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TOWARD THE FURTHER UNDERSTANDING OF THE PRZYBYLSKI' STAR PHENOMENON

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This paper proposes an updated scenario, which explains the Przybylski's star phenomenon, based on the assumption that it is a binary star, whose secondary component is a γ-ray source. A number of important additions are made allowing a more critical consideration of the provisions of the paper published earlier by Andrievsky in 2022. First, a new approach is proposed to estimate the number of the γ-quanta emitted by the γ-ray pulsar, and irradiating the Przybylski's star deep atmosphere layers. Second, additional sources of the free photo-neutrons are considered. Third, a critical qualitative analysis is carried out concerning the influence of the Compton effect on the γ-quanta population, which after leaving the γ-ray pulsar magnetosphere as a fan-beam, irradiate the Przybylski's star surface. Specific geometry of this binary system and its physical properties may explain uniqueness of the Przybylski's star.

Keywords: Stars – Chemically peculiar stars – Przybylski's star

1. INTRODUCTION

In [1] a new scenario to explain the unusual properties of Przybylski's star was proposed. This unique star was discovered in 1961 by Polish astronomer Antoni Przybylski in Australia. As is known, in the spectrum of this star one can detect a huge number of lines belonging to s-process elements (rare earth), such as Ce, Pr, Nd, Sm and others. This peculiarity may indicate the high-energy processes affecting the atmosphere of this star (or have affected it in the past), and leading to the generation of free neutrons. Their reactions with the seed nuclei (in particular, iron-peak nuclei) in the processes of the slow neutron captures (neutron capture, and the following β^-decay) gradually produce the nuclei of the above s-process elements. A few hypotheses that were proposed up to date in order

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to explain the Przybylski's star phenomenon, as well as observed properties of this star, are considered in detail in [1]. In addition, [2–4] attempted to search for spectral lines of such elements as deuterium, technetium and promethium, whose nuclei are also formed by the free neutron captures (the last two radioactive elements are ususally considered as s-process elements). The search gave the negative results, and this was explained in the above mentioned papers.

2. BASIC MODEL ASSUMPTION

Hypotheses put forward before 2022 failed to explain the Przybylski's star phenomenon. In 2022 [1] described a new scenario, which as seemed to be able to help in understanding this star spectroscopic peculiarity. This scenario was based on a supposition that Przybylski's star is a binary star, whose companion is a low-mass neutron star being the γ-ray source. Specific geometrical and physical features of this binary system made this star an unique object of our Galaxy. Assumptions: first of all, the orbits of both components lie in the plane of the picture. This excludes the detection of the periodical line shift in the spectrum of Przybylski's star (observational fact). Secondly, the rotation axes of both components are nearly collinear (which is a completely natur al assumption), and are directed towards the observer. Since in this case we see Przybylski's star polar-on, it makes this star the "very slow"rotator (observational fact).

Secondary component of the binary system is a neutron star. One component of the electric field in the pulsar's magnetosphere is parallel to the magnetic lines. Charged particles, which are born near the neutron star surface, are accelerated in this strong electric field aligned with magnetic field to the high energies, and they can escape the neutron star surface within the outer gap in the magnetosphere. Their trajectories are modulated by the open curved magnetic field lines, and they emit the curvature radiation in the γ-ray range [5]. γ-rays should be produced very close to (or outside) the light cylinder. This radiation can propagate approximately in the orthogonal direction relative to the rotation axis of the neutron star (namely, in the direction of the Przybylski's star) if the rotation and magnetic axes are at a certain angle to each other (see, for examle, a very instructive illustration in [6], Fig.1).

In the outer gap model, the γ radiation propagates within a fairly large solid angle, and this fact makes it possisble for such a fan-beam to irradiate the surface of the Przybylski's star, even at a fairly large distance betweeen the components. In other words, for the Przybylski's star, a neutron star is a γ-ray pulsar. In contrast, the pencil-beam radiation from the polar cap of the neutron star does not affect the surface of the Przybylski's star atmosphere. The outer gap model was discussed, for example, in [7], Takata et al. [8], [9], [10] etc.

