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Neutron Stars Evolution in Magnetic Fields

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Abstract

Observations indicate that magnetic fields on neutron stars span at least the range 10^{18-15} G, corresponding to a range of magnetic fluxes similar to that fund in white dwarfs and main sequence starts. The observational evidence is discussed, as well as the possible origin of the field, and the associated phenomenology ("classical", millisecond, and binary pulsars, "magnetars", etc.). Particular attention is given to physical processes potentially leading to magnetic field evolution. In our study, we first briefly describe theoretical models of the formation and evolution of the magnetic field of neutron stars, paying special attention to field decay processes. We had present important observational results related to the field properties of different types of compact objects: magnetars, cooling neutron stars, radio pulsars and sources in binary systems. After that, we discuss which observations can shed light on the obscure characteristics of neutron star magnetic fields behavior.

Key words: neutron stars; magnetic field; radio pulsars; magnetars.

Introduction

Neutron stars are dense, compact remnants of evolved starts, with degenerate fermions compressed by strong gravitational fields[1]. Their structure is set almost entirely by one parameter, their mass. The latter can be measured with some accuracy only in binary systems containing a pulsar, where its distribution is found to be consistent with a narrow Gaussian, centered at $1.35M_{\odot}$ and with width $0.04\ M_{\odot}$[2] presume that neutron stars are essentially all identical. A wide range of rotation rates and magnetic fields, together with the presence or absence of mass-transferring binary companions, allow for a rich phenomenology. Among single neutron stars, we distinguish "classical" pulsars, millisecond pulsars, soft gamma-ray repeaters, anomalous x-ray pulsars, and inactive, thermal x-ray emitters. Magnetic fields play an essential role by accelerating particles, by channeling these particles or accretion flows, by producing synchrotron emission or resonant cyclotron scattering, and by providing the main mechanism for angular momentum loss from non-accreting stars. It is even speculated that in some objects the magnetic field may be the main energy source for the observed radiation.

The strongest magnetic fields are found in neutron stars (NSs), where they control whether NSs are seen as normal radio pulsars, magnetars, dim isolated cooling NSs, or something else[3]. Magnetic fields and neutron stars are therefore intertwined, and understanding the formation and evolution of NS magnetic fields will significantly advance our understanding of the NS population, and vice versa. A systematic study of the NS population will help to understand the formation and evolution of their magnetic fields. Large-scale, poloidal magnetic fields control the spin-down of NSs. Typically; large-scale magnetic fields are assumed to be dipolar, as this component diminishes most slowly with distance from the star. Later, it was shown that the rotation of magnetised NSs causes an electric potential to develop at the polar caps. This potential is strong enough that it can extract particles from the NS surface and fill the NS magnetosphere with them. It was further shown that charged particles can also be created in the magnetic field by a split of high-energy photons[4]. Recent three-dimensional numerical simulations[5] demonstrated that NS spin-down depends on the poloidal dipole field B_p as follows:

$$P\dot{P} = \left(\kappa_0 + \kappa_1 \sin^2 \alpha\right)\beta B_p^2 \qquad (1)$$

where P is the star's spin period, $\dot{P}$ is its time derivative, β is a constant, which contains the star's moment of inertia, and α is the angle between the orientation of the magnetic dipole and the rotation axis. The numerically found coefficients are $\kappa_0 \approx 1$ and $\kappa_1 \approx 1.2$. The same calculations show that the obliquity angle evolves slowly as follows:

$$\frac{d\alpha}{dt} = -\kappa_2 \beta \frac{B_p^2}{P^2} \sin\alpha \cos\alpha \qquad (2)$$

The numerically found coefficient $\kappa_2 \approx 1$. Radio polarisation measurements demonstrate that this angle seems to evolve on a ~10^7 year timescale[6], leading to a situation where the orientations of the magnetic dipole and rotational axis eventually align.

