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PRESUPERNOVAE AS POWERFUL NEUTRINO SOURCES*

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In this report, some research results of the neutrino astrophysics group at the Institute of Physics of Jagellonian University are presented `http://ribes.if.uj.edu.pl/psns`. It is shown that neutrinos emitted by presupernovae located within a few kpc from Earth could be detected by new generation of neutrino detectors. We encourage planners of the future neutrino experiments to include presupernova neutrino measurements on their agenda.

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1. Introduction

The possibility of detection of neutrinos emitted by presupernovae was for the first time proposed in [2]. In this paper, we considered pair-annihilation neutrinos from very hot plasma, whose flux can be quite unambiguously calculated provided thermal properties of the stellar interior are known. In contrast to solar neutrinos, the flux is composed of both neutrinos and antineutrinos which is clearly advantageous as far as detection possibility is concerned.

We estimated the signal produced in neutrino observatories by the pair-annihilation neutrinos emitted from a 20 $M_{\odot}$ presupernova star at last stages of nuclear burning. During the Si-burning phase one expects of order of 1 neutrons/day/kiloton of water to be produced by antineutrinos from a star located at a distance of 1 kpc.

Stars at advanced stages of evolution when heavier nuclei are burnt in thermonuclear reaction are often referred to as neutrino-cooled stars. This is because the energy flux emitted by such stars is dominated by neutrinos

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with electromagnetic energy flux essentially negligible. Nearby candidate for such a presupernova is Betelgeuse (β-Ori) at a distance of order of 100 pc. Other candidates include such stars as Mira Ceti, Antares, Ras Algheti, 2 Vel, Sher25 and Eta Carinae.

In the following, brief summary of stellar evolution is presented. Then calculations of the spectrum of pair-annihilation neutrinos is outlined. The method of converting the water Cherenkov detectors into efficient detectors of presupernova neutrinos is discussed. Finally, counting rates for some detectors are shown.

2. Presupernovae as neutrino-cooled stars

Theory of stellar evolution predicts that heavy stars, with initial masses above 9 $M_{\odot}$, are able to ignite carbon ^{12}C and all other exothermic nuclear reaction in their cores. Less massive stars do not produce high enough central temperature to ignite carbon before the onset of electron degeneration. Corresponding pressure stabilizes the star which gradually cools down becoming carbon white dwarf.

Heavy stars at the last stages of nuclear burning develop dense and hot cores where the heavier nuclei are burnt, and finally the iron aggregates. When the iron core is big enough the collapse occurs and the star ends its life in a supernova explosion.

The last main stages of nuclear burning for a 20 $M_{\odot}$ star, carbon, neon, oxygen and silicon burning, last, respectively, 300 yrs, 140 days, 180 days and 2 days [3]. The photon luminosity for such a star is about $10^5 L_{\odot} = 4 \times 10^{38}$ erg/s. It remains constant until the collapse of the core, as the core is thermally decoupled from the surface on 300 yrs time scale. The neutrino luminosity during the C, Ne, O and Si burning steadily grows and is 7×10^{39} erg/s, 1×10^{43} erg/s, 7×10^{43} erg/s and 3×10^{45} erg/s, respectively. Already at the carbon burning, the neutrino luminosity is 20 times greater than the photon luminosity and still grows becoming 10^7 times the photon luminosity at the silicon burning.

The strong increase in energy output in the form of the neutrino flux is a result of the inner structure of the star: the central temperature, $T_{\rm c}$, and the central density, $\rho_{\rm c}$, continuously grow. The thermal energy, $k_B T_{\rm c}$, at the C, Ne, O and Si burning is, respectively 0.07 MeV, 0.15 MeV, 0.18 MeV and 0.32 MeV. The central density is 2.7×10^5 g/cc, 4×10^6 g/cc, 6×10^6 g/cc and 5×10^7 g/cc, respectively. This is rather high density, of a few hundred kg/cc up to 50 tons/cc.

3. Detection of presupernovae neutrinos

Our main task is to assess the possibility of detection of neutrinos and antineutrinos emitted by presupernovae.

Up to now neutrinos from two astrophysical sources, the Sun and the supernova SN1987A, have been detected at Earth.

Solar neutrinos were detected with sub-kiloton detectors, because of relatively small distance to the Sun and its continuous emission. Supernova neutrinos carry enormous energy of 10^{53} ergs released in gravitational collapse of the stellar core. This makes their detection possible from quite large distances, but such events are rare.

