ASTRONOMY
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Stars as galactic neutrino sources

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Abstract. Theoretical expectations concerning stars as neutrino sources are presented according to detailed evaluations of the stellar evolutionary histories for an extended grid of stellar masses. Neutrino fluxes and cumulative neutrino yields are given for both 'thermo-nuclear' and 'cooling' neutrinos all over the nuclear life of the stars and along the final cooling as White Dwarfs. Predictions concerning the galactic and the cosmic neutrino background are presented and discussed.

Key words: Sun: particle emission – stars: evolution – stars: general

1. Introduction

The fusion of H into He in the solar interior has to be accompanied by the emission of about 10^{38} neutrinos per second. Thus at the earth surface one expects a flux of the order of 10^{11} neutrinos cm^{-2} sec^{-1}. The successful detection of these solar neutrinos in several experiments over the world has raised the attention to the Sun as a neutrino source, originating in the same time (see e.g. Bahcall 1989, Bahcall et al. 1995) the long debated problem of the discrepancy between experimental data and theoretical predictions.

All stars that are burning and/or have been burning H in the Universe can be regarded as cosmic sources of both photons and neutrinos, thus simultaneously contributing to the background of those particles. Clearly this stellar neutrino flux is expected to be much smaller than the solar one; however the amount and the energy of stellar neutrinos contributing to the neutrino background appears as an interesting question to be addressed in the frame of the present theoretical knowledge of stellar evolutionary structures. A first step in such a direction has been recently presented by Hartmann et al. (1994), assuming all stars in their initial (Main Sequence, MS) phase. A quick inspection of the stellar evolutionary scenario reveals that such an assumption

has to be regarded only as a first approximation to the problem. As a matter of fact, we know, e.g.,that low mass main sequence stars burn H into He through the proton-proton chain, thus emitting a mixture of neutrinos from pp, ^{7}Be and ^{8}B reactions. In the meantime, we know that in the same structures the largest amount of He is produced at higher temperatures in the Red Giant stage, where H burning is dominated by CNO reactions. Accordingly, one can easily predict that all along the life of a low mass star CNO neutrinos will eventually dominate the yield, in spite of the MS behaviour.

Moreover, the burning of H into He is not the only way used by stars to produce neutrinos. In the advanced phases of stellar evolution, neutrinos can be produced not as a by-product of thermo-nuclear reactions (*thermo-nuclear neutrinos*) but directly at expenses of the thermal energy of stellar matter. According to current physics, *cooling* neutrinos can originate from several processes, as plasmon decay (plasma-neutrinos) or photon-electron collisions (photoneutrinos). Their energy however is lower by about two orders of magnitude than the energy of thermo-nuclear neutrinos; their detection is thus even more difficult than the detection of neutrinos from nuclear burning.

In this paper, we will discuss all these neutrino sources following the evolution of a suitable sample of stellar structures all along the major phases of H and He burning. The investigation will be completed by discussing the relevant contribution given by neutrinos from cooling White Dwarf (WD) structures. In the next section we will discuss the properties of thermo-nuclear neutrino sources. Sect. 3 will be devoted to cooling neutrinos both during the nuclear life of a star and in the final WD structures. An evaluation of the expected galactic and extragalactic neutrino background will close the paper.

2. Thermo-nuclear neutrinos

Before entering detailed evolutionary computations, one can have a quick look on stellar neutrino sources by recalling that a fusion of four protons into a He nucleus produces 2 ν and about 27 MeV of energy which is degraded into eV photons. On this simple basis, one expects 1 ν every 10^7 photons leaving a star. One concludes that stellar neutrinos are closely correlated

with star luminosity. In other words, the neutrino sky should look very similar to the normal sky of photons, provided that the transparency of interstellar clouds to neutrinos is taken into account. Bearing in mind such a scenario, the production of both 'thermo-nuclear' and 'cooling' ν can be evaluated by following the evolution of a suitable set of stellar models as chosen to cover the whole scenario of evolutionary expectations.

Numerical computations have been performed by adopting the FRANEC evolutionary code, whose physical inputs have been already reported in the literature (see, e.g., Castellani et al. 1993, and references therein). Here we only add that rates for plasma neutrino production are from Haft et al. (1994), photoneutrinos are from Itoh et al. (1989), neutrinos from pair annihilation processes are from Munakata et al. (1985a,1985b), bremstrahlung neutrinos from Dicus et al. (1976), as corrected by Richardson et al. (1982) and neutrinos produced by recombination processes are from Beaudet et al. 1967. However, we shall see that in normal stellar evolution the bulk of 'cooling' neutrino production is given by plasma and photoneutrinos only.

Evolutionary computations have been performed over the whole H and He burning phases for stars with population I composition (Y=0.27 Z=0.02 but the model of $1 M_\odot$ for which we adopted Y=0.28 as predicted by the calculations of standard solar models) and for selected values of the stellar mass: M=0.8, 0.9, 1, 3, 5, 7, 9, 16 and 20 $M_\odot$. The choice of the lower limit follows the evidence that a 0.8 $M_\odot$ model spends more than an Hubble time in its central H burning MS phases. As a consequence, one expects that stars with $M \leq 0.8 M_\odot$ are still in the phase of central H burning, where the luminosity scales with the stellar mass according to already known laws (see, e.g., Alexander et al. 1997) and the energy production is dominated by the ppI chain so that only pp neutrinos are produced.

