2.2 MeV Gamma-Ray Emission from Accreting Strongly Magnetized Neutron Stars

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Presence of 2.2 MeV gamma-ray emission in strongly magnetized accreting neutron stars was proposed a long time ago, but still has not been detected. The line should form due to the capture of neutrons produced through spallation processes of ^{4}He and heavier ions in the atmosphere of the neutron star. The detection of 2.2 MeV gamma-ray line can give us an independent method to constrain neutron star equation of state and provide valuable insights into nuclear reactions occurring in extreme gravitational and magnetic fields at the stellar surface. According to previous research in the field, the flux of 2.2 MeV gamma-ray line should be scaled with the mass accretion rate onto neutron star surface. However, we show that in bright X-ray pulsars, high mass accretion rate results in radiative force that decelerates accretion flow above stellar surface, which suppresses effectiveness of neutron production in the atmosphere of a star and further emission of gamma-ray line. Combining estimations of accretion flow deceleration above neutron star surface and effectiveness of neutron production, the optimal luminosity of a neutron star for detection of 2.2 MeV γ-ray line is calculated.

Keywords: neutron stars- luminosity: accretion- gamma rays: nuclear reactions

Introduction

X-ray pulsars (XRPs) are accreting strongly magnetized neutron stars (NSs) in close binary systems. The surface magnetic field in these objects is expected to be $\sim 10^{12}$ G. When material from a companion star in a binary system accretes onto a strongly magnetized NS, it accelerates along the magnetic field lines under the influence of gravity and reaches velocity $\sim 0.5c$ in close proximity to the NS's surface.

Transformation of accretion flow kinetic energy into heat results in temperatures $\gtrsim 10^7$ K in the atmosphere of a star and strong emission in the X-ray energy band from the polar regions of the NS. Conditions present in the upper atmosphere of the NS, such as high velocity of accretion flow that lands onto the stellar surface, large pressure, and high temperature, are sufficient to cause a number of nuclear reactions. In particular, collisions of ^{4}He, which is present in the accretion flow, with atmospheric protons result in the partial destruction of these nuclei, leading to the release of neutrons and ^{3}He.

$$^4\mathrm{He} + p \longrightarrow {}^3\mathrm{He} + p + n. \quad (1)$$

The neutrons produced in this process are fractionally captured by protons, emitting 2.2 MeV photons[1]:

$$p + n \longrightarrow {}^2\mathrm{H} + \gamma_{2.2} \quad (2)$$

Production of neutrons requires high velocity of the accretion flow. This condition is typically satisfied in XRPs of low luminosity ($L \lesssim 10^{37}$erg s^{-1}). However, the accretion flow entering the atmosphere of NS can be decelerated by radiative force that start to affect accretion dynamics at luminosity level $\sim 10^{37}$erg s^{-1}. According to theoretical estimations[2,1] that are confirmed by recent observations[3], the flow can be completely stopped above the surface of a NS at so-called critical luminosity $L^* \sim 10^{37}$ erg s^{-1} . Thus, accretion luminosity of an NS affects the velocity of the material, reducing its kinetic energy, which directly impacts the liberation of neutrons in the upper layers of the atmosphere, and subsequently the emission of the gamma-ray line. Previous work in the field estimates that the emission of 2.2 MeV photons should be proportional to the luminosity in XRP[4] This paper focuses on demonstrating how the final velocity of accretion flow depends on X-ray luminosity and making approximations about the probability of producing unscattered 2.2 MeV photons. Based on the obtained results, a model is constructed to describe the relation between gamma-ray luminosity and X-ray luminosity, suggesting the optimal luminosity of the NS, at which emission of the gamma-ray line is maximized.

