ON THE ORIGIN OF “SPIDER” PULSARS

A.O. ALLAHVERDIEV, A.I. ASVAROV, S.O. GUSEYNOVA, H.I. NOVRUZOVA
Institute of Physics, Ministry of Science and Education, Republic of Azerbaijan
a.asvarov@gmail.com, lab31astro@gmail.com

A new explanation for the origin of a new type of binary millisecond pulsars (spiders) has been proposed.

Keywords: pulsars, binary millisecond pulsars.

INTRODUCTION

Neutron stars are the end products of massive star evolution whose cores collapse during supernova explosions. The number of observed pulsars of all types is more than ~3000. They are detected as radio (~2500) and/or gamma-ray (~300) pulsars. Usually, the study of pulsars is provided by using the well-known "period – a first derivative of the period diagram", the so-called $P - \dot{P}$ diagram, as these two quantities can be determined with high accuracy by observations (Manchester et al., 2005). The majority of pulsars are single objects, but relatively rarely pulsars are found in binary systems (~600). In the above diagram (Figure 1), they are located in the lower left part.

The overwhelming majority of binary pulsars are millisecond pulsars (MSP), spin parameters of which imply that these pulsars have a weak surface magnetic field of $B_s \sim 10^7 - 10^{10}$ Gs and are old objects with characteristic time $\tau \sim 10^9 - 10^{10}$ years. Usually, MSPs are considered as the ones that undergo reacceleration in binary systems due to accretion at the final stages of the evolution of binary companion stars. When mass transfer ends, the end-stage type binary system (MSP + white dwarf) are formed. Till to Fermi-LAT era (2008), nearly all known field binaries were obtained in these end-stage systems. And since then ~ 60 MSP with small orbital period (P_{orb} < 1 day) low-mass, non-degenerate companions have been revealed. These very compact binary systems were named “spiders” because of evaporative effects due to energetic wind of companion pulsar. At present 44 black widows and 26 redbacks are catalogued (Halpern et al., 2022, Hui & Li, 2019). Here we suggest new approach to establish the origin of these objects.

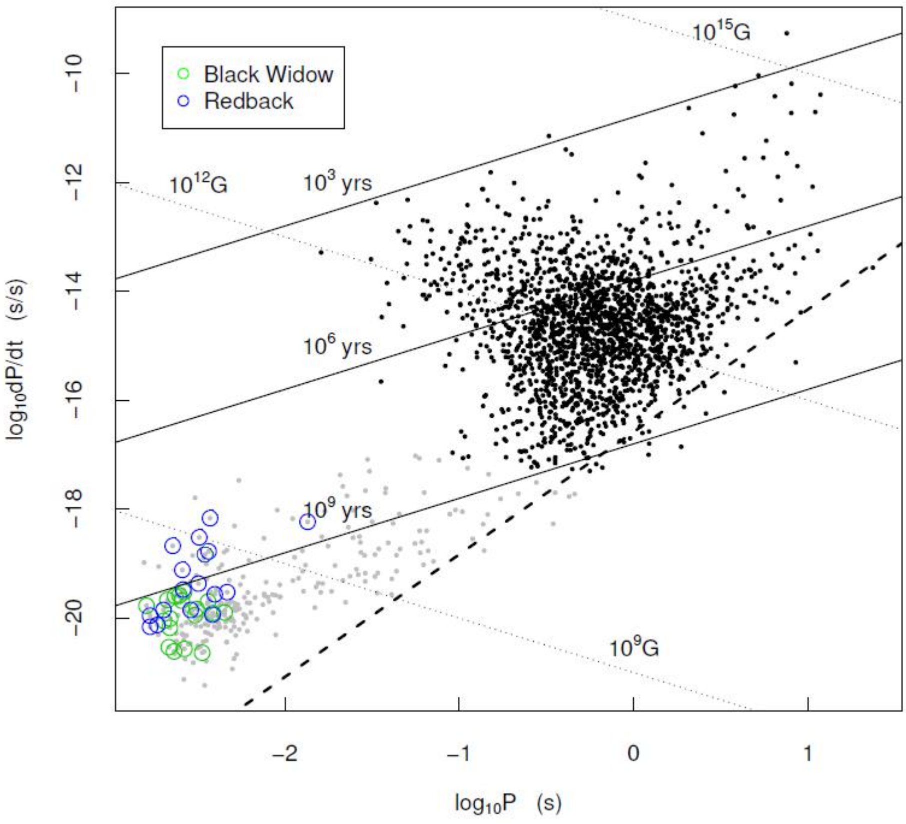

Fig. 1. $P - \dot{P}$ diagram of all currently known pulsars. Some spider pulsars also are shown.

