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SOLAR GAMMA FLUX INDUCED BY SUPERNOVA NEUTRINOS

I. HORVAT and T. PRODANOVIĆ

Department of Physics, University of Novi Sad,
Trg Dositeja Obradovića 4, 21000 Novi Sad, Serbia
E–mails: super.nova.horvat@gmail.com, prodanvc@if.ns.ac.yu

Abstract. Supernova (SN) explosions release a burst of neutrinos. In order to get an "early" signal and an estimate of the energy released in a nearby supernova explosion, we explore processes that neutrinos would induce in hydrogen-rich environments: $p + \bar{\nu}_{\mathrm{e}} \rightarrow n + e^{+}$. We consider the accompanying positron annihilation with an electron, which results in a production of gamma-rays of 0.511 MeV. Our idea is to use the Sun, as a hydrogen- rich environment, to detect this kind of events indirectly, before an optical display of supernova. We theoretically estimate 0.511 MeV gamma - ray flux induced in the surface layer of the Sun.

1. INTRODUCTION

At the end of the nuclear fuel production, star undergoes gravitational collapse. During a core-collapse supernovae (type II or Ic) a huge amount of energy is released, of the order of magnitude $\sim 10^{53}$erg. Almost the entire energy, about 99% is radiated away in the form of neutrinos, while only 1% is mechanical energy of expeling outer layers of just exploded star. In the case of nearby supernova, a fraction of neutrino flux would reach the Sun, where in its outer, hydrogen-rich layers they would then interact with protons producing positrons and free neutrons. Furthermore, neutron capture on proton then results in 2.2 MeV gamma line emission, while positrons annihilate with electrons, producing 0.511 MeV line (Lu et al. 2007). The basic idea of this paper is to give a theoretical estimate of the gamma-ray flux induced by a neutrino flux from a nearby supernova, which will efficiently escape from the outer layers of the Sun and thus could be potentially detectable by the gamma-ray instruments in the Earth's orbit. This could represent a new kind of signal and a useful indicator of supernova process, before an optical display. For the most optimistic assessment, in this paper we consider only 0.511 MeV gamma line and we assume that all annihilation processes as well as positron thermalization happen instantaneously. Due to neutrino's weak interaction with the ordinary matter, they are the first signal which will be released from the supernova explosion. This allows us to detect this kind of event before we could detect it visually. It is certain that in the case of Galactic nearby supernova, a fraction of neutrinos will reach the neutrino detectors on the Earth. However, there is a reasonable worry that the saturation of detectors might occur, like it happened in the case of 1987A SN. If that would be the case then one would be unable to determine the total neutrino flux neither the total amount of energy released. We choose the Sun, as our largest natural neutrino detector because of the large number of targets with which neutrinos could interact, and as a sort of neutrino-to-gamma ray signal converter, because of the numerous gamma-ray detectors oriented toward the Sun. Besides being the first signal, studying neutrinos and its consequent, associated gamma-ray flux is important for a few more reasons. We have the opportunity to explore the latest phases of the stellar evolution as well as conditions in the inner core of just exploding star. As additional motivation we also instance the lack of visible supernovae through the history, since the stellar mass function predicts much more SN events than it was observed. Thus our method could be a good indicator of supernovae known as "quiet supernovae" or "neutrino bombs".

2. NEUTRINOS

There are two main processes which lead to neutrino production in the supernova event. Neutronization of matter is the secondary process, giving approximately 6% of total SN neutrinos. This process is also known as the capture of highly energetic electron onto proton, which gives neutron and an electron neutrino.

$$p + e^- \rightarrow n + \nu_e \tag{1}$$

The dominant channel is the production of thermal neutrinos, which arise in the extreme environments such as the core of a star that is about to undergo supernova explosion. When the temperature is of order $\sim 10^9$ K $\gamma\gamma \rightarrow \nu\tilde{\nu}$ interaction emerges. Production of neutrino-antineutrino pairs occurs for all neutrino flavors. Neutrino signal lasts only for $\sim$ 10s and starts immediately after the shock wave is launched. Shock propagates with velocity of about 0.1 c so it needs from a few hours up to a few days time to emerge, and thus the associated photon emission is delayed compared to the neutrino emission. Mass of the iron core of a future supernova is weakly dependent to the mass of the progenitor star. Thus we can consider neutrino emission to be universal (Takahashi et al. 2003). Also, in order to make the most optimistic prediction, we neglect neutrino oscillations and assume that all neutrinos produced at supernova would reach the Sun with no losses to the flavor.