Physical model

In this work, we use the CGS system of units and examine a binary system composed of a neutron star (NS) with a mass $M_{\mathrm{NS}} = 1.4M_\odot$ and a radius $R_{\mathrm{NS}} = 10$ km. The companion star's details are not as critical for the analysis. The mass-radius

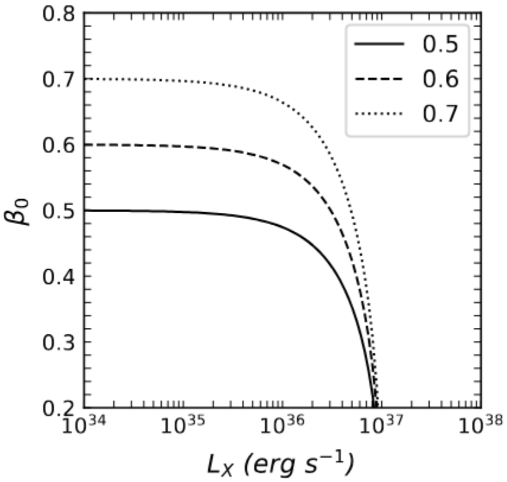

Figure 1: Dependence of the final dimensionless velocity of material on luminosity of accreting NS, where various curves correspond to different initial velocities: $\beta_{ff} = 0.5$ (solid), $\beta_{ff} = 0.6$ (dashed) and $\beta_{ff} = 0.7$ (dotted).

relation, given by the equation of state, affects the free-fall velocity at the NS surface:

$$v_{ff} = \sqrt{\frac{2GM}{R}} \tag{3}$$

The free-fall velocity, in turn, affects the efficiency of free neutron production and, consequently, the rate of proton-neutron recombination. Therefore, for comparison, we consider a few different dimensionless free-fall velocities $\beta_{\text{ff}} \equiv v_{\text{ff}}/c$ that cover reasonable combinations of NS mass and radius: $\beta_{\text{ff}} = 0.5$, $\beta_{\text{ff}} = 0.6$, and $\beta_{\text{ff}} = 0.7$. The model assumes a solar abundance of chemical elements, with helium comprising approximately 25%. This helium abundance is typical for the outer layers of normal stars that contribute material to the accretion process in a binary system. If the helium abundance deviates from the solar value, the luminosity in 2.2 MeV photons would also change. The critical luminosity of XRP is taken to be $L^* \approx 10^{37}$ erg s^{-1}, which corresponds to a magnetic field strength $B \approx 10^{12}$ G[5]. Although this value can vary depending on the magnetic field strength at the NS's surface - higher values tend to increase L^* - following estimations are applicable even for cases with stronger magnetic fields, though they will tend to yield higher values.

Deceleration of matter due to X-ray luminosity

The kinetic energy of accreting matter per nucleon exceeds the binding energy of nucleons in atomic nuclei of ^{4}He, allowing them to be broken down and liberate free neutrons[4].

Coulomb collisions play a role in limiting neutron production by setting the minimum kinetic energy required for particle interactions that lead to neutron formation. Thus, velocity of accretion flow at the top of the atmosphere of a NS plays a crucial role in production of free neutrons: lower velocity of the flow reduces the efficiency of neutron production. At high mass accretion rates and correspondingly high luminosity, X-ray photons produced at the NS surface can transfer their momentum to accretion flow due to the Compton scattering, which is expected to the major process of interaction between radiation and matter at high temperatures. The transfer of momentum causes radiation pressure and, at sufficiently large luminosities $L_X \approx L^*$, the matter stops above the NS's surface, creating accretion columns[6 ,5]. This deceleration reduces the kinetic energy of particles involved in collisions, thereby decreasing the efficiency of free neutron production and the subsequent formation of 2.2 MeV photons. Therefore, as nuclei enter the atmosphere of the NS, they are decelerated by multiple processes, reducing their energies and thus the number of nuclei that undergo spallation. The dependence of the energies of nuclei on the NS's luminosity can be estimated by first investigating how the final velocity of matter is related to the luminosity. The luminosity of a NS is related to the final velocity[7] as

