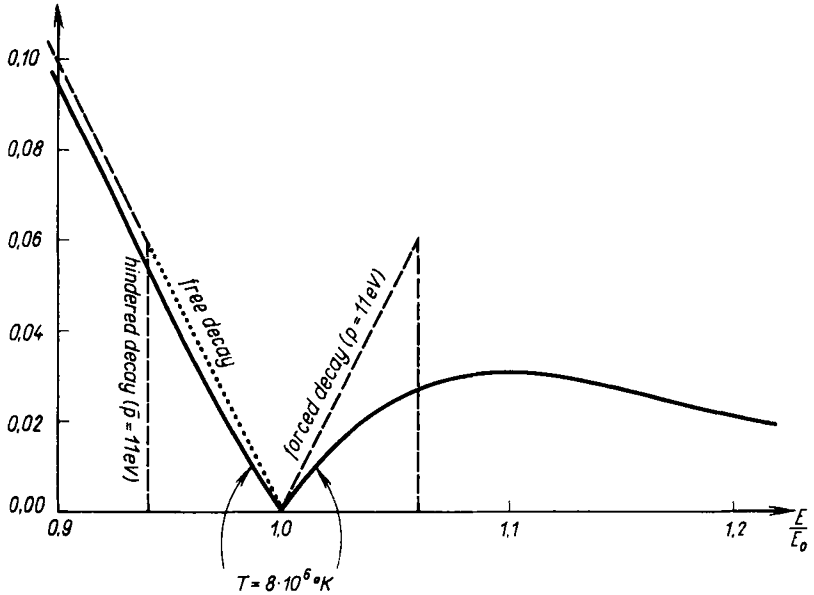

Fig. 1

Measurement of the β-spectrum is not suitable for the observation of the μ neutrinos. Here the experimental possibilities are much more restricted. From the reaction

$$\bar{\nu}_\mu + p^+ \to n + e^+$$

one obtains for the density of the $\bar{\nu}_\mu$-s of GeV energy the value $\varrho(\bar{\nu}_\mu) < 10^{-28}$ gcm^{-3} [18]. Such high energies, however, cannot occur with astronomical abundance even in "hot" matter. In the case, when $\varepsilon(\nu_\mu) < m_\mu c^2$, the only possibility for the direct detection is given by the decay spectrum of the muon [16]. The occupation of the ν_μ states accelerates the μ^+ decay (via the reaction $\nu_\mu + \mu^+ \to e^+ + \nu$), whereas the occupation of the $\bar{\nu}_\mu$ states slows it down (because of the Pauli principle). The energy spectrum of the μ decay (Fig. 2 and enlarged parts in Fig. 3) is represented by

$$f(E) = 192 \int_{1/2-E}^{1/2} \left(-\frac{1}{2} + E + F\right)(1 - E - F)\left(1 - N_{\bar{\nu}_\mu}(F)\right) dF, \text{ if } E < \frac{1}{2},$$

$$f(E) = 192 \int_{E+1/2}^{\infty} \left(\frac{1}{2} - E + F\right)(1 - E + F)\, N_{\nu_\mu}(F)\, dF\,, \quad \text{if } E > \frac{1}{2}\,. \tag{5}$$

