10.18524/1810-4215.2022.35.268673

AN ENIGMA OF THE PRZYBYLSKI STAR

S.M. Andrievsky[1,2,3]

[1] Astronomical Observatory, Odessa National University of the Ministry of Education and Science of Ukraine, Shevchenko Park, 65014, Odessa, Ukraine, *andrievskii@ukr.net*
[2] Institut für Astronomie und Astrophysik, Kepler Center for Astro and Particle Physics, Universität Tübingen, Sand 1, 72076 Tübingen, Germany,
[3] GEPI, Observatoire de Paris, Université PSL, CNRS, 5 Place Jules Janssen, F-92190 Meudon, France

ABSTRACT. A new scenario to explain the Przybylski star phenomenon is proposed. It is based on the supposition that this star is a component of a binary system with a neutron star (similar to the hypothesis proposed earlier by Gopka, Ul'yanov & Andrievskii). The main difference with previous scenario is as follows. The orbits of the stars of this system lie in the plane of the sky (or very close to this plane). Thus, we see this star (and its companion) nearly polar-on, and therefore we cannot detect the orbital motion (spectral line based) from the Przybylski's star spectrum. In relation to the Przybylski star, the neutron star is a γ-*ray pulsar* for it. A neutron star is a source of relativistic particles and radiation emitted from the certain parts of its surface. The topology of this radiation strongly depends on the the magnetic field configuration of the neutron star. Existing models suppose that 1) high-energy electron-positron pairs and hard radiation are produced in the (magnetic) polar zones. Accelerated charge particles that move along magnetic lines emit electromagnetic quanta. In this model the radio-emission is genetically linked with the emission of the γ-quanta. 2) Another model of the outer gap is based on the assumption that there is a vacuum gap in the outer magnetosphere of the neutron star, which arises due to the constant escape of charged particles through the light cylinder along the open magnetic field lines. The direction of such escape may be roughly orthogonal to the rotation axis. If the rotation axes of the Przybylski star and the neutron star are close in direction (or even aligned), charged particles and hard radiation ejected in the approximately orthogonal direction at a large solid angle can enter the Przybylski's star atmosphere, causing there different physical processes. As a possible source of the free neutrons could be the nuclear reactions between high-energy γ-quanta and nuclei of some atoms in the Przybylski's star atmosphere gas. As a result, photoneutrons can be generated. Large enough neutron flux can be produced in the reactions with quite abundant element of the atmosphere gas (for example, helium). The photoneutrons produced in these reactions are rapidly thermalized and, as resonant neutrons, react with seed nuclei in the s-process. It should be also noted that together with s-process elements, the deuterium nuclei could be formed as a result of the interactions of the free resonant neutrons with the hydrogen atoms, but this issue has not yet been worked out.

