*Cosmic Magnetic Fields:*
*From Planets, to Stars and Galaxies*
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# Pulsars & Magnetars

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**Abstract.** The largest magnetic field encountered in the observable Universe can be found in neutron stars, in particular in radio pulsars and magnetars. While recent discoveries have slowly started to blur the distinction between these two classes of highly magnetized neutron stars, it is possible that both types of sources are linked via an evolutionary sequence. Indications for this to be the case are obtained from observations of the spin-evolution of pulsars. It is found that most young pulsars are heading across the top of the main distribution of radio pulsars in the $P-\dot{P}$-diagram, suggesting that at least a sub-class of young pulsars may evolve into objects with magnetar-like magnetic field strengths. Part of this evolutionary sequence could be represented by RRATs which appear to share at least in parts properties with both pulsars and magnetars.

**Keywords.** Pulsars: general – stars: neutron – stars: magnetic fields

## 1. Introduction

The highest magnetized objects in the known Universe are neutron stars (NSs) with magnetic fields estimated to reach $10^{15}$ Gauss or above. The creation and maintenance of such large field strengths remains an important and unsolved astrophysical problem. It is therefore useful to review the evidence for such estimates and to critically study the made assumptions when deriving such numbers. The importance of the answers anticipated and sought for in this process go beyond the mere understanding of neutron stars, but they have relevance for the evolution of cosmic magnetic fields in general, stellar evolution, and studies of the Milky Way and cosmic ray production.

## 2. Manifestations of magnetized neutron stars

Neutron stars are observed in many flavours, including those as dim isolated NSs, as normal and radio millisecond pulsars, as magnetars, as Rotating Radio Transients (RRATs) or as part of X-ray binary systems. We will concentrate here only on those manifestations that are believed† to have very large magnetic fields. In all discussed cases, the identification of the observed object class with NSs is safe, and general properties can be assumed (see e.g. Lyne & Smith 2005 for a summary): With possible variations due to the unknown Equation-Of-State, the radius of a NS lies between 10 and 15 km. Masses have been measured very accurately for an increasing number of binary NSs and are found in a range between $1.2M_{\odot}$ and $\sim 2M_{\odot}$. NSs therefore represent the most extreme matter in the observable Universe with densities in their interior that vastly exceeds that of any known matter on Earth. The result is a peculiar high-temperature super-fluid super-conductor. We can expect that the super-conductivity plays an important role in the maintenance of the enormous magnetic field strengths which range from

† or "observed" – the reader can make up her/his mind after reading this review!



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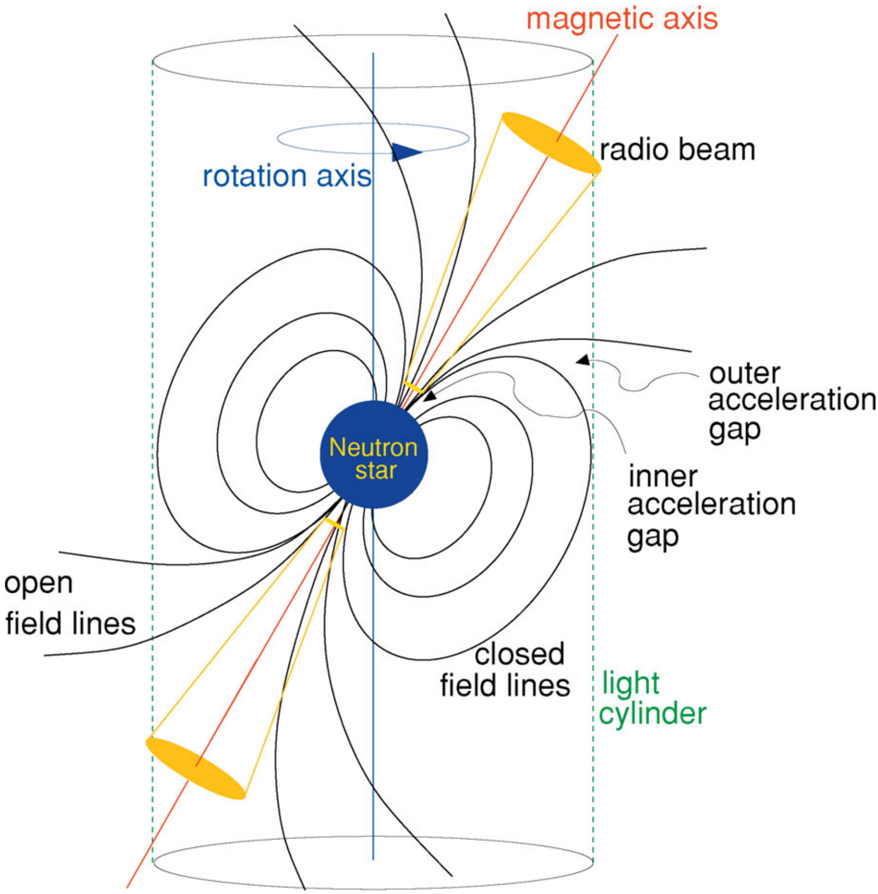


