The Magnetar Connection

Tanmay Tushar Chowhan\textsuperscript{1}, Sushan Konar\textsuperscript{2}, Sarmistha Banik\textsuperscript{1}\textsuperscript{3}

\textsuperscript{1}Dept. of Physics, BITS Pilani, Hyderabad Campus, Shameerpet Mandal, Hyderabad-500078, India.
\textsuperscript{2}NCRA-TIFR, Pune 411007, India

Abstract. We investigate the combined evolution of the dipolar surface magnetic field ($B_s$) and the spin-period ($P_s$) of known magnetars and high magnetic field ($B_s \gtrsim 10^{13}$ G) radio pulsars. We study the long term behaviour of these objects assuming a simple ohmic dissipation of the magnetic field. Identifying the regions (in the $P_s$-$B_s$ plane) in which these neutron stars would likely move into, before crossing the death-line to enter the pulsar graveyard, we comment upon the possible connection between the magnetars and other classes of neutron stars.

Keywords. stars: neutron, (stars:) pulsars: magnetic fields, pulsars : evolution.

More than fifty years have passed since the discovery of neutron stars. In this period, $\sim$3500 neutron stars, belonging to many distinct observational classes have been observed. This has led to an important direction of neutron star research, in trying to find a unification scheme (evolutionary or otherwise) connecting these different observational classes. In particular, the connection between different types of isolated neutron stars (for example, the Magnetars, RRATs, CCOs, XDINS, and ordinary radio pulsars), via the route of magnetic field evolution, has received serious attention in recent years (Kaspi 2011). Therefore, it is worthwhile to study the time-trajectory of such isolated neutron stars in the spin-period - surface magnetic field ($P_s$-$B_s$) plane to understand possible connections between different observational classes. With this aim, we consider the evolution of the magnetars and the high magnetic field ($B_s \gtrsim 10^{13}$ G) radio pulsars.

The exact nature of the magnetic field of neutron stars is not yet clearly understood. In this work, we assume a purely crustal field (the currents supporting the field are entirely confined to the crust) evolving due to simple ohmic dissipation given by -

$$\frac{\partial B}{\partial t} = -\frac{c^2}{4\pi} \nabla \times (\frac{1}{\sigma} \nabla \times B).$$

(1)

We use the formalism for field evolution developed by Konar (1997). The effectiveness of ohmic dissipation for field evolution has recently been reiterated by Ertan & Alpar (2021) by providing an explanation for the minimum spin-period seen in the millisecond pulsars. The free parameters of the model, entering the above equation through the electrical conductivity ($\sigma$), are - a) the density ($\rho_c$) at which the currents are concentrated, and b) the impurity content ($Q$) of the crustal material. Since there is no way of knowing the exact parameter values applicable for a particular neutron star, we calculate the trajectory of each object assuming the following ranges for these parameters - a) $\rho_c \sim 10^{13} - 10^{11}$ gm.cm$^{-3}$, b) $Q \sim 0.0 - 0.05$.

The fundamental measured quantities of a neutron star are its spin-period ($P_s$) and the period derivative ($\dot{P}_s$). For the rotation-powered pulsars (as well as the Magnetars) the large-scale dipolar magnetic field, at the surface, is derived from the following relation
The current locations of the magnetars, the high magnetic field radio pulsars along-with the region where they evolve into, in the $P_s$-$B_s$ plane. A number of RRATs have also been shown for comparison.

(Manchester & Taylor 1977) -

$$B_s = 3.2 \times 10^{19} \left( \frac{P_s}{s} \right)^{1/2} \left( \frac{P_s}{s^3} \right)^{1/2} G.$$  \hspace{1cm} (2)

assuming that the magnetic dipole radiation is solely responsible for the spin-down of the pulsar.

We track the evolutionary trajectories of - a) 19 Magnetars, and b) 65 radio pulsars (with $B_s \gtrsim 10^{13}$ G, beginning with their current values of $P_s$ and $B_s$. [The present values of $P_s$ and $B_s$ for both the radio pulsars and the Magnetars have been obtained from the ATNF pulsar catalog.] Thereafter, with each incremental change in $B_s$, we dynamically calculate $P_s$. The Magnetars are evolved for $2 \times 10^5$ years and the radio pulsars for $5 \times 10^5$ years. The timescales are chosen such that the trajectories are arrested before they reach the death-line (Chen & Ruderman, 1993) shown as a purple dashed line in Fig.[1].

Our results are shown in Fig.[1]. The shaded areas in red and blue correspond to the regions where the Magnetars and the radio pulsars are found at the end of the evolution. Interestingly, most of the currently known RRATs are located within this region. In a recent work, we have shown that the population of RRATs do not have a positive correlation (statistically speaking) with the population of nulling pulsars, as is usually assumed (Abhishek et al. 2022). The current results, connecting the RRATs to magnetars and high-magnetic field radio pulsars through an evolutionary pathway, appear to corroborate this statistical conclusion.

References

Abhishek et al., 2022 astro-ph, 2201.00295  
Chen K., Ruderman M., 1993, ApJ, 402, 264  
Ertan, Ü & Alpar, M. A., 2021 MNRAS, 505, L112  
Kaspi V. M., 2011, ApJ, 741, L13A  
Konar, S., 1997 PhD thesis, Indian Institute of Science, Bangalore  
Manchester, R. N., Taylor, J. H. 1977, Pulsars, W. H. Freeman, San Francisco, p.36  
Manchester, R. N., Hobbs, G.B., Teoh, A. & Hobbs, M., 1993-2006 (2005), AJ, 129