Keywords: Stars: chemically peculiar

АНОТАЦІЯ. Запропоновано новий сценарій пояснення феномену зорі Пшибильського. Він ґрунтується на припущенні, що ця зоря є компонентом подвійної системи з нейтронною зорею (подібно до гіпотези, запропонованої раніше Гопкою, Ульяновим та Андрієвським). Основна відмінність від попереднього сценарію полягає в наступному. Орбіти зір цієї системи лежать у картинній площині (або дуже близько до цієї площини). Таким чином, ми бачимо цю зорю (і її супутника) майже в полярному положенні, і тому ми не можемо виявити орбітальний рух за спектром зорі Пшибильського. По відношенню до зорі Пшибильського нейтронна зоря є гамма-пульсаром. Нейтронна зоря є джерелом релятивістських частинок і випромінювання, що випускається певними ділянками її поверхні. Топологія цього випромінювання сильно залежить від конфігурації магнітного поля нейтронної зорі. Існуючі моделі припускають, що високоенергетичні електрон-позитронні пари і жорстке випромінювання утворюються в (магнітних) полярних зонах. Прискорені заряджені частинки, які рухаються вздовж магнітних ліній, випромінюють електромагнітні кванти. У цій моделі радіовипромінювання генетично пов'язане з випромінюванням гамма-квантів. Інша модель базується на припущенні, що в зовнішній магнітосфері нейтронної зорі є вакуумний проміжок, який виникає внаслідок постійного витікання заряджених частинок через світловий циліндр вздовж відкритих силових ліній магнітного поля. Напрямок такої міграції може бути приблизно ортогональним до осі обертання зорі. Якщо осі обертання зорі Пшибильського і нейтронної зорі близькі за напрямком (або навіть співпадають), заряджені частинки і жорстке випромінювання, що викидаються в приблизно ортогональному напрямку у великому тілесному куті, можуть входити в атмосферу зорі Пшибильського, викликаючи там різні фізичні процеси. Можливим джерелом вільних нейтронів можуть бути ядерні реакції між високоенергетичними гамма-квантами і ядрами деяких атомів у газі атмосфери зорі Пшибильського. Як наслідок, можуть генеруватися фотонейтрони. Досить великий потік нейтронів може бути отриманий в реакціях з досить поширеним елементом газу атмосфери (наприклад, Гелієм). Фотонейтрони що утворюються в цих реакціях, швидко втрачають енергію і, вже як резонансні нейтрони, реагують із зародковими ядрами ядрами в s-процесі. Слід також зазначити, що разом з елементами s-процесу ядра Дейтерію могли б утворитися в результаті взаємодії вільних резонансних нейтронів з атомами Гідрогену, але це питання ще не опрацьоване.

Ключові слова: Зорі: хімічно пекулярні

1. Introduction

The Przybylski star (HD 101065) is probably one of the most mysterious objects in our Galaxy. Its spectrum is crowded with lines of various elements. Some of them are identified as lines of rare-earth elements (even at higher ionization stages than expected from the value of the star effective temperature), and others are not identified.

Since the first spectroscopic observation of this star and the first published papers, noting the enormously strong line blanketing in its spectrum (Przybylski 1961, Kron & Gordon 1961), more than sixsty years have already passed, and no acceptable explanation for this phenomenon has yet been given (see, nevertheless, Gopka, Ul'yanov & Andrievskii 2008).

One of the first attempts to identify the lines of chemical elements in the spectrum of this star was made by Cowley et al. (1977). The authors were able to identify many lanthanide lines, but the identification of the lines of the iron-peak elements proved to be uncertain.

However, earlier Wegner & Petford (1974) derived the abundances in the Przybylski star from red spectra. They identified the lines of the iron-peak elements and found that the abundances of these elements are close to solar values, while the abundances of the rare-earth elements are increased by about five orders of magnitude.

A later detailed examination of the high-resolution *IUE* spectrum of this star in the 1900–3200 Å range confirmed the presence of the lines of the iron-peak ions: Ti, Cr, Mn, Fe (Wegner et al. 1983).

Cowley & Mathys (1998) analyzed CASPEC spectra in the visual range and confirmed the presence of the iron lines (mildly deficient iron abundance, of about –1 dex compared to the solar value). They also found that the rare-earth elements are enhanced by about four orders of magnitude. This finding was confirmed later by Cowley et al. (2000). Cowley et al. (2004) also suggested the presence of radioactive Pm I, Pm II, Tc I, and possibly Tc II lines in the spectrum of this star.

Goriely (2007) attempted to explain the existence of radioactive elements such as Tc and Pm in the Przybylski's star atmosphere. This author proposed spallation mechanism of nucleosynthesis as a possible origin of the discussed chemical anomalies, but he does not specify the nature of the particles that could cause such nucleosynthesis.

Mkrtichian et al. (2008) found the following parameters of this star: $M = 1.52\ M_{\odot}$, $T_{\rm eff} = 6622$ K, $L = 6.31\ L_{\odot}$. According to Mkrtichian et al. (2008), HD 101065 appears to be a prime candidate to possess a very long rotation period. Using the same effective temperature, Shulyak et al. (2010) derived the abundances of 52 chemical elements in this star. These authors found that the abundances of rare-earth elements are increased by about 3–4 orders of magnitude.