Timing observations of NSs provide us with measurements of spin period P, its time derivative $\dot{P}$, and $\ddot{P}$, in some cases, even second and third time derivatives $\ddot{P}$ and $\dddot{P}$. The instantaneous rotational period is approximated using the Taylor expansion as follows:

$$P(t) = P_0 + \dot{P}(t - t_0) + \frac{\ddot{P}}{2}(t - t_0)^2 + \frac{\dddot{P}}{3!}(t - t_0)^3 + \ldots, \qquad (3)$$

where P_0 is the initial spin period and t_0 is the epoch when the period and period derivatives were measured. For non-accreting radio pulsars $\dot{P} > 0$ due to spin-down; thus, knowledge of P and $\dot{P}$ allows us to estimate B_p. Nevertheless, the most frequently used equation is as follows[7]:

$$B_p = 3.2\times 10^{19}\sqrt{P\dot{P}}\ G \qquad (4)$$

It is easy to derive that the differential Equation (1) has the following solution if the magnetic field and obliquity angle do not evolve with time:

$$\frac{P^2(t)}{2} - \frac{P_0^2}{2} = P\dot{P}t = \left(\kappa_0 + \kappa_1 \sin^2\alpha\right)\beta\, B_p^2 t \qquad (5)$$

In the limit of initial spin period $P_0 << P(t)$, we can obtain the following:

$$\tau_{ch} = \frac{P(t)}{2\dot{P}} \qquad (6)$$

In a simplified picture, the pulsar evolution in the $P-\dot{P}$ plane proceeds along the lines of constant magnetic field. A pulsar is born somewhere in the upper left corner of this diagram and descends towards the death line, crossing lines of constant spin-down age. After the pulsar crosses the death line, it becomes radio silent. In our study, we show that NSs might have very different paths. They could rise (dipolar magnetic field increases) and fall (dipolar magnetic field decays).

One of the characteristics used to study magnetic field evolution is the braking index. It is computed as follows:

$$n = 2 - \frac{P\ddot{P}}{\dot{P}^2} \qquad (7)$$

Besides dipolar poloidal magnetic fields, NSs could also have (1) small-scale poloidal fields, and (2) large- or (3) small-scale toroidal fields in the crust. The presence of small-scale poloidal fields is often discussed as an essential mechanism, which increases the curvature of open field lines, and thus leads to the activation of the pulsar mechanism in long-period radio pulsars. Arcs of poloidal magnetic fields can be seen in phase-resolved X-ray spectroscopy because such arcs trap electrons, thereby forming absorption lines by inverse Compton scattering. These arcs are located at small distances from the NS, and therefore, form phase-dependent absorption features. However, there is also an alternative explanation that these absorption spectral features are, in fact, proton cyclotron lines[8]. This complicated magnetic field structure results in non-trivial field evolution and many interesting observational consequences. The main tendency of the field evolution is decay. At relatively early stages of a NS's life $\left(\le 10^6\,\text{yrs}\right)$, it can be dependent on the NS cooling if the star is not too massive to switch on rapid neutrino losses. Thus, field and thermal evolution are interrelated[9], as field decay provides heating. The latter effect is especially pronounced in magnetars, where field evolution is governed by its restructuring, due to a Hall cascade. This process can end in a so-called Hall attractor—another hypothetical stage under active study.

Formation of Neutron Stars

Neutron stars are the most magnetised objects in the universe, with field strengths up to at least 10^{15} G. There are two leading hypotheses for the formation of such powerful magnetic fields: (1) fossil field origin and (2) dynamo at the proto-NS stage. Modest growth of the magnetic field can also be obtained, due to thermoelectric effects[10], but magnetar-scale fields can hardly be reached this way. Modern MHD simulations[11] showed that strong stellar magnetic fields could be formed as a result of stellar merger. Authors[11] found that a star that is born as a result of a merger has a magnetic field of ≈9 kG, which is compatible with values for some strongly magnetised massive stars[11]. The compact object is formed only from the core of the massive progenitor star. Thus, it is incorrect to substitute the whole stellar radius in the estimate of magnetic field amplification due to flux conservation. At most, a few percent of the total progenitor magnetic flux can be used for the formation of a NS field. This brings us to the conclusion that some additional field amplification is necessary to explain magnetar-scale fields.