$$L(\beta_0) \simeq L^* \left(1 - \frac{\beta_0^2}{\beta_{ff}^2}\right) \tag{4}$$

where $L^* \approx 10^{37}$erg s^{-1} is the critical luminosity of XRP, β_{ff} is the initial free-fall velocity of the material at NS surface, and $\beta_0 < \beta_{ff}$ is the final dimensionless velocity affected by the radiative force. Rearranging the equation gives the dependence of the final velocity as a function of luminosity:

$$\beta_0^2 \simeq \beta_{ff}^2 \left(1 - \frac{L}{L^*}\right) \tag{5}$$

In the case of $L_X \approx L^*$, radiative force exceeds the gravitational attraction and material is decelerated in close proximity to a stellar surface. As expected, at greater luminosity, the final velocity of the material should decrease rapidly and eventually reach zero at the critical value (see Figure 1). At low luminosity level ($L \ll L^*$), the final velocity is weakly affected by radiative force and remains almost the same as the initial free-fall velocity. While material is decelerating in the atmosphere, it might strike a proton, resulting in production of ^{3}He and the liberation of a neutron. The neutron travels an additional depth at pre-collision velocity before thermalizing through repeated scatterings with atmospheric protons. At certain depth, it either recombines with a proton, producing Deuterium and emitting 2.2 MeV photons[8], or is absorbed by ^{3}He. Thus, only those neutrons that are liberated in excess of initial ^{4}He spallation will produce 2.2 MeV photons. Furthermore, the energy budget impacts the yield of unscattered 2.2 MeV photons and should be taken into account.

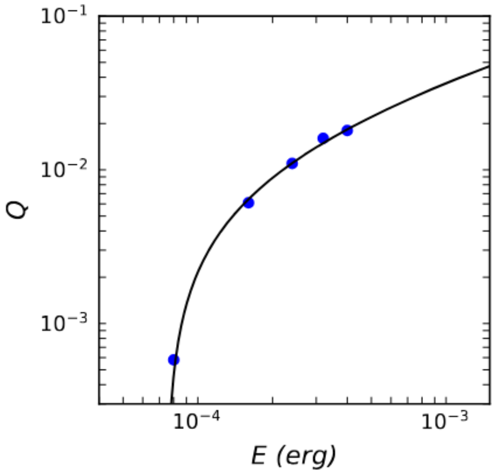

Figure 2: Approximated dependence of the Q factor, which represents yield of unscattered 2.2 MeV gamma-rays per accreted ^{4}He nucleus as a function of initial energy of the nucleus, where blue dots represent given data. Accuracy of the approximation is 97.3%.

Energy dependence of unscattered 2.2 MeV gamma-rays

A thermal neutron will drift downward to Compton depth of order unity, thus recombining and producing an unscattered 2.2 MeV photon less than 10% of the time. Therefore, if every accreted ^{4}He produced a free neutron, only 0.2 unscattered 2.2 MeV photons would appear[4]. This number of unscattered photons per accreted ^{4}He nucleus, the Q factor, strongly depends on the initial energy of the nucleus, E, and can be approximated by the following equation, using a set of data[4]

$$Q \approx aE^b + cE^d \tag{6}$$

where

$$\begin{aligned} a &= 2336.85, \quad b = 0.277409 \\ c &= -2335.94, \quad d = 0.277368 \end{aligned} \tag{7}$$

are the coefficients that approximate given set of points. The resulting curve can be seen on Figure 2. Note, that the approximation is not physically motivated. It just fits the values for the Q factor presented in the literature.

$$\text{Accuracy} = 100 \times \left(1 - \frac{\text{Mean Absolute Error}}{\text{Mean of Actual Values (Q)}}\right) = 97.3\% \tag{8}$$

