

NEUTRINOS FROM PRE-SUPERNOVA STAR* **

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Analysis of the massive star properties during C, Ne, O & Si burning *i.e.* the neutrino-cooled stage, leads to the simplified neutrino emission model. In the framework of this model we have simulated spectrum of the antineutrinos. Flux normalized according to the massive star model with explicitly given neutrino luminosity allow us to predict signal produced in water Cherenkov detectors. The results are discussed from the point of view of the possibility of the *core-collapse* supernova event prediction in advance of a few days.

PACS numbers: 29.40.Ka, 95.85.Ry, 97.60.–s, 97.60.Bw

1. Introduction

In this paper, we will overview problems discussed in more detail in our article “Detection possibility of the pair-annihilation neutrinos from neutrino-cooled pre-supernova star” [1]. The conference presentation can be viewed from the Epiphany 2004 homepage [2].

Until now, one has detected neutrinos from two specific astrophysical sources: the Sun and supernova SN 1987A. Solar neutrinos were detected because of proximity, and steady, uninterrupted emission. They were first detected by Raymond Davis chlorine detector at Homestake. Neutrinos from supernova 1987A, located far away, in our neighbor galaxy, The Large Magellanic Cloud, were detected because of extremely strong neutrino burst. This short burst that lasted about 1 minute carried enormous energy of 10^{53} ergs released in the gravitational collapse of the stellar core.

* Presented at the Cracow Epiphany Conference on Astroparticle Physics, Cracow, Poland, January 8–11, 2004.

** This research is partially supported by the Polish State Committee for Scientific Research (KBN), grants 2P03B 110 24 and PBZ-KBN-054/P03/2001.

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There exist a number of the proposed astrophysical neutrino sources expected to be possible to detect in the future, *e.g.* collapse of super-massive ($M > 100 M_{\odot}$) stars [3]. We would like to present here our proposition which is detection of the neutrino-cooled stars.

2. Neutrino-cooled stars

Neutrino-cooled star is a well-known astrophysical object, but under new, much more relevant name. This terminology was introduced in the excellent textbook of Arnett [4]. Shortly speaking, neutrino-cooled star is almost the same object as massive star or pre-supernova star, but at different evolutionary stage.

By the definition, massive star, is a star which is able to explode as the *core-collapse* supernova. Theory of the stellar evolution tell us that initial mass of such star is about 8–9 M_{\odot} or more. We define:

- Neutrino-cooled star — the massive star after ignition of the carbon burning.
- Pre-supernova star — the massive star at the onset of the collapse.

The word ‘*onset*’ is not very precise. One defines frequently the last model computed by the stellar evolution hydrostatic code as a pre-supernova star. Usually, the sequence of models is terminated if the inward velocity at some point (*e.g.* at the edge of the ‘Fe’ core) exceeds some previously defined value of *e.g.* 1000 km/s [5]. Nevertheless, from the external observer point of view, it is not a very big mistake, to refer to neutrino-cooled star as pre-supernova, because the evolution after carbon ignition is very rapid. It takes only 300 years for 20 M_{\odot} star to exhaust whole fuel. This time is very short compared to both the entire lifetime of a star (~ 10 mln years) and the Kelvin–Helmholtz timescale of hydrogen envelope ($\sim 10\,000$ years).

Introduction of the neutrino-cooled stars is not only the matter of enriched astrophysical terminology, but also reflects the important physical differences between these stars and *e.g.* the main sequence stars. The massive stars after carbon ignition are completely different from other stars.

Basic comparison of typical neutrino-cooled star, represented by the 20 M_{\odot} model of Woosley [6], and the main sequence star, represented by the Sun, reveals some very important facts. Lifetime of massive star is very short, about 10 million years, compared to 10 billion years for the Sun. Neutrino-cooled stage lasts only about 300 years. This is relatively short period. That is why some of astrophysicists think about neutrino-cooled events rather than neutrino-cooled stars.

The most important difference between these two stars is the process of cooling. Comparison of the photon and neutrino luminosities of our stars,

lead to the following conclusions. Neutrinos are only a small part ($\sim 2\%$) of the Solar energy budget. The opposite situation takes place in neutrino-cooled stars. The neutrino luminosity is impressively big, up to $10^{12} L_{\odot}$. The photon luminosity of $10^5 L_{\odot}$ is almost negligible¹ compared to the neutrino luminosity. The neutrino luminosity of $10^{12} L_{\odot}$ could explain the name: neutrino-cooled star, especially if we realize that this is 10^7 times more than the photon luminosity.