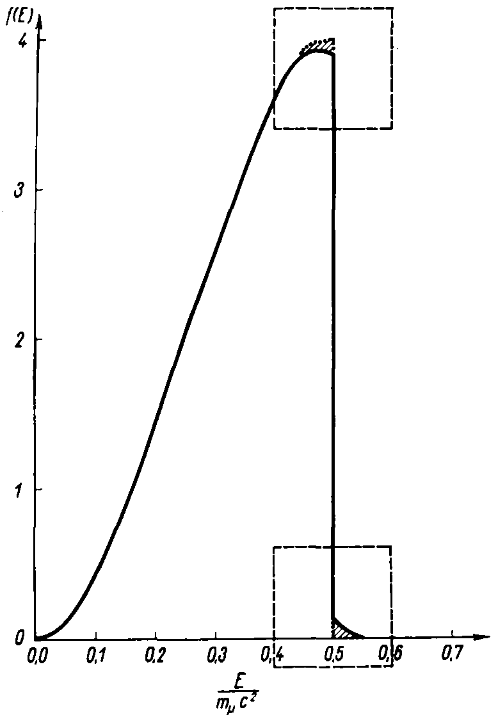

Fig. 2

Here E is the energy of the emitted positron, F is the energy of the muon-neutrino in $m_\mu c^2$ units. In principle, eq. (5) makes possible to determine the ν_μ and $\bar{\nu}_\mu$ background, but this method is very inaccurate, the upper limit for the density of the low energy muon-neutrinos obtained from the present experimental datas being $\varrho(\nu_\mu) + \varrho(\bar{\nu}_\mu) < 10^6 \text{ g cm}^{-3}$. One does not obtain a more accurate value by comparing the measured and calculated values of the lifetime of μ [16] either.

Taking into account that the detection methods are far more inaccurate in the case of the μ neutrinos than in the case of β neutrinos, it is evident that research should be concentrated on the latter. The "everyday" ν radiation of the stars can well be estimated (§ 1), any observed departure from this estimated value would point to the existence of "hot matter". As we have seen in § 2 one cannot imagine such without ν emission. As a matter of fact, in the case of ν measurements the Sun, in the case of $\bar{\nu}$ measurements the Earth, causes unpleasant background effects [1]. (The ν_μ measurement is not disturbed by the atmospheric background.) In this respect the hardness ($\varepsilon(\nu) \gg 1$ MeV) of the ν radiation emitted by the "hot matter" could help.

In order to estimate optimistically the practical possibilities, let us consider e.g. the center of our Galaxy. At our Earth an intensity $I(\nu) \sim 10^{10}\ \nu$ $\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ can be said to be observable with the help of the present techniques for neutrinos of several MeV energy. (For neutrinos of an energy about GeV

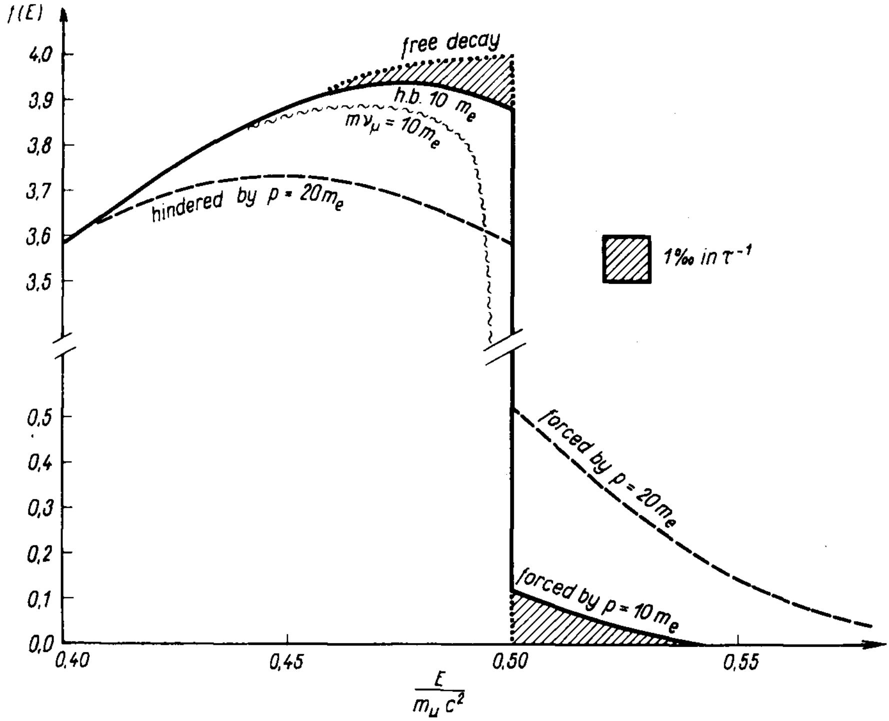

Fig. 3

the absorption cross section is a million times as high as for neutrinos of energy about MeV.) This means that the neutrino radiation of a hyperstar at the center of our Galaxy could be observed, if its neutrino luminosity would be about $10^{48} - 10^{50}$ erg s^{-1}, which could be supplied already by a specific energy liberation $\sim 10^{10}$ erg $\mathrm{g}^{-1}\ \mathrm{s}^{-1}$. Such values certainly occur in certain periods of the evolution of a hyperstar. (This needs a mean temperature $1 - 2 \cdot 10^9$ °K inside the hyperstar.)