The original idea, which was aimed to explain the phenomenon of the Przybylski star, was first proposed by Gopka, Ul'yanov & Andrievsky (2008). (It should be noted that Martinez & Kurt 1990 having analyzed the photometric observations, concluded that the Przybylski star could be a binary system, but these authors suggested a brown dwarf as a companion). Gopka, Ul'yanov & Andrievsky (2008) supposed that this unique star is a binary star, whose companion is a neutron star. The high-energy processes occuring on the surface of the neutron star surface, may be responsible for the significantly increased abundance of heavy elements in the Przybylski star. For example, according to the authors' qualitative statement, a neutron star emits electron-positron pairs, and if they reach the Przybylski's star atmosphere, reactions occur at the stellar surface producing free neutrons and protons (a weak process). On the other hand, γ-quanta can produce some nuclear transformations. The authors considered the deceleration of the particles ejected by a neutron star in the electric field of the atomic nuclei in the gas of the stellar atmosphere. At the time, this very interesting idea was not properly elaborated, and unfortunately, it was not also properly considered and cited in the literature by specialist who have dealt with this problem.

This paper considers a modification of the above scenario, first proposed by Gopka, Ul'yanov & Andrievskii (2008). In our further consideration, only the basic hypothesis that the Przybylski star is a binary system containing a neutron star, will be retained. The observed properties of this unique star will be explained on the basis of this modified hypothesis.

2. The Przybylski Star is a Binary System

Following to Gopka, Ul'yanov & Andrievskii (2008), we assume that the Przybylski star is a component of the binary star, whose companion is a neutron star. The (many) lines in the spectrum of the Przybylski star are quite sharp, and we would be able to easily detect their periodic shifts with a time. Why cannot we detect the orbital motion (spectral line based) from the Przybylski's star spectrum? The simplest solution is that the orbits of the stars of this system lie in the plane of the sky (or very close to this plane). Thus, we see this star (and its companion) nearly polar-on, and this conclusion is also indirectly supported by the finding of Mkrtichian et al. (2008), who state that this star (in this sense) is a "slow rotator".

Nevertheless, such an assumption immedately raises another question: can we detect the proper motion anomaly of this star caused by a periodic change of its position in space? Przybylski star is located at the distance of about 100 pc from the Sun (*GR*3, *SIMBAD*). The most precise *GR*3 and *Hipparcos* astrometrical data from Kervella et al. (2019) do not show for this star the proper motion anomaly. These authors indicate the mass of this star of about 1.5 $M_\odot$ (see, also Mkrtichian et al. 2008). It is possible that both components have close masses, since a great majority of the neutron stars with well-defined masses have masses close to 1.5 $M_\odot$ (Stairs 2004). Despite the fact that the photocenter of the system can be offset to the Przybylski star ($L_{\rm NS}/L_{\rm PS}$ should be much less than 1), the comparable masses may hide the effect of changes in proper motion as a function of a time. It is also possible that the neutron star has a much smaller mass compared to the Przybylski star, therefore the proper motion of the Przybylski star appears to be undetectable (Valentim et al. 2011 show that the neutron star sample contains objects with masses less than 1 $M_\odot$).

A neutron star is a source of relativistic particles and radiation emitted from the certain parts of its surface. The topology of this radiation strongly depends on the the magnetic field configuration of the neutron star. In the literature, the following tradional pulsar high-energy emission models are discussed: the polar cap model, the slot gap and the outer gap model (see, e.g. Harding 2001, Harding 2009, Barnard 2021).

The first model assumes that high-energy electron-positron pairs and hard radiation are produced in the (magnetic) polar zones. Accelerated charge particles that move along magnetic lines emit electromagnetic quanta. In this model the radio-emission is genetically linked with the emission of the γ-quanta.

The model of the outer gap is based on the assumption that there is a vacuum gap in the outer magnetosphere of the neutron star, which arises due to the constant escape of charged particles through the light cylinder along the open magnetic field lines. In some particular cases, the direction of such escape may be roughly orthogonal to the rotation axis (see, for example, Hirotani 2013, Fig. 1, Brambilla et al. 2018, Figs. 14–15).

