A highly resistive layer within the crust of X-ray pulsars limits their spin periods

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The lack of isolated X-ray pulsars with spin periods longer than 12 s raises the question of where the population of evolved high-magnetic-field neutron stars has gone. Unlike canonical radiopulsars, X-ray pulsars are not subject to physical limits to the emission mechanism nor observational biases against the detection of sources with longer periods. Here we show that a highly resistive layer in the innermost part of the crust of neutron stars naturally limits the spin period to a maximum value of about 10–20 s. This highly resistive layer is expected if the inner crust is amorphous and heterogeneous in nuclear charge, possibly owing to the existence of a nuclear ‘pasta’ phase. Our findings suggest that the maximum period of isolated X-ray pulsars may be the first observational evidence for an amorphous inner crust, whose properties can be further constrained by future X-ray timing missions combined with more detailed models.

It has long been hoped that stringent constraints could be placed on the equation of state of dense matter from astrophysical measurements of neutron stars, the compact remnants of the explosion of massive stars. Up to the present time, however, despite important breakthrough discoveries1–13 we still fall short (see, for example1, for a recent review). Most neutron stars are observed as radiopulsars with magnetic fields in the ~1012–1015 G range, that spin down owing to magneto-dipole radiation losses, while converting a fraction of their rotational energy into electromagnetic radiation. The traditional wisdom that, when the star is not accreting matter from a companion star in a binary system, its main energy source comes from rotational energy, was shattered with the discovery of the so-called magnetars, a class that includes anomalous X-ray pulsars and soft gamma-ray repeaters5 (SGRs). At present, there are over 20 of these (mostly young) neutron stars characterized by high X-ray quiescent luminosities (generally larger than their entire reservoir of rotational energy), short X-ray bursts6, sometimes exhibiting giant flares7, and/or transient pulsed radio emission8.

In the most successful model9, magnetars are believed to be endowed with large magnetic fields, B ~ 1014–1015 G, which explains their large periods (2–12 s), compared with those of normal isolated radiopulsars (mostly in the range 0.1–1 s). Relatively high fields are also observed in a class of nearby thermally emitting neutron stars usually known as the magnificent seven. These are objects with magnetic fields of ~1013 G, intermediate between magnetars and radiopulsars, but their periods also cluster in the same range as for magnetars. Although there are hints pointing to an evolutionary link between magnetars, nearby isolated X-ray pulsars, and some high-B radiopulsars, a complete grand unification theory is still lacking10. Interestingly, some sources (for example, 1E 1841–045, SGR 0526–66 and SGR 1806–20 among others) are known to be young and they already have periods from 7 to 12 s. With their present estimated dipolar fields, they should easily reach periods of 20 or 30 s in a few thousand more years. This seems in contradiction with a steady pulsar spin-down rate. Where is the population of evolved high-magnetic-field neutron stars with long periods? Why do none of the middle-age magnetars, or the older X-ray pulsars, have longer periods?

For rotation-powered radiopulsars, the strong dependence of the radio luminosity and the beaming angle on the rotation period, and the selection effect of several radio surveys for long spin periods, result in the lack of observed radiopulsars with periods longer than a few seconds. For X-ray pulsars, however, there is no reason to expect any selection effect. We plot in Fig. 1 the spin period distribution of isolated X-ray pulsars and X-ray binary pulsars, showing that there are no observational limitations to the detection of slow periods in X-ray binaries. When other torques are present (accretion), X-ray pulsars with rotation periods of hundreds or even thousands of seconds are clearly observed. The fact that no X-ray-emitting isolated neutron star has been discovered so far with a period >12 s must therefore be a consequence of a real physical limit and not simply a statistical fluctuation11,12. The easiest and long-standing answer is that the magnetic field decays as the neutron star gets older13 in such a way that its spin-down rate becomes too slow to lead to longer rotation periods during the time it is still bright enough to be visible as an X-ray pulsar. In this scenario, low-field magnetars13 are simply old magnetars whose external dipolar magnetic field has decayed to normal values14,15. However, no detailed quantitative predictions supported by realistic simulations have been able to reproduce the observational limits. This is the purpose of this work.

