SOME EVOLUTIONARY ASPECTS OF THE BINARY STELLAR SYSTEMS CONTAINING NEUTRON STAR

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ABSTRACT. The obvious lack of the binary stellar systems that contain neutron stars (NS) is observed at present. Partly it is caused by the fact that it is very difficult to detect neutron star in a binary system if this relativistic component does not manifest itself as a radio pulsar. Among 1879 pulsars that are listed in the ATNF pulsar catalogue, only 141 pulsars are known to be the companions in binary systems. Only 81 objects having median mass estimation of more than 0.2 $M_\odot$ constitute the binary systems with pulsars. Nevertheless, such systems should be much more numerous and their investigation is of the great interest because thier structure and evolution can certainly help in our understanding of many unique properties that are seen in some stars.

Introduction

Some difficulties of a detection of the NS as sources of the radio emission (http://www.atnf.csiro.au/research/pulsar/psrcat/) are discussed in Refs. (McLaughlin et al., 2006; Kondrattiev et al., 2008; Kondrattiev et al., 2009; Malofeev et al., 2007; Zakharenko et al., 2010). Analysis of the different stages of the close binary system evolution with a NS, as one of the companion stars, shows that at the early stage of this evolution the ultra-relativistic electron-positron plasma produced and ejected by NS can hit the atmosphere gas of its companion normal star. At the same time, an usual stellar wind of the normal star will eventually screen NS magnetic field. During some period both winds from NS and normal star will create sources of X-ray emission located at the surfaces of both companions.

The detection of the annihilation line at 511 keV from such systems could be considered as observed manifestation of the above mentioned interaction between NS and normal star in the binary system, in addition to the detection of X-ray radiation. An appearance of the chemical composition anomalies in the companion star atmosphere can also be possible in this case.

There are papers (Tutukov et al., 1985; Iben et al., 1997; Fedorova & Tutukov, 1994; Fedorova & Tutukov, 1992; Fedorova, 1997) in which two most probable evolutionary scenarios are proposed. The first scenario is connected with an expansion of the donor under the action of the X-ray and gamma-ray radiation generated by the NS (acceptor) (Fedorova, 1997). In this scenario, the generation of X-ray and gamma-ray radiation by the NS is a result of accretion of the wind of a companion star. The expansion of the upper layers of the donor in this model is caused by the energy absorption of the NS X-ray and gamma-radiation in the relatively deep layers of the donor. This model implies that donor fills its entire Roche lobe and its material is lost through the first Lagrangian point.

According to this scenario, under the influence of the hard radiation emitted by NS, the donor (companion normal star) passes through the cyclic stages of the orbital period change. At the same time, as a whole, the orbital period decreases, similarly to that as this occurs in cataclysmic binary stars (Fedorova & Tutukov, 1994; Fedorova & Tutukov, 1992; Fedorova, 1997).

Moreover, this scenario predicts the secular increase of the semi-major axis due to an increase of the Roche lobe radius of the donor, and corresponding increase of the mass exchange rate. The most contrasting manifestation of this effect should be observed in the range of the hard radiation fluxes from 10^{10} to 10^{12} $erg/(\cdot cm^2$ sec), and for the range of the donor masses from 0.1 to $2.0 M_\odot$. This process must occurs in the so-called Jeans mode (Gopka et al., 2007), when for a long time the conditions $a_m \cdot (M_1 + M_{NS}) = const$ are satisfied, where a_m is the size of the semi-major axis, M_1 is the mass of the donor, M_{NS} is the mass of the NS (acceptor).

