Injection of heavy nuclei by a pulsar in the massive binary

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Abstract

We consider propagation of relativistic heavy nuclei injected by a young pulsar into the radiation field of a massive companion. If the binary system is close enough, then the nuclei suffer multiple photodesintegrations in collisions with thermal photons coming from the massive star. Some neutrons and charged particles, which are dissolved from the nuclei, can collide with the massive star producing neutrinos. We calculate neutrino fluxes for different impact parameters of particles onto the massive star applying as an example the parameters of the Cyg X-3 system.

1. Introduction

Some close massive binaries contain neutron stars as a compact objects (e.g. Cyg X-3, PSR B1259-63). In collision of the massive stellar wind with the pulsar wind a shock wave is created, which separates the pulsar wind region from the region dominated by the magnetic field and the wind of the massive star. Massive stars of the Wolf-Rayet or OB type have strong surface magnetic fields, of the order of $10^2 - 10^4$ G, and massive and fast winds, $\dot{M}_{\rm WR} = (0.8-8)\times 10^{-5}$ $M_\odot$ yr^{-1} and $V_{\rm WR} = (1-5)\times 10^3$ km s^{-1}. We discuss the consequences of injection of heavy nuclei by the pulsar into the radiation field of the massive companion.

2. Relativistic nuclei inside the massive binary

Pulsars can accelerate heavy nuclei to energies corresponding to a significant part of the total electric field potential drop through the pulsar polar cup region, $E_{\rm Fe} = \chi Ze\sqrt{L_{\rm em}/c}$, where $L_{\rm em}$ is the energy loss rate of the pulsar, Ze is the charge of nuclei, c is the velocity of light, and $\chi \leq 1$ [1]. We assume that these nuclei are accelerated with the rate corresponding to the Goldreich & Julian charge density at the light cylinder radius of the pulsar. If the pulsar in the Cyg X-3 system has the period 12.59 ms and the surface magnetic field 5×10^{11} G [2], the maximum Lorentz factors of iron nuclei can be as high as expected for the Crab pulsar, i.e. $\sim 3\times 10^7$. These nuclei propagate radially through the pulsar

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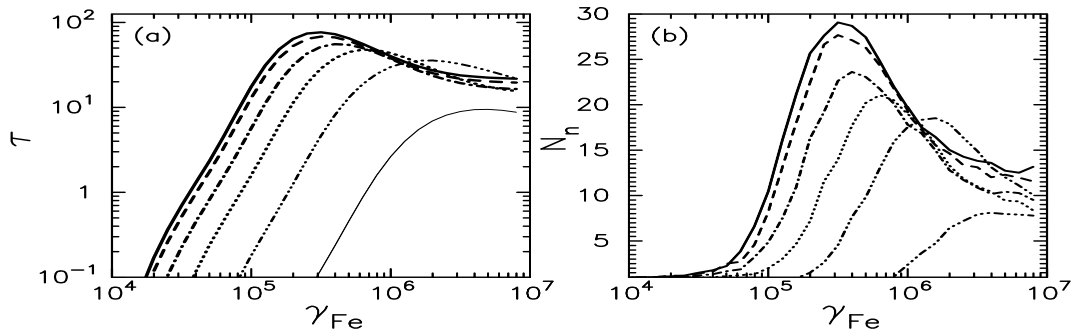

Fig. 1. (a) The optical depths for iron nuclei during their propagation in the pulsar wind zone up to the pulsar termination shock. Specific curves correspond to different angles of iron injection in respect to the direction defined by the centres of the pulsar and the massive star: $\alpha = 0^{\rm o}$ (full), 30$^{\rm o}$ (dashed), 60$^{\rm o}$ (dot-dashed), 90$^{\rm o}$ (dotted), 120$^{\rm o}$ (dot-dot-dot-dashed), and 150$^{\rm o}$ (thin full). (b) The number of dissolved nucleons from the primary iron nuclei during their propagation in the pulsar wind zone for the angles defined above.

wind zone (PWZ) and disintegrate in collisions with thermal photons from the close massive companion. The pulsar wind is confined around the pulsar due to its interaction with the massive stellar wind. The geometry of created termination shock of the pulsar wind is described by the parameter $\eta = L_{\rm em}/(c\dot{M}_{\rm WR}V_{\rm WR})$. We take $\dot{M}_{\rm WR} = 4\times 10^{-5}$ M$_\odot$ yr^{-1} and $V_{\rm WR} = 1400$ km s^{-1} for the WR star in the Cyg X-3 system. The distance of the shock from the massive star is then given by $\rho = \sqrt{\eta}D/(1+\sqrt{\eta})$, where D is the separation of the stars.