The grid of evolutionary models has been chosen so as to regularly cover with a sufficient number of different masses the three mass ranges where different evolutionary behaviours are expected, namely i) the range of low mass stars where stellar cores undergo electron degeneracy during both the H shell and the subsequent He shell burning phases, ii) the range of intermediate mass stars where electronic degeneracy becomes efficient only in the C,O stellar cores during He shell burning phases, and finally iii) massive stars where H, He and C are progressively and quietly ignited in not degenerate stellar cores.

All models have been followed from the initial Zero Age Main Sequence phase up to the carbon ignition or, alternatively, to the onset of thermal pulses marking the end of the Early Asymptotic Giant Branch Phase. In this last case, evolutionary computations have been supplemented with the cooling sequence of a 0.6 $M_\odot$ C-O white dwarf, assumed to be representative of the final stage of both low and intermediate mass stars. One has to notice that H and He burning cover the whole life of low and intermediate mass stars, whereas in massive stars more advanced nuclear burning phases and further neutrino production occur before the final disruption as supernova. However, assuming a 1 $M_\odot$ iron core in the pre supernova models, one easily estimates that in these rapid phases of evolution the transformation of 1 $M_\odot$ of C into Fe produces a total amount

of $\approx 10^{56}$ neutrinos, which can be regarded as a marginal contribution to the $\approx 10^{58}$ neutrinos soon produced by the SN. Note that the quoted amount of neutrinos represents about 10 percent of the total amount of neutrinos produced by H burning. This is what one can predicts on very general grounds, since H burning already produced He nuclei with the same number of neutrons and protons; to reach $^{56}_{26}$Fe two further neutrons over 26 already formed must be produced, correspondingly accounting for 2/26 of the total final amount of neutrinos. The actual ratio is moderately larger, because of the occurrence in stellar matter of a not negligible amount of original He.

Fig. 1 shows the time behaviour of the neutrino production rate in models with 1, 3 and 16 $M_\odot$, chosen as representative of the three quoted evolutionary classes. Increasing the stellar mass the central temperature of MS models increases. As a consequence low mass stars start burning H via the pp chain, whereas in heavier MS stars the CNO cycle becomes progressively the dominant mechanism; thus for stars with $M \geq 1.5 M_\odot$, CNO neutrinos are dominant also in the MS phase. Moreover, as well known, increasing the stellar mass the stellar luminosity (in photons) increases, driving a corresponding increase of the neutrino production rate, which in a 22 $M_\odot$ MS model is about $10^{5.5}$ times that of a 0.8 $M_\odot$.

As a general rule, the evolution off MS increases both central temperatures and stellar luminosities. As a consequence, in Fig. 1 one finds that the neutrino production rate tends to increase all along the H burning phases, whereas CNO neutrinos become progressively more and more abundant. As already known, one finds that even in low mass stars H burning is eventually dominated by CNO reactions. After the ignition of central He burning, the only source of thermo-nuclear neutrinos is the residual efficiency of a H burning shell, and the neutrino production rate is not more directly correlated to the photon luminosity of the stars, which is partially powered by the triple α reactions where no neutrinos are emitted.