The second scenario describes evolutionary evaporation of the donor due to the presence of the so-called induced stellar wind. In this case, it is assumed that the hard radiation of acceptor heats the relatively thin upper layers of the donor, which have the low density. Cooling in this scenario is achieved due to an induced stellar wind that leads to the gradual evaporation of the donor. In contrast to the first scenario, in this case the size of the semi-major axis of the binary system will decrease with a time. At the early stages of evolution, this decrease is caused by the loss of the binary system moment of inertia due to the stellar wind. However, in the case of an extremely close binary system the gravitational radiation losses must play a more significant role. The qualitative analysis of the interaction in the close binary system with a young NS, as one of the components (Gopka et al., 2007; Gopka et al., 2010; Gopka et al., OAP-20, 2007; Gopka et al., 2008), shows that at the early stage of this evolution heating of the upper atmosphere of the companion can be achieved not only due to the NS hard radiation, but also due to its ultra-relativistic electron-positron plasma ejection. In this case, plasma ejected by NS can hit the atmosphere layers of the companion star. The depth of the heating is supposed to be not uniform. Such an ununiformity can be connected with a concrete geometry of the magnetic field in the donor atmosphere (Ulyanov, 2010). For example,as far as the synchrotron energy losses are proportional to the component of the magnetic field perpendicular to the charge flow, zones near the magnetic poles will be heated at larger depths compared to other zones of the donor atmosphere. Let us note that ionization will be the basic source of energy loss for the ultra-relativistic electrons and positron, which have relatively low kinetic energies (Ginzburg, 1979). These losses will occur in the upper and relatively thin layers of a companion star (Ulyanov, 2010).

Detailed analysis of different types of the losses of the ultra-relativistic electron-positron plasma in the companion atmosphere was performed in (Ulyanov, 2010). The losses caused by the inverse Compton effect, that takes place near the companion (because of an interaction of the electron-positron ultra-relativistic plasma with optical photons), are not essential in comparison with other basic types of the energy losses (Ulyanov, 2010; Ginzburg, 1979). During this period of binary system evolution both winds create the sources of X-ray radiation on the surfaces of companion stars. As it was already mentioned, observational manifestation of such an interaction (besides the X-ray radiation) might be detection of the annihilation line at 511 keV (Ulyanov, 2010; Kontorovich et al., 2010). An appearance of the chemical anomalies in the atmosphere of the companion is also possible (for instance, some lines of the unstable radioactive isotopes were registered in spectra of some stars) (Gopka et al., 2005; Gopka et al., 2008).

An interaction of two objects in the system containing NS can lead to the gradual screening of the NS magnetic field, and corresponding weakening of the ultra-relativistic plasma flow. This may cause the "switch off" of the X-ray and gamma-ray sources of radiation in the atmosphere of the normal companion star. At the same time, X-ray emission from the NS surface can become stronger. Further evolution strongly depends on the diffusion of the NS magnetic field through the acquired accretion crust.

Observation Data

Let us examine the observational facts available at present that characterize evolution of the binary systems which contain NS.

There is ATNF catalogue (http://www.atnf.csiro.au/research/pulsar/psrcat/), where important properties are gathered for all pulsars. In this catalogue, the listed pulsars are the members of binary systems with primary companions of different types. In fact these are close binary systems. After examining of the whole amount of available data in ATNF catalogue, one can make the following conclusions:

1) in the binary systems the secular decrease of the magnetic field strength on the pulsar surface is observed (Fig. 1.);

2) the well known effect of the evolutionary decrease of the pulsar rotation period is observed;

3) the general stabilization of the pulsar kinematic parameters connected with the decreasing of the magnitude of $\dot{P}$ and with an increase of the so-called characteristic age $Age = P/(2\dot{P})$, (where Age is characteristic age of pulsar, P is the period of the rotation of NS around its own axis, $\dot{P}$ is the first-order derivative of the P) is observed (Fig. 2.);

4) on average, for the lower masses of the normal companions, the decrease of the semi-major axis is observed (excluding the companion mass range from $0.1M_{\odot}$ to $2M_{\odot}$) (Fig. 3.);

5) the mass decrease of the normal companion as a function of an increase of the pulsar characteristic age is observed (Fig. 4.).