Up to the time the paper [2] appeared no other stellar sources of neutrinos have been considered detectable. In that paper we considered the feasibility of detection of giant astrophysical sources of neutrinos, namely presupernovae which are massive stars at late stages of their evolution. Such stars, during C, Ne, O and Si burning phases, emit neutrinos copiously and are really neutrino-cooled stars.

The structure of such evolutionary advanced stars is different from main sequence stars like the Sun. The solar neutrino luminosity is 7.8×10^{31} erg/s. The maximum neutrino luminosity during Si burning exceeds 3×10^{45} erg/s — a value larger by a factor of 3.85×10^{13}. The neutrino energy flux at Earth from such a star and from the Sun are equal for a star at a distance 6.2×10^{6} a.u., *i.e.* 30 pc away. This indicates that neutrino-cooled stars could be detected at astronomical distances. Actually, because of a different spectrum and the presence of antineutrinos, neutrino detectors are able to detect them from distances of order of 1 kpc.

To estimate the total neutrino flux from pair annihilation in the hot plasma inside a 20 $M_\odot$ star one can consult the paper [4] where contribution of the most important neutrino emission processes of the stellar plasma is shown as a function of temperature and density. It is clear that for the central temperature and density range during C, Ne, O and Si burning, neutrinos produced by thermal processes are the most important component of the neutrino flux balancing the nuclear energy generation in the central region of the star. Actually, so-called photoneutrinos and neutrinos from plasmon decay may contribute to the total neutrino flux, depending on physical conditions [4]. This assumption is valid up to the silicon burning. At this phase the amount of neutrinos produced by weak nuclear reactions (beta decays, electron capture) increases, and finally dominates the neutrino flux.

4. Spectrum of presupernovae neutrinos

The crucial step in calculating the response of various detectors to presupernova neutrinos is to obtain the spectrum of antineutrions and neutrinos [2]. In the hot plasma, the dominating reaction is

$$e^{+}+e^{-}\rightarrow\nu_x+\bar{\nu}_x\,.$$

There are two Feymann diagrams, corresponding to $W^{\pm}$ and Z^0 exchange, which are important. We calculate the spectrum [5] verified with the Monte-Carlo simulation [6]. Both, electrons and positrons are described by Fermi–Dirac (FD) distributions. Conditions in the central region of the presupernova star define FD distribution parameters, *i.e.* the temperature and the chemical potential. The latter one is obtained from the density ρ_{c}. In the simulation we pick up electron and positron four-momenta from FD distributions, transform to the center-of-mass frame, distribute neutrino momentum directions randomly, and convert neutrinos energy back to the rest frame. Every single event is counted with the square of the matrix element as a weight.

The neutrino spectrum and antineutrino spectrum are different because of the chemical potential which increases with the central density, however, the total number of neutrinos and antineutrinos is the same.

It is important to note that mean neutrino and antineutrino energy increase with the central temperature of the stellar core. At the carbon burning stage the mean energy is about 0.7 MeV and it exceeds 2 MeV at the silicon burning.

Other contribution to the presupernova neutrino spectrum from plasmon decay are calculated in [8] and from weak nuclear processes in [7].

In Fig. 1 in [2], the spectrum of neutrinos from a presupernova star at 1 kpc is compared to that of solar neutrinos and in Fig. 2 to the spectrum of geoneutrinos.

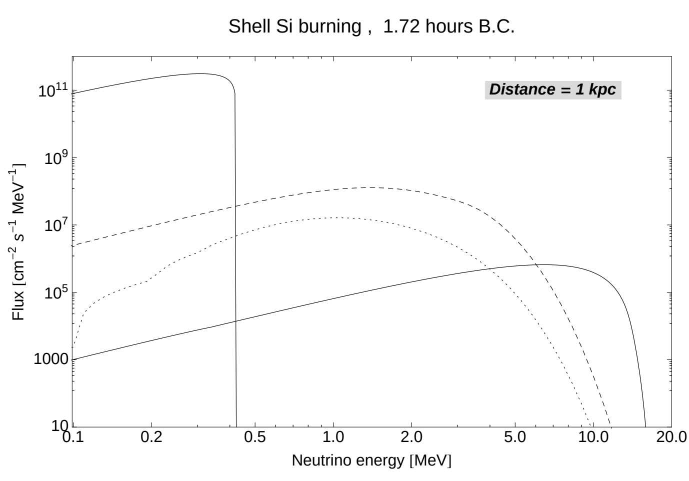

Fig. 1. Neutrino spectrum from presupernova at 1 kpc burning Si compared to pp and B solar neutrino spectrum.