More modern three-dimensional simulations of the supernova explosion confirm that strong convection develops in a proto-NS. If some magnetic field is present, the convection can increase it by many orders of magnitude and produce both poloidal and toroidal components. However, a rapid rotation is required to form a strong dipolar component[12]. If a NS does not rotate rapidly enough, it might result in a stochastic dynamo, which generates strong small-scale fields with a weak dipolar component. Newborn NSs can pass through an episode of fall-back accretion, which could bury the magnetic field deep in the crust. This fall-back accretion continues for days and months (much longer than the crust solidification time, which is about ≈10s)[13], with a decreasing mass accretion rate of up to 3×10^2 $M_\odot$/year at the beginning. The total accreted mass can reach 0.1 M, or even larger. However, smaller values might be more typical. The pressure of the magnetic field with strength of $\sim 10^{12}$ G is not enough to stop this accretion, so such fields could be buried deep within the crust at densities sometimes exceeding 10^{12}g.cm^{-3}. Overall, NSs are born with a range of magnetic field strengths (10^{11}–10^{15} G) and shapes (dipolar, multipolar, toroidal), due to stochastic processes during the dynamo amplification. Some NSs (central compact objects) are born with a strongly suppressed dipolar component, either due to fall-back accretion or due to features of the dynamo amplification process. These stars might be expected to grow their dipolar field component with time. Other NSs might be born with stronger poloidal magnetic fields combined with even stronger "hidden" (crust-confined) toroidal magnetic fields. This variety of initial fields should lead to a great diversity of observational appearances[14].

Theory of Evolution

Magnetic fields could be present both in the NS crust and core. When the NS core cools down, it turns into a superconductor. Researchers often assume that protons in the core form a Type I superconductor, and thus, expel any magnetic field due to the Meissner effect. In this case, only the magnetic field evolution in the crust is modeled[15]. If the core is a Type II superconductor, the magnetic field should be concentrated into isolated vortices. Alternatively, the core might demonstrate a mixture of these two states (Type-1.5 superconductor). Which types of superconductivity could be present in a NS core is a matter of active scientific.

If a magnetic field is present in the core, its evolution differs significantly from that of fields in the crust. A NS crust is formed of a lattice, where only electrons can move freely. In contrast, the core is expected to have multiple charge carriers. Therefore, the main drivers for magnetic field evolution in the crust are its finite conductivity.

Crustal Magnetic Field

Goldreich and Reisenegger[16] suggested the most commonly used framework for theoretical studies of NS magnetic field evolution. They started with one of Maxwell's equations (Faraday's law) as follows:

$$\frac{\partial \vec{B}}{\partial t} = -c\nabla \times \vec{E}, \qquad (8)$$

where $\vec{B}$ and $\vec{E}$ are the magnetic and electric fields, respectively. They supplemented this equation with Ohm's law to derive the following:

$$\frac{\partial \vec{B}}{\partial t} = -c\nabla \times \left(\frac{1}{4\pi e n_e} \left(\nabla \times \vec{B}\right) \times \vec{B} + \frac{c}{4\pi\sigma} \nabla \times \vec{B} \right) \qquad (9)$$

where σ is the electrical conductivity (inversely proportional to resistivity), n_e is the local electron number density, and e is the elementary charge. The first term on the right side of this equation corresponds to the Hall Effect, and the second to the Ohmic decay. Note also that the magnetic field described here is the field within the NS itself, which cannot be directly measured. It is only the portion of the field, which extends outward from the star that can be observed, and it is only the large-scale, dipolar part that affects the spin-down.

Hall Evolution

Hall evolution was studied mostly numerically in multiple articles since[16]. Analogously it is possible to write an estimate for the timescale of Hall evolution as follows:

$$\tau_{Hall} = \frac{4\pi e n_e L^2}{cB(t)} \qquad (10)$$

where B is the local instantaneous magnetic field, and L is the typical spatial scale of the associated electric currents. Compared with linear Ohmic evolution, the applicability of this timescale is very limited. Hall evolution is strongly nonlinear, coupling different spatial scales and poloidal and toroidal components of the magnetic field together.