Fig. 2 shows the thermo-nuclear neutrino yield for the models in Fig. 1 while Fig. 3 shows the total yield of thermo-nuclear neutrinos for all the stars in our sample, until the ignition or at the end of He burning, as labeled. Massive stars have much larger production rate but not too much total yield of thermo-nuclear neutrinos. This is because massive stars have much shorter lifetimes. In all cases the total number of neutrinos (mainly CNO neutrinos) is of the order of 10^{56} - 10^{57}, linearly increasing with the mass (as can be seen in the lower panel of Fig. 3 the behaviour is linear at least for masses in the range $3 M_\odot < M < 20$ $M_\odot$). The total yield of thermo-nuclear neutrinos, as given by the integral of the neutrino production rate over time, is directly related to the amount of H converted into He. The previous result is, thus, an evidence that the total amount of He produced at the end of the nuclear burnings grows linearly with the mass of the star. One also notes that at the ignition of He burning the stars have already produced the total amount of neutrinos from the pp chain while the CNO neutrinos continue to be produced in the H shell active during the He burning phases (upper panel of Fig. 3).
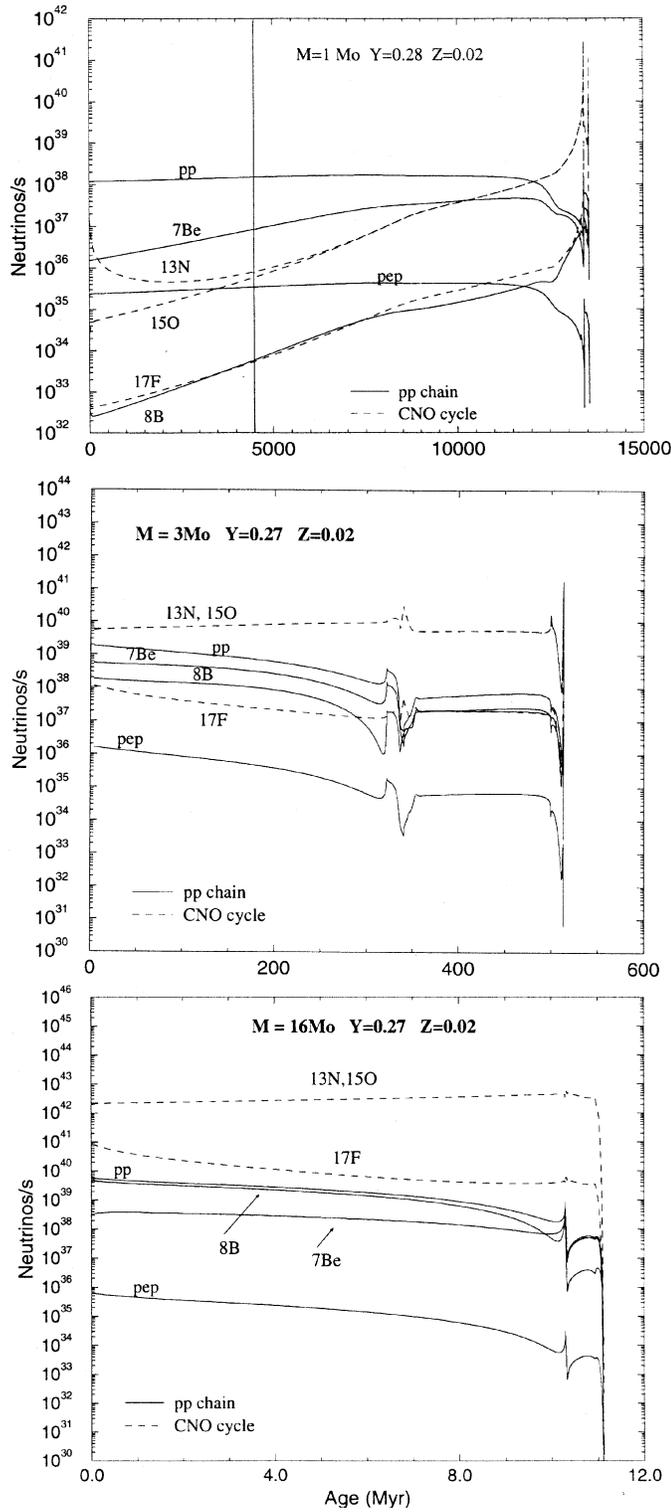
Fig. 1. Neutrino production rate as a function of time for 1, 3 and 16 $M_\odot$ models. The vertical line in the 1 $M_\odot$ model marks the predictions of the Solar Standard Model, as taken at the solar age of 4.6 Gyr.
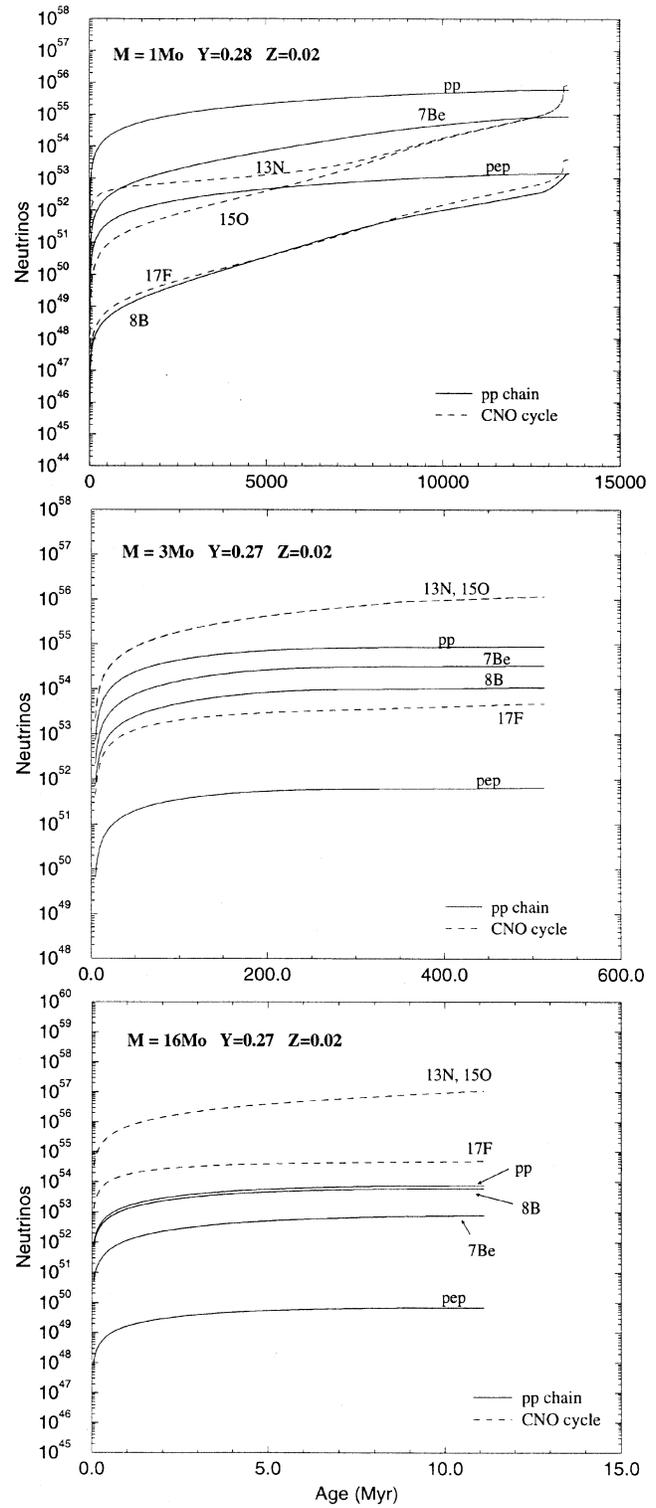
Fig. 2. Thermo-nuclear neutrino yield for the models in Fig. 1.