In contrast to the previously mentioned model, the outer gap model assumes that the γ-ray beam has a different spatial direction compared to the direction of the radio emission. Moreover, the outer gap γ-ray beam has a much larger solid angle compared to the radio-beam. The angle between the direction of the emitted photons and the open magnetic field lines could be quite large for not extremely high-energy particles (the angle is proportional to $(1-\beta^2)^{0.5}$, here $\beta = \frac{v}{c}$). If the rotation axes of the Przybylski star and the neutron star are close in direction (or even aligned), charged particles and hard radiation ejected in the approximately orthogonal direction at a large solid angle can enter the Przybylski's star atmosphere, causing there different physical processes.

The polar cap model with an angle between rotation and magnetic axes of about 90 degrees is not excepted either. Such an extreme case, when the magnetic dipole axis is orthogonal to the rotation axis in the neutron star was considered, for example, by Sturrock (1971). In this case, the Przybylski's star atmosphere may be exposed to radiation emitted in the polar cone.

Thus, in the cases considered above, the neutron star, in relation to the Przybylski star, is a γ-ray pulsar for it.

3. Free Neutron Source

To explain the high abundance of *s*-process elements in the atmosphere of this star, we must find a source of free termalized neutrons. Intuitively it is clear that such a source must be associated with the flux of high-energy particles and hard radiation emitted by the neutron star, which interact with the gas of the Przybylski's star atmosphere.

Here we propose as a possible source of the free neutrons the nuclear reactions between high-energy γ-quanta and nuclei of some atoms in the atmospheric gas. As a result, so-called *photoneutrons* can be generated. Large enough neutron flux can be produced in the reactions with quite abundant element. The best choice could be helium. Several years ago Tornow et al. (2012) considered photodisintegration cross-section of the reaction at the giants dipole resonance peak:

$$\gamma + {}^4\mathrm{He} = {}^3\mathrm{He} + n$$

Cross-section of this reaction has a maximum value for the γ-photons with energies of about 26 MeV. This energy is a boundary value between the energies characteristic of soft and hard γ-ray pulsars, and is regarded as the energy, which is typical for medium γ-ray pulsars (Kuiper & Hermsen 2015). Since the peak value of the cross-section of above reaction is about 2 Millibarn (Tornow et al. 2012), it is clear that γ-quanta have a quite large free path length in the star. Therefore they penetrate to a deep layers of the star (under the atmosphere), where the probability of reactions is much higher. (Short-scale) convection should then lift the reaction products into the atmosphere.

Other reactions with the rather abundant elements in the stellar atmosphere can also produce the free photoneutrons. For example, the following reaction has a giant dipole resonance at energy of about 20 MeV (Pywell et al. 1983):

$$\gamma + {}^{28}\mathrm{Si} = {}^{27}\mathrm{Si} + n$$

γ-quanta can be produced in the electron-positron interaction in the pulsar magnetosphere or in the Przybylski's star atmosphere in the interactions between positrons and local electrons. For this, the free positrons must reach the stellar surface.

The newly born free neutrons with energies of about MeV must be thermalized for reactions of s-process to occur. Neutron thermalisation can be quickly achieved by their collisions with atmospheric protons (hydrogen nuclei), since collisions with light nuclei take away a significant fraction of the energy of initially hot neutrons. For example, after one act of collision a neutron loses some part of its energy, which can be estimated by the following formula (Levin 1979; E_0 and E_1 are the initial energy and the final energy before and after one act of interaction, respectively):

$$E_1/E_0 = 1 - \epsilon/2,$$

$$\epsilon = \frac{4A}{(A+1)^2},$$

where A is the mass number of the nucleus. Numerical estimate gives a value of about 0.5 of the initial energy in one interaction. If the born photoneutrons have typical energies of 10–20 MeV, after about ten collisions with the nuclei of the most abundant element, they gain energies of the order of several KeV. For such resonant neutrons the absorption cross-sections of atomic seed nuclei, including nuclei of heavy elements, are high. Therefore, a large amount of s-process elements can be formed in the star. It is interesting to note, that the iron-peak elements, whose seed nuclei (iron, nickel, in particular), are also transformed into nuclei of heavier species in the s-process, do show a mild deficiency (about one order of magnitude) in the Przybylski's star atmosphere (Cowley et al. 1977, Cowley et al. 2000). It should be noted, that Shulyak et al. (2010) consider deficiency of Si, Ca, Fe, Ni, Ba as a result of the stratification in the stellar atmosphere.

