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The Neutron Star Zoo

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Abstract. Since their discovery 50 years ago, neutron stars have continually astonished. From the first-discovered radio pulsars to the powerful "magnetars" that emit sudden bursts of X-rays and γ-rays, from the so-called Isolated Neutron Stars to Central Compact Objects, observational manifestations of neutron stars are surprisingly varied, with most properties totally unpredicted. The challenge is to cement an overarching physical theory of neutron stars and their birth properties that can explain this great diversity. Here I briefly survey the disparate neutron star classes, describe their properties, highlight recent results, and describe efforts at "grand unification" of this wealth of observational phenomena.

Keywords. stars: neutron, (stars:) pulsars: general, X-rays: bursts, stars: magnetic fields

1. Introduction

At first thought, even 50 years post-discovery, neutron stars might be considered to be simple objects. As gravitationally collapsed objects with gravitational redshifts of tens of percent, they are close cousins of black holes, which are notoriously free of "hair." Yet as described in this brief review, neutron stars are by contrast rather hirsute. The variety of observational manifestations of neutron stars was certainly not predicted; indeed John Wheeler is reported as having been surprised, upon the discovery of the first radio pulsars, that neutron stars come with a "handle and a bell" (Manchester & Taylor 1977). One goal of broad studies of the neutron star population's diversity is to understand its origin given the limited number of potentially free parameters, such as mass, magnetic field, initial spin, geometry, composition, and age.

This is an observationally driven review in which the properties of the apparently distinct types of neutron stars are considered. The challenge is to identify similarities in phenomena among different types of sources, in the hope of elucidating common physical processes. Ultimately, when combined with detailed physical models (unconsidered here due to lack of space), we hope to constrain fundamental physics related to the behaviour of matter at ultra-high density and in the highest magnetic fields known in the Universe. Related but more in-depth reviews on this subject are by Kaspi (2010), Harding (2013), and Tauris *et al.* (2015). Note that this review considers exclusively non-accreting neutron stars that have been unaffected by binary evolution, i.e. not "recycled" by accretion from a binary companion. The latter are considered elsewhere in these proceedings.

2. Radio Pulsars

Radio pulsars, the cause célèbre of this conference, have as their defining observational properties regular radio pulsations, with typically narrow pulses having duty cycles of a few percent. This emission is generally stable when averaged over many (usually a few dozens to hundreds of) pulses, with differing amounts of pulse-to-pulse variability

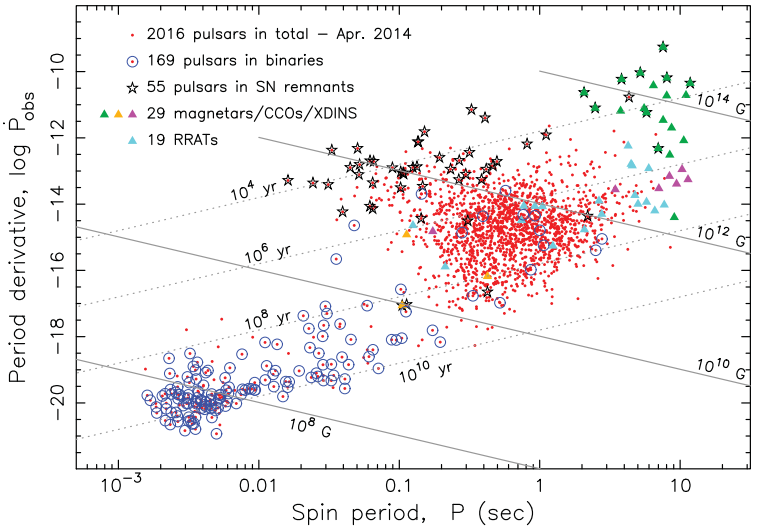

Figure 1. P-$\dot{P}$ diagram (from Tauris *et al.* 2015). Red points are the known radio pulsars; those circled in blue are binaries. Stars represent supernova remnant associations, and magnetars, CCOs and INSs (see following text) are represented by green, yellow and pink symbols, respectively. RRATs are shown in cyan. Lines of constant characteristic age are shown dashed, and lines of constant spin-inferred dipolar surface magnetic field strength are solid. See the online version for colour.

seen in different sources. Their pulse-averaged radio spectra are generally steep and non-thermal. Many are strongly linearly polarized, some circularly. Over 2500 radio pulsars are known today†. As a population they are concentrated in the Galactic plane and in spiral arms, unsurprising given their formation in the core-collapses of massive stars. However, the known population is likely a small fraction of the true one, and suffers from strong selection biases (e.g. Faucher-Giguère & Kaspi 2006, Bates *et al.* 2014).