The neutrino pulse emitted by a hypernova explosion could be detected at a distance of a 100 million light years, if the neutrino luminosity of the hypernova reached the value 10^{55} erg s^{-1}. This is not unimaginable at all, since we know that the total energy set free in such an explosion may exceed the value of 10^{60} erg [20]. The question is only, whether the mean free path of the β neutrinos is not very small compared with the dimensions of the hyperstar. As CHIU has suggested recently [21], under special conditions the mean energy loss of a dense hyperstar can be caused by the muon-neutrino luminosity. In this case the possibilities of observation would be much more unfavourable, as we have shown just above. In spite of all these problems, it can not be excluded, that the observation of neutrino radiation will give a direct proof of the hypothesis of hypernova explosion and gravitational collapse.

Appendix
Neutrino production in the Hayashi—Cameron model

The giant star considered in the HAYASHI—CAMERON model remains in the main sequence of the HERTZSPRUNG—RUSSEL diagram during its first period of evolution, for $1{,}56 \cdot 10^8$ years. The temperature in its central region reaches only $5{,}85 \cdot 10^7$ °K, therefore in this period exclusively the H $\rightarrow$ He transmutation produces neutrinos. Meanwhile the hydrogen content of the convective core of the star decreases from the initial 90% to 62%. This means that $7{,}3 \cdot 10^{33}$ g hydrogen is fusioned into helium, i.e. about $N = 2{,}2 \cdot 10^{57}$ neutrinos are produced. A neutrino obtains an energy of $0{,}4 \cdot 10^{-6}$ erg in the $p - p$ fusion and $1{,}3 \cdot 10^{-6}$ erg in the C—N cycle. Since in the case of a giant star this latter process plays an overwhelming role, from the produced energy of $4{,}4 \cdot 10^{52}$ erg an amount of $E(\nu) = 2{,}85 \cdot 10^{51}$ erg is carried away by the neutrino radiation.

When the star has exhausted its central H content the gravitational contraction begins. When the central temperature reaches $1{,}5 \cdot 10^8$ °K, the reaction 3 He $\rightarrow$ C starts, which does not produce any neutrinos. Therefore one needs to take into account only the neutrino production of the H shell which surrounds the He shell. During $3{,}37 \cdot 10^5$ years about $0{,}027\ M_\odot = 8{,}4 \cdot 10^{32}$ g hydrogen has been transformed into helium exclusively in the C—N cycle (since the temperature is higher than $1{,}6 \cdot 10^7$ °K in the whole zone), therefore $E(\nu) = 3{,}25 \cdot 10^{50}$ erg. If the temperature at the centre is $3{,}16 \cdot 10^8$ °K also the thermal neutrino radiations starts, by means of the Compton neutrino production:

$$\gamma + e^- \rightarrow e^- + \nu + \bar{\nu} . \tag{6}$$

Taking into account the temperature distribution given by different models, and the cross section of the process (6) given in [6], we obtain the estimate

$$6{,}4 \cdot 10^{46} \text{ erg} < E(\nu, \bar{\nu}) < 3 \cdot 10^{48} \text{ erg.}$$

This is scarcely 5% of the energy supplied by the thermonuclear β neutrinos.

In the central zone the exhaustion of He again causes gravitational contraction. With the increasing temperature a great variety of nuclear reactions starts, which makes the estimation of the neutrino emission rather complicated. In this period, which lasts about $5 \cdot 10^4$ years, the luminosity of the star — supposing a central zone containing only pure C^{12} or Ne^{20} — can be characterized by

$$L_{\text{opt}} = 3.5 \cdot 10^{28} \text{ erg s}^{-1}, \quad \text{or} \quad 4.6 \cdot 10^{38} \text{ erg s}^{-1},$$

$$L_\nu = 1.02 \cdot 10^{38} \text{ erg s}^{-1}, \quad \text{or} \quad 2.5 \cdot 10^{39} \text{ erg s}^{-1}.$$

Thus the neutrino emission reaches the order of magnitude of the optical radiation, and is about equally composed of the processes (1) and (6). The emitted neutrino energy during the whole period is

$$E_s(\nu) \sim E_{\text{th}}(\nu, \bar{\nu}) \sim 10^{51} \text{ erg},$$

which is nearly $^1/_3$ of the optical energy.