In earlier works, it was noticed that Equation (9) has some similarity to the vorticity equation[17]; it was thus suggested that Hall evolution generates some kind of turbulence-like behaviour. Therefore, any large-scale magnetic field would evolve through a cascade-like process towards smaller scales. This behaviour results in acceleration of the magnetic field decay. That is, the Hall cascade is not a dissipative process by itself, but if the scale of currents diminishes with a characteristic time shorter than τ_{Ohm} for an (initial) large spatial scale, then the cascade determines the rate of magnetic energy dissipation. As B decreases, τ_{Hall} becomes longer, and finally the Hall cascade becomes unimportant. The same is true for initially low fields, typical for most radio pulsars.

Closely related to this feature is the idea of a Hall equilibrium—a magnetic field configuration where the Hall term is identically equal to zero. In most of these works, the field is computed directly from the requirement that the Hall term $\nabla\times\left(\frac{1}{4\pi e n_e}(\nabla\times\vec{B})\times\vec{B}\right)=\vec{0}$ in which case one must additionally consider the question of whether the solution is stable or not. In contrast, if direct time-stepping calculations seem to evolve toward 'frozen turbulence' solutions, then they are necessarily evolving towards a stable Hall equilibrium.

Further work in Hall instabilities has also considered more local aspects, such as instabilities that can develop in small-scale current sheets. The depth-dependence of the electron number density n_e plays an important role in many of these instability modes. The nonlinear development of some of these modes also suggests that the energies released in the form of Ohmic heating can be enough to power magnetar activity.

Observations

Magnetic field evolution cannot be observed directly yet, as astronomical measurements are not numerous and precise enough. Moreover, the computed poloidal dipolarmagnetic field B_p depends on the same quantities as characteristic age τ_{ch}. Therefore, these two quantities cannot be used together. This is why this problem is so different from the NS cooling, where the usage of τ_{ch} as an age estimate is very common. However, multiple data pointing towards magnetic field evolution exist. In some cases, observational results seem to be robust, while in others, alternative interpretations are still possible. Evidence in favour of field decay comes from observations of energy release (bursts or continuous activity), spin parameters, or properties of surface emission. In this section, we discuss several types of objects (including both isolated and binary NSs) and present existing arguments in favour of magnetic field evolution coming from observations of these sources.

1. ***Magnetars:*** In the first place, magnetars are young NSs whose activity is due to the energy release of strong electric currents supporting their magnetic field. This energy output can happen in a transient manner—we then observe short magnetar flares, or energy can be released more or less gradually in the crust (quiescent emission), which results in additional heating of the NS surface up to several million Kelvin—a factor of a few times larger than the hottest NSs of the same age without additional heating. These two types of activity seem to be linked with each other, which is visible during so-called outbursts—prolonged periods of enhanced activity[18]. During these periods, the surface temperature increases as does the rate of flares.
2. ***Magnificent Seven :*** The Magnificent Seven (M7), also known as X-ray Dim Isolated Neutron Stars (XDINS), are nearby cooling isolated NSs. They are characterised by dominance of thermal surface emission. Magnetic fields of these seven sources are mainly estimated either from P, $\dot{P}$ measurements, or from spectral features interpreted as proton cyclotron lines. All field values are in the range of 10^{13}–10^{14} G, i.e., just below those of magnetars. No bursts have ever been detected from any of the M7 objects. This points to a significantly lower rate of magnetic energy release and, probably, to a more relaxed field structure. The M7 objects are considered to be possible descendants of magnetars. Spin periods of the M7 NSs are compatible, with practically vertical tracks going down from the magnetar region in the P– $\dot{P}$ diagram in correspondence with the scenario of rapid decay of strong magnetic field on a timescale few $\lesssim$ hundred thousand years[19].