The typical pulsar rotation period P is a few hundred milliseconds and all known radio pulsars are observed to be spinning down (i.e. $\dot{P} > 0$) once external factors, like acceleration in a binary or in the gravitational potential of a globular cluster, are accounted for. The only known exceptions to the spin-down rule are pulsar glitches, discussed in more detail elsewhere in these proceedings. Glitches are sudden spin anomalies, usually spin ups, seen usually in young pulsars, and are thought to be due to transfer of angular momentum from within the stellar interior.

Figure 1 shows a classic P-$\dot{P}$ diagram. The swarm of known sources is apparent in the few-hundred-millisecond range. The very short-period millisecond pulsars (discussed elsewhere in these proceedings) are believed to be recycled by a previous binary evolutionary phase. Lines of constant characteristic age, $P/2\dot{P}$, show that the typical radio pulsar is roughly 10^7-yr old, however pulsars of only $\sim 10^3$ yr are also known and often associated with observed supernova remnants. This supports the general reliability of characteristic ages as true age indicators. Lines of constant spin-inferred dipolar surface magnetic field strength, $B = 3.2 \times 10^{19}(P\dot{P})^{1/2}$ G, are also included, and show that the typical radio pulsar has field strength of $\sim 10^{12}$ G. Such field strengths have been independently observed in some accreting neutron stars (e.g. Coburn *et al.* 2002).

Radio pulsars, though most easily observed in the radio band, emit across the electromagnetic spectrum. Many dozen have been detected at X-ray energies, with two main

† See the online pulsar catalog at www.atnf.csiro.au/people/pulsar/psrcat/.

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types of emission seen. Thermal X-ray emission is characterized by broad pulses thought to emanate from the surface, and is subject to stong gravitational light bending. Non-thermal X-ray emission is from the magnetosphere and is beamed, resulting in generally narrow pulses (see, e.g. Kaspi, Roberts & Harding 2006 for a review). Dozens of pulsars have now been detected at γ-ray energies as well, with emission also being non-thermal (see review in these proceedings). All this electromagnetic emission is accompanied by a relativistic particle outflow that results in often spectacular "pulsar wind nebulae," of which the Crab Nebula is the most famous example.

Importantly, all the above emission, from the radio through the γ-ray, and including the pulsar wind, is powered ultimately by the pulsar's spin-down luminosity, that is, the rate of loss of its rotational kinetic energy, $\dot{E} = 4\pi^2 I \dot{P}/P^3$, where I is the stellar moment of inertia. One possible exception to this rule is thermal X-ray emission arising from initial stellar cooling following formation, which in principle need not be bounded by $\dot{E}$, though generally is, due to inherent faintness (but see below).

2.1. *Rotating Radio Transients*

One notable radio-emitting neutron star is the Rotating Radio Transient (RRAT; McLaughlin *et al.* 2006). RRAT emission is, in contrast to that of radio pulsars, highly sporadic, with one brief (typically few ms) pulse seen very occasionally (typically every few minutes to hours). However, in practically all observed RRATs, underlying short periodicities to the pulses have been seen, with periods similar to those of conventional radio pulsars (see Fig. 1). RRATs spin down with comparable $\dot{P}$s as well. This, and the fact that RRAT spectra appear similar to those of radio pulsars, strongly suggest that RRATs are a subset of radio pulsars with particularly strong pulse-to-pulse variability. Indeed some otherwise conventional radio pulsars show "mode changing" and/or "nulling" behaviour in which, respectively, the average pulse profile takes on more than one different form, or becomes temporarily undetectable over many rotations. RRAT emission could be an extreme form of nulling and not otherwise distinct. However, our knowledge of the RRAT population is sparse due to the greater challenge in finding them; only ∼120 are presently known†. Modern radio pulsar surveys now routinely also search for single dispersed pulses; foreseen large-scale searches for Fast Radio Bursts (as planned for the CHIME telescope; see Ng *et al.*, these proceedings) are also likely to find many RRATs.