Possible Interpretation of the Observation Data

It is easy to interpret the first three dependences mentioned above (items 1-3 and Fig. 1-2. The secu-

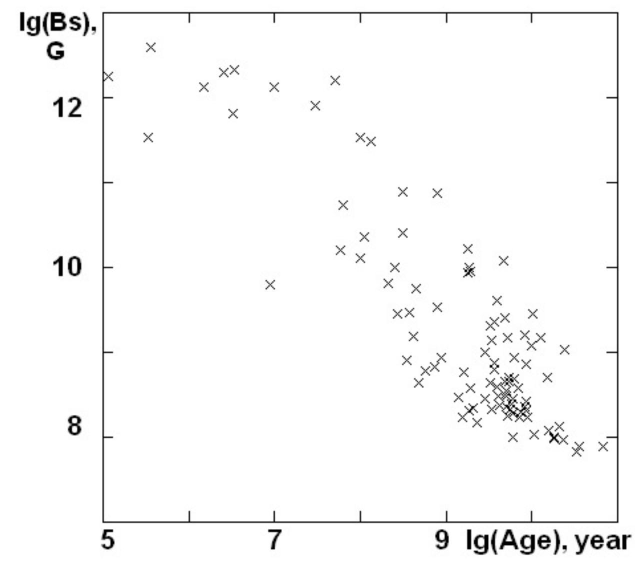

Figure 1: Distribution of the magnitude of the surface strength of magnetic field (B_s) of pulsars in binary systems as a function of their characteristic ages ($Age = \tau$).

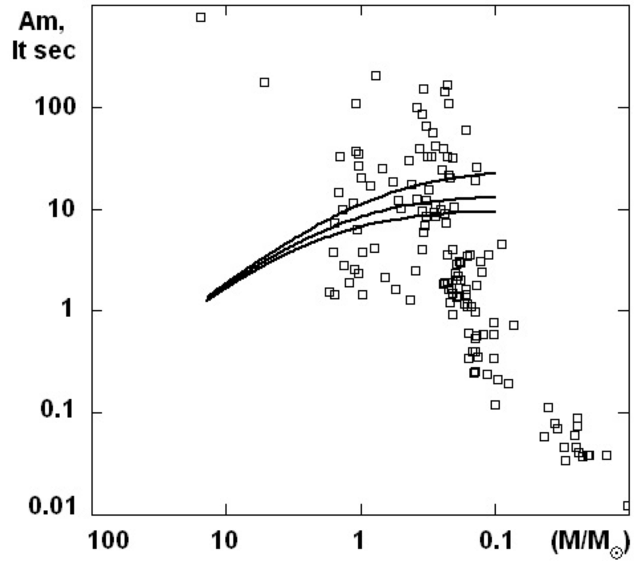

Figure 3: Distribution of th magnitude of the semi-major axis of the binary systems (a_m) depending on the median mass of the normal companions. Solid lines illustrate qualitative behaviour under the Jeans mode conditions corresponding to $0.8M_\odot, 1.4M_\odot, 2.0M_\odot$ pulsar masses (respectively from the top to bottom).

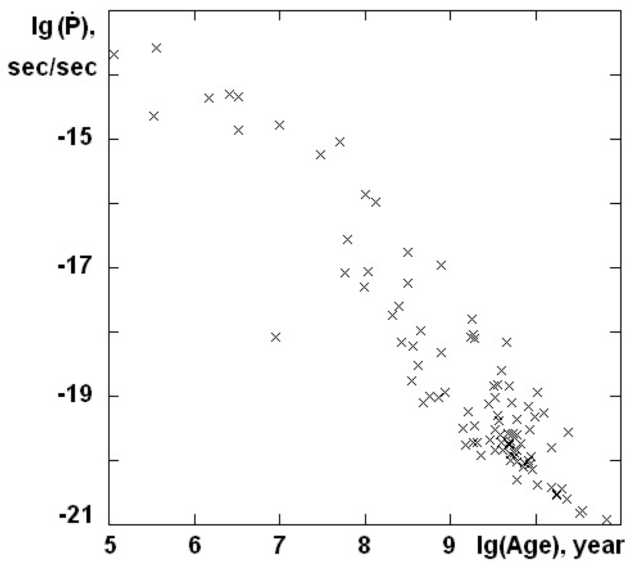

Figure 2: Distribution of the first derivatives for the pulsar rotation periods ($\dot{P}$) as a function of pulsar characteristic ages.