Table 1 Actual and approximated values of Q with residuals

E	Q (Actual)	Approximation	Residuals
8.0×10^{-5}	5.8×10^{-4}	4.6×10^{-4}	1.2×10^{-4}
1.6×10^{-4}	6.1×10^{-3}	6.4×10^{-3}	-0.3×10^{-3}
2.4×10^{-4}	1.1×10^{-2}	1.1×10^{-2}	0
3.2×10^{-4}	1.6×10^{-2}	1.5×10^{-2}	0.1×10^{-2}
4.0×10^{-4}	1.8×10^{-2}	1.8×10^{-2}	0

The plot describes the set of data with approximately 97.3% accuracy, meaning there is still some small uncertainty in the estimations, which slightly impacts the results of further calculations; however, this impact is insignificant. As the energies of nuclei increase, so too does the yield of unscattered 2.2 MeV photons due to increased intensity of initial spallation, which releases more free neutrons. This provides important insights into the production of unscattered gamma-rays in highly luminous NS: if the velocity of matter depends on radiation pressure and is decreased by its influence, so too is the energy, and thus the Q factor in general. By combining obtained equations (5) and (6), the dependence of the yield of 2.2 MeV gamma-rays and how it is affected by the X-ray luminosity are calculated. Since the typical velocity of material within the NS's atmosphere is around 50-60% of the speed of light, a relativistic expression for kinetic energy is considered, and the following equation is obtained

$$Q = 2336.85\left[m_n c^2(\gamma - 1)\right]^{0.277409} - 2335.94\left[m_n c^2(\gamma - 1)\right]^{0.277368} \tag{9}$$

where m_n is the mass of a neutron, and c is the speed of light. The graph shows (see Figure 3) that at luminosities $L_X \approx L^*$, due to the fact that velocity drops, the Q factor decreases as well. Therefore, the formation of the 2.2 MeV gamma-ray line is not expected at very high accretion rates because they create strong radiation pressure, which counteracts the material and stops it above the surface, preventing the liberation of neutrons and their subsequent recombinations with atmospheric protons.

The dependence of 2.2 MeV luminosity on X-ray luminosity

The purpose of this work is to obtain the relation between the 2.2 MeV gamma-ray luminosity and the X-ray luminosity of NS:

$$L_{2.2} = E_{2.2} Q \left(\frac{Y}{4}\right) \frac{L_X R_{\mathrm{NS}}}{G M_{\mathrm{NS}} m_{\mathrm{p}}} \simeq 6.7 \times 10^{-4} Q L_X \tag{10}$$

where $E_{2.2} = 3.5 \times 10^{-6}$ erg is the energy of a 2.2 MeV γ-ray photon, Y is the mass fraction of helium, m_p is the mass of a proton, and G is the gravitational constant. In the case when $L_X \ll L^*$, $L_{2.2}$ should be proportional to X-ray luminosity times the factor 6.7×10^{-4}[4]. However, due to the Q factor and its dependence on X-ray luminosity, at certain point, the curve reaches its maximum and starts decreasing until it reaches zero at the critical value (see Figure 4). At this point, the radiation pressure is so great that it stops all the material above the surface of the NS, preventing the formation of the gamma-ray line.

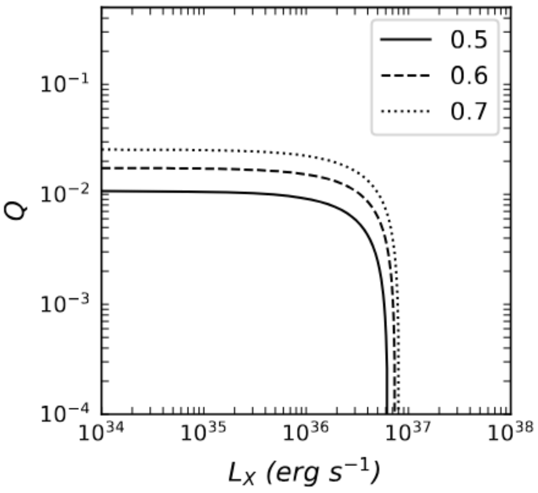

Figure 3: The Q factor dependence as a function of NS's luminosity for different initial velocities of material: $\beta_{ff} = 0.5$ (solid), $\beta_{ff} = 0.6$ (dashed), and $\beta_{ff} = 0.7$ (dotted) in close proximity to the critical luminosity $L^* \approx 10^{37}\,\mathrm{erg\,s^{-1}}$.