**Figure 1.** Toy model for the pulsar-like otating neutron star and its magnetosphere (not drawn to scale!).

$10^8$ Gauss in millisecond pulsars, over typically $10^{12}$ Gauss in normal pulsars to $10^{15}$ Gauss in magnetars.

## 2.1. *Pulsars*

Most of the NSs known are observed as radio pulsars. The nearly 2,000 objects currently known are classified in two groups, i.e. the old recycled or millisecond pulsars and the younger, normal pulsars. Periods range from 1.4 ms to 8.5 s † and, in all cases, are found to increase slowly with time. Spin-down rates are typically observed from $\dot{P} \sim 10^{-12}$ for the very youngest pulsars to $\dot{P} \sim 10^{-21}$ for the oldest pulsars. This increase in rotation period reflects the loss of rotational energy that is converted in electromagnetic radiation.

Even though radio emission accounts for only a tiny fraction (say, $10^{-6}$ to $10^{-4}$) of the total "spin-down luminosity" of these *rotation-powered NSs*, most pulsars are only visible at radio frequencies. While pulsars are normally rather weak radio sources, the emission is coherent and highly polarized, and the result of an emission process that is only poorly understood at best. In our basic understanding (see Lorimer & Kramer 2005 for more details, Fig. 1), the magnetized rotating neutron star induces an electric quadrupole field which is strong enough to pull out charges from the stellar surface (the

† see for instance `http://www.atnf.csiro.au/research/pulsar/psrcat/`

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electrical force exceeds the gravitational force by a factor of $\sim 10^{12}$!). The magnetic field forces the resulting dense plasma to co-rotate with the pulsar. This *magnetosphere* can only extend up to a distance where the co-rotation velocity reaches the speed of light‡. This distance defines the so-called light cylinder which separates the magnetic field lines into two distinct groups, i.e. *open and closed field lines*. The plasma on the closed field lines is trapped and co-rotates with the pulsar. In contrast, plasma on the open field lines can reach highly relativistic velocities and can leave the magnetosphere, creating the observed radio beam at a distance of a few tens to hundreds of km above the pulsar surface.

The location of the pulsar beam within the open dipolar field line region allows us to relate the beam radius, $\rho$, to the emission height, $r_{\rm em}$ and the rotation period, i.e.

$$\rho = \sqrt{\frac{9\pi r_{\rm em}}{2cP}}. \tag{2.1}$$

The scaling of $\rho \propto P^{-1/2}$ is indeed observed (see e.g. Lorimer & Kramer 2005) and can be viewed as evidence that the field structure is dipolar in the emission region.

