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THE MAGNETAR ORIGIN OF PULSARS

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In this work I suggest the idea that all neutron stars experienced at birth an ultrafast decay of their magnetic fields from their initial values to their current surface values. If the electromagnetic energy radiated during this field decay is converted into kinetic and rotational energies of the neutron star then the decay time is of the order of 10^{-4} s provided that the initial magnetic fields lie in the range of 10^{15}-10^{16}G and the initial periods in the range 1-20 ms. THIS SUGGESTS THAT ALL NEUTRON STARS ARE BORN WITH MAGNETIC FIELDS TYPICAL OF MAGNETARS AND PERIODS TYPICAL OF MILLISECOND PULSARS. The origin of this ultrafast field decay points to magnetic instabilities, which are inevitable during the birth of neutron stars.

The Larmor formula for the power radiated by a time varying magnetic dipole moment $P = 2\ddot{\mu}^2/(3c^3)$ and the estimate $\ddot{\mu} \sim \mu_0/\tau^2$, where τ is the characteristic time in the field decay law $B(t) = B_0 e^{-t/\tau}$, imply the equation $P \simeq 2\mu_0^2/(3c^3\tau^4)$ which can be used together with $\mu_0 = B_0 R^3/2$ to yield the power radiated by a neutron star of radius R and an initial magnetic field B_0:

$$P \simeq \frac{B_0^2 R^6}{6c^3\tau^4} \qquad (1)$$

Consider now the specific time τ_s elapsed during the field decay from the initial field B_0 to the current surface magnetic field B_s. The condition $B(\tau_s) = B_s$ and the law $B(t) = B_0 e^{-t/\tau}$ imply $B_s = B_0 e^{-\tau_s/\tau}$, or equivalently, $\tau_s = \tau \ln(B_0/B_s)$ which can be used with Eq. (1) to yield the electromagnetic energy radiated during τ_s, that is, $E_{\rm rad} \simeq \tau_s P$, or explicitly:

$$E_{\rm rad} \simeq \frac{B_0^2 R^6 \ln(B_0/B_s)}{6c^3\tau^3} \qquad (2)$$

If this energy is converted into kinetic energy $E_{\rm kin} = Mv^2/2$ and rotational energy $E_{\rm rot} = 4\pi^2 M R^2 (P_0^{-2} - P_s^{-2})/5$, where M, v, P_0 and P_s are the mass, space velocity, initial and current periods, then energy conservation reads

$$\underbrace{\frac{B_0^2 R^6 \ln(B_0/B_s)}{6c^3\tau^3}}_{E_{\rm rad}} = \underbrace{\frac{Mv^2}{2}}_{E_{\rm kin}} + \underbrace{\frac{4\pi^2 M R^2}{5}\left(\frac{1}{P_0^2} - \frac{1}{P_s^2}\right)}_{E_{\rm rot}} \qquad (3)$$

This implies

$$\tau = \left(\frac{5B_0^2 R^6 \ln(B_0/B_s) P_s^2 P_0^2}{3c^3 M (5v^2 P_s^2 P_0^2 - 8\pi^2 R^2 (P_0^2 - P_s^2))}\right)^{1/3} \qquad (4)$$

If neutron stars are born with magnetic fields of magnetars and periods of MSP then (details in arXiv:1104.5060)

$$\tau \approx R/c \qquad (5)$$

Therefore the time decay from B_0 to B_s is of the order of

$$\tau_s \sim 10^{-4} \text{ s}$$

This field decay is ultrafast!

From Eqs. (3) and (5) it follows that

$$\frac{B_0^2 R^3 \ln(B_0/B_s)}{6} = \frac{Mv^2}{2} + \frac{4\pi^2 M R^2}{5}\left(\frac{1}{P_0^2} - \frac{1}{P_s^2}\right) \qquad (6)$$

And

$$B_0 = B_s e^{W([\sigma v_\perp^2 + \lambda(P_0^{-2} - P_s^{-2})]B_s^{-2})/2} \qquad (7)$$

Where W is the Lambert function defined as the inverse of $f(x)=xe^x$ satisfying $W(x)e^{W(x)} = x$ and

$$\sigma = 2.52 \times 10^{16} \text{gr cm}^{-3}; \lambda \approx 2.65 \times 10^{29} \text{G}^{-2} \text{ s}^{-2}$$

RESULTS

Interval: 2 s $< P_s \leqslant 8.5$ s. There are 9 neutron stars in this interval. The average values of this set are $\widetilde{P_s} = 4.82$ s, $\widetilde{B_s} = 3.14 \times 10^{13}$G and $\widetilde{v_\perp} = 226.55$ km/s. If one assumes $\widetilde{P_0} = .02$ s then Eq. (7) predicts $B_0 = 7.8 \times 10^{15}$G.

Interval: 1 s$\leqslant P_s \leqslant 2$ s. There are 29 pulsars in this set of neutron stars. The average values are $\widetilde{P_s} = 1.32$ s, $\widetilde{B_s} = 4.17 \times 10^{12}$ G and $\widetilde{v_\perp} = 261.55$ km/s. If $\widetilde{P_0} = .02$ s then $B_0 = 6.78 \times 10^{15}$G.

Interval: .02 s$\leqslant P_s < 1$ s. There are 130 neutron stars with periods in this interval. The corresponding average values are $\widetilde{P_s} = 0.41$ s, $\widetilde{B_s} = 1.28 \times 10^{12}$G and $\widetilde{v_\perp} = 409.06$ km/s. Equation (7) predicts that if $\widetilde{P_0} = .02$ s then $B_0 = 6.42 \times 10^{15}$G. According to Eq. (7), the Crab pulsar B0531+21 with $v_\perp = 141$ km/s, $P_s = .033$ s and $B_s = 3.78 \times 10^{12}$G was born with $B_0 \approx 5.8 \times 10^{15}$G if $P_0 = .019$

Isolated millisecond pulsars in the interval: .0015 s $\leqslant P_s < .009$ s. There are 9 pulsars in this set of neutron stars. The average values are $\widetilde{P_s} = 0.005$ s, $\widetilde{B_s} = 2.59 \times 10^8$G and $\widetilde{v_\perp} = 60.11$ km/s. One can consider a very small change in the period by assuming, for example, the average initial period $\widetilde{P_0} = .0049$ s. Under this assumption Eq. (7) predicts $B_0 = 3.65 \times 10^{15}$G.

Another implication of Eq. (6)

$$v_\perp = \sqrt{k_1 B_0^2 \ln(B_0/B_s) - k_2 (P_0^{-2} - P_s^{-2})}$$

$$k_1 = 7.9365 \times 10^{-17} \text{cm}^2\text{s}^{-2}\text{G}^{-2}$$

$$k_2 = 1.0528 \times 10^{-13} \text{cm}^2$$

If a pulsar with $B_s = 10^{12}$G and $P_s = .5$ s was born with $B_0 = 6.308 \times 10^{15}$G and $P_0 = .02$ s then $v_\perp = 367.8$ km/s, which implies the space velocity v = 450 km/s. This is the average velocity for pulsars suggested by Lyne and Lorimer (1994).