Fig. 4. Evolutionary behaviour of the central temperature and density for models in our sample. The dashed line labeled with WD shows the cooling trajectory of a typical 0.6 M$_\odot$ White Dwarf. The dominant mechanism for cooling neutrino production is indicated in each region.
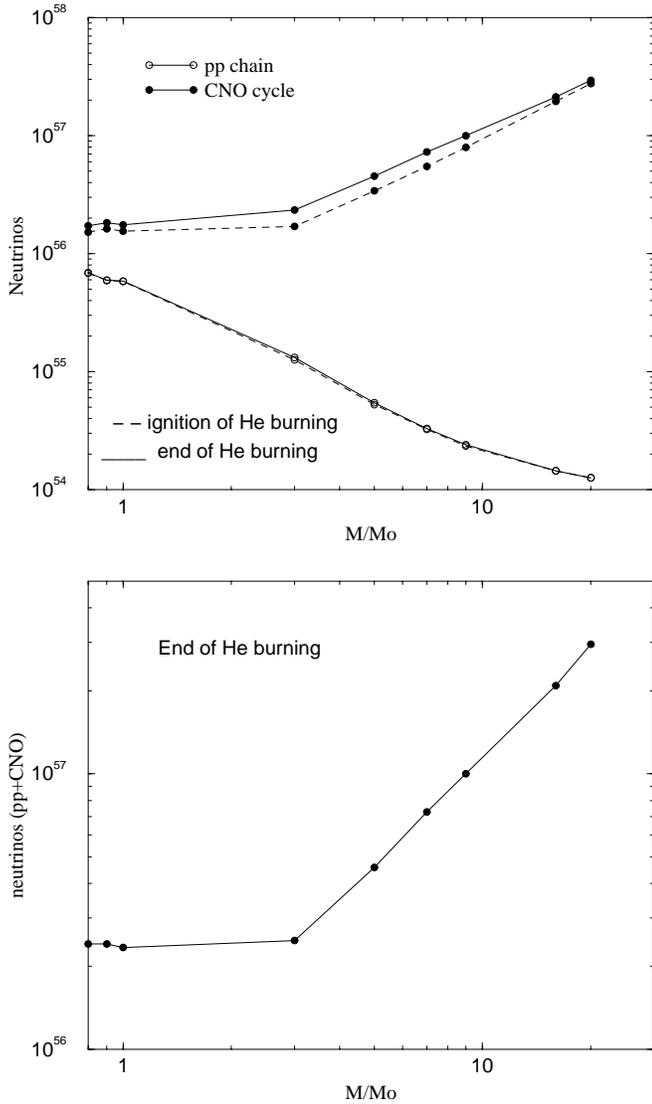

Fig. 3. Upper panel: Total yield of thermo-nuclear neutrinos as a function of the stellar mass until the ignition of He burning (dashed line) and at the end of the He burning phase (solid line) for the pp chain (open circles) and the CNO cycle (filled circles). Lower Panel: Total yield of thermo-nuclear neutrinos (pp chain + CNO cycle) at the end of He burning.

3. Cooling neutrinos

As an approach to the problem of cooling neutrinos, Fig. 4 shows the evolutionary path of central conditions for selected models in our sample as compared with the regions in which the labeled mechanisms are the dominant for the cooling neutrino production.

It appears that during their nuclear life, stellar interiors can be mainly affected either from photoneutrino or plasma neutrino emissions. According to Fig. 4, plasma-neutrinos are important for low and intermediate mass stars only. For these structures, plasma neutrino cooling is essentially efficient in selected episodes, when neutrino production affects the thermal evolution of degenerate He and/or C+O stellar cores. Fig. 5 discloses
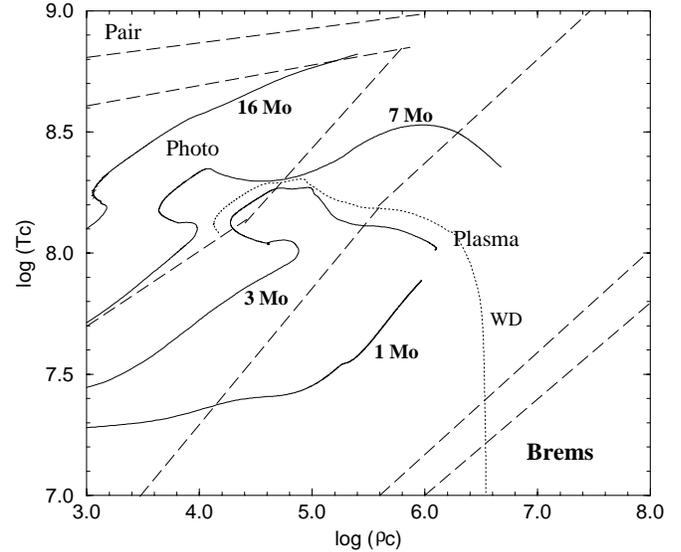
the total yield of photo or plasma neutrinos produced until the ignition of He burning or at the end of the He burning phase for the various investigated masses.