## 2.2. *Magnetars*

Magnetars are slowly rotating neutron stars for which magnetic fields are inferred that are even stronger than those estimated for pulsars (see Section 3). Currently, 13 magnetars are confirmed† and are observed as variable X-ray/$\gamma$-ray sources which show common, short energetic bursts (i.e. in case of the so-called *Soft-Gamma-Ray Repeaters* (SGRs) of which 4 are known) or long flares and rare and soft short bursts (i.e. in case of the so-called *Anomalous X-ray Pulsars* (AXPs) of which 9 are known). Observations during bursts allow the detection of rotation periods which range from 2 to 12 s. Spin-down is also detected with values from $\dot{P} \sim 10^{-13}$ to $10^{-10}$. The burst luminosity commonly exceeds the spin-down luminosity which is given by

$$\dot{E} = -I\Omega\dot{\Omega} = 4\pi^2 I\dot{P}P^{-3} = 3.95\times 10^{31}\ {\rm erg\ s^{-1}} \left(\frac{\dot{P}}{10^{-15}}\right)\left(\frac{P}{\rm s}\right)^{-3}, \tag{2.2}$$

where $\Omega = 2\pi/P$ is the rotational angular frequency, $I$ the moment of inertia, and the last equality holds for a canonical moment of inertia of $I = 10^{45}$ g cm$^2$. Consequently, the objects cannot be rotation powered but a different source of energy must exist. In the most commonly applied model of Duncan & Thompson (1992), the source of energy results from the energy stored in huge magnetic fields. Indications for this are also obtained from the giant flares observed in SGRs: the bright, spectrally hard initial spike is followed by a tail of thermal X-ray emission which is strongly modulated at the spin frequency of the neutron star. This feature is interpreted as a "trapped fireball" after a significant shift in the NS crust occurred. Estimating the magnetic field necessary to contain the plasma one indeed obtains fields in excess of $10^{14}$ G. Furthermore, features in X-ray spectra interpreted as cyclotron lines support such estimates. Finally, magnetars are considered to be young sources as associations of several magnetars with supernova remnants suggests. (For a recent more detailed review of magnetar properties, see Kaspi

‡ Strictly speaking, the Alfvén velocity will determine the co-rotational properties of the magnetosphere.

† see `www.physics.mcgill.ca/ pulsars/magnetar/main.html` for updated information

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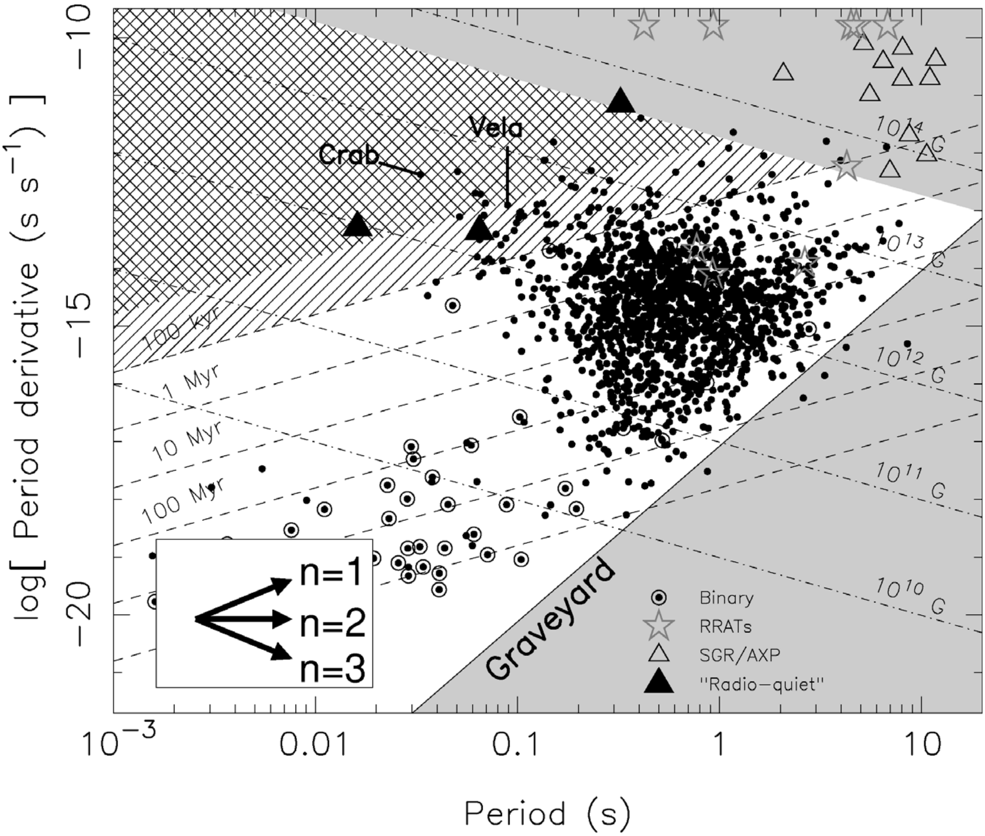