3. Magnetars

Magnetars are the most volatile members of the neutron-star population, showing spectacular X-ray and soft γ-ray bursts (few hundred ms long) and outbursts (days to months). They exhibit relatively slow, few-second X-ray pulsations (see Fig. 1) and spin down regularly with $\dot{P}$s that imply, remarkably, magnetic fields of $10^{14} - 10^{15}$ G (see Fig. 2) and ages of a few $10^3 - 10^5$ yr. Several are found in supernova remnants. Crucially, magnetar emission, certainly in outburst but often in quiescence, has luminosity much higher than is available from spin-down. This is the reason an alternate energy source is needed; in the standard magnetar model (Thompson & Duncan 1995, 1996), active decay of a high internal magnetic field is the ultimate power supply.

Over two dozen magnetars are presently known‡. While magnetars were previously classified by apparent radiative activity into "Anomalous X-ray Pulsars (AXPs)" (less activity) and "Soft Gamma Repeaters (SGRs)" (more activity), today the line between

† See the "RRATalog" at http://astro.phys.wvu.edu/rratalog/.
‡ http://www.physics.mcgill.ca/ pulsar/magnetar/main.html

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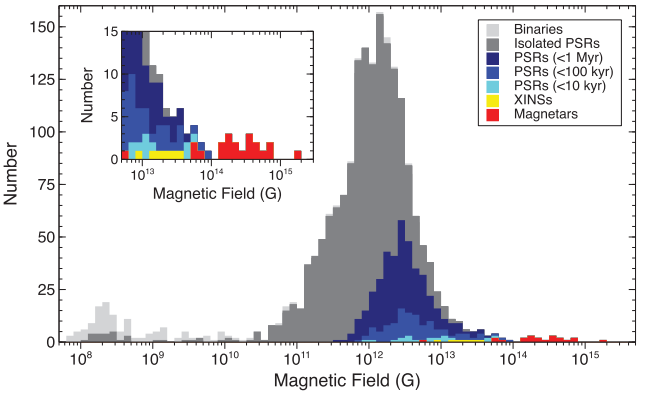

Figure 2. Histogram showing the distribution of magnetic field of all known radio pulsars, INSs, and magnetars for which P has been measured. Inset: Zoom-in on $B > 5 \times 10^{12}$ G, showing the relative locations of the INSs and magnetars more clearly. From Olausen & Kaspi (2014). See the online version for colour.

these two categories has grown blurry and these terms are used less and less. For recent, comprehensive reviews, see Turolla, Zane & Watts (2015) or Kaspi & Beloborodov (2017).

Magnetars share some interesting properties with radio pulsars beyond just their proximity on the P-$\dot{P}$ diagram. Magnetars' spatial distribution in the Galaxy is akin to that of the youngest radio pulsars, i.e. highly concentrated in the disk. Some sources having obvious magnetar properties have spin-inferred B fields that are clearly in the radio pulsar range (e.g. Rea *et al.* 2010). Magnetars occasionally exhibit radio pulsations (4 have been seen thus far; e.g. Camilo *et al.* 2006), albeit more strongly variable and with flatter spectra than in conventional radio pulsars. One magnetar, Swift J1834.9−0846, shows evidence for a wind nebula akin to those seen near energetic young pulsars (Younes *et al.* 2016). Finally, magnetars are very frequent glitchers, like young radio pulsars. However, in contrast to those in radio pulsars, magnetar glitches tend to be accompanied by radiative events, usually X-ray bursts or long-term flux enhancements. Moreover, magnetar glitches often have remarkable recoveries involving few-week periods of strongly enhanced spin-down and even effective over-recoveries (e.g. Dib & Kaspi 2014). Also, at least one anti-glitch has been observed in a magnetar (Archibald *et al.* 2013).

Magnetar X-ray spectra typically show three components: a thermal term with $kT \sim 0.3 - 0.6$ keV, a steep declining power-law below ∼10 keV, and a rising power law above ∼10 keV (e.g. Kuiper *et al.* 2006, Enoto *et al.* 2017). However, the "transient magnetars," which are very faint in quiescence but can have X-ray outbursts with flux increases of several orders of magnitude, appear to have softer, generally thermal spectra in quiescence, at least to the limit of detectability (e.g. Camero *et al.* 2014).