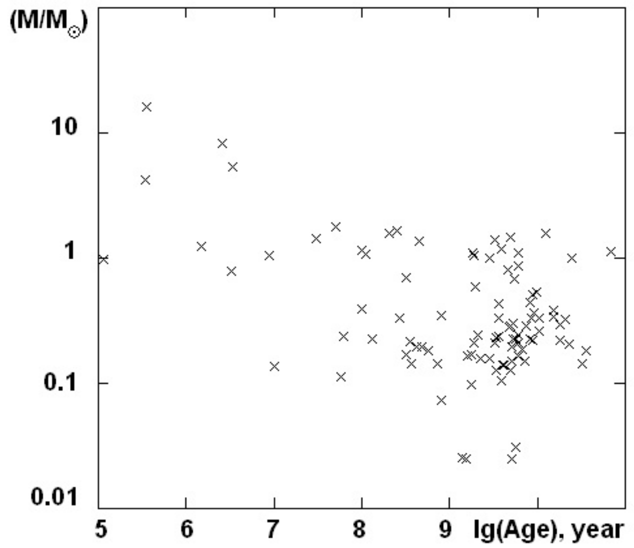

Figure 4: Distribution of the median mass of the normal companions ($M/M_\odot$) as a function of the pulsar characteristics.

lar decrease of the magnetic field strength on the pulsar surface (Fig. 1.) most probably is connected to its screening with the material falling on the pulsar surface from its normal companion. This possibility was indicated in a number of papers (for example, see Bisnovatyi-Kogan, 2006 and references therein). Here we will only note that the rate of accretion must correlate with the intensity of the hard radio emission, produced with the same particles via the warming-up of pulsar surface up to extremely high temperatures. The second aspect is the fact that the magnetic field will be preserved inside the core of pulsar/NS for a long time, but when the accretion stops the magnetic field must float to its surface as a result of diffuse processes. The threshold value of magnetic induction on the NS surface, above which we observe the NS as a radio pulsar, according to the ATNF catalog data corresponds to $B_s > 6.7 \cdot 10^7$ Gauss.

Similar explanation involves the evolutionary decrease of the pulsar rotation periods. In this case (Fig. 2.), the so-called effect of the slight twist occurs, when the donor twists the pulsar, increasing its torque. The effect is connected with an increase of the conservatism of such kind of the binary system (Fig. 2.). This is confirmed by the decrease in the first-order derivative of the pulsar rotation period. When the magnetic field strength on the pulsar surface decreases, the corresponding decrease in the kinematic losses of pulsar (caused either by magneto-dipole emission or by current losses) takes place. It is quite probable that the accretion on pulsar surface is stabilized or completely discontinued as pulsar characteristic age increases.

Items 4, 5 (Fig. 3-4) can be grouped together due to the fact that total mass of both companions, sizes of semi-major axes and orbital periods are coupled via the third Kepler law. Although the general trend (Fig. 4) probably indicates to a decrease of the mass of the NS companion in the binary systems, the behavior of these systems in the range of the masses $M_1 \in [0.1M_\odot; 2M_\odot]$ should be considered in more detail. For example, in the range of masses $M_1 \in [0.1M_\odot; 2M_\odot]$ the companion normal star can loose very rapidly part of its mass as a result of the tidal destruction, directed explosions, or a series of the directed micro explosions/bursts.

Conclusions

The analysis of the presented data shows that in the close binary systems containing NS, the secular decrease of the magnetic field strength on the NS surface is observed. This decrease of the magnetic field strength most probably is connected with the accretion from the companion star on the NS surface. A threshold below which the NS/pulsar cannot be observed as a radio source is about $6.7 \cdot 10^7$ Gauss.

The observed secular decrease of the first derivative of the rotation period of the pulsars most likely corresponds to the fact that between the pulsar and its companion star a deep negative feedback is established, which effectively suppresses any fluctuations in the rate of the accretion on the NS surface and/or fluctuation in the luminosities of the hard radiation.