**Figure 2.** The $P$–$\dot{P}$ diagram shown for a sample consisting of radio pulsars, 'radio-quiet' pulsars and magnetars, i.e. soft-gamma repeaters (SGRs) and anomalous X-ray pulsars (AXPs). Lines of constant characteristic age $\tau_c$ and magnetic field $B$ are also shown. The single hashed region shows 'Vela-like' pulsars with ages in the range 10–100 kyr, while the double-hashed region shows 'Crab-like' pulsars with ages below 10 kyr. The grey regions are areas where radio pulsars are not predicted to exist by theoretical models. The inset at the bottom-left indicates the expected direction of movement for pulsars with a braking index of $n = 1$, 2 and 3, respectively.

2007.) Small ages are also obtained from *characteristic age* estimates, given by

$$\tau_{\rm c} \equiv \frac{P}{2\dot{P}} \simeq 15.8\ {\rm Myr} \left(\frac{P}{\rm s}\right) \left(\frac{\dot{P}}{10^{-15}}\right)^{-1} \tag{2.3}$$

which is also applied to normal pulsars. This estimate assumes that the spin period at birth is much shorter that the present value and that the spin-down is dominated by magnetic dipole radiation. We discuss these assumptions in the following.

## 3. Magnetic field estimates

In addition to cyclotron lines in isolated NS and magnetars, the most common estimate for the magnetic field is obtained from the observed spin-down of the NSs, using

$$B = 3.2 \times 10^{19} {\rm G}\ \sqrt{P\dot{P}} \simeq 10^{12}\ {\rm G} \left(\frac{\dot{P}}{10^{-15}}\right)^{1/2} \left(\frac{P}{\rm s}\right)^{1/2}. \tag{3.1}$$

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which assumes a canonical NS with a moment of inertia $I = 10^{45}$ g cm$^2$ and radius $R = 10$ km. More importantly, it assumes that the spin-down is dominated by the emission magnetic dipole radiation and that the magnetic axis is perpendicular to the rotation axis.

### 3.1. *Spin-evolution & braking indices*

If the spin-down is dominated by "dipole braking", the magnetized NS behaves like a rotating bar magnet, and the change in angular spin-frequency can be written as

$$\dot{\Omega} = -\left(\frac{2|\mathbf{m}|^2 \sin^2 \alpha}{3Ic^3}\right)\Omega^3 \propto -\Omega^n \tag{3.2}$$

where $\mathbf{m}$ is the magnetic dipole moment and $\alpha$ the angle between magnetic and rotation axis. The usage of the *braking index* $n$ is a general way of describing the spin-evolution of NSs. Here, it takes a value of $n = 3$. Ideally, the assumption of magnetic dipole braking can be verified by determining the braking index from observations which is in principle possible by measuring $\ddot{\Omega}$ since

$$n = \frac{\Omega\ddot{\Omega}}{\dot{\Omega}^2}. \tag{3.3}$$

However, this is an extremely difficult task, as significant $\ddot{\Omega}$-values can only be expected for young pulsars where the spin-down is largely influenced by timing noise and the recovery from glitches rather than by a regular long-term spin-down. Eleven braking indices have been measured reliably at the time of writing, ranging from $n = 1.1$ to $n = 2.9$, i.e. in all cases $n < 3$ (Espinoza *et al.* in prep.).