Transient magnetars thus raise several interesting questions: How many more quiescent transient magnetars are out there, hard to detect until they go into outburst? Why are apparently the majority of magnetars so faint in quiescence? Are transient magnetars in quiescence high-B radio pulsars? The fairly unbiased nature of all-sky X-ray monitors makes answering the first question a matter of time. That most are so faint in quiescence could be the norm, whereas the first-studied magnetars, far brighter in quiescence, could have abnormally high B fields. We discuss the third question next.

3.1. *High-Magnetic-Field Radio Pulsars*

If magnetars represent sources at the high-end of the neutron-star magnetic field distribution, it seems reasonable to expect magnetar-like emission from high-B radio pulsars

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Kaspi & McLaughlin (2005). This was suggested as being in the form of enhanced thermal emission, perhaps from active field decay, in young, high-B radio pulsars. Several studies have shown strong evidence for this; young, high-B radio pulsars appear to have higher blackbody temperatures relative to lower-B counterparts of the same age (e.g. Zhu *et al.* 2011). Indeed, the observed kTs of young, high-B radio pulsars are closer to those of transient magnetars in quiescence, suggesting a possible relationship.

Magnetar-like bursts and outbursts might also expected from high-B pulsars – and indeed have been observed. PSR J1846−0258 is a 0.4-s rotation-powered X-ray pulsar (albeit radio quiet) with $B = 5 \times 10^{13}$ G. In 2006 it underwent a brief metamorphosis to a magnetar-like state in which the X-ray flux abruptly rose, short magnetar-like bursts were emitted, and a large glitch occured (Gavriil *et al.* 2008). More recently, the 0.4-s radio pulsar PSR J1119−6127 also exhibited a large magnetar-like outburst (Archibald *et al.* 2016). These observations demonstrate unambiguously the link between magnetars and radio pulsars, with magnetic field being the likely factor determining observational properties. Theoretical studies that provide the physical underpinnings for this link support this conclusion (e.g. Perna & Pons 2011, Viganò *et al.* 2013).

4. Isolated Neutron Stars & Central Compact Objects

Two very sparsely populated "mini-classes" of neutron stars warrant attention. The "Isolated Neutron Stars (INSs),"† sometimes called "X-ray Dim INSs (XDINSs)," are relatively faint, nearby (<1 kpc) X-ray pulsars with few-second periods and spin-inferred B in the range $1 - 3 \times 10^{13}$ G (see Figs. 1 & 2) but thus far have shown no radio emission (e.g. see Turolla 2009). Currently it is thought these are off-beam radio pulsars that are particularly visible because of enhanced thermal emission due to a higher-than-typical B field. They may even be descendants of magnetars, although if so, the inferred large INS population could imply a large magnetar birth rate.

Meanwhile, the "Central Compact Objects (CCOs)"‡ are difficult to classify neutron stars that reside in centres of supernova remnants. CCOs are X-ray sources and show no evidence of radio emission. The most famous is the CCO in the young Casseopia-A supernova remnant; no pulsations have yet been seen from it (e.g. Heinke & Ho (2010)). Three other CCOs, in the young supernova remnants PKS 1209−52, Kes 79 and Puppis A, have had X-ray pulsations at a few hundred ms and relatively low spin-down rates detected; these imply surprisingly low B fields ($10^{10} - 10^{11}$ G) given their relatively high X-ray luminosities (e.g. Halpern & Gotthelf 2010, 2011). The latter remain unexplained. Also interesting is that the slow spin-down rates imply very long lives with time scales of several Gyr to reach typical pulsar death lines. That three are found in very young (< 2 kyr) remnants implies a very large (of order 10^6) population in the Galaxy, yet in the relevant region of the P-$\dot{P}$ diagram (Fig. 1), there is a dearth of radio pulsars. If any such CCO were shown to have radio pulsations, that would be problematic from a population standpoint. On the other hand, if they are physically unable to produce radio pulsations, that would also be mysterious. One remarkable CCO in supernova remnant RCW 103 shows a 6.7-hr X-ray periodicity of yet unknown origin as well as distinctly magnetar-like behaviour (D'Aì *et al.* 2016); it is discussed elsewhere in these proceedings.