The evolutionary decrease of the semi-major axis of the binary systems and the simultaneous decrease of the mass of the normal star companions over the large time intervals testifies in a favour of the hypothesis about evolutionary evaporation (or destruction with the subsequent evaporation) of the companion star.

This hypothesis is also supported by the presence of numerous single millisecond pulsars with a large characteristic age, whose companion stars are not seen.

In the range of companion masses from $0.1M_\odot$ to $2M_\odot$, the most complex manifestation of the evolutionary phenomena in the binary systems are observed. It is quite probable that in this mass range the Jeans accretion mode operates.

References

http://www.atnf.csiro.au/research/pulsar/psrcat/

M.A.McLaughlin, A.G.Lyne, D.R.Lorimer, M.Kramer, A.J.Faulkner, R.N.Manchester, J.M.Cordes, F.Camilo, A.Possenti, I.H.Stairs, G.Hobbs, N.D'Amico, M.Burgay, J.T.O'Brien: *Nature*, 2006, **439**, 817.

V.I.Kondrattiev, M.Burgay, A.Possenti, M.A.McLaughlin, D.R.Lorimer, R.Turolla, S.Popov, S.A.Zane: *40 Years of Pulsars, Magnetars and More*, 2008, American Institute of Physics, Montreal.

V.I.Kondrattiev, M.A.McLaughlin, D.R.Lorimer, M.Burgay, A.Possenti, R.Turolla, S.B.Popov, S.A.Zane: *Astrophys. J.*, 2009, **702**, 692.

V.M.Malofeev, O.I.Malov, and D.A.Teplykh: *Astrophys. Space Sci.*, 2007, **308**, No.1, 211.

V.V.Zakharenko, A.V.Markova, Y.Y.Vasylyeva: *Radio Physics and Radio Astronomy*, 2010, **15**, No.3, 263.

A.V.Tutukov, A.V.Fedorova, E.V.Ergma, L.R.Yungel'son: *Pis'ma Astron. Zh.*, 1985, **11**, 123.

I.J.Iben, A.V.Tutukov, A.V.Fedorova: *Astrophys. J.*, 1997, **486**, 955.

A.V.Fedorova, A.V.Tutukov: *Astronomy Reports*, 1994, **38**, 377.

A.V.Tutukov, A.V.Fedorova: *Astronomicheskii Zhurnal*, 1992, **69**, 271.

A.V.Fedorova: *Dual Stars*, 1997, Spaceinfo Pub., Moscow.

V.F.Gopka, O.M.Ulyanov, S.M.Andrievsky: *Origin of Matter and Evolution of Galaxies*, 2007, American Institute of Physics, Sapporo.

V.F.Gopka, O.M.Ulyanov, S.M.Andrievsky: *Origin* *of Matter and Evolution of Galaxies*, 2010, American Institute of Physics, Osaka.

V.F.Gopka, O.M.Ulyanov, S.M.Andrievsky: *Odessa Astron. Publ.*, 2007, **20**, 62.

V.F.Gopka, O.M.Ulyanov, S.M.Andrievsky: *Kinematics and Physics of Celestial Bodies*, 2008, **24**, 36.

O.M.Ulyanov: *Origin of Matter and Evolution of Galaxies*, 2010, American Institute of Physics, Osaka.

V.L.Ginzburg: *Theoretical Physics and Astrophysic*, 1979, Pergamon Press, Oxford.

V.M.Kontorovich, O.M.Ulyanov, A.B.Flanchik: *Origin of Matter and Evolution of Galaxies*, 2010, American Institute of Physics, Osaka.

V.F.Gopka, A.V.Yushchenko, S.Goriely, A.Shavrina, Y.K.Woon: *Origin of Matter and Evolution of Galaxies*, 2005, American Institute of Physics, Tokyo.

V.F.Gopka, A.V.Yushchenko, V.A.Yushchenko, I.V.Panov, Ch.Kim: *Kinematics and Physics of Celestial Bodies*, 208, **24**, 89.

G.S. Bisnovatyi-Kogan: *Physics Uspekhi*, 2006, **49**, 53.