Fig. 1a shows the optical depth for the iron nuclei on extraction of a single nucleon, during their propagation through the PWZ up to the termination shock, as a function of the observation angle measured in respect to the direction defined by these stars. The binary system with the parameters expected for the Cyg X-3 is considered, i.e. separation of the NS and the WR stars, $3.6R_\odot$, the radius of the massive star, $1.6R_\odot$, its effective temperature, 1.4×10^5 K. Fig 1b shows the number of nucleons dissolved from the iron nuclei. It is found that many nucleons are extracted from the parent iron nuclei if their Lorentz factors are above $\sim 10^5$.

A part of extracted neutrons impinge onto the massive star and produce neutrinos in collisions with the matter. We calculate the neutrino spectra from multiple interactions of neutrons taking into account the matter density effects which determine the decay of pions into neutrinos or their interaction with matter. The absorption of produced neutrinos during their propagation through the stellar interior is also included. Fig. 2a shows the spectra of neutrinos for different impact parameters of neutrons with Lorentz factors 10^6 and 10^7. These spectra are strongly modified by the neutrino absorption during their propagation through the WR star (the density profile derived from the model 35 described in Fig. 3a by

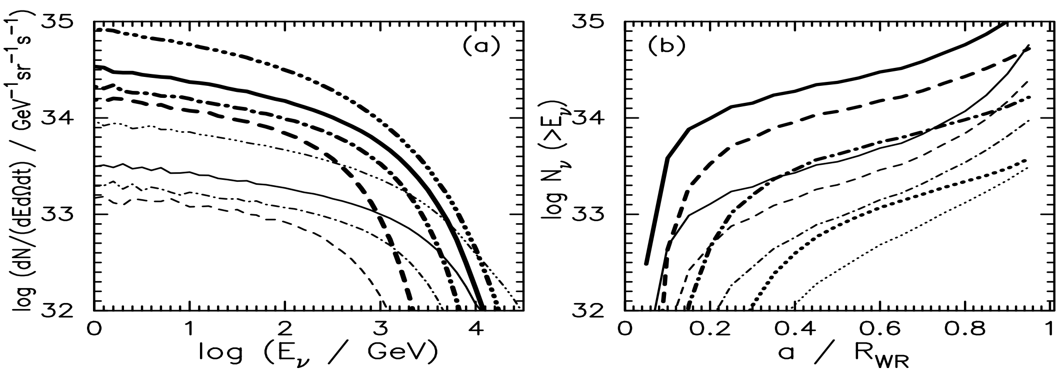

Fig. 2. (a) Spectra of neutrinos produced by the neutrons, with the Lorentz factors 10^6 (thick curves) and 10^7 (thin), falling onto the massive star with the impact parameter: 0.8 (dashed curves), 0.6 (dot-dashed), 0.4 (dotted), and 0.2 (dot-dot-dot-dashed). (b) Corresponding to (a) integral neutrino fluxes as a function of the impact parameter for the observer in the orbital plane of the binary system at energies above 10^2 GeV (full curve), 3×10^2 GeV (dashed), 10^3 GeV (dot-dashed), and 3×10^3 GeV (dotted).

Woosley et al. [4]). The integrated fluxes of neutrinos as a function of the impact parameter for the cases mentioned above are shown in Fig. 2b. Such neutrino light curves should be observed for the eclipsing massive binary systems. Note that only neutrinos produced relatively close to the limb of the WR star can pass through the star without significant absorption.

3. Propagation of hadrons in the magnetic field

Protons from disintegration of nuclei in the PWZ pass the shock region and propagate in the stellar wind following the magnetic field structure. For some magnetic field structures and energies of injecting particles, they can be focused onto the surface of the massive star. We calculate the paths of protons in the massive star magnetic field adopting the magnetic field model in the wind of the massive star [3]. This magnetic field structure is determined by the parameters of the Wolf-Rayet stars such as the mass loss rate, the rotational velocity, and the wind velocity. Fig. 3 shows the paths of protons injected from different places at the pulsar wind termination shock with the Lorentz factors 10^6 and 10^7. Some of these protons can impinge onto the massive star producing neutrinos at large angles to the plane of the binary system. Therefore, we predict also significant fluxes of neutrinos from the non-eclipsing binary systems. These fluxes depend on the value of the impact parameter as shown in Fig. 2. Detailed light curves of neutrinos produced by protons for different viewing angles in the case of non-eclipsing binary systems will be shown during the conference.