3. ***Central Compact Objects***: Another peculiar type of NSs with relatively high surface thermal emission are central compact objects in supernova remnants. They have temperatures of $\lesssim 2 \times 10^6$ K for typical ages of a few thousand years. In several cases, the high temperatures of such objects can be explained by standard cooling without direct URCA processes and with light element accreted envelopes[20]. However, in some cases, additional information does not allow such a solution. The hypothesis of hidden magnetars is based on the idea that strong fall-back accretion just after a supernova explosion can result in submergence of magnetic field. During the subsequent evolution, the field slowly re-emerges, due to diffusion through the outer plasma layer.
4. ***Radio Pulsars with Seemingly Growing Dipolar Magnetic Field***: The spin-down of a radio pulsar is mainly determined by the dipolar field, as it decreases less rapidly with distance from the star than other multipoles do. In the simplified standard picture, the decaying magnetic field might result in $n > 3$, and the growing field in $n < 3$. Of course, the real picture is somewhat more complicated. Still, in some cases, $n \neq 3$ might indicate field decay or growth[21].

5. ***High-Mass X-ray Binaries***: High-mass X-ray binaries (HMXBs) are systems where the primary star is more massive than $\sim 8\ M_{\odot}$, and the secondary is a NS or a black hole. In our study, we are interested only in systems where the secondary star is a NS. The class of HMXBs can be divided into several subclasses; in most of them, a donor is either a Be-star or a supergiant. Be/X-ray binaries are identified by the presence of Hα emission. In the case of supergiant binaries, the massive star is evolved and has left the main sequence already. In both cases, the mass transferred onto a NS interacts with a rotating magnetic field; this is the primary reason why we observe unusual X-ray activity. The formation of Be/X-ray binaries is a complicated process that involves a non-conservative mass transfer prior to a supernova explosion. This mass transfer spins up the secondary star and allows a formation of the decretion disk. Due to the supernova explosion, the NS orbit gains a large eccentricity and inclination. Therefore, a NS interacts with the decretion disk only occasionally close to the periastron passages[22].

At the moment, none of them provide clear signatures. In some cases, analyses already performed nevertheless demonstrate interesting results; in others, we can expect significant progress in the very near future. In a lowest-order approximation, the magnetic fields of standard isolated radio pulsars might evolve mainly due to the Ohmic decay caused by impurities. The timescale of this process is expected to be longer than $\sim 10^7$ years, due to several reasons: (1) we observe a large number of isolated radio pulsars, and their formation rate, even without magnetic field decay, is comparable to the supernova rate in the Galaxy (2) we observe radio pulsars which move towards the Galactic disk from large distances, which means that their magnetic fields survive on timescales comparable to the vertical oscillation period in the Galaxy (~100 Myr)[4] and (3) there are strongly magnetized NSs ($B \sim 10^{12}$–10^{13} G) in HMXBs, which have ages of $\sim 10^7$ years. Hot and cold spots on a NS surface could be created by any one or more of the following effects: (1) temperature of NS deeper layers channeled by magnetic fields, (2) surface heating by inverse currents in the magnetosphere, (3) heating by interaction of accreting material from a stellar companion, and (4) rotochemical reactions. Different mechanisms are typical for NSs at different stages of their evolution[23]. Thus, for magnetars, it is important how heat is generated in the crust and transferred towards the surface[9]—possibly in combination with some heating from magnetospheric currents.

To study the evolution of magnetic fields, we need to measure present-day field values and structure as precisely as possible. This is a highly non-trivial task. Some data about field topology can be obtained by the modeling of pulse profiles of magnetars; in rare cases, information is derived from phase-resolved spectroscopy[9]. Still, new sources of information are welcomed. Polarisation measurements can become an effective new tool to probe structure of NS magnetospheres, especially in the case of strong fields. Large magnetic fields produce quantum-electrodynamical effects, which influence the polarisation of emission propagating through the magnetosphere. The surface emission of NSs might also be polarised. This combination results in a complicated picture, where parameters of polarisation depend on the atmosphere of the NS value of the field, its topology, and orientation of spin and field relative to the line of sight[24].