### 3.2. *Divas and increasing fields*

The spin characteristics of pulsars can be displayed in a $P - \dot{P}$-*diagram* where we plot logarithms of $P$ and $\dot{P}$ and lines of constant magnetic field and age using Eqns. 3.1 & 2.3 (see Fig. 2). Young pulsars are located in the top-left corner while the majority of NSs can be found in the central region near $P \sim 0.6$s and $\dot{P} \sim 10^{-15}$. Magnetars are in the top-right corner overlapping in parts with high-B-field pulsars which we discuss in Section 4.1. If the braking index $n = 3$, NSs evolve along constant magnetic field lines, while for $n = 2$ they move horizontally and for $n < 2$ they move up in the diagram. Note that for $n < 3$ the magnetic field appears to increase with time. Figure 3 demonstrates that this increase is particularly rapid for $n < 2$ which is the case for four measured pulsars. But also the inferred characteristic age is affected. Figure 3 also shows that NSs lie about their age in terms of displayed characteristic age which becomes smaller than the true age for $n < 3$. In fact, pulsars do not seem to age at all for $n = 1$.

In summary, a large number of young pulsars are heading across the top of the main distribution of radio pulsars in the $P - \dot{P}$-diagram. All young pulsars with measured braking index have $n < 3$, so that the effective magnetic fields increase with time. At the same time, the characteristic ages increase only slowly or even decrease with time. We therefore conclude that the evolution of some young pulsars is consistent with travel to region occupied by magnetars (see Lyne 2004)!

### 3.3. *Assumptions revisited*

In order to verify the startling conclusions that some young pulsars may evolve to possibly become magnetars, we ought to review some of the made assumptions in the above analysis. Firstly, all braking indices measured so far suggest that the spin-down is not solely determined by magnetic dipole radiation. Indeed, using the discovery of intermittent pulsars, Kramer *et al.* (2006) provided first observational evidence that a significant

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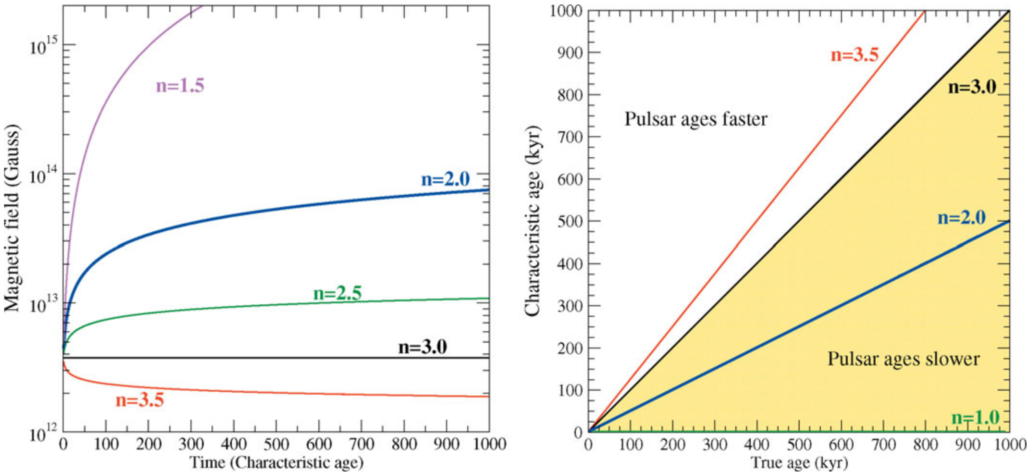


**Figure 3.** Evolution of the inferred magnetic field and the characteristic age for different values of the braking index. The left panel shows that the evolution of the magnetic field appears to increase for $n < 3$. The right panel demonstrates the deviation of characteristic age from true age.

fraction of spin-down torque is also provided by a particle wind and its magnetospheric current. One can only assume that the estimated field is therefore overestimated. In case of intermittent pulsars, the error may be as small as $\sim 20\%$. Secondly, the mentioned result that the beam radii of pulsars scale with $\propto P^{-1/2}$ suggests that the assumption of dipolar fields is correct. This is also supported by modelling the eclipses of pulsar A in the Double Pulsar where the observations are consistent with a simple dipolar magnetosphere of pulsar B (Breton *et al.* 2006). However, the movement of the pulsars in the $P - \dot{P}$-diagram can also be interpreted as a change in magnetic inclination angle $\alpha$. Such changes should, however, become visible in changes of the pulse profile and its polarisation characteristics.