Between $8 \cdot 10^8$ °K and 10^9 °K there is no considerable liberation of nuclear energy, the thermal radiation of the star must be supplied by the gravitational contraction. The evolution is extraordinarily quick, it scarcely lasts 200 years. During this time the thermonuclear β-decays do not produce neutrinos at a rate which could be compared to that produced during the former periods, $E_\beta(\nu) \approx 0$. On the other hand, because of (6)

$$E_{\text{th}}(\nu, \bar{\nu}) = 3.5 \cdot 10^{46} \text{ erg}.$$

(If there would be a nuclear energy source, which could produce the luminosity given above of the star for a longer time, the period of the evolution considered could be taken to have lasted longer and then $E_{\text{th}}(\nu, \bar{\nu})$ would have a larger value.

At central temperature if 10^9 °K the Ne →Fe transition series is initiated. Calculating with a neon core of mass $M = 0.114\, M_\odot = 3.42 \cdot 10^{33}$ g, then Ne → Fe reaction chain represents the liberation of $2.4 \cdot 10^{51}$ erg energy. The optical luminosity of the star core is smaller by an order of magnitude than its neutrino luminosity, therefore the process (6) and the reactions

$$\gamma + Z \to Z + e^- + e^+, \qquad e^- + e^+ \to \nu + \bar{\nu}$$

are the main forms of the energy emission. Thus in this period

$$E_{\text{th}}(\nu, \bar{\nu}) = 2.4 \cdot 10^{51} \text{ erg}.$$

During the formation of the Fe-core of mass 0.11 $M_\odot$ — 0.15 $M_\odot$ which is the final period of the stellar evolution the neutron ratio increases to more than 50%, therefore the thermonuclear reactions are accompained again by β-decays. The number of the neutrinos produced in these decays can be neglected as compared to that of the other processes. The core is heated from 10^9 °K to $5 \cdot 10^9$ °K, the central density increases from 10^5 g cm^{-3} to $125 \cdot 10^5$ g cm^{-3} and the internal energy increases from $6.1 \cdot 10^{16}$ erg g^{-1} to $30.5 \cdot 10^{16}$ erg g^{-1}. This corresponds to a total energy increase of $1.2 \cdot 10^{51}$ erg. Because of the virial theorem this is just equal to the emitted energy of which only a few percent is optical radiation. Therefore

$$E_{\text{th}}(\nu, \bar{\nu}) = 1.2 \cdot 10^{51} \text{ erg} .$$

At this stage the supernova explosion may occur, during which also heavy elements (and the neutrons) are produced. These emit $\bar{\nu}$-radiation. But if we suppose that the concentration of the heavy elements inside a star, the mass of which is several times that of the sun, is similar to the terrestrial one, the rate of production of the elements heavier than Fe is so slow that $E_\beta(\nu)$, due to their production, and $E_\beta(\bar{\nu})$, due to their subsequent radioactive decay (e.g. natural terrestrial radioactivity), are very small:

$$E_\beta(\nu) < 10^{49} \text{ erg}, \qquad E_\beta(\bar{\nu}) < 10^{48} \text{ erg} .$$

The values obtained here are summarized in the Table at the end of § 4.

Note added in proof: The most accurate upper limit of the cosmic neutrino flux in the MeV region is given by the recent measurement of RAYMOND DAVIS (BNL-Preprint No. 7660): $\varrho(\nu) < 10^{-28}$ g cm^{-3}.

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КОСМИЧЕСКАЯ ЧАСТОТА НЕЙТРИНО И КОСМОГОНИЯ

Л. ФОДОР, Ж. КОВЕШИ и Г. МАРКС

Резюме

Оценивается плотность космических нейтрино как продуктов термоядерных реакций звёзд и супернов. Наблюдение большей плотности нейтрино указывало бы на сигнулярное (дозвездное) состояние материи. Подробно истолкуются гравитационное влияние нейтринного фона и непосредственные возможности наблюдения мягкой компоненты нейтринного излучения двух видов.