Let us approximately estimate the flux of γ-quanta entering the Przybylski's star atmosphere. Since we do not know the specific characteristics of its hypothetical companion, it will be sufficient to use theoretical estimates of the target values. From the analytical outer gap solution, one can see that the typical pulsed γ-ray luminosities are in the range $10^{35} - 10^{36}$ erg s^{-1} (Hirotani 2013, Fig. 3). Another arbitrary value is the distance between components. For this value we will adopt 3×10^4 R$_\odot$, which is ten times larger than the distance between components of the close binary system (3×10^3 R$_\odot$, according to Tutukov & Yungelson 1993). In this case, the flux at the boundary of the Przybylski's star atmosphere should be about 10^4 γ-quanta per cm^2 s^{-1}. The ages of the soft-to-medium γ-ray pulsars does not exceed $10^5 - 10^6$ yrs (Kuiper & Hermsen 2015, Fig. 29). More than 10^{17} γ-quanta irradiating during this time each cm^2 of the stellar atmosphere perhaps may be able to produce a sufficient amount photoneutrons whose interaction with the seed nuclei is responsible for the Przybylski's star chemical peculiarity.

If the free electrons emitted by the pulsar magnetosphere manage to reach the stellar surface, an additional possible source of free neutrons can be activated:

$${}^{N}_{Z}A + e^- = {}^{N-1}_{Z-1}A + n + \nu$$

Another consequence of the high-energy material interaction with atmosphere gas is its inevitable local heating. As a result one can expect to detect the atoms in the ionization stages, which are not typical for the Przybylski's star effective temperature. Indeed, in several studies the detection of some ions in the second ionization stage was reported (like, Pr III, Nd III, Dy III, Er III, Th III, see, for example, Cowley et al. 2000).

The local atmosphere heating can also be responsible for the photometric variability of the Przybylski star with quite short period, which is not typical for the main-sequence star ($P \approx 12$ min, Kurtz 1978, Kurtz & Wegner 1979). A new period of oscillation (approximately 17 min) was discovered by Ofodum & Okeke (2016).

4. Time of Existence of Abundance Anomalies

Kuiper & Hermsen (2015) noted that soft γ-ray pulsars are all fast rotators and much younger than high-energy γ-ray pulsars. How long can the abundance anomaly in the Przybylski star caused by the γ-ray pulsar persist? To estimate the time of the meridional circulation for mixing the surface and deep gas of the star, we use the formula from Sweet (1950):

$$t = 8 \times 10^{12} \frac{M^3}{LR^4} \frac{1}{\Omega^2} \text{ years}$$

Here all values are in solar units. The mass of the Przybylski star, as stated above, is 1.5 $M_\odot$, its radius and rotation velocity according to Kurtz (1980) are 1.3 $R_\odot$ and 17 km s^{-1}, respectively, and the luminosity of the star is about 6.3 $L_\odot$ (Mkrtichian et al. 2008). Thus, the characteristic time of the mixing process turns out to be high (comparable to the lifetime of the main sequence stage).

5. Concluding Remarks

Below I summarize the above discussion of the Przybylski's star chemical peculiarities. I emphasize that I propose only a hypothesis, which takes an additional step towards our understanding of this unique object.

1. The Przybylski star is a component of a binary star, the other component of which is a neutron stars. Both components have a similar mass of about 1.5 solar masses (it is also quite possible that the neutron star has a lower mass than the Przybylski star).

2. In this binary system, the orbits of its components lie in the plane of the sky (or quite close to it).

3. In relation to the Przybylski star, the neutron star is a *γ-ray pulsar* for it. The rotation axes of both components may be aligned or close to it. The γ-ray pulsar emits high-energy particles/photons toward the surface of the Przybylski star either approximately orthogonal to the rotation axis (magnetic axis is either aligned with ratational axis or tilted at some angle relative to it; outer gap model), or within the polar cone (magnetic axis is orthogonal to the rotation axis). Radiated high-energy particles and photons enter the atmosphere of the Przybylski star, causing various physical processes there.