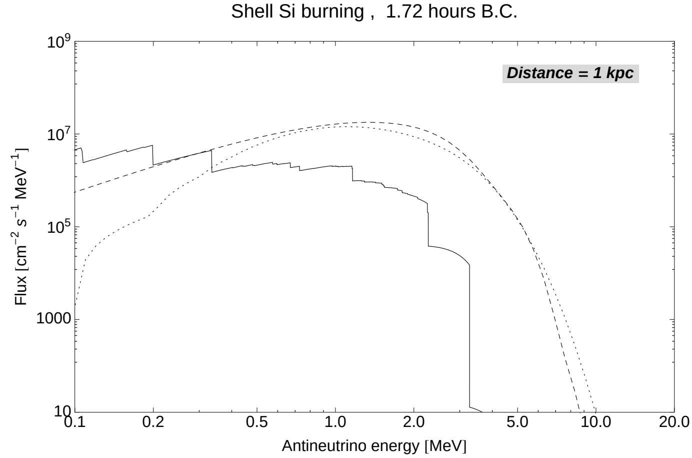

Fig. 2. Presupernova antineutrino spectrum from Fig. 1 compared to that of geoneutrinos.

5. Response of detectors to presupernova neutrinos

Because of low, due to large distance, neutrino flux from candidate stars undergoing advanced stages of nuclear burning, very large detectors are needed in order to detect the signal. There are proposals of next generation water Cherenkov detectors for proton decay searches, UNO and Hyper-Kamiokande, with 440,000 and 540,000 tons of water in fiducial volumes, respectively. We include here also detectors employing Liquid Scintillator (LS) that will be capable of detecting supernova neutrinos. The low energy threshold for recoil electrons and the scintillation light are their most important advantages over water Cherenkov detectors.

Because of the presence of antineutrinos, the most promising reaction as far as the detection of presupernova neutrinos is concerned, is the inverse β-decay

$$\bar{\nu}_e + p \to n + e^+ \,.$$

The cross-section is large, the energy threshold is low, and there is a delayed coincidence between positron annihilation and neutron capture signals.

Let consider the silicon burning stage of a 20 $M_\odot$ star at 1 kpc. The number of neutrons produced per one day in SuperKamiokande (32 kt of H_2O), UNO and HyperKamiokande is, respectively, 41, 560 and 687. Generally, one finds the silicon burning neutrinos to produce 1.27 neutrons/day/kiloton of water for a star 1 kpc away. SuperKamiokande is the best currently working detector for a such an observation, with 41 events per day, but needs a modification for making neutron detection possible.

To make detection of pre-supernova antineutrinos feasible we propose to supplement the existing and future water Cherenkov detectors with some addition of NaCl or $GdCl_3$ (see the proposition made by Beacom and Vagins GADZOOKS! [9]) to the water. Neutrons produced in inverse β-decay are captured by Gd or Cl nuclei producing high energy (above 8 MeV) gamma cascades. The addition of neutron absorbers is very important, because in a pure light water neutrons are captured by protons and produce not detectable 2.2 MeV gamma cascades, *e.g.* energy threshold in SK is about 5 MeV. This modification has been proved to work in the salt phase of solar neutrino detection in the SNO detector. The addition of NaCl to the kiloton of heavy water increased the neutron capture efficiency and the associated Cherenkov light. Direct detection of positrons produced in the inverse β-decay is discussed in [6].

Very promising seem to be the LS detectors of 5 kt mass. In Fig. 3 we show neutrino interaction rate in such a detector (*e.g.* LENA) for neutrinos emitted by Betelgeuse. As one can see, the counting rate should exceed the solar neutrino range half a year before the collapse.