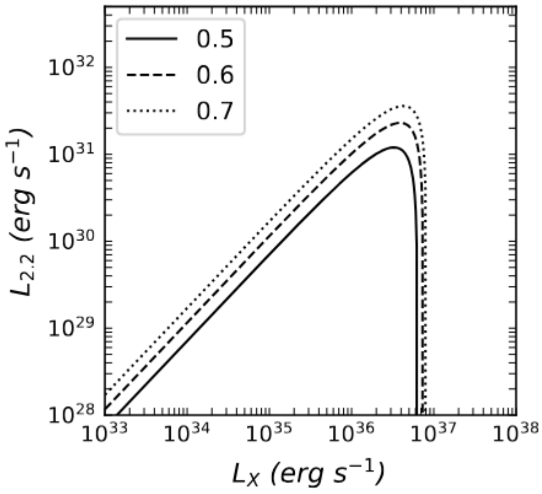

Figure 4: Final luminosity in 2.2 MeV gamma-ray line as a function of NS's luminosity for initial velocity of accreting material β_{ff} = 0.5 (solid), β_{ff} = 0.6 (dashed) and β_{ff} = 0.7 (dotted).

The maximum yield of the gamma-ray line is estimated to be $L_{2.2} \approx 3.7 \times 10^{31}\mathrm{erg\ s^{-1}}$ and should occur at an X-ray luminosity $L_X \approx 4.3 \times 10^{36}\mathrm{erg\ s^{-1}}$, which is approximately $L_X \approx 0.5L^*$, assuming a free-fall velocity of material $\beta_{ff} = 0.5$. The gamma-ray luminosity, as previously discussed, depends on the initial velocity profile of the accreting material. For greater free-fall velocities, greater gamma-ray luminosity is obtained at approximately the same intensity of X-ray luminosity. Thus, to detect 2.2 MeV line, it is not necessary to search for the brightest X-ray pulsars, since gamma-ray luminosity is proportional to X-ray luminosity only up to a certain point, after which it decreases rapidly. Since the luminosity of the NS is variable over time due to multiple factors such as accretion processes, nuclear reactions happening in the atmosphere of the star, or fluctuations of magnetic field strength, it is necessary to find a neutron star with the estimated optimal luminosity in order to detect the greatest gamma-ray line.

Flux of the 2.2 MeV γ-ray in X-ray transient V 0332+53

Currently, there are no space missions capable of detecting photons in the MeV energy range. This range will become accessible with the launch of gamma-ray spectrometers like the Compton Spectrometer and Imager (COSI), which is expected to launch in 2027. Therefore, to demonstrate the basic ideas of our estimations, we apply them to bright Galactic X-ray transient V 0332+53. The transient hosts NS, where surface magnetic field is measured to be $\sim 3 \times 10^{12}G$ and located at distance $D \approx 7kpc$. During the outbursts, V 0332+53 shows accretion luminosity as high as $4 \times 10^{38}\mathrm{erg\ s^{-1}}$. Observational data confirmed the critical luminosity of the pulsar[3] to be $L^* \approx 10^{37}\mathrm{erg\ s^{-1}}$. Assuming typical NS's mass $M = 1.4M_\odot$, radius R = 10km, the estimated maximum luminosity in the 2.2 MeV gamma-ray line is expected to be

$$L_{2.2} \approx 4 \times 10^{31}\mathrm{erg\ s^{-1}}$$

Using the expression for the flux

$$F_{2.2} = \frac{L_{2.2}}{4\pi D^2} \tag{11}$$

the maximum luminosity in the line for transient $\mathrm{V0332+53}$ is calculated to be

$$F_{2.2} \approx 7 \times 10^{-15}\mathrm{erg\ cm^{-2}\ s^{-1}}$$

or

$$F_{2.2} \approx 2 \times 10^{-9}\gamma\,\mathrm{cm^{-2}\ s^{-1}}$$

Summary

We have investigated the formation of the 2.2 MeV gamma-ray line, focusing primarily on how the NS's accretion luminosity influences its formation. We argue that the emission of the 2.2 MeV line depends on the luminosity of X-ray pulsar. The optimal Xray luminosity of the NS should be approximately half of the critical luminosity at a given magnetic field strength in order to produce the greatest 2.2 MeV gamma-ray line emission. Assuming that magnetic field strength is $B \approx 10^{12} G$ and the critical luminosity $L^* \approx 10^{37}$erg s^{-1}, luminosity in 2.2 MeV line is calculated to be $L_{2.2} \approx 4 \times 10^{31}$erg s^{-1} (for $\beta_{ff} = 0.5$). Additionally, based on the obtained estimations and the observational data from the X-ray transient V 0332+53, which confirmed the critical luminosity to be $L^* \approx 10^{37}$erg s^{-1}, we estimate the greatest gamma ray line flux for this object to be $F_{2.2} \approx 2 \times 10^{-9} \gamma\, \mathrm{cm}^{-2} \mathrm{s}^{-1}$, assuming typical parameters for the NS. Moreover, higher free-fall velocities of the accretion matter right above the surface of NS result in a higher emission of the gamma-ray line at approximately the same X-ray luminosities due to a more effective conversion of accretion energy into the production of free neutrons in the atmosphere of an NS. Therefore, finding fast-accreting matter would be beneficial for the observation of more intense line. The current model assumes a chemical composition of the NS's atmosphere similar to that expected in the case of relatively low magnetic fields. To the best of our knowledge, no simulations currently predict the chemical composition of atmospheres in XRPs. These estimations should influence the strategy of future observations of the 2.2 MeV lines, which are expected to be detected in the coming years. All photons emitted from the NS surface, including 2.2 MeV photons, undergo gravitational redshift and photon energy for a distant observer E^∞ is related to the photon's energy emitted at the NS surface E_0 as

$$E^\infty = E_0 \left(1 - \frac{2GM}{Rc^2}\right)^{1/2} \tag{12}$$

Thus, a distant observer will detect these photons at energies lower than 2.2 MeV. By detecting the redshifted photons, it becomes possible to measure the gravitational redshift, which is directly linked to the mass M and radius R of a NS. Therefore, observation of redshifted 2.2 MeV gamma-ray line can constrain NS's equation of state, providing insights into the behavior of matter under extreme conditions such as high pressure and density. Further study should consider what happens to the already formed gamma-ray photons and what fraction of photons are able to escape the strong magnetic field and reach our telescopes. Indeed, as photons escape, there is a chance to produce electron-positron pairs in the strong magnetic field due to the process of electron-photons pair creation typical for magnetic fields $\gtrsim 3 \times 10^{12} G$[9]. Electron-positron pairs will tend to annihilate each other, resulting in production of 511keV photons[10] and possibly radio emission, which is already detected in some XRPs[11], [12] Additionally, detailed nuclear reactions and the abundance of protons in the atmosphere should be considered, since intensive nuclear reactions may change chemical composition of NS's atmosphere while producing heavier elements, ultimately impacting the emission of the 2.2 MeV gamma-ray line. The MeV band remains the least explored region of the electromagnetic spectrum. However, upcoming gamma-ray spectrometers, such as the Compton Spectrometer and Imager (COSI, set to launch in 2027)[13] and the MeV Astrophysical Spectroscopic Surveyor (MASS)[14], will enable detailed observations of this band, achieving sensitivities close to our theoretical predictions for gamma-ray fluxes.

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