The long-term life in the interior of a neutron star is very dynamic. As the star cools down, the internal magnetic field is subject to a continuous evolution through the processes of Ohmic dissipation, ambipolar diffusion and Hall drift16,17. Soon after birth (from hours to days, at most) protons in the liquid core undergo a transition to a superconducting phase and a solid crust is formed. The neutron star crust (see ref. 18 for a comprehensive review) is for the most part an elastic solid, comprising a Coulomb lattice of normal spherical nuclei. It is only about 1 km thick (10% of the star radius) and contains 1% of its mass; however, it is expected to play a key role in various observed astrophysical phenomena (pulsar glitches19, quasi-periodic oscillations in SGRs (ref. 20), thermal relaxation in soft X-ray transients21 and so on) Among all of the ingredients that determine the magneto-rotational evolution of a neutron star, one key issue is the magnetic diffusivity in the region

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suggest that the crust of neutron stars will be unstable. The relevant nuclear parameters also determine global properties such as the radius and moment of inertia, and have been proposed to have a potential observational effect in the crust oscillation frequencies. The impurity parameter formalism must then be high to reproduce the molecular dynamics results. We will set $Q_{\text{imp}} = 0.1$ in the outer crust, but let it vary in the inner crust, to phenomenologically explore the instability of our results to this important parameter. We consider four models (A, B, C, D) with a high $Q_{\text{imp}}$ only in the pasta region, $\rho > 10^{14} \text{ g cm}^{-3}$, but low $Q_{\text{imp}}$ in the rest of the inner crust, one model (E) with $Q_{\text{imp}} = 0.1$ everywhere, and another model (J) corresponding to the extrapolation of the values calculated in refs 30,31 at a few densities. The profiles of $Q_{\text{imp}}$ as a function of density and the corresponding profiles of electrical resistivity are shown in Fig. 2, and the summary of the properties of each model is given in Table 1.

As the initial model, we have chosen a neutron star born with an initial dipolar field of $B = 3 \times 10^{12} \text{ G}$ (at the pole). We refer to Section 2 in ref. 37, Section 4 of ref. 38, and references therein, for all details about the magnetic field geometry, the equation of state employed and other microphysical inputs. The evolution is followed for $10^6$ years using the new two-dimensional code developed in ref. 23, to which we refer for technical details. In Fig. 3 we show the value of the magnetic field at the pole as a function of age for the different models. During the first $\sim 30,000$ years, the field is dissipated by a factor $\sim 2$ for all of the models, with slight differences due to the different neutron star masses and $\Delta \mu_{\text{crust}}$. In this regime, the neutron star crust is still warm and electron screening of impurities is not the dominant process. Thereafter, as the star cools, the evolution strongly depends on the impurity parameter in the inner crust. For low values of $Q_{\text{imp}}$ (model E), the field almost stops to dissipate and remains high, with some oscillations due to the Hall term in the induction equation. In contrast, a large value of $Q_{\text{imp}}$ (models A, B, C) results in the dissipation of the magnetic field by one or even two orders of magnitude between 0.1 and 1 Myr. Models D and J, both with moderate values of $Q_{\text{imp}}$, show an intermediate dissipation rate. These differences in the time evolution of the magnetic field have a clear observational effect that we discuss now.

Figure 1 | Period distribution of isolated neutron stars (dashed) and neutron stars in binary systems (solid).

Table 1 | Summary of the properties of the neutron star models considered in this work: mass (in solar masses), moment of inertia (in units of $10^{45} \text{ g cm}^{-2}$), thickness of the crust and of the pasta phase, and maximum value of the impurity parameter.

| Model | $M (M_\odot)$ | $I_{\text{LS}}$ | $\Delta R_{\text{crust}}$ (km) | $\Delta R_{\text{pasta}}$ (km) | $Q_{\text{imp}}$ |
|-------|---------------|---------------|-----------------|-----------------|-------------|
| A     | 1.10          | 0.962         | 0.94            | 0.14            | 100         |
| B     | 1.40          | 1.327         | 0.70            | 0.10            | 100         |
| C     | 1.76          | 1.755         | 0.43            | 0.07            | 100         |
| D     | 1.40          | 1.327         | 0.70            | 0.10            | 10         |
| E     | 1.40          | 1.327         | 0.70            | 0.10            | 0.1         |
| J     | 1.40          | 1.327         | 0.70            | 0.00            | 23         |