The appearance of the Hall attractor stage could manifest itself in the stagnation of the field decay and a specific field configuration in the crust and outside of a NS. The first manifestation can be visible either in spin evolution, or simply in conservation of a relatively large field value. The second one might be visible in thermal maps and/or in polarisation data. In this subsection, we discuss three approaches already used to probe the existence of the Hall attractor stage in different types of NSs. Some of these results are already briefly summarised[25]. The authors[26] used the modified pulsar current approach to demonstrate that data on mid-age pulsars (~few 10^5 yrs) can be better interpreted by allowance of moderate field decay by a factor of ~2. The nature of this field decay is uncertain. In addition, it is not clear what switches off this decay (if field decrease is not terminated, then values rapidly become too small to be in correspondence with the observations).

The age of a radio pulsar is an important characteristic that is essential to constrain its magnetic evolution. There are multiple age estimates available at the moment for different objects: (1) spin-down age τ_{ch}; (2) age of associated supernova remnant τ_{SNR} (3) a group of kinematic ages τ_{kin}; and (4) thermal age τ_{therm}. All these techniques have certain caveats and can be applied only to some radio pulsars. The most commonly used estimate for the age of a pulsar is spin-down age. This estimate depends on the instantaneous strength of the dipolar magnetic field as follows:

$$\tau_{ch} = \frac{\mathrm{P}}{\dot{\mathrm{P}}} = 10^{39}\frac{\mathrm{P}^2}{2\mathrm{B}_\mathrm{p}^2}\, s = 16 Myr \left(\frac{\mathrm{P}}{1\sec}\right)^2 \left(\frac{B_p}{10^{12} G}\right)^{-2} \qquad (11)$$

The period is an integral over time, and thus, requires longer times to adapt to a new magnetic field value. So, if the dipole field grows by a factor of two, for example, the spin-down age decreases by a factor of four. Therefore, if there is an alternative estimate for the NS age, the significant mismatch between different age estimates could indicate that the dipole field recently experienced significant growth or decay.

Conclusions

The subject of magnetic fields in neutron stars has still much to offer and to demand from us. Little is known about the structure of the field, but nevertheless there is a rich phenomenology asking to be interpreted. The origin and evolution of the field is as uncertain as in all other kinds of stars. Interesting physics is at play, and there may be connections between the magnetic fields of neutron stars, their white dwarf cousins, and the main-sequence progenitors of both. It is likely that advances in the understanding of the respective magnetic fields will support each other if sufficient communication is maintained among the communities of experts. Overall, for some objects, three (or even four) age estimates could be available simultaneously. Let us consider here what it means if two of these estimates coincide and the third differ drastically. Three different combinations are possible: (1) $\tau_{therm} \approx \tau_{ch}$ (2) $\tau_{therm} \approx \tau_{kin}$ and (3) $\tau_{ch} \approx \tau_{kin}$. In the first case, a different τ_{kin} suggests either that the association is wrong and the NS was born in a different place, or the NS was born from a runaway star. In the second case, a different τ_{ch} could indicate unusual magnetic field evolution, such as the fast decay or growth of the magnetic field. In the third case, a different τ_{therm} could indicate that there is an additional source of heat, such as a rotochemical reaction, or that the NS is cooling more rapidly because some neutrino process operates more efficiently.

References:

1. Shapiro, S.L. & Teukolsky, S.A. 1983. Black Holes, White Dwarfs and Neutron Stars (New York: Wiley).
2. Thorsett, S.E. & Chakrabarty, D. 1999. ApJ, 512, 288.
3. Perna, R.; Pons, J.A.; Viganò, D.; Rea, N. The many lives of magnetized neutron stars. Astron. Nachrichten 2014, 335, 715.
4. Ruderman, M.A.; Sutherland, P.G. Theory of pulsars: Polar gaps, sparks, and coherent microwave radiation. Astrophys. J. (1975) 196, 51–72.
5. Philippov, A.; Tchekhovskoy, A.; Li, J.G. Time evolution of pulsar obliquity angle from 3D simulations of magnetospheres. Mon. Not. R. Astron. Soc. (2014) 441, 1879–1887.
6. Tauris, T.M.; Manchester, R.N. On the evolution of pulsar beams. Mon. Not. R. Astron. Soc. (1998) 298, 625–636.
7. Lorimer, D.R.; Kramer, M. Handbook of Pulsar Astronomy; Cambridge Observing Handbooks for Research Astronomers; Cambridge University Press: Cambridge, UK, (2004) Volume 4.
8. Tiengo, A.; Esposito, P.; Mereghetti, S.; Turolla, R.; Nobili, L.; Gastaldello, F.; Götz, D.; Israel, G.L.; Rea, N.; Stella, L.; *et al*. A variable absorption feature in the X-ray spectrum of a magnetar. Nature (2013) 500, 312–314.
9. Aguilera, D.N.; Pons, J.A.; Miralles, J.A. 2D Cooling of magnetized neutron stars. Astron. Astrophys. (2008) 486, 255–271.
10. Urpin, V.A.; Yakovlev, D.G. Thermogalvanomagnetic effects in white dwarfs and neutron stars. Sov. Astron. (1980) 24, 425.
11. Schneider, F.R.N.; Ohlmann, S.T.; Podsiadlowski, P.; Röpke, F.K.; Balbus, S.A.; Pakmor, R.; Springel, V. Stellar mergers as the origin of magnetic massive stars. Nature (2019) 574, 211–214.
12. Raynaud, R.; Guilet, J.; Janka, H.T.; Gastine, T. Magnetar formation through a convective dynamo in protoneutron stars. Sci. Adv. (2020) 6, eaay2732.
13. Pons, J.A.; Reddy, S.; Prakash, M.; Lattimer, J.M.; Miralles, J.A. Evolution of proto-neutron stars. Astrophys. J. (1999) 513, 780–804.
14. goshev, A.P.; Popov, S.B.; Turolla, R. Unifying neutron stars getting to GUNS. Astron. Nachrichten (2014) 335, 262–267.
15. Gourgouliatos, K.N.; Hollerbach, R. Magnetic axis drift and magnetic spot formation in neutron stars with toroidal fields. Astrophys. J. (2018) 852, 21.
16. Bransgrove, A.; Levin, Y.; Beloborodov, A. Magnetic field evolution of neutron stars - I. Basic formalism, numerical techniques and first results. Mon. Not. R. Astron. Soc. (2018) 473, 2771–2790.
17. Goldreich, P.; Reisenegger, A. Magnetic field decay in isolated neutron stars. Astrophys. J. (1992) 395, 250.
18. Kitchatinov, L. Stability of a force-free Hall equilibrium and release of magnetic energy. Astron. Nachrichten (2019) 340, 475–482.
19. Turolla, R. Isolated neutron stars: The challenge of simplicity. In Neutron Stars and Pulsars; Astrophysics and Space Science Library; Becker, W., Ed.; Springer: Berlin/Heidelberg, Germany (2009) Volume 357, p. 141.
20. Yakovlev, D.G.; Pethick, C.J. Neutron star cooling. ARAA (2004) 42, 169–210.
21. Muslimov, A.; Page, D. Delayed switch-on of pulsars. Astrophys. J. (1995), 440, L77.
22. Ho, W.C.G. Magnetic field growth in young glitching pulsars with a braking index. Mon. Not. R. Astron. Soc. (2015) 452, 845–851.

23. Reig, P. Be/X-ray binaries. Astroph. Space Sci. (2011) 332, 1–29.
24. Caiazzo, I.; Heyl, J.; Turolla, R. Polarimetry of magnetars and isolated neutron stars. In Astronomical Polarisation from the Infrared to Gamma Rays; Mignani, R., Shearer, A., Słowikowska, A., Zane, S., Eds.; Springer International Publishing: New York City, NY, USA, (2019) Volume 460, p. 301.
25. Popov, S.B.; Igoshev, A.P.; Taverna, R.; Turolla, R. Looking for Hall attractor in astrophysical sources. J. Phys. Conf. Ser. (2017) 932, 012048.
26. Igoshev, A.P.; Popov, S.B. Modified pulsar current analysis: Probing magnetic field evolution. Mon. Not. R. Astron. Soc. (2014) 444, 1066–1076.