To imagine how big the neutrino luminosity is, let us make some very rough estimates. We will refer to our knowledge of supernova and solar neutrinos. Peak neutrino luminosity from *core-collapse* supernova reaches 2.5×10^{53} erg/sec $\sim 10^{20} L_{\odot}$, but it lasts only a few milliseconds [7]. The average neutrino luminosity during ~ 100 seconds of the main proton-neutron star cooling phase is $\sim 10^{51}$ erg/sec *i.e.* $\sim 10^{17} L_{\odot}$. This is still five orders of magnitude greater than the neutrino luminosity of $\sim 10^{12} L_{\odot}$ during silicon burning. If we take into account much longer time of silicon burning of a few days ($\sim 10^5$ seconds), we realize that the total amount of pre-supernova neutrinos may reach 1% of the total energy released during the *core-collapse* supernova event. In other words, if we are able to detect supernova neutrinos from ‘ x ’ kiloparsecs, we could possibly detect Si-burning neutrinos from distance of ‘ $x/10$ ’ kpc. Unfortunately, the energy of 10–20 MeV, typical for supernova neutrinos, is highly unlikely for pre-supernova neutrinos. Additionally, from the experimental point of view, it is much more difficult to detect the same number of the neutrinos but emitted in much longer time.

Solar neutrinos appear to have energy similar (on average) to pre-supernova neutrinos [1]. We may then ask a simple question: *From what distance neutrino-cooled star will “shine” on the “neutrino sky” like the Sun?* Precisely, from what distance D to the massive star, the neutrino flux on the Earth will be the same for both the neutrino-cooled star and for the Sun? Very simple expression gives the required distance in astronomical units:

$$D = \sqrt{\frac{10^{12} L_{\odot}}{0.02 L_{\odot}}} = 6.2 \times 10^6 \text{ AU}, \quad (1)$$

as only $0.02 L_{\odot}$ of the energy released in the Sun’s core is carried off by the neutrinos. Distance (1) is equal to thirty parsecs or 100 light years.

One of the closest, known at the moment, stars, similar to our neutrino-cooled star, is Betelgeuse (β Ori), 185 parsecs away. This is five times further away than (1), so we may conclude that the detection of neutrinos from such star is impossible, because simply no such close star exists!

Fortunately, this is a wrong conclusion, because the neutrino emission from the pre-supernova star is different compared to the solar neutrinos.

¹ This value is still a hundred thousands times greater than the solar luminosity L_{\odot} .

3. Pair-annihilation neutrinos

3.1. Spectrum of the pair-annihilation neutrinos

In the neutrino-cooled stars the energy generation is balanced by the neutrino emission. Energy sources are the nuclear reactions and gravitational energy. They are balanced by the emission of the thermal and weak-nuclear neutrinos. The former dominates, but the latter is progressively more intense and finally (during Si burning) becomes the most important [9]. A lot of processes can produce thermal neutrinos [10]. The most dominant process is annihilation of the electron-positron pairs into neutrinos. This process requires very high temperature of $\sim 10^9$ K.

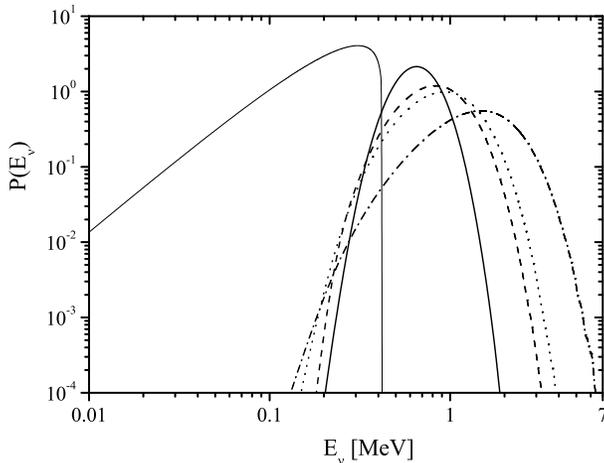


Fig. 1. Normalized spectrum of the pair-annihilation neutrinos ($\bar{\nu}_e$) emitted during C (solid), Ne (dashed), O (dotted) and Si (dot-dashed) burning stage [1] and the solar pp neutrinos (thin line) [8]. Average $\bar{\nu}_e$ energy is 1.85 MeV during Si burning, but spectrum extends up to ~ 6 MeV. The solar neutrino spectrum is known to be more complicated. Possibly, the same holds for the pre-supernova star, but this requires further research. See also Fig. 1 of Ref. [1] or [2] where the massive star is at distance of 1 kpc, while the Sun is still at distance of 1 AU.