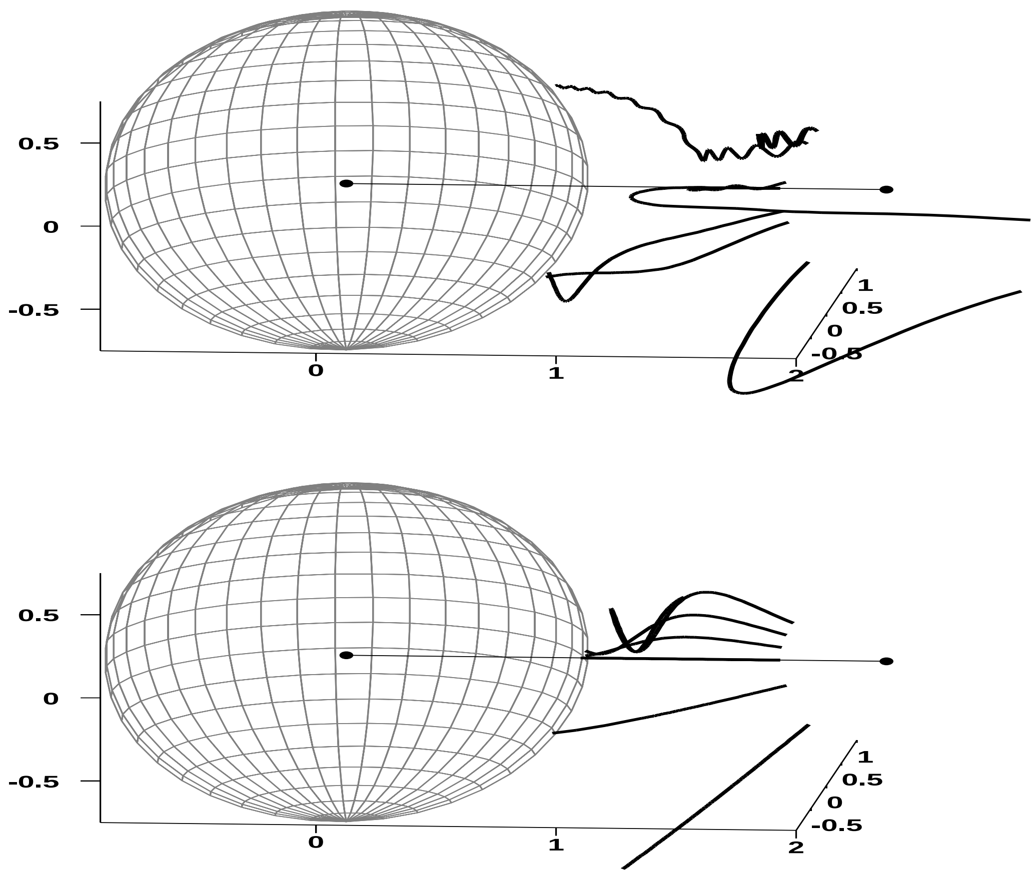

Fig. 3. Three-dimensional paths of protons with different Lorentz factors, $\gamma_{\rm p}$, in the magnetic field surrounding the massive star. (upper figure) Protons injected from the pulsar termination shock at the angle $\alpha = 0^{\rm o}$, $40^{\rm o}$, and $50^{\rm o}$ with $\gamma_p = 10^6$ (above the plane of the binary system), and at the angle $0^{\rm o}$, $20^{\rm o}$, $30^{\rm o}$, and $40^{\rm o}$ with $\gamma_p = 10^7$ (below). (bottom figure) For $\alpha = 0^{\rm o}$, $10^{\rm o}$, $20^{\rm o}$, and $30^{\rm o}$ with $\gamma_p = 10^6$ (above the plane of the binary), and $20^{\rm o}$, and $50^{\rm o}$ with $\gamma_p = 10^7$ (below). The surface magnetic field of the massive star is 3×10^3 G (upper figure) and 3×10^2 G (bottom).

This work is supported by the KBN grant No. 5P03D 025 21.

4. References

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