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is the effective moment of inertia of the star.

\[ I \text{ is the speed of light.} \]

The energy balance equation between \( D \) and \( P \) diagram for magnetars, X-ray isolated neutron stars and

\[ \frac{4}{3} \pi \rho \]  

indicating that the period has reached an asymptotic value

\[ Q \]  

We plot the

\[ Q \text{ erg s}^{-1} \]

in

\[ B \]

Fig. 2 | Impurity parameter \( Q_{\text{imp}} \) (left) and electrical resistivity (right) as a function of density for the four models with \( M = 1.4M_\odot \). We plot the resistivity for two different temperatures to show more clearly the regions where the temperature-independent disorder resistivity dominates.

\[ \text{Figure 2} \]

\[ \text{Figure 3} \]

\[ \text{Figure 4} \]

\[ \text{Figure 2} \]

\[ \text{Figure 3} \]

\[ \text{Figure 4} \]

calculations of the spin-down luminosity of an oblique rotator\(^{39}\) can be well approximated by

\[ \dot{E} = \frac{B^2 R^6 \Omega^4}{4 c^3} (1 + \sin^2 \alpha^2) \]

where \( R \) denotes the neutron star radius, \( \Omega = 2\pi / P \) is the angular velocity, \( \alpha \) is the angle between the rotational and the magnetic axis, and \( c \) is the speed of light. The energy balance equation between radiation and rotational energy losses gives

\[ I \Omega \dot{\Omega} = \frac{B^2 R^6 \Omega^4}{4 c^3} (1 + \sin^2 \alpha^2) \quad (1) \]

where \( I \) is the effective moment of inertia of the star.

Numerically integrating equation (1) with \( B_\delta(t) \) obtained from our simulations, we can obtain evolutionary tracks in the \( P - \dot{P} \) diagram, which allows a close compare with observed timing properties of X-ray pulsars. This is shown in Fig. 4, where we compare with the theoretical trajectories of a neutron star up to an age of 10 Myr to the sample of isolated X-ray pulsars with the largest rotation periods. The most important qualitative difference is that, for models with high \( Q_{\text{imp}} \), the evolution tracks become vertical after \( \sim 10^9 \) yr, indicating that the period has reached an asymptotic value but its derivative steadily decreases. The particular upper limit of \( P \) depends on the neutron star mass, the initial field and the value of \( Q_{\text{imp}} \), but this gives a natural explanation to the observed upper limit to the rotation period of isolated X-ray pulsars, and the observed distribution with objects of different classes clustering in the range \( P = 2 - 12 \) s although \( \dot{P} \) varies over six orders of magnitude. Models J and D (moderate impurity parameter) follow similar trajectories to models A, B and C, but reaching slightly longer periods at late times. Conversely, in model E (low impurity in the pasta region) the period keeps increasing owing to the slower dissipation of the magnetic field, which in principle predicts that pulsars of longer periods (20–100 s) should be visible. In models D and E, the slow release of magnetic energy through Joule heating keeps the neutron star bright and visible much longer than for the rest of the models. The luminosity of models D and E, at an age of a few million years, is \( \approx 10^{32} \) erg s\(^{-1} \), high enough for sources a few kiloparsecs away to be detectable with present X-ray instruments.

Other possible torque mechanisms, which would enter as extra terms in equation (1), such as stellar wind or accretion from a fallback disk, could act only in the early stages of a neutron star life and may contribute to explain the observed large values of \( P \) in some objects. Furthermore, the effective moment of inertia \( I \) may also vary with time as the superfluid part of the core grows during the first hundreds of years. A simple phenomenological model for the rotational evolution of the normal and superfluid components and its observational implications have been discussed in ref. 40. Note, however, that the main conclusion of our calculations is not affected: if there is a highly disordered inner crust, either due
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Author contributions

I.A.P. and D.V. contributed to developing the model, performed the calculations and wrote the manuscript. N.R. contributed to writing the manuscript and selected and checked the observational data.

Additional information

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Competing financial interests

The authors declare no competing financial interests.