Radio pulsars — two old questions  
(in blessed memory of Ya.N.Istomin)

Vasily Beskin$^{1,2}$

$^1$ P.N.Lebedev Physical Institute, Moscow 119991, Russia, beskin@lpi.ru
$^2$ Moscow Institute of Physics and Technology, Dolgoprudny 141701, Russia

Abstract. We draw attention to two unanswered questions in radio pulsars’ theory. The first one concerns the inclination angles $\chi$ between magnetic and rotation axes. We show that the very existence of interpulse pulsars indicates that all possible angles are realized. The second one is the question of the break of the death line on the $P\dot{P}$-diagram. We show that this break can be easily explained by a very mechanism of secondary plasma generation.

Keywords: neutron stars, radio pulsars.

1 Introduction

More than 50 years have passed since the discovery of radio pulsars. However, we still do not know the mechanism of their coherent radio emission, e.g., the direction of evolution of the inclination angle $\chi$. Some questions, formulated in the early years, were not further discussed. Here we outline the solution to one of such forgotten questions connecting with the possible range of inclination angles.

The second question concerns the so-called death line, i.e., the line limiting from below the population of pulsars on the $P\dot{P}$-diagram that has a break at $P \approx 0.1$ s. As we show, this break can be easily explained by the well-known feature of secondary plasma. This work is dedicated to the blessed memory of Ya.N. Istomin, as well as B.V. Komberg, with whom we discussed these issues back in the 70s.

2 Inclination angle

If we take almost any catalog of the inclination angles $\chi$, we find that these angles lie in a range of $0 < \chi < 90^\circ$. But this does not mean that there are no
radio pulsars with the inclination angle $\chi$ in a range of $90^\circ < \chi < 180^\circ$. This is simply because most of the existing methods for determining this angle do not distinguish between $\chi$ and $180^\circ - \chi$.

On the other hand, acute and obtuse angles between the axes correspond to two principally different physical conditions because for $\chi < 90^\circ$, the longitudinal current flowing along open magnetic field lines (with its sign determined by the sign of the Goldreich & Julian (1969) charge density $\rho_{GJ} = -\Omega B / 2\pi c$) requires the outflow of negative charges from the star surface. By contrast, for the angles $\chi > 90^\circ$, the surface should eject positive ones. Hence, in models of plasma generation, in which the ejection of particles from the surface plays a significant role, these are two fundamentally different cases. Recall that in Ruderman & Sutherland (1975) model, particle creation is insensitive to axis orientation.

\[ \delta = \chi + \beta \left( \frac{R}{h} \right)^{1/2} \]

Here $R$ is the star radius. As shown from Table 1, for most pulsars, the angles $\delta$ for the main pulse and the interpulse correspond to different signs of the charge density. The uncertainty for two pulsars is apparently associated with a...
significant difference between the values of $h_{MP}$ and $h_{IP}$ (the accuracy of which is low). For other pulsars, our conclusion depends only slightly on the values of $h$. Thus, one can conclude that plasma ejection from the surface of a neutron star does not affect the process of particle production in the polar regions.

Table 1. Interpulse pulsars data taken from Johnston & Kramer (2019). All the angles are measured in degrees, and the radiation heights $h$ are in km.

| PSR        | $P(s)$ | $\chi_{MP}$ | $\beta_{MP}$ | $\chi_{IP}$ | $\beta_{IP}$ | $h_{MP}$ | $h_{IP}$ | $\delta_{MP}$ | $\delta_{IP}$ |
|------------|--------|-------------|--------------|-------------|--------------|---------|---------|---------------|---------------|
| J0627+0705 | 0.48   | 94.0        | -8.6         | 86.0        | -0.6         | 380     | 160     | 93            | 86            |
| J0905-5157 | 0.35   | 90.4        | -3.6         | 89.5        | -2.8         | 970     | 40      | 90            | 88            |
| J0908-4913 | 0.11   | 83.6        | 7.4          | 96.4        | -5.4         | 60      | 70      | 87            | 94            |
| J1549-4848 | 0.29   | 87.3        | 2.3          | 92.7        | -3.2         | 130     | 110     | 88            | 92            |
| J1722-3712 | 0.24   | 87.4        | -5.6         | 92.6        | -10.9        | 110     | 300     | 86            | 91            |
| J1739-2903 | 0.32   | 94.6        | -2.2         | 85.4        | 7.1          | 240     | 200     | 94            | 87            |
| J1828-1101 | 0.07   | 82.7        | 7.3          | 97.3        | -7.3         | 35      | 45      | 87            | 94            |
| J1935+2025 | 0.08   | 93          | -13          | 87          | -7           | 200     | 30      | 90            | 83            |

3 Death line

At the time of this writing, 3177 pulsars was already discovered (Manchester et al. 2005). This rather rich statistics clearly shows that the line limiting from below the population of pulsars on the $P\dot{P}$-diagram has a break at $P \approx 0.1$ s (see Fig. 2, left panel). Here we show that this break can be easily explained by the well-known feature of secondary plasma production.

Indeed, for pulsars with periods $P < 0.1$ s, the radiation reaction becomes significant, so the energy of primary particles does not reach the values dictated by the potential drop (see, e.g., Jones 2021). Recently, we carried out a detailed study (Beskin & Litvinov 2022) that took into account many still neglected phenomena, such as the role of high-energy $\gamma$-quanta in the synchrotron radiation spectrum, the possible wide distribution in moments of inertia, and, naturally, the effects of general relativity. In particular, the conclusion about the role of the radiation reaction for fast pulsars was confirmed.

A detailed analysis of this issue will be presented in a separate work. In the same article, we only show that even for standard values of the polar cap size and the parameters of a neutron star (and for dipole magnetic field!), taking into account the above effects significantly changes the position of the death line.
The right panel in Fig. 2 shows the position of the death line obtained from the condition of the absence of particle production for two models of pulsar braking (see Beskin & Litvinov 2022 for more detail). The dashed lines correspond to the classic death line (Chen & Ruderman 1993), for which, by the way, unrealistic magneto-dipole losses were assumed. As we can see, regardless of the model of pulsar evolution, for $P > 0.1$ s, the death line locates one order of magnitude lower than the classical one. On the other hand, at $P < 0.1$ s, the slope becomes noticeably flatter (it corresponds to proportionality $\dot{P} \propto P^2$). Since our death line is still above many pulsars, a more detailed consideration is required, which we plan to carry out in the very near future.

I thank A. Philippov and A. Timokhin for the useful discussions. This work was supported by Russian Foundation for Basic Research, grant 20-02-00469.
Bibliography

Beskin, V. S. & Litvinov, P. E. 2022, MNRAS, 510, 2572
Chen, K. & Ruderman, M. 1993, ApJ, 402, 264
Goldreich, P. & Julian, W. H. 1969, ApJ, 157, 869
Johnston, S. & Kramer, M. 2019, MNRAS, 490, 4565
Jones, P. B. 2021, MNRAS, 506, L26
Manchester, R. N., Hobbs, G. B., Teoh, A., & Hobbs, M. 2005, ApJ, 129, 1993
Ruderman, M. A. & Sutherland, P. G. 1975, ApJ, 196, 51