131, H.Javid ave, AZ-1143, Baku
Institute of Physics
E-mail: jophphysics@gmail.com

FORMATION OF SPIDER PULSARS AND MAGNETO-ROTATIONAL MECHANISM

It is well known that more than 70% of the progenitors of the pulsars enter the binary systems, but among the pulsars the number of the binary pulsars is too small (~6%). (Manchester etal., 2005). More plausible explanation for this contradiction (the small percentage of binary pulsars) is to involve Blaauw effect, according to which in the past, the disruption of the double system were occur when one of the two components became a SN and as by-effect runaway stars are appeared. This mechanism is considered as the more plausible one, but this mechanism is effective only when a considerable part of the mass of collapsing star is lost during the time scale much shorter than orbital period of the system. The orbital periods of binary star systems varies from ~10^4 sec (contact binaries) up to hundreds of years (De Marco & Izzard, 2017). And according to Blaauw theory if the collapse time of star more than orbital period of binary system, no disruption will occur. And it is obvious that the closer the binary, the smaller the orbital period. It is interesting to check: may the collapse time be more than orbital period in close binary system? Unfortunately up to day, there is no final theory for the explaining the collapse of star. This event is one of the complicated events in star life. Up today one of more detailed explosion mechanisms is magneto-rotational mechanism (for review, see Nicholl et al., 2017, Bisnovatyi-Kogan, 2011).

The main idea of this mechanism is as follows (Bisnovatiy-Kogan, 1971). As it is well known to maintain hydrostatic equilibrium with its delicate balance between pressure gradient between various layers of star and gravity, the two types of dynamical time scales, namely, the free fall and expansion time scales must be comparable, since stability of star requires that the star should be able to respond with equal rapidity to expansion (due to thermal energy) or contraction (due to gravity) away from the equilibrium point. And this combined time scale is the hydrodynamic time. As mentioned in (Bisnovatiy-Kogan, 1971), a supernova explosion will ensue if the momentum transfer time of angular momentum to the far outer layer of stars would be much longer than hydrodynamic time scale. According this mechanism, as the rotational energy would be dominant with respect to gravitational energy in the precollapse stage of star (due to different dependence on the linear size of the star), time scale of the collapse (in other words, the collapse timescale) in this case will be determined, in general, by the rate of angular momentum transfer via electromagnetic effects. As an order of magnitude, this time can be calculated by using the following formula (Bisnovatyi-Kogan, 1971, 2011)

$$\tau_m \cong \frac{\rho R v}{H^2} \qquad (1.1)$$

where R, v ρ, H are the radius, the rotational velocity, the outer density and magnetic field in the collapsing star, respectively. Just before the collapse, when the star size approaches neutron star radius, in rough equilibrium between rotation and gravity we can assume the following commonly used values for mentioned quantities: $v \sim 10^{10}\ \mathrm{cm/sec}$ and $R \sim 10^6\ \mathrm{cm}$ (Bisnovatyi-Kogan, 2011). Under this assumptions we get

$$\tau = 10^6 \frac{\rho_8}{H_9^2}\ \mathrm{sec} \qquad (1.2)$$

here ρ_8 - in units of $10^8\ \mathrm{gr\ cm^{-3}}$, H_9 - in units of 10^9 Gs and these values are typical for stars just before collapse, therefore the above shown designations were used. For a typical pulsar, the collapse will take place nearly with hydrodynamic time, but for weakly magnetized pulsars the situation will dramatically changed and that is why it is interesting to ascertain, is there binary pulsar systems that have orbital period no more than ~10^6 sec. According to existing MSP catalogue (http://astro.phys.wvu.edu/GalacticMSPs/), orbital periods of about 100 out of 413 binary pulsar systems are less than the abovementioned value.

And as it is mentioned above, new observations (mainly, due to Fermi-LAT data) allows to divide MSPs in binary systems into three sub-classes. These sub-classes are redback, black widow and huntsman pulsars and are distinguished by the companion star’s mass or the binary’s orbital period (Roberts, 2013). Huntsman pulsars are categorized by orbital periods that is more than 5 days and sub-giant companions. Redbacks host companion stars with masses Mcs ~ 0.2 -0.4 M⊙, while black widows host less massive companion stars Mcs.< 0.1 M⊙ (Roberts 2013; Chen et al. 2023). Redbacks and black widows both have short orbital periods of ~ hours (Knight etal., 2023).