As expected, during H burning plasma neutrino cooling is efficient only in less massive stars, where degenerate He cores develop during the H shell burning phase. However, over the range of both low and intermediate mass stars the final yield of plasma-neutrinos is only weakly dependent on the star mass, with a total amount of the order of $5 \cdot 10^{55}$ neutrinos. The reason for such a behaviour is that by increasing the mass, the time spent in the later phases of He burning where neutrino cooling attains a renewed efficiency increases, balancing the decreasing production of neutrinos in the previous H-shell burning phase.

The same figure shows that for M $\geq 3 M_\odot$ the total yield of photoneutrinos can be largely competitive with plasma-neutrinos. At the end of H burning the amount of photoneutrinos dominates over the total yield of plasma-neutrinos by several orders of magnitude. During the latest evolutionary phases of intermediate mass stars the plasma-neutrino production rate sensibly increases and the total yield of plasma and photoneutrinos at the end of He burning is of the same order of magnitude for stars from 3 to about 9 M$_\odot$ (lower panel in Fig. 5). For larger masses the plasma-neutrino production decreases while the photoneutrino emission remains almost constant at least until 16 M$_\odot$.

Both low and intermediate mass stars experience a further episode of neutrino emission during their last phase of cooling as WD, almost completely due to plasma neutrinos (see Fig. 4). Evolutionary computations have already disclosed that the cooling neutrino production affects the cooling of a WD structure just after the exhaustion of nuclear burnings.

Fig. 6 compares the time behaviour of the plasma-neutrino production rate for a 0.6 M$_\odot$ WD, with the time behaviour of

Fig. 6. Time behaviour of the plasma-neutrino production rate from a 0.6 M$_\odot$ White Dwarf (dashed line and right scale) as compared with the time behaviour of the stellar luminosity (solid line and left scale). The big dot shows the initial phase of cooling.
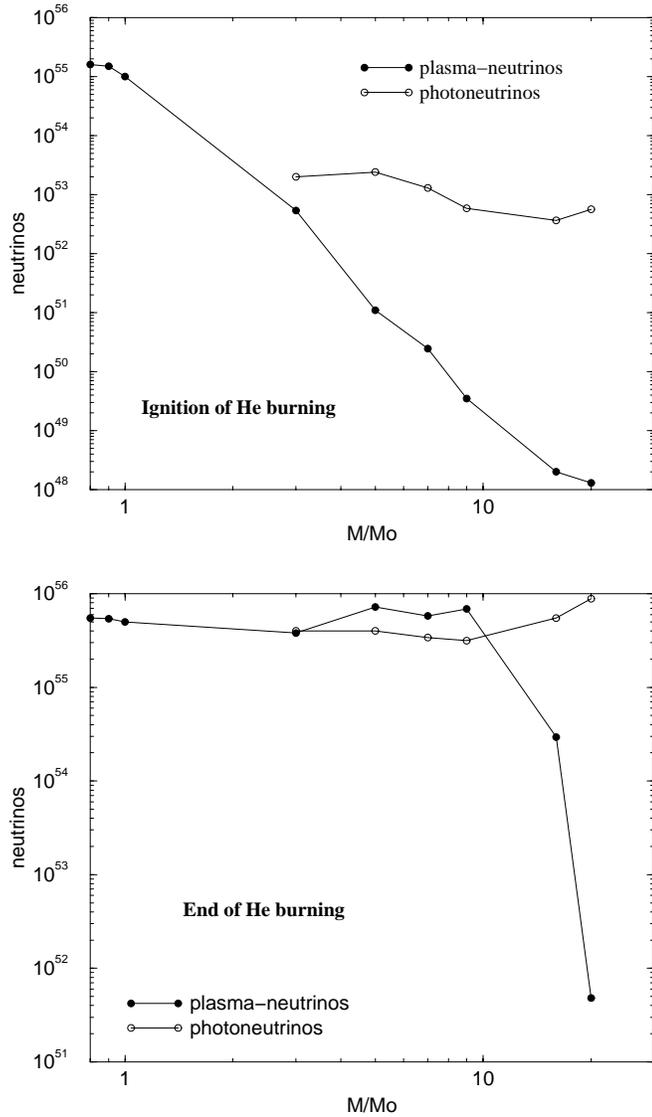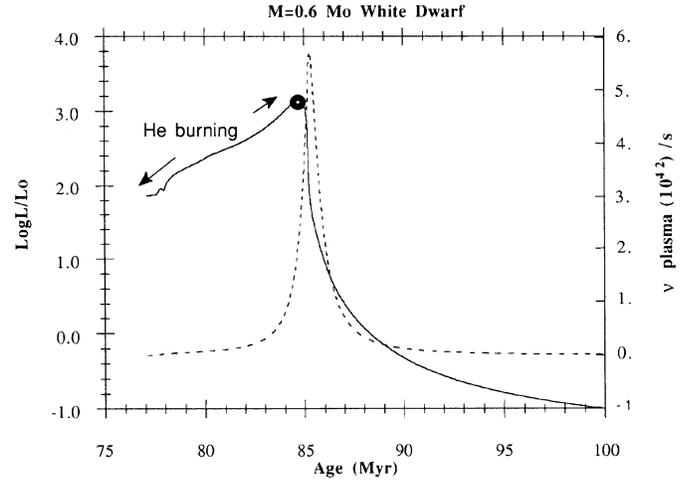
Fig. 5. Total yield of plasma and photo neutrinos until the ignition of He burning (upper panel) and at the end of He burning phase (lower panel) as a function of the stellar mass.