3. GENERAL CASE: NEUTRINO-INDUCED GAMMA RAYS

A fraction of neutrinos created in the supernova reaches the Sun. The average energy of neutrino released from SN event is $\epsilon = 16$MeV (Takahashia et al. 2003.). We choose to explore gamma-ray production in the outer layers of the Sun because gamma photons will escape efficiently only from these layers. Again, for the purpose of obtaining the most optimistic estimate we will take the resulting gamma-ray flux to be isotropic [1] and neglect any variations in neutrino flux similar to the day-night variations of Solar neutrino flux detected on Earth. Once they reach the Sun, electron antineutrinos will be absorbed by the protons and the production of neutrons and positrons then follows:

[1] or anisotropic but with having our gamma-ray detector to serendipitously face that side of the Sun from which the highest flux of gamma rays induced in this way will emerge.

$$\tilde{\nu}_e + p \rightarrow n + e^+ \ . \tag{2}$$

A fraction of free neutrons created in such a way then captures onto protons producing deuterium and a gamma-ray at 2.2 MeV

$$n + p \rightarrow {}^2H + \gamma \ . \tag{3}$$

However, this process will not be considered in this work due to its small total flux, despite a higher gamma photon energy. The main reason is that most of free neutrons, before being radiatively captured by protons, are captured by ^{3}He. On the other hand, highly energetic positrons that were created will annihilate with free or bound electrons, giving rise to two 0.511 MeV gamma-rays

$$e^+ + e^- \rightarrow 2\gamma \ . \tag{4}$$

The emission of this annihilation line follows the neutrino emission and lasts for about 10 s (Lu et al. 2007).

Positrons can lose their energy through many processes. For the Sun's surface conditions, the most dominant one is due to excitation of free electrons in plasma. Energy loss as well as annihilation process depends on the conditions and ionization of the environment. Positrons can annihilate directly or first form positronium (Ps) - a short lived bound state of electron and positron (in a singlet or triplet state), with free or bound electron, where positronium state will also end in 0.511 MeV annihilation line. In the case of Ps production of 3 gamma photons also occurs, but less frequently and contributes to a continuum, rather than a line. We thus omit this channel, since it is significantly reduced by the transition from the triplet to the singlet state (Share et al. 2003).

Direct annihilation is more likely to happen before thermalization, in the relativistic regime, where energy of positron is still large enough 21.2 MeV. Since thermalization will happen within the period of 1s, only about 12% annihilate directly (4% of positrons will form Ps states in this regime as well). After positrons go through the process of thermalization, positron energy drops below 250 eV down to 2 eV and they dominantly form Ps, about 85% (Lu et al. 2007). This regime is known as a non-relativistic regime.

4. 0.511 MeV LINE FLUX

After we determine how gamma lines can be produced and deciding on the dominant channel, we go on to estimate the 0.511 MeV gamma ray flux which would be emitted in this process from the Sun, and could thus be potentially observable by detectors in the Earth's orbit. Annihilation gives two 0.511 MeV photons. However, due to scattering effects only a fraction of created photons will escape the outer layers of the Sun and go on to be detected. Photon mean free path, which represents this escape probability, in this environment can be approximated by:

$$\lambda_{\mathrm{mfp}} = \frac{1}{n_{\mathrm{e}}\sigma_{\mathrm{c}}} \ . \tag{5}$$

For a photon with energy around 1 MeV the most dominant interaction is Compton scattering. Mean free path λ_{mfp} of the produced photons depends on electron number density n_e and cross-section for Compton scattering σ_c. Positron formation rate is defined as:

$$\frac{dn_{e^+}}{dt} = \int_{\epsilon_{\rm th}}^{\infty} n_p \sigma_{\tilde{\nu}_e} \phi_{\nu_e} dE \tag{6}$$

where we used the following notation:

- n_{e^+} is the positron number density;
- n_p is the neutron number density;
- $\sigma_{\tilde{\nu}_e,p}$ is the cross section for the reaction $\tilde{\nu}_e + p \rightarrow n + e^+$;
- ϕ_{ν_e} is the neutrino flux from the supernova in the units of $\left[\mathrm{MeV^{-1}cm^{-2}s^{-1}}\right]$.

Integrating over the relevant energy range, where $\epsilon_{\rm th} = 1.8$MeV (Totani et al. 1998) is a threshold energy of neutrino, that is required for this reaction. We get:

$$\frac{dn_{e^+}}{dt} = n_p \langle \sigma_{\tilde{\nu}_e,p} \rangle \Phi_{\tilde{\nu}_e} \tag{7}$$

where we have defined weighted cross - section as:

$$\langle \sigma_{\tilde{\nu}_e,p} \rangle = \frac{\int_{\epsilon_{\rm th}} \sigma_{\tilde{\nu}_e,p}(E) \phi_{\nu_e} dE}{\int_{\epsilon_{\rm th}} \phi_{\nu_e} dE} \ . \tag{8}$$

Also, we have defined $\Phi_{\tilde{\nu}_e}$ as a total energy-integrated neutrino flux in the units of $\left[\mathrm{cm^{-2}s^{-1}}\right]$ where $\epsilon_{\rm th} < \epsilon$.