As it was mentioned, in the outer gap model the fan-beam radiation propagates within the rather large angle if the Lorentz factor $\Gamma = \frac{1}{\left(1-\frac{v^2}{c^2}\right)}$ is not very large (it is true for moderate energies of particles). In this case, for beaming the flat angle $\alpha \sim \frac{1}{\Gamma}$. Of course, the physical parameters of the neutron star, as well as geometrical parameters of the binary system are not known. The angular velocity of the neutron star rotation may vary from 0.1 to $1000\,\mathrm{rad s}^{-1}$, magnetic field strength - from 10^5 to 10^{10}Tl, electric field potential drop can be about 10^{16} V.In [11], the Lorentz factor $\Gamma = \frac{e\Delta\phi}{m_e c^2}$ for electrons in extreme case can achieve 10^{10}. This value can be smaller and may change during the pulsar evolution (typical value for electrons is about 10^7). Fr equency of the emitted quanta can be found using the following expression:

$$\nu_c = \frac{3c}{4\pi r_c}\Gamma^3 \tag{1}$$

The curvature radius r_c of the open magnetic field lines in this specific case is unknown, but it is known that for mild γ-ray pulsars the energy range is from MeV to about 0.1 TeV .

Solid angle of the γ-ray fan-beam is

$$\Theta = \frac{\pi}{\Gamma^2} \tag{2}$$

and it may vary in the range from approximately 10^{-8} to 10^{-20}. According to [12] the distance between components of a close binary star is $D \approx 3000R_\odot$. If we adopt this value as an arbitrary parameter of the binary system, and consider the mild energy regime, then the irradiated area on the Przybylski's star surface will be

$$S = D^2\Theta \approx 5 \times 10^{28} \times 3 \times 10^{-14} \approx 10^{15}\ \mathrm{cm}^2 \tag{3}$$

for $\Gamma = 10^7$ (in our model we assume that the fan-beam hits on the surface of the Przybylski's star). In reality, the irradiated spot area can be either larger (say, $\approx 10^{21}$ cm^2 for $\Gamma = 10^4$), or smaller, depending on Γ value. Note that the total area of the Przybylski's star disc is about 10^{22} cm^2 [13] (gives the radius of the Przybylski's star as 1.3R$_\odot$).

It is known that pulsed energy emitted by the γ-ray pulsar is about $L = 10^{35} - 10^{36}\mathrm{ergs}^{-1}$ [6]. If this energy is emitted within the discussed outer gap solid angle then the irradiated area on Przybylski's star will be hit by about $10^{36}\mathrm{ergs}^{-1}/10^{-5}\mathrm{erg} \approx 10^{41}\gamma$-quanta per sec (for quanta with an energy of about ten MeV , i.e. 10^{-5}erg).

For a rough estimate of the irradiated area 10^{13} cm^2, we get the γ-ray flux of about $10^{23}\mathrm{erg\,cm}^{-2}\ \mathrm{s}^{-1}$.

The typical lifetime of a pulsar is about 10^7 years [14], therefore the total fluence (total number) of γ-quanta, which irradiate the certain area on the Przybylski's star surface during this time can be quite large (approximately, 10^{55}).

3. γ-QUANTA AND FREE NEUTRONS

How γ-quanta can produce free neutrons? [1] proposed a mechanism of the free photoneutons formation in reactions between γ-quanta and α particles in the Przybylski's star deep layers (it is reasonable to limit consideration of particle interactions in the convective zone, since only in this case the convective flows transport the products of the reaction between free neutrons and seed nuclei to the stellar surface, and this makes them accessible to detection by spectroscopic analysis).

The reaction cross-section ${}^4_2\mathrm{He}(\gamma,\mathrm{n}){}^3_2\mathrm{He}$ is close to $1-2$mb in the energy range between 30 and 70 MeV with a peak value of about 3.5 mb at about 30 MeV [15]. The following reactions at the same energy can also contribute to the production of free neutrons:

$$\gamma + {}^{12}_{6}C = {}^{11}_{6}C + n \tag{4}$$

$$\gamma + {}^{14}_{7}N = {}^{13}_{7}N + n \tag{5}$$

$$\gamma + {}^{16}_{8}O = {}^{15}_{8}O + n \tag{6}$$

$$\gamma + {}^{28}_{14}Si = {}^{27}_{14}Si + n \tag{7}$$

For instance, the last reaction has a giant dipole resonance at 26 MeV [16]. Despite the fact that these nuclei are less abundant than α particles, the reaction cross-sections are larger than those of the reaction ${}^4_2\mathrm{He}(\gamma,n){}^3_2\mathrm{He}$. The question arises: where in the Przybylski's star the listed above reactions occur? Since we do not know the internal structure of the Przybylski's star, as a very rough approximation we will use the internal structure of the Sun (the difference in the effective temperature is about $600-800$ K, $\mathrm{T_{eff,PS}} = 6400$ K from Hα line, and $\log g = 4.2$, [17]; $\mathrm{T_{eff,PS}} = 6600$ K, [18]; $\mathrm{T_{eff,PS}} = 6131$ K from GDR3). According to [19], at the bottom of the outer convective zone (it occupies about 30% of the stellar radius,or even slightly more with overshooting) the density reaches about 0.1 g $\mathrm{cm^{-3}}$. Therefore, the proton concentration there is about 10^{23} $\mathrm{cm^{-3}}$. Since the helium nuclei in the stellar atmospheres, as a rule, are about ten times less abundant than protons, the concentration of the α particles in this zone is $N \approx 10^{22}$ $\mathrm{cm^{-3}}$. As mentioned above, the cross-section σ for the γ-quanta interaction with α particles is about $1-3$mb, so the optical thickness for the γ-quanta of about unity will be reached at the bottom of the convective zone in the shell of size:

$$d \approx \frac{1}{\sigma N} \approx 10^5 \text{ cm}. \quad (8)$$

In this shell at the bottom of convective zone γ-quanta can already react with nuclei of the elements mentioned above, thus forming in this way fast free photoneutrons. Fast neutrons can lose their energy through elastic collisions with protons and become resonant intermediate neutrons, which can react with seed nuclei in the s-process. This can be achieved through the following scheme:

$$\frac{\Delta E}{E} = 1 - \frac{2A}{(A+1)^2}, \quad (9)$$

where A is the mass of target (obviously, the energy loss will be highest for the lower mass targets). ΔE and E are the fraction of energy lost in one collision and the neutron initial energy, respectively. About twenty collisions are needed to reduce the neutron energy from tens of MeV to less than keV (intermediate or resonant neutrons). The energy loss (thermalization) occurs very quickly. Only such intermediate neutrons can be captured by the seed nuclei (for example, the nuclei of iron-peak elements).

4. POTENTIAL PROBLEMS OF THE PROPOSED HYPOTHESIS

γ-quanta that penetrate into the internal layers of Przybylski's star may lose part of their energy due to the Compton effect. The int eraction with free electrons can be charact erized by the cross-section:

$$\sigma = \pi a^2 \frac{m_e c^2}{h\nu} \times \left(\ln \frac{h\nu}{m_e c^2} + 3 \right), \quad (10)$$

where a is the electron radius, m_e is the electron mass. γ-ray scattering can reduce the energy of quanta. Such a decrease depends on the angle of scattering:

$$\Delta\lambda = \frac{h}{m_e c} \times (1 - \cos(\theta)). \quad (11)$$

If the angle is small or equal to zero, then the γ-quanta energy loss will be small or absent at all. Of course, this process may decrease the flux of γ-quanta that can penetrate deep enough into Przybylski's star atmosphere. Nevertheless, there are two points that mitigate this possible problem. First, we are interested in γ-quanta that have energies of about tens of MeV (for the reactions listed above to be effective). It is quite possible that γ-quanta born in the neutron star magnetosphere have initially energies of hundreds of MeV, and after the scattering they gain the energies of tens MeV. Second, the Compton effect has the largest efficiency near the electron energies, which are close to the $m_e c^2$ value, that is 0.5 MeV. Efficiency of the Compton scattering decreases rapidly with energy increase, and become almost negligible at about tens of MeV.