## 4. Population overlap?

Another way of learning more about the possible evolution from pulsars to magnetars is to study the properties of objects which lie at the "border" of the particular population by sharing some of each other properties. Here we encounter pulsars with magnetar-like spin properties, magnetars that radiate radio emission and RRATs which may be considered as a possible missing link.

### 4.1. *High-B field pulsars*

A number of young radio pulsars is now known (e.g. McLaughlin *et al.* 2003) that occupy a region in the $P - \dot{P}$ diagram which was traditionally associated with magnetars (see Fig. 2). In particular, the magnetic field estimate lies above the quantum critical field where standard pulsar radio emission is not necessarily expected (e.g. Lorimer & Kramer 2005). However, none of the pulsar properties, e.g. the emission characteristics at X-ray or radio frequencies, does show really similarities with those of magnetars (e.g. Gonzale *et al.* 2007).

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### 4.2. *Radio-loud magnetars*

A more interesting development of recent years is the discovery of radio emission from two magnetars (Camilo *et al.* 2006, 2007). In both cases, for AXP J1810−197 and for 1E 1547.0−5408, the radio emission is detected with the magnetar's rotation period of $P = 5.5$ s and $P = 2.1$ s, respectively. Both sources had a previous X-ray burst that may have triggered the radio emission, as pre-burst radio observations did not reveal a source at the magnetars' position. Therefore, magnetic field rearrangements may be responsible for the radio switch-on but a failed failed radio detection of another AXP after burst (SGR 1627-41, Camilo & Sarkissian 2008), shows that such a rearrangement may be necessary but not sufficient (cf. Halpern *et al.* 2008). A comparison of magnetar radio and pulsar radio emission is intriguing, i.e. some properties are similar but many features are very different: unlike pulsars, the magnetar radio spectrum is flat and changing with time; unlike pulsars, there is a rough alignment between radio and X-ray arrival times; unlike pulsars, pulse profiles are not stable but change dramatically with time and frequency; the emission is $\sim 100\%$ polarized but unlike pulsars the polarisation position angle swing is changing with time. Some emission properties may be explainable by non-dipolar fields (e.g. Kramer *et al.* 2007) but overall it is unlikely that magnetars are simply variations of normal radio pulsars. However, it is indeed not inconceivable that they are linked in terms of evolution. This would solve another problem, namely the notion that current birth rate estimates suggest that the derived number of neutron stars is too large to be sustained by the Galactic core collapse supernova rate (Keane & Kramer 2008).

### 4.3. *RRATs*

The missing link in an evolutionary scenario could be provided by the recently discovered Rotating Radio Transients (RRATs, McLaughlin *et al.* 2006): RRATs appear as transient radio sources (more than 11 are known at the moment) which show bursts with durations between 2 and 30 ms. The average interval between to events ranges from 4 min to 3 hr. While the signals are hence repeating, the total emission time is less than 1 s per day, suggesting that many more RRATs remain undiscovered in the Galaxy. Even though the signals arrive Poisson-distributed, underlying periods have been discovered, ranging from $P = 0.4$ s to $P = 6.9$ s (mean $= 3.5 \pm 0.8$ s). These periods and the detection that they increase with time lead to the identification of RRATs with rotating NSs. This was confirmed later when RRAT J1819−1458 was also discovered as an X-ray source which was modulated with the radio period of $P = 4.3$ s and which showed features of a young, cooling NS (McLaughlin *et al.* 2007). Moreover an also detected spectral feature may be interpreted as a cyclotron line, leading to $B \sim 10^{14}$ G which is consistent with the value derived from the source's spin-down properties, $B = 0.5 \times 10^{14}$ G. However, in order to proof the speculation that RRATs are the evolutionary link between radio pulsars and magnetars, magnetar-like high-energy bursts need to be detected. So far, this has not been possible, in particular since the position of most RRATs is yet too uncertain for an appropriate analysis.