We have calculated spectrum of the pair-annihilation neutrinos [1]. The result is presented in Fig. 1 together with solar pp neutrinos. Actually, neutrino spectrum of the pre-supernova star is possibly more complicated due to numerous nuclear and thermal processes. Little is known about this spectrum. Besides our calculations of the pair-annihilation process, only the spectrum of the six e^- capture processes on the ‘Fe’ nuclei during Si shell burning has been calculated [11]. Some of these neutrinos have energy of ~ 8 MeV. This indicates that detailed study of neutrino-cooled star neutrino

spectrum may reveal “solar $^8\text{B } \nu_e$ equivalent”, leading to much easier and well-understood detection techniques compared to those discussed in this article.

As we can see (Fig. 1), the spectrum is different, and in some energy range, close to 1–2 MeV, the detection of the neutrino-cooled star may be easier than the detection of the solar pp neutrinos. But the most important difference, not visible in Fig. 1, is the presence of antineutrinos. Pair-annihilation neutrinos are produced in the reaction:

$$e^+ + e^- \longrightarrow \nu_x + \bar{\nu}_x, \quad (2)$$

where $x = e, \mu, \tau$. About 1/3 of the flux is in the form of the electron antineutrinos [1]. In contrast, the Sun does not emit antineutrinos of any flavor at all.

3.2. Detection using inverse β decay

As we have pointed out ([1], Sec. 5) the presence of the antineutrinos is very important, because we may use very efficient reaction of inverse beta-decay for the detection purpose:

$$\bar{\nu}_e + p \longrightarrow n + e^+. \quad (3)$$

This reaction for the Si burning neutrinos has large spectrum-averaged cross-section $\bar{\sigma}_{\text{Si}} \simeq 0.7 \times 10^{-43} \text{ cm}^2$ [1]. This is 3 times more than *e.g.* the cross-section for elastic neutrino–electron scattering.

3.3. Event rates in H_2O

We have estimated event rate, which is the number of reactions (3) induced by the pair-annihilation neutrinos in the water. Event rate r is:

$$r [\text{day}^{-1}] = f \bar{\sigma}_\alpha [\text{cm}^2] N \phi_\alpha [\text{cm}^{-2} \text{ day}^{-1}], \quad (4)$$

where f is $\bar{\nu}_e$ fraction, $\bar{\sigma}$ is the averaged cross-section, N is the number of targets, ϕ is the flux on Earth; $\alpha = \text{C, Ne, O, Si}$ refers to a burning phase. During silicon burning, for $20 M_\odot$ star, from distance of 1 kpc, in one kiloton of water, pair-annihilation neutrinos will produce 1.3 neutrons per day [1]. This result is easy to remember: we have approximately one reaction per day in one kiloton of the water from distance of 1 kiloparsec. This is relatively high event rate, especially in the volumes of the future megaton-scale detectors: Hyper-Kamiokande [12] and UNO [13].

Let us summarize:

- giant source of the electron antineutrinos has been identified;

- reaction with large cross-section for the detection purposes has been chosen;
- expected reaction (3) rate in the water is relatively high.

The most confusing problem is how to detect the products of the reaction (3) in giant volumes of water detectors.

3.4. Inverse β decay in water detectors

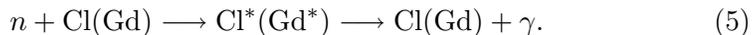
The detection of the reaction (3) products in water is very difficult. The positron energy $E_{e^+} \simeq E_\nu - 1.8$ MeV is too low to produce detectable Cherenkov light. Neutrons are captured on protons, producing invisible 2.2 MeV gamma-ray cascade. Nevertheless, chance for detection exists, as it is discussed in the next subsections.

3.5. Detection of e^+

Both e^+ and e^- are detected in water detectors via emission of Cherenkov light. In Super-Kamiokande detector, reaction (3) rate for Si burning neutrinos from star at distance of 1 kpc is 41/day. Because of the threshold energy only a fraction of positrons produced by (3) will be detected². This fraction very strongly depends on the actual value of threshold (*cf.* Table I). For single events threshold may be as low as ~ 4 MeV in SK [14], but still only 0.7% of reactions (3) could be detected. Without dramatic improvements of experimental technique detection of positrons alone seems to be hopeless.

3.6. Detection of neutrons

We are able to detect neutrons produced by reaction (3) if we dissolve in water some efficient neutron absorber. In SNO [15] neutrons are detected using capture on Cl (dissolved salt) nucleus. Other proposed method is to dissolve GdCl_3 in water [16], with gadolinium being very effective neutron absorber. Neutrons will be captured on these (Cl, Gd) nuclei:



The excited nucleus emits cascade of the gamma-rays with total energy of ~ 8 MeV. High energy photons hit electrons, and scattered electrons (with energy above detector threshold) radiate Cherenkov light. Cherenkov light is detected by the photomultipliers.