(photon) luminosity showing that the plasma-neutrino emission is relevant only in the initial phases of WD, lasting for about 2 Myr and with a peak emission of $\approx 6 \cdot 10^{42}$ ν/s.

As a whole one expects from each WD a total yield of $\sim 3 \cdot 10^{56}$ neutrinos, slightly larger than the amount of cooling neutrinos produced in the previous phases, of the same order of magnitude as thermo-nuclear neutrinos emitted all along the life of low and intermediate mass stars. However the energy of plasma/photo neutrino pairs (20–50 KeV) is sensibly lower than that of thermo-nuclear neutrinos and thus their (future) detection will be correspondingly even more difficult.

Summarizing, stellar evolution gives us some relevant indications:

i) during their thermo-nuclear phase stars emit 10^{56} - 10^{57} thermo-nuclear ν, (almost) linearly depending on the stellar mass,

ii) in all cases the total yield of ν is dominated by the CNO contribution,

iii) during their nuclear life stars emit 3-5$\cdot 10^{55}$ photoneutrinos, and a similar number of plasma-neutrinos, these latter only for masses ≤ 9 M$_\odot$,

iv) The emission of plasma neutrino pairs by cooling WDs produces about 10^{56} neutrinos, i.e., a number of the same order of magnitude of the number of cooling neutrinos in previous nuclear phases.

4. Galactic neutrinos

Adopting from Cox & Mezger (1989) a galactic disk luminosity of $4.5 \cdot 10^{10}$ L$_\odot$, the thermo-nuclear neutrino production rate is easily found as $8 \cdot 10^{48}$ s^{-1}. To obtain more detailed predictions, one needs to estimate the neutrino fluxes from stars of various ages and chemical composition. As expected on very general grounds, and confirmed by numerical experiments (Raimondo 1995), assumptions about the original composition of the stellar structures play a minor role in our problem. Passing from a solar composition to extreme metal poor populations (Z=0.0001), for each given mass the total amount of neutrinos emitted by a star keeps constant within, about, 10%. Differences in the various types of neutrinos can reach a factor 2 or 3, depending on the stellar mass. To reach an order of magnitude estimate we will neglect the effects of chemical composition, interpolating the evolutionary results discussed in the previous sections to determine a theoretical value of both thermo-nuclear and cooling neutrino production rates for each value of the stellar mass and for each assumption about the age of the structure. A similar data base can thus be used to estimate the contribution of stars in our galaxy to the flux of neutrinos expected on earth.

However, to predict the neutrino spectrum one needs a model for the galactic stellar population. For this purpose we followed the galactic model of Bahcall (1986). We distributed $6 \cdot 10^{10}$ M$_\odot$

Table 1. Estimated production rate of thermo-nuclear neutrinos and of cooling neutrino-antineutrino pairs from the Galaxy

Reactions s^{-1}	Disk	Bulge	Total
ν_{pp}	$1.4\ 10^{48}$	$1.9\ 10^{47}$	$1.6\ 10^{48}$
ν_{7Be}	$1.4\ 10^{47}$	$1.8\ 10^{46}$	$1.5\ 10^{47}$
ν_{8B}	$5.7\ 10^{45}$	$4.0\ 10^{44}$	$6.1\ 10^{45}$
ν_{13N}	$2.7\ 10^{48}$	$2.9\ 10^{47}$	$3.0\ 10^{48}$
ν_{16O}	$2.7\ 10^{48}$	$2.9\ 10^{47}$	$3.0\ 10^{48}$
plasma (stars)	$2.5\ 10^{48}$	$2.1\ 10^{47}$	$2.7\ 10^{48}$
plasma (WD)	$4.8\ 10^{48}$	$5.8\ 10^{47}$	$5.4\ 10^{48}$
photo	$4.0\ 10^{46}$	0	$4.0\ 10^{46}$

Table 2. Estimated neutrino fluxes at the earth surface.

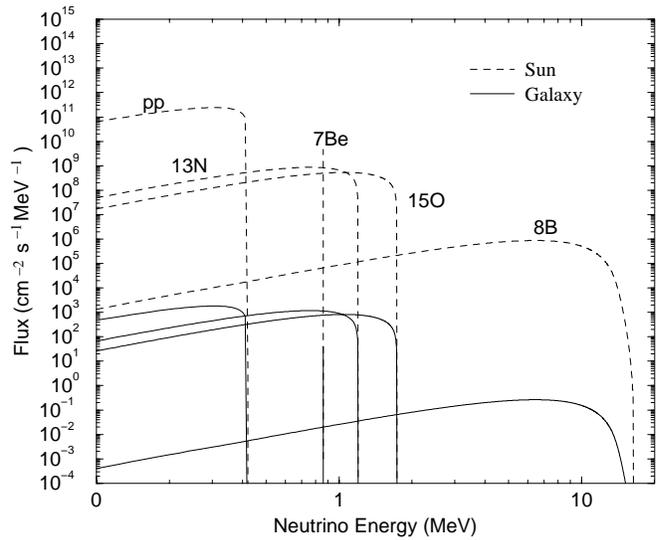| Flux cm^{-2} s^{-1}	Disk	Bulge	Total
ν_{pp}	420	22	442
ν_{7Be}	42	2	44
ν_{8B}	1.8	0.05	2
Total pp			488
ν_{13N}	810	33	843
ν_{16O}	810	33	843
Total CNO			1686
plasma (stars)	750	24	774
plasma (WD)	1440	67	1507
photo	12	0	12