## 5. Conclusions

Most young pulsars are heading across the top of the main distribution of radio pulsars in the $P - \dot{P}$-diagram. This begs the question how the crowded area in this diagram is populated. Either these young pulsars have no evolutionary link to the population of old pulsars (i.e. separate populations) or magnetic fields start to decay before $\tau \sim 100$ kyr. All young pulsars have $n < 3$, hence the effective magnetic fields increase with time while characteristic ages increase only slowly or even decrease with time As a result, the

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evolution of some young pulsars is consistent with travel to the $P-\dot{P}$-region occupied by magnetars (see also Lyne 2004). For $n=1$, the travel time from the current position to those of magnetars is about 10 kyr for the Crab pulsars. If that is the case, magnetars are much older than their characteristic ages indicate. This would also explain the relative paucity of SGR/AXP SNR associations and the large offset of SGRs from SNR centres, without invoking massive velocities. However, questions remain such as to whether there is a continuum of pulsars along the evolutionary tracks, or as to whether RRATs are an intermediate phase? It is clear that LOFAR and later the SKA surveys will solve this problem!

**Acknowledgements**

I would like to thank the organizers for a successful and enjoyable meeting.

## References

Breton, R. P. *et al.* 2008, *Science* 321, 104
Camilo, F. & Sarkissian, J. 2008, *The Astronomer's Telegram*, 1558
Camilo, F., Ransom, S. M., Halpern, J. P., Reynolds, J., Helfand, D. J., Zimmerman, N., & Sarkissian, J. 2006, *Nature* 442, 892
Camilo, F., Ransom, S. M., Halpern, J. P., & Reynolds, J. 2007, *ApJ* 666, L93
Duncan, R. C. & Thompson, C. 1992, *ApJ* 392, L9
Gonzalez, M. E., Kaspi, V. M., Camilo, F., Gaensler, B. M., & Pivovaroff, M. J. 2007, *Ap&SS* 308, 89
Halpern, J., Gotthelf, E., Reynolds, J., Ransom, S., & Camilo F. 2008, *ApJ* 676, 1178
Kaspi, V. 2007, *Ap&SS* 308, 1
Keane, E. & Kramer, M. 2008, *MNRAS* 391, 2009
Kramer, M., Lyne, A. G., O'Brien, J. T., Jordan, C. A., & Lorimer, D. R. 2006, *Science* 312, 549
Kramer, M., Stappers, B. W., Jessner, A., Lyne, A. G., & Jordan, C. A. 2007, MNRAS 377, 107
Lorimer, D. R. & Kramer, M. 2005, *Handbook of Pulsar Astronomy*, Cambridge University Press
Lyne, A. G. & Smith, F. G. 2005, *Pulsar Astronomy*, 3rd ed. Cambridge University Press, Cambridge
Lyne, A. G., 2004, in Camilo, F., Gaensler, B. M., eds, *Young Neutron Stars and Their Environments*, IAU Symposium 218, Astronomical Society of the Pacific, San Francisco, p. 257
McLaughlin, M. A. *et al.* 2003, *ApJ* 591, L135
McLaughlin, M. A. *et al.* 2006, *Nature* 439, 817
McLaughlin, M. A. *et al.* 2007, *ApJ* 670, 1307

## Discussion

Reich: If the apparent increase in **B**-field can also be interpreted as a change in $\alpha$, do you see changes in the profile of the Crab pulsar?

Kramer: No. We monitor the Crab now for 40 years and have looked carefully at possible profile changes. Apart from changes potentially caused by changing instrumentation, we have found no evidence for profile changes.

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