4. The source of free neutrons is the nuclear reactions in the Przybylski star between the high-energy (MeV) γ-photons and nuclei of the abundant element helium. The photoneutrons produced in these reactions are rapidly thermalized and, as resonant neutrons, react with seed nuclei in the s-process.

5. Here we also note that together with s-process elements, the deuterium nuclei can be formed as a result of the interactions of the free thermalized neutrons with the hydrogen atoms. This issue will be discussed in the next paper.

Acknowledgements. SMA is grateful to the *Vector-Stiftung at Stuttgart, Germany*, for support within the program "2022–Immediate help for Ukrainian refugee scientists"under grants P2022-0063 and P2022-0064. Especial thanks to Prof. K. Werner and Dr. V. Suleimanov for their help with organizing his stay in the Institute of Astronomy and Astrophysics of the Tübingen University.

This research has made use of the *SIMBAD* database, operated at CDS, Strasbourg, France.

References

Barnard M.: 2021, *arXiv210310486.*

Brambilla G., Kalapotharakos C., Timokhin A.N., Harding A.K., Kazanas D.: 2018, *ApJ*, **858:81**, (14pp).

Cowley C.R., Cowley A.P., Aikman G.C.L., Crosswhite H.M.: 1977, *ApJ*, **216**, 37.

Cowley C.R., Mathys G.: 1998, *A&A*, **339**, 165.

Cowley C.R., Ryabchikova T., Kupka F., Bord D.J., Mathys G., Bidelman W.P.: 2000, *MNRAS*, **317**, 299.

Cowley C.R., Bidelman W.P., Hubrig S., Mathys G., Bord D.J.: 2004, *A&A.*, **419**, 1087.

Gopka V.F., Ul'yanov O.M., Andrievskii S.M.: 2008, *KPCB*, **24**, 36.

Goriely S.: 2007, *A&A*, **466**, 619.

Harding A.K.: 2001, *AIPCP*, **558**, 115.

Harding A.K.: 2009, *ASSL*, **357**, 521.

Kervella P., Arenou F., Migrand F., Thévevin F.: 2019, *A&A*, **623**, A72.

Kron G.E., Gordon K.C.: 1961, *PASP*, **73**, 267.

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

Kurtz, D.W.: 1978, *IBVS*, **No. 1436**.

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

Kurtz D., Wegner G.: 1979, *ApJ*, **232**, 510.

Levin V.E.: 1979, *Nuclear reactions and nuclear reactors, Moscow, Atomizdat (in Russian).*

Martinez P., Kurtz D.W.: 1990, *MNRAS*, **242**, 636.

Mkrtichian D., Hatzes A., Saio H., Shobbrook R.R.: 2008, *A&A*, **490**, 1109.

Ofodum C.N., Okeke P.N.: 2016, *NewA*, **43**, 42.

Przybylski A.: 1961, *Nature*, **No. 4766**, 739.

Pywell R.E., Berman B.L., Jyri J.W., Woodworth J.G., McNeill K.G., Thompson M.N.: 1983, *PhysRevC*, **27**, 960.

Shulyak D., Ryabchikova T., Kildiyarova R., Kochukhov O.: 2010, *A&A*, **520**, A88.

Stairs I.H.: 2004, *Sci*, **304**, 547.

Sturrock P.A.: 1971, *ApJ*, **164**, 529.

Sweet P.A.: 1950, *MNRAS*, **110**, 548.

Tornow W., Kelley J.H., Raut R., Rusev G., Tonchev A.P., Ahmed M.W, Crovell A.C., Stave S.C.: 2012, *PhysRew C85*, **061001 (R)**.

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

Valentim R., Rangel E., Horvath J.E.: 2011, *MNRAS*, **414**, 1427.

Wegner G., Petford A.D.: 1974, *MNRAS*, **168**, 557.

Wegner G., Cummins D.J., Byrne P.B., Stickland D.J.: 1983, *ApJ*, **272**, 646.