of stars in the galactic disc, $1 \cdot 10^{10}$ M$_\odot$ in the galactic bulge, neglecting the contribution from the 1–$3 \cdot 10^9$ M$_\odot$ expected in the galactic halo. Again, we remark that these figures are to be taken as order-of-magnitude estimates. As a matter of the fact, the 'what you see is what you get' model by Fich & Tremaine (1991) gives for the disk a larger mass; $M_{disk} \simeq 10^{11}$ M$_\odot$, with only a minor contribution from interstellar matter. Interesting enough, one finds that even these order of magnitude estimates give constraints on the history of Star Formation Rate (SFR): adopting, e.g., a SFR constant with time one cannot reproduce the galactic M/L ratio for any reasonable assumption about the Initial Mass Function (IMF).

According to indications given in the recent literature (see, e.g., De Marchi & Paresce 1997) we adopted a Salpeter IMF for masses larger than 0.2 M$_\odot$ and a flat distribution below this limit, down to 0.1 M$_\odot$. With this choice, the galactic M/L is well reproduced by a disk with SFR of the form exp(-t/τ) with τ of the order of 2.5 Gyr. For the galactic bulge, a single episode of star formations 10^{10} years ago automatically accounts for the bulge luminosity (L$_{bulge} \simeq 5 \cdot 10^9$ L$_\odot$) as estimated by Cox & Mezger (1989). To evaluate the galactic neutrino production rate we used a Monte Carlo technique, randomly disseminating stars with masses and ages constrained by the above prescriptions, adding the contribution of the single sources to the final net galactic neutrino production rate. Table 1 gives the total neutrino production rate by the Galaxy according to the above quoted assumptions. It appears that in both disk and bulge populations the neutrino production is dominated by CNO neutrinos, as expected since the total photon luminosity is dominated by the most luminous, CNO burning stars. Moreover the balance among the various nuclear sources of neutrinos appear not too much dependent from the age of the stellar population.

Table 2 gives the neutrino fluxes on earth showing the contribution of the disk and of the bulge. As a whole, the Galactic neutrino flux is $\approx 2 \cdot 10^3$ cm^{-2} s^{-1} thermo-nuclear neutrinos which appears in agreement with the predictions by Hartmann et al. (1994) quoted in the introduction of this paper. A similar figure is found for cooling neutrinos. Fig. 7 shows the energy spectrum of galactic thermonuclear neutrinos compared with

Fig. 7. Galactic neutrino spectrum (continuos line) compared with the solar neutrino spectrum from Bahcall & Ulrich 1988 (dashed line). The neutrino fluxes from continuos sources are given in the unit of number per cm^2 per second per MeV and the line fluxes are given in number per cm^2 per second.

the theoretical solar neutrino spectrum from Bahcall & Ulrich 1988.

It is interesting to notice that present estimates of the galactic neutrino background appear in fair agreement with the corresponding background of photons. As quoted in the introduction of this paper, one expects neutrino and photon fluxes to be fairly stringently correlated, with 2 expected neutrinos every 26.7 MeV in photons (clearly this is true only in the approximation in which one neglects the energy arising from He burning which is expected to be a minor fraction of the total luminosity emitted by the Galaxy). For the galactic background Mathis et al. (1983) give the photon flux on earth in the wavelenght range 0.09-8 μm, due only to stars: $1.3 \cdot 10^{10}$ eV s^{-1} cm^{-2}, which would imply a neutrino flux of about 950 ν cm^{-2} s^{-1}. in agreement with present theoretical expections.
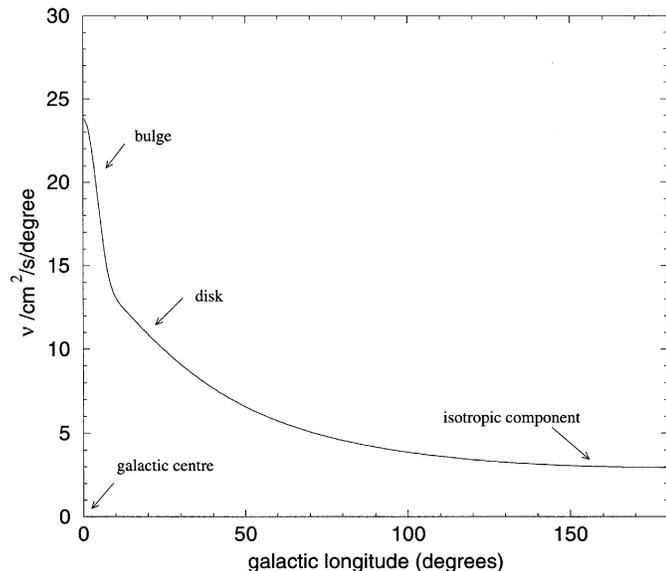
Fig. 8. The angular distribution of the total neutrino flux for the present galactic model (see text) in terms of the galactic longitude ϕ (the center of the Galaxy is at ϕ=0).