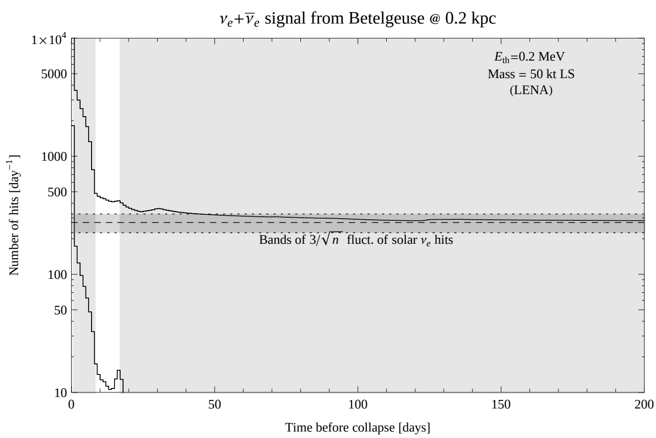

Fig. 3. Interaction rate in hits per day for 50 kt LS detector (LENA) for neutrinos from the star Betelgeuse.

For comparison, in Fig. 4, the signal for a presupernova located 10 kpc away is shown for the same detector as in Fig. 3. In this case, the warning could be issued only about one hour before the collapse.

6. Recent developments

All recent results we obtained can be found in [1]. In particular, Odrzywołek [7] has calculated the weak neutrinos spectrum from nuclear statistical equilibrium. This contribution becomes increasingly important with

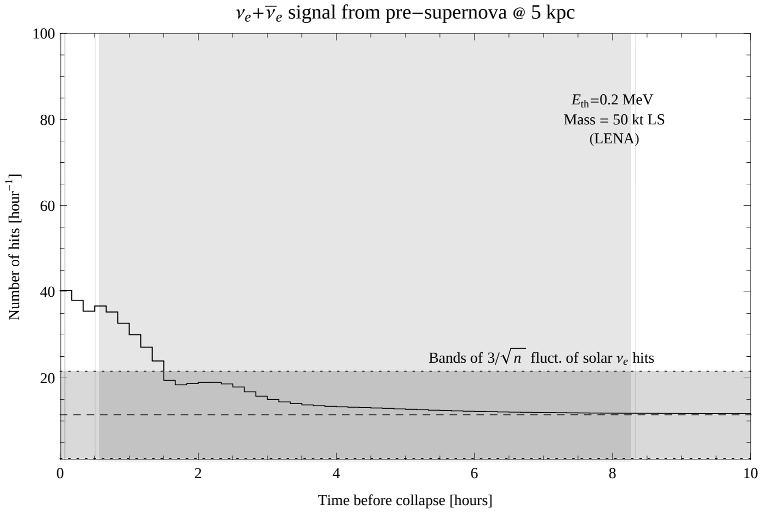

Fig. 4. Interaction rate for the same detector as in Fig. 3 for neutrinos from the presupernova 5 kpc away.

the growth of the central temperature. The total neutrino flux increases significantly at the last stages of the Si burning. In Fig. 5 it is shown that this flux matches the neutrino energy flux from the electron capture which dominates at the onset of the collapse of the stellar core.

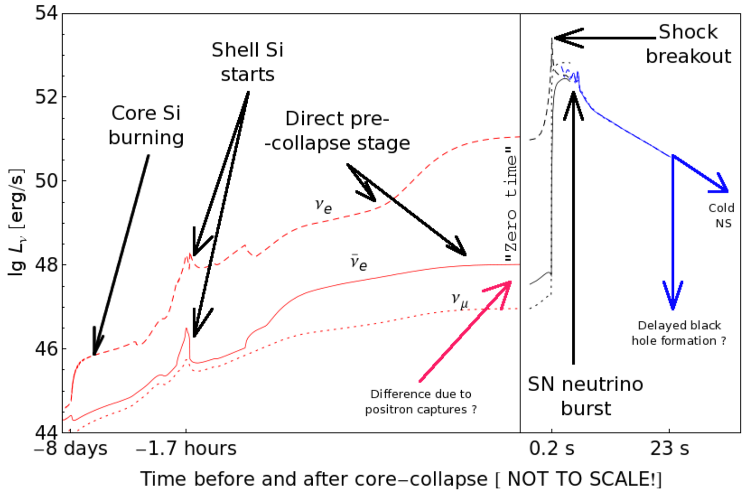

Fig. 5. Neutrino energy flux from presupernova during the last stages of nuclear burning and during the collapse of the core. Time zero denoted the onset of dynamical collapse, when electron capture dominates.

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