NEW IDEA ABOUT THE FORMATION OF SPIDER PULSARS

It is obvious that for a quite wide range of parameters used in formula (1.2), the collapse time of a rotating star is much longer than pure hydrodynamic time that is in range 10^{-2} ~10^{-4} sec (Bisnovatyi-Kogan, 1971, 2011). The value of magnetic field strength for most pulsars is (~10^{12} Gs), so the collapse occur almost at the hydrodynamic time. But for the weakly magnetized pulsars (~10^9 Gs), the collapse time scale (because of inversely squared dependence on magnetic field strength) would be considerably longer than orbital period of binary system and that is why the condition that lead to the disruption of the pair might not be the case. This means that pulsars that enter binary system and have less value of magnetic field at birth could give birth to the spider pulsars. Naturally, this scenario does not exclude the possibility the forming of weakly magnetized pulsars because of dumping of magnetic field due to accretion in binary systems. While the details of the magnetic field decay is still a subject under discussion (e.g., Konar, 2010), it is believed that the surface field of the neutron stars can be somehow buried by the accretion. As for the acceleration of spider pulsars, having very low-mass companion it was easier for them to achieve such smaller periods as they have had enough time before becoming neutron star to accrete considerable amount of matter from companion star. The low value of magnetic field in its turn also was more favorable for accreting of matter from companion. So, in average, pulsars in spider systems should be more massive and have smaller periods than other pulsars in binary systems. We suggest that alongside with the commonly accepted way about the forming weakly magnetized binary pulsars, described development of events might have taken place at least for some pulsars. Candidate of such systems are spider pulsars.

DISCUSSION AND CONCLUSION

If this scenario for the formation of spider pulsars throughout magneto-rotational mechanism is valid, it means that the value of magnetic field of pulsars at birth may show some dispersion of strengths that already were found in white dwarfs and other type of stars, say, in Main Sequence stars. It is in good agreement with the idea that pulsars at birth may have a wide range of magnetic field strength and may appear in any part of $P-\dot{P}$ diagram (Beskin et al.,1988).

We argue that numbers of binary millisecond pulsars, namely newly distinguished out of millisecond pulsars - spider pulsars may have been formed through this mechanism. So, we claim that very close (contact, tight) binary systems with pulsar that has low magnetic field strength at birth, evolve to give birth of spider pulsars, if magneto-rotational mechanism of explosion is at work.

[1] *V.S. Beskin, A.V. Gurevich & Y.N. Istomin.* Astroph. and Space Science,1988, 146, 205.

[2] *G.S. Bisnovatyi-Kogan.* Soviet Astronomy, 1971, 14, 653.

[3] *G.S. Bisnovatyi-Kogan.* Relativistic astrophysics and physical cosmology, Moscow, URSS, 2011, 376 p. (in Russian).

[4] *A. Blaauw.* Bull.Astron.Inst.Neth., 1961,15,265.

[5] *A.H. Knight, A. Ingram, J.van den Eijnden, J.K.Douglas.* Buisson, Lauren Rhodes, Matthew Middleton, 2023,(arXiv: astro-ph/2301.13864.

[6] *S. Konar.* Mon. Not. R. Astron. Soc. 2010, 409, 259–268.

[7] *A.G. Lyne. R.N. Manchester and J.H. Taylor.* ApJ, 1985, 213, 613.

[8] *R.N. Manchester, G.B. Hobbs.* Teoh. A. & Hobbs, M., Astron. J., 129, 1993-2006 (2005)

[9] *O. Marco, R.G. Izzard.* Publications of the Astron. Soc. Australia, 2017, 34, 35.

[10] *M. Nicholl, J. Guillochon, E. Berger.* 2017, ApJ, 850, 55.

[11] *J. Chen, M. Cadelano*. Pallanca, etal., 2023, (arXiv: astro-ph/2303.11263).

[12] *J.P. Halpern, K.I. Perez, and S. Bogdanov.* (arXiv: astro-ph/2207.08198).

[13] *C.Y. Hui, K.L. Li.* High Energy Radiation from Spider Pulsars. Galaxies 2019, 7, 93.

[14] *M.S.E. Roberts.* 2013, in Neutron Stars and Pulsars: Challenges and Opportunities after 80 years, ed. J. van Leeuwen, Vol. 291, 127.