Emission of PeV neutrinos from magnetars

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Introduction

Both from the physical and astronomical point of view magnetars, being extremely interesting objects have attracted many in the recent past. These objects open up a path to study and observe several phenomena taking place in extreme magnetic field conditions not feasible elsewhere [1].

They born with characteristics found similar in neutron stars but with magnetic fields much larger than the quantum critical value $B_{QED} = 4.4 \times 10^{13}$ G, at which the energy between Landau levels of electrons equals their rest mass. Their magnetic fields are at least $10^2 - 10^3$ times stronger than those of the typical neutron stars observed as radio pulsars powered by the loss of rotational energy, or shining in X-rays thanks to the accretion of matter from binary companion stars [2]. Magnetic field is the ultimate energy source of all the observed emission from magnetars.

Here, in a young magneter if the spin-down power takes over the magnetic field driven power then these objects might emit PeV ν_μs and γ-rays through photo-meson production by protons/ions with degraded radiation field into the UV-A or B range from X-ray or UVC.

PeV neutrinos and gamma-rays from magnetars

Photo-meson production

There has been an unanimity among researchers in particle astrophysics over half a century that ultra-high energy (UHE) protons and/or heavier ions emitted by cosmic accelerators (e.g. pulsars, young magnetars) are affected by the presence of the ambient matter or radiation fields, and finally materialized through the reactions given below [3]:

$$p+\gamma \to \Delta^+ \to \begin{cases} p + \pi^o \to p + 2\gamma \\ n\pi^+ \to n + e^+ + \nu_e + \nu_\mu + \bar{\nu_\mu} \end{cases}$$

The final products of all neutrino flavours along with γ-ray keeps the ratio approximately as $\nu_e : \nu_\mu : \nu_\tau : \gamma = 1 : 2 : 0 : 2$ at the sources but the process of neutrino oscillation turns this into a ratio of $\nu_e : \nu_\mu : \nu_\tau : \gamma = 1 : 1 : 1 : 2$ while observing at earth.

For common magnetars the surface magnetic field is of the order of 10^{15} G, the $\gamma - \gamma$ pair production process due to $\gamma - B$ interaction starts within few stellar radius. The rest of common magnetars are all high-energy γ-ray emitters with energies from few hundreds to thousands MeV ascribed by the outer gap model [4]. The exotic photon splitting process causes a transformation of the UV and X-ray photons of the ambient field very near the stellar surface into UV radiation comprising only UV-A and UV-B types with average photon energy $\approx 10 - 20$ eV. Interaction of UHE protons with this modified UV radiation field through photomeson production will generate PeV ν and γ-rays which will be detected on earth.

Basic model and photomeson threshold

An extension of earlier estimation of young pulsars to newly born magnetars, it reveals that protons or heavier ions undergo acceleration near the magnetar's surface by polar caps to energies nearly at 10^{17} eV when the magnetar's magnetic moment vector μ and $\mathbf{\Omega}$ parameter satisfy the strong condition, $\mu.\mathbf{\Omega} < \mathbf{0}$. These UHE protons will interact with soft UV-A and UV-B photons coming out from the magnetar's surface, the Δ resonance state may occur satisfying the kinematic threshold condition for Δ^+ creation. The photomeson pro-

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duction threshold for a p to reach the Δ^+ state is something where the kinetic energies of the proton (ϵ_p) and UV-A/B photon (ϵ_γ) would satisfy

$$\epsilon_p \epsilon_\gamma (1 - cos\theta_{p\gamma}) \geq 0.3\ GeV^2, \quad (1)$$

where $\theta_{p\gamma}$ is the incident angle between the proton and photon as measured in the laboratory frame. In a young magnetar, the typical photon energies near the surface are 10 decade smaller than a young pulsar due their intense magnetic field with values $2.8kT_\infty(1 + z_g) \sim 0.04$ keV, where $z_g \sim 0.4$ being the gravitational red shift. This implies that the proton threshold energy $\epsilon_{p,Th}$ for the Δ^+ resonance state lies in the range $10^{16} - 10^{17}$ eV.

The neutrino and gamma-ray fluxes on earth

The UHE proton flux emitted from the polar cap region would have a value

$$\Phi_{PC} \simeq c f_d (1 - f_d) n_o A_{PC}, \quad (2)$$

where A_{PC} denotes polar cap area and it is $\eta(4\pi R^2)$ in which η accounts the ratio of polar cap area to the magnetar surface area.

It is seen from the process in photomeson production that charge-changing reaction goes on just $\frac{1}{3}$-rd of the reaction time, about three high-energy ν (or a pair of $\nu_\mu, \bar{\nu_\mu}$) will accompany with four high-energy γ-rays when a significant number of such reactions proceed successfully. These νs will arrive at earth without changing the flux and energy but same does not hold for γ-ray flux due to QED effect. The factor f_s accounts reduction in flux due to photon splitting.

In the UV-A/B dominated radiation field of magnetar where accelerated ions by a polar cap will suffer interaction. For a young magnetar with surface temperature T_∞, the UV-A/B photon density very adjacent to the star surface area is $n_\gamma(R) = (a_{SB}/2.8k)\left[(1 + z_g)T_\infty\right]^3$, a_{SB} being the Stefan-Boltzmann constant. A numerical value of $n_\gamma(R)$ could be approximated as $9 \times 10^{19} T^3_{0.1\ keV}$. The photon density increases due to splitting and at the same time will decrease with the increase of radial distance from the stellar surface, and the overall photon density reduces roughly to $n_\gamma(r) \simeq n_\gamma(R) f_m (R/r)^2$ at r in the work, where factor f_m comes from the multiplication of X-ray or UV-C photon due to splitting. Now, the conversion probability for $p \to \Delta^+$ via UV-A/B interaction along the distance from R to r is given by (LB) $P_c(r) = 1 - P(r)$, where $dP/P(r) = -n_\gamma(r)\sigma_{p\gamma}dr$ with $P(r) \sim exp(-10^{-3} f_m)$ corresponding to $\epsilon_\gamma \sim 0.05$ keV and conversion to continue in the range from R to $1.2R$. To keep P_c close to the mean values as obtained for many pulsars then f_m has to be ~ 10. The total flux of ν/γ-ray coming out from the disintegration of Δ^+ resonance state is

$$\Phi_{\nu/\gamma}(r \simeq 1.2R) = 2c\xi A_{pc} f_d (1 - f_d) n_o P_c, \quad (3)$$

with ξ is 4/3 and 2/3 for γ-ray and ν_μ respectively. If now the duty cycle factor f_b of the γ-ray/ν_μ is taken into account, the phase averaged γ-ray/ν_μ flux on the Earth from a magnetar at a distance d is given by

$$\Phi_{\nu_\mu,\bar{\nu_\mu}/\gamma} \simeq 2c\xi\zeta\eta f_b f_s f_d (1 - f_d) n_o \left(\frac{R}{d}\right)^2 P_c. \quad (4)$$

In equation (4), the flavor ratio of ν at their production centre to a very large distance like at a detection level on earth is different due to well known ν oscillation, and the effect is represented by the parameter ζ (1/2 and 1 for ν_μ's and γ-rays whereas f_s is 1 for ν_μ but not yet known for γ-rays).

References

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