Fig. 8 shows the angular distribution of the total neutrino flux in terms of the galactic longitude, ϕ. One can distinguish three components:
i) an isotropic component, due to the nearest stars, of about 3 ν cm^{-2}s^{-1}degree^{-1}. This contribution is reduced to $\approx$1 ν cm^{-2}s^{-1}degree^{-1} if we include in the computation only stars distant from the Sun more than 1 Kpc.
ii) the contribution of the bulge which decreases rapidly to zero in few degrees away from the direction of the galactic center.
iii) the disk component, which, in agreement to the adopted star distribution, decreases to about 1/3 for a galactic longitude of about 50°.
One notes that stars within 1 Kpc^3 from the Sun contribute by about 1/3 to the total neutrino flux.

5. Cosmic background

From the estimate of the neutrino output of our Galaxy one easily obtains a corresponding estimate of the stellar contribution to the cosmic background of neutrinos if, on the average, galaxies radiated over all the time as our own Galaxy does at present time. As a matter of fact, the density of neutrinos can be simply obtained by multiplying the neutrino production rate per galaxy by the spatial density of galaxies in the Universe and by the time elapsed since the appearance of galaxies. The flux is finally given by the neutrinos density times the speed of light. We already found that our Galaxy produces about $8 \cdot 10^{48}$ ν/s. Since, on the average, galaxies are slightly more massive than our own Galaxy, let us scale this figure to a mean galaxy with about 10^{11} M$_\odot$, thus adopting a neutrino production rate of about $1 \cdot 10^{49}$ ν/s. For such a rough estimate of the cosmic background one can multiply the galactic neutrino production rate for the mean density of galaxies (0.01 Mpc^{-3}, see e.g. Peebles 1971) and for

a reference galactic age of 10 Gyr. For thermo-nuclear neutrinos, the result is a background density of 10^{-9} ν cm^{-3} and a flux of 40 ν cm^{-2} s^{-1}. A corresponding figure is for cooling neutrinos. We already noted that the balance among the various nuclear sources of neutrinos is not dramaticaly dependent from the stellar population, thus data in previous Tables 1 and 2 could also be used to give a rough estimate of the relative abundances of thermo-nuclear neutrinos and the corresponding energy spectrum.

One may finally notice that the comparison between observational values and theoretical predictions is not a safe procedure for the cosmic background due to the presence of sources other than nuclear which contribute to this quantity (e.g. the active galactic nuclei). However, one can adopt the present theoretical result as a rough estimate of the stellar contribution to the cosmic background. If one takes into account that galaxies are suggested to have been more luminous in the past, the present result can be regarded as a lower limit for the contribution to the cosmic neutrino background given by stars during their 'normal' thermo-nuclear life and their final cooling phase.

As a whole, one finds that the above estimates are only marginally affected by the adopted model of the galaxy, the key parameter remaining the assumed galactic luminosity. In particular, reasonable variations of the adopted IMF affects the galactic M/L and/or the SFR but with negligible influence on the given order of magnitudes for neutrinos backgrounds. For the sake of comparison, one may recall that the additional contribution by supernovae to the cosmic neutrino background has been estimated of the order of $\approx$1 ν cm^{-2} s^{-1} (Woosley et al. 1986, Hartmann et al. 1994). A figure, however, to be regarded as a lower limit, since several arguments suggest a possible increase of the fluxes up to one or two orders of magnitudes (see Krauss et al. 1984, Woosley et al. 1986). In this context, one may notice that if a SN emits $3 \cdot 10^{53}$ erg under the form of neutrinos with mean energy 13 MeV (Woosley et al. 1986), the total neutrino yield is given by $1 \cdot 10^{58}$ ν. It follows that in our Galaxy 2 SN per century would give the same yield of neutrinos given by all the quiescent stars in the Galaxy.

6. Final remarks

We presented detailed evolutionary computations for estimating the total yield of neutrinos (both from nuclear and cooling origin) produced by stars of various masses all along their nuclear life and the final cooling as WD. Adopting a reasonable modelization of the Galaxy we predicted the flux of stellar neutrinos at the earth surface, giving also a lower limit for the flux of cosmic neutrinos. In all cases, we find that CNO neutrinos dominate the flux, with a distribution among the various nuclear sources which appears not considerably dependent on the assumed stellar population.

Before closing the paper, it may be worth noticing that the adopted galactic M/L ratio, as taken from the current literature, does not support the often quoted nuclear evidences for a larger luminosity of galaxies in the past, as far as our own Galaxy is concerned. According to an argument early presented by Hoyle

& Tayler (1964), and recently reviewed by Reeves (1994), if the energy presently emitted by a "mean" spiral galaxy is evaluated of the order of $2 \cdot 10^{-13}$ eV/nucleon s^{-1}, and if this energy output remained constant over the time, thus one finds that all along the life of galaxies, only 1.4% of H can have been converted in He, against the observational evidences which suggest an increase of the abundance by mass of He of the order of 5%. This led to the hypothesis that galaxies were more luminous in the past.

However, adopting for the Galaxy, as we did, L$\simeq 4 \cdot 10^{10}$ L$_\odot$ and M$\simeq 7 \cdot 10^{10}$ M$_\odot$, one would derive an energy output per nucleon about 6 times larger, or 4 times larger if one assumes a galactic mass of $1 \cdot 10^{11}$ M$_\odot$. Accordingly, one finds that for a constant luminosity 5–8% of H is allowed to have been converted in He, in agreement with observational constraints. We do not claim that the galactic luminosity was constant in the time: we only drive the attention on this matter to stimulate further discussion on a point that is well beyond the purpose of this paper.

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