² In contrast, supernova $\bar{\nu}_e$'s produce e^+ well above detector threshold, with almost 100% detection efficiency.

TABLE I

Number of the detectable positrons for given detector threshold in Super-Kamiokande. The neutrino energy E_ν required to produce positron of energy E_e (including rest mass) is greater than $E_\nu = E_e + \Delta$, where $\Delta = m_n - m_p$ is difference between neutron and proton mass. Using coincidence with n capture on Cl or Gd, reduction of the threshold may be possible, as indicated by an arrow.

$E_{\text{th}}^{\bar{\nu}_e}$ [MeV]	$E_{\text{th}}^{e^+}$ [MeV]	Detectable positrons (day) ⁻¹	
1.8	0.5	41	
3.0	1.7	22	
4.0	2.7	6.5	↑
5.0	3.7	1.2	SK
6.0	4.7	0.2	
7.0	5.7	0.0	

SNO experiment has proved that neutron detection efficiency with the use of this method is close to 100% [15]. Nevertheless, high background level (*e.g.* ~ 100 events/day for Super-Kamiokande) allow us to detect neutrino signature of the massive star silicon burning stage only for a few very close stars, *e.g.* Betelgeuse [17].

3.7. Coincidence detection of both e^+ and n

Overall detection efficiency for low (\sim few MeV) energy antineutrinos by reaction (3) can possibly be greatly improved if coincidence of neutron capture and e^+ Cherenkov light will be used. Using coincidence, we are able to reduce detector threshold [15]. This is extremely important (*cf.* Table I), because number of detectable events rises very fast with reduced threshold energy. Hopefully, values as low as 2.5 MeV for recoil electron energy could be reached [16]. Such low value of the threshold, for silicon burning antineutrinos with spectrum presented in Fig. 1 allow us to detect 10% of reactions (3) occurrences in the water Cherenkov detectors. These coincidence events could be distinguished from background signal much easier than single neutrons. In scintillator detectors, *e.g.* KamLAND, gammas from annihilation of the positron produced in the reaction (3) give additional 1 MeV of the detectable energy.

4. Conclusions

If we solve all problems related to the detection of neutrons and positrons, produced by antineutrinos in water Cherenkov or other detectors in the reaction (3) new, amazing possibility will open.

In Super-Kamiokande detector, enhanced by dissolved neutron absorber (NaCl, GdCl₃) the signal produced by the neutrinos from Betelgeuse (15 M_{\odot} red giant at distance 185 pc) during Si burning could be ~ 1000 events/day *i.e.* 10 times more than current background level [17]. Therefore, prediction of supernova explosion for nearby stars in advance of a few days is possible. Unfortunately only a few such close stars exist³, with extremely small explosion probability in, say, next 100 years. Therefore, the question is from what distance we will be able to detect Si burning neutrinos. In Super-Kamiokande, detection of neutrons captured by the Cl or Gd is possible only if the number of events exceeds background signal of ~ 100 events/day. Such neutron signal results from 20 M_{\odot} star at distance of ~ 600 pc. Much more promising is detection using coincidence of n capture with e^+ . Assuming that every single such coincidence event/day with e^+ energy above 2.5 MeV can be distinguished from the background, we get the maximum observation range of 2 kpc. This is close to gravitational radiation from *core-collapse* supernova detection abilities of LIGO I detector of 5 kpc [19].

If megaton-scale detectors, like proposed Hyper-Kamiokande (540 kilotons) [12] or UNO (440 kilotons) [13] do appear, we will be able to extend observational range significantly. We may expect, for Hyper-Kamiokande, increase of detectable stars range by a factor of $\sqrt{540/32} \simeq 4$ due to target volume much larger than Super-Kamiokande (of only 32 kilotons). Up to a distance of 8 kpc we expect to find 35% of the Galaxy disk stars [20]. For the closest massive stars (Betelgeuse, γ^2 Vel), such giant detectors allow us even to attempt detection of Ne and O burning antineutrinos with number of reactions (3) of 2/day and 45/day, respectively. These burning stages precede core collapse by a few months. This could give us insight into pre-supernova star burning processes, and establish initial conditions for *core-collapse* supernova explosion. It could also provide us with very early warning of subsequent core collapse. This would allow scientists to prepare all available observational devices, being down *e.g.* due to maintenance, especially gravitational radiation detectors. It could help not to miss the most expected astrophysical event.

³ One of them is binary system γ^2 Velorum at distance of 258 pc, which consists of $\sim 9.5 M_{\odot}$ Wolf-Rayett star and $\sim 30 M_{\odot}$ O star [18].

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