In summary, the proliferation of apparently different types of isolated neutron stars is unpredicted and at first glance surprising. Although we have made great progress over

† A misleading name since most radio pulsars are also 'isolated' yet are not INSs.

‡ Also a misleading name since some radio pulsars are central to supernova remnants yet are not CCOs.

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the past several decades, there remain many open and interesting questions, including: Why are many magnetars so faint in quiescence? Do Isolated Neutron Stars and Central Compact Objects produce radio emission? These issues are addressed to varying degrees in these proceedings. One important limiting factor in solving outstanding questions is the paucity of known sources in most categories. However, in this regard, the future is bright, with many current and future surveys, notably in the radio and X-ray regimes, that should greatly increase the numbers of known neutron stars. We look forward to the next 50 years of neutron stars!

References

Archibald, R. F., Kaspi, V. M., Ng, C.-Y., Gourgouliatos, K. N., Tsang, D., Scholz, P., Bearmore, A. P., Gerels, N., & Kennea, J. A. 2013, *Nature*, 497, 591
Archibald, R. F., Kaspi, V. M., Tendulkar, S. P., & Scholz, P. 2016, *ApJ*, 829, L21
Bates, S. D., Lorimer, D. R., Rane, A., & Swiggum, J. 2014, *MNRAS*, 439, 2893
Camero, A. *et al.* 2014, *MNRAS*, 438, 3291
Camilo, F., Ransom, S. M., Halpern, J. P., Reynolds, J., Helfand, D. J., Zimmerman, N., & Sarkissian, J. 2006, *Nature*, 442, 892
Coburn, W. *et al.* 2002, *ApJ*, 580, 394
D'Aì, A., *et al.* 2016, *MNRAS*, 463, 2394
Dib, R. & Kaspi, V. M. 2014, *ApJ*, 784, 37
Enoto, T., Shibata, S., Kitaguchi, T. Suwa, Y., Uchide, T., Nishioka, H., Kisaka, S., Nakano, T., Murakami, H., Makishima, K. 2017 *ApJS*, 231, 8
Faucher-Giguère, C.-A. & Kaspi, V. M. 2006, *ApJ*, 643, 332
Gavriil, F. P., Gonzalez, M. E., Gotthelf, E. V., Kaspi, V. M., Livingstone, M. A., Woods, P. M. 2008 *Science*, 319, 1802
Halpern, J. P. & Gotthelf, E. V. 2010, *ApJ*, 709, 436
Halpern, J. P. & Gotthelf, E. V. 2011, *ApJ*, 733, L28
Harding, A. K. 2013, *Front. Phys.*, 8, 679
Heinke, C. O. & Ho, W. G. 2010, *APJ*, 719, L167
Kaspi, V. M. & Beloborodov, A. 2017, *ARAA*, 55, 261
Kaspi, V. M. & McLaughlin, M. A. 2005 *ApJ*, 618, L41
Kaspi, V. M. 2010, *PNAS*, 107, 7147
Kaspi, V. M, Roberts, M. S. E., & Harding, A. K. 2006, *Compact Stellar X-ray Sources*, Cambridge Astro. Ser., 39, 279
Kuiper, L, Hermsen, W., den Hartog, P. R., Collmar, W. 2006 *ApJ*, 645, 556
Manchester, R. N. & Taylor, J. H. 1977, *Pulsars*, Freeman, San Francisco
McLaughlin, M. A. *et al.* 2006, *Nature*, 439, 817
Olausen, S. A. & Kaspi, V. M. 2014, *ApJS*, 212, 6
Perna, R. & Pons, J. A. 2011 *ApJ*, 727, L51
Rea, N. *et al.* 2010 *Science*, 330, 944
Tauris, T. M. *et al.* 2015, *Proc. Adv. Astr. SKA*, 39
Thompson, C. & Duncan, R. 1995, *MNRAS*, 275, 255
Thompson, C. & Duncan, R. 1996, *ApJ*, 473, 322
Turolla, R. 2009, *Astr. Space Sci.*, 357, 141
Turolla, R., Zane, S. & Watts, A. L. 2015 *Rep. Prog. Phys.*, 78, 6901
Viganò, D., Rea, N., Pons, J., Perna, R., Aguilera, D., & Miralles, J. