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High energy neutrinos from fast spinning magnetars

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Abstract

Fast spinning magnetars are discussed as strong sources of high energy neutrinos. Pulsars may be born with a short rotation period of milliseconds with the magnetic field amplified through dynamo processes up to $\sim 10^{15}$–10^{16} G. As such millisecond magnetars (MSMs) have an enormous spin-down power $\sim 10^{50}\,\mathrm{erg\,s^{-1}}$, they can be potentially a strong, extragalactic high-energy neutrino source. Specifically, acceleration of ions and subsequent photomeson production within the MSM magnetosphere are considered. As in normal pulsars, particle acceleration leads to electron–positron pair cascades that constrains the acceleration efficiency. The limit on the neutrino power as a fraction of the spin-down power is calculated. It is shown that neutrinos produced in the inner magnetosphere have characteristic energy about a few $\times 100$ GeV due to the constraint of cooling of charged pions through inverse Compton scattering. TeV neutrinos may be produced in the outer magnetosphere where ions can be accelerated to much higher energies and the pion cooling is less severe than in the inner magnetosphere. High energy neutrinos can also be produced from interactions between ultra-high energy protons accelerated in the magnetosphere and a diffuse thermal radiation from the ejecta or from the interaction region between the MSM wind and remnant shell. The detectability of neutrinos in the early spin-down phase by the current available and planned neutrino detectors is discussed.

Keywords: Cosmic rays; Pulsars; Neutrinos; Particle acceleration; Nonthermal radiation

1. Introduction

Young pulsars are generally considered as an important high-energy neutrino source [9,41,37,36]. Particles can be accelerated either in the magnetosphere by a rotation-induced electric field (e.g. [24,27] and references therein), or in the pulsar wind, e.g. by large amplitude waves [21,41,3,47,34] or magnetic field reconnection [33] and interact with thermal photons from the star's surface or protons in the remnant to produce high energy neutrinos. There is strong observational evidence for pulsars with an extremely strong magnetic field exceeding the quantum electrodynamics (QED) critical field $B \gg B_c \approx 4.4 \times 10^{13}$ G, called

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magnetar [52]. Soft gamma-ray repeaters (SGR) and anomalous X-ray pulsars (AXP) are believed to be slowly rotating magnetars [45]. The possible existence of fast spinning magnetars has also been proposed (e.g. [47,10,51,38,18]). Such MSM may be formed from an accretion-induced collapse, in which the magnetic field is amplified exponentially to 10^{15}–10^{16} G by dynamo amplification [13,16]. If such fast spinning magnetars exist they are by far the most energetic pulsars with a typical spin-down power 10^{49}–$10^{50}\,\mathrm{erg\,s^{-1}}$ for a magnetic field $B_0 = 10^{15}$ G and a rotation period $P = 1$ ms, which is about 10^{12} times more powerful than the Crab pulsar. MSMs spin down rapidly, producing powerful transient gamma-ray emission within a typical spin-down time $\sim (1/2)I\Omega_0^2/L_{\rm E} \approx 10^3$ s, where Ω_0 and $I \approx 10^{45}\,\mathrm{g\,cm^2}$ are the initial angular velocity and inertial moment of the pulsar, and $L_{\rm E}$ is the spin-down luminosity due to the magnetic dipole radiation. As in normal pulsars, rotation-driven acceleration leads to gamma-ray emission and in particular, acceleration of ions may lead to photopion production through either proton–photon or proton–proton interactions, producing neutrinos. Thus, MSM can be a potentially observable source of high-energy neutrinos during its initial spin-down phase.

Neutrinos originating from magnetospheric acceleration has been considered by several authors for normal young pulsars [41,37,7,8]. Neutrinos from slowly rotating magnetars were discussed recently by Zhang et al. [53]. However, as such slow rotators have a much lower spin-down power than the Crab pulsar (by a factor of 10^5), the corresponding luminosity of rotation-powered neutrino emission is marginal even for a km scale neutrino detector. So far, in most of the magnetospheric-origin models for neutrino emission, the constraints by pair production and radiation reaction were not considered. Magnetospheric acceleration arises from a rotation-induced electric field in the open field line region due to that the charge density of outflowing charged particles deviates from the corotation charge density, referred to as the Goldreich–Julian (GJ) density. Pair cascades tend to screen out the accelerating electric field and send a backflow of opposite-charged particles that can reverse the sign of the electric field. Therefore, pair cascades can strongly limit the fraction of the spin-down power going into particle acceleration and constrain the neutrino luminosity. There are extensive discussions on neutrino emission resulting from particle acceleration in the pulsar wind or at the wind termination shock (e.g. [9,41,6,20,36,32]). In these models, it is generally hypothesized that protons (or ions) can be accelerated efficiently to ultra-high energy. Although acceleration in the pulsar wind can be efficient in the sense that most of the Poynting flux that is thought to be dominant near the pulsar is converted to particle kinetic energy, as supported by the observational evidence from the Crab nebula [17], the specific acceleration mechanism is poorly understood (e.g. [30]) and there is no reliable estimate of the maximum energy of accelerated protons.

In this paper, we explore the magnetospheric origin of neutrinos from MSMs in which, compared to normal young pulsars, acceleration processes are strongly modified by both the supercritical magnetic field and rapid rotation. There are basically two classes of model for particle acceleration in the pulsar magnetosphere: the polar gap model, in which acceleration is assumed to occur near the polar cap (PC), and the outer gap model, in which the acceleration region is located in the outer magnetosphere. There is also a variant between the two, called the slot gap model [1,35]. We consider these two cases separately and comment briefly on the slot gap model in Section 6. For acceleration near the PC we extend the polar gap model for normal pulsars [27,24] to MSMs. Since the steady gap model may not be realistic as pair cascades are likely nonstationary and time-dependent, we emphasize the energetics of polar gap acceleration rather than a specific gap model. The energetics, described by the acceleration efficiency, which is defined here as the ratio of pair-production limited potential to the maximum potential (across the PC), determining how much of the spin-down power goes into particle acceleration, can be determined from the relevant free path for pair production. A pair may be produced through interaction of a Lorentz boostered thermal photon with the Coulomb field of an ultrarelativistic ions. The more efficient pair pro-