Finally, we have the total gamma-ray flux as follows:

$$\Phi_\gamma = 2 \frac{1}{4\pi} \frac{\langle \sigma_{\tilde{\nu}_e,p} \rangle}{\sigma_c} \Phi_{\tilde{\nu}_e} \frac{R_\odot^2 \pi}{d^2} \ . \tag{9}$$

Since annihilation line emission follows the neutrino burst we integrate over the neutrino emission time. This defines the gamma-ray line fluence - total number of γ photons radiated in the solid angle of the Sun, in the 10 s long interval, which will be detected by the unit area of the detector in the Earth's orbit:

$$F_\gamma = \frac{1}{2} \frac{\langle \sigma_{\tilde{\nu}_e,p} \rangle}{\sigma_c} \frac{R_\odot^2}{d^2} \frac{1}{4\pi D^2} \frac{E_{tot,\tilde{\nu}_e}}{\langle \epsilon_{\tilde{\nu}_e} \rangle} \tag{10}$$

where

- $\langle \epsilon_{\tilde{\nu}_e} \rangle = 16$MeV is the average energy per neutrino
- $E_{tot,\tilde{\nu}_e} = 10^{53}$erg is the total energy released in SN process
- D is the SN distance
- $R_\odot$ is the Solar radius
- d is Earth-Sun distance
- $\langle \sigma_{\tilde{\nu}_e,p} \rangle = 1.87 \times 10^{-41}\mathrm{cm}^2$ is the cross section for the neutrino absorption on protons (Lu et al. 2007)
- $\sigma_c = 2.87 \times 10^{-25}\mathrm{cm}^2$ is the Compton scattering cross section.

5. RESULTS

We find the normalized value for the nearby SN at the distance of $D = 1$kpc, with adopted total energy released, to be :

$$F_\gamma = 2.33 \times 10^{-8} \left(\frac{D}{1\text{kpc}}\right)^{-2} \left(\frac{E_{tot,\tilde{\nu}_e}}{10^{53}\text{erg}}\right) \ . \tag{11}$$

As an example, we calculate the total gamma-ray flux which could be expected for η Carinae - the nearest candidate for the next supernova in our Galaxy. Because of its enormous mass, estimated to be greater than 120 Solar masses, supernova that would arise from it could be a pair-instability supernova, similar to SN2006gy (Smith et al. 2007). This type of event releases much more energy than regular supernovae. The total radiated energy of supernova SN2006gy $\sim 10^{51}$erg is by a factor of ~ 100 larger than what one would expect from a typical supernova where conversion between kinetic energy of the blast and energy that is radiated is $\sim 1\%$. Thus, in the best-case estimate, we will take that the total (neutrinos+blast energy) released energy for η Carinae could be of the order of 10^{54} erg. Of course, if pair-instability supernovae are non-standard in the sense that conversion from kinetic to radiated energy is much more efficient, the total released energy we have adopted here will be an overestimate. But since this is still an opened question we take energy to be $E_{tot,\tilde{\nu}_e} = 10^{54}$erg. Since η Carinae is at the distance $D = 2.3$kpc we get:

$$F_\gamma = 1.30 \times 10^{-7}\text{cm}^{-2} \ . \tag{12}$$

6. CONCLUSION

We have shown in the previous section the expected neutrino-induced 0.511 MeV gamma-ray fluence in the case of η Carinae. However, this is still below the sensitivity of instruments available at the moment. Advanced Compton Telescope (ACT), which is ideal for the detection of the narrow gamma lines, has projected sensitivity of $5 \times 10^{-7}\text{cm}^{-2}\text{s}^{-1}$, with an angular resolution of $\sim 1\%$ and a spectral resolution of $0.2 - 1\%$ over the energy range of $0.2 - 10$MeV. Although it is the same order of magnitude, ACT requires an exposure time of 10^6s, which means that more sensitive detectors are needed. If we could detect such a line, it would be of great significance for investigating processes which occur before the explosion itself. Since neutrinos are coming from the central core, we could explore conditions in the core and improve our knowledge about the latest phases of the stellar evolution. In this way, we could gain not only the total energy released in the explosion, but also the luminosity of neutrinos for every flavor. Exploring the η Carinae in such a manner could provide very valuable information regarding its variable nature, and process known as "fake" supernova, which η Carinae had been through 130 years ago.

Neutrino detectors have been significantly improved since the first supernova's neutrino detection. The very first detection was 20 years ago, when 1987A SN "occurred". Kamiokande II and IMB had detected 11 and 8 thermal antineutrinos, respectively, while Baskan detected 5 neutrinos created in neutronization process. Even there were only few events, saturation happened and hence it was impossible to precisely determine the total neutrino flux and consequently the total energy. Super Kamiokande is projected to detect even between 4000 and 6000 events of neutrino detection (Totani et al. 1998), but there is worry that in the case of nearby supernova a saturation still might occur.

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