In [20] considered stratification of the elements in the atmospheres of pulsating roAp stars. Since the author considered the Przybylski's star as a coolest representative of the whole class, she indirectly supports an idea of stratification in the Przybylski's star atmosphere as a factor of the chemical pecularity formation. Perhaps this process can participate to somehow in the Przybylski's star phenomenon. However, regarding the low temperature of this star and an expected strong convection, which should erase any surface chemical anomalies, this explanation does not seem very realistic.

Finally, in case of a certain disposition of the orbits of the binary system components, we should detect the Przybylski's star cyclic proper motion variation. It was not detected from the combined Gaia+Hipparcos data [21]. The possible reason may be as follows. If the binary system under discussion consists of a main sequence component and a neutron star of about half less its mass, then taking into account the distance between the close binary components of about 3000R$\odot$ (see above), we should expect that the distance of the Przybylski's star from the center of mass should be something about 1000R $\odot$. The distance to the Przybylski's star is about100 pc (SIMBAD, GDR3). Therefore, the spatial angular deviation from the center of mass will not exceed $\approx 2 \times 10^{-5}$ arcsec, while the spatial resolution of Gaia equipment is not better than 2.4×10^{-5} arcsec. Thus, either such a motion was not detected by the Gaia instruments, or it is on the level of the measurement errors.

5. CONCLUSION

Let us summarize the above reasoning. For this the main assumptions of the discussed phenomenological hypothesis can be listed as follows:

1. Przybylski's star is a component of the binary system, where the secondary component is a neutron star. Rotation axes of both components are nearly codirected towards the observer, while their orbits both lie in the picture plane. In such a case we do not register the radial velocity variation for the Przybylski's star. At the same time observationally this star is known as very "slow"rotator.

2. A neutron star is a γ-ray pulsar for the Przybylski's star. If we adopt for such a pulsar the outer gap model, then the emitted γ-rays will be directed approximately orthogonally to its rotation axis (provided there is a corresponding tilt between rotational axis and magnetic axis). In this favorable case, the γ

quanta can irradiate the Przybylski's star atmosphere, causing there the highenergy processes that can lead to the production of free neutrons.

3. The size of the irradiated area on the surface of the Przybylski's star depends on the distance between components and the solid angle of the γ-radiation fanbeam. The latter, in turn, depends on the Lorentz factor.

4. Many of the above-mentioned physical properties of the binary model of the Przybylski's star are unknown and can only be of an estimated nature. If such a system, containig a main sequence star and a neutron star (the source of γ-rays) actually formed tens of millions years ago, an initial "fine-tuning" of its geometrical and physical parameters could lead to the formation of a remarkable chemical peculiarity of the primary component, which is currently considered one of the most unique observed objects in the sky - Przybylski's star.

REFERENCES

1. Andrievsky S. M., 2022, OAP **35**, 13

2. Andrievsky S. M., Kovtyukh V. V. 2023, AN, **34420133**

3. Andrievsky S. M., Korotin S. A., Werner K., 2023a, AN, **34430056**

4. Andrievsky S. M. et al., 2023b, AN, **34430077**

5. Harding A.K. et al., 1978, ApJ, **225**, 226

6. Hirotani K., 2013, ApJ, **766**, 98

7. Hirotani K., Harding A. K., Shibata S., 2003, ApJ, **591**, 334

8. Takata J., Shibata S., Hirotani K., 2004, MNRAS, **354**, 1120

9. Hirotani K., 2006, ApJ, **652**, 1475

10. Takata J., Chang H.-K., Shibata S., 2008, MNRAS, **386**, 748

11. Tomczak I., Petri J., 2023, A&A, **676A**.128

12. Tutukov A.V., Yungelson L.R., 1993, ARep, **37**, 411

13. Kurtz D.W., 1980, MNRAS, **191**, 115

14. Kuiper L., Hermsen W., 2015, MNRAS, **449**, 3827

15. Tornow W. et al., 2012, PhRvC85, **061001** (R)

16. Pywell R.E. et al., 1983, PhRvC, **27**, 960

17. Shulyak D. et al., 2010, A&A,**520**, A88

18. Mkrtichian D. et al., 2008, A&A, **490**, 1109

19. Ogden Abell G., 1955, ApJ, **121**, 430

20. Ryabchikova T., 2008, CoSka, **38**, 257

21. Kervella P. et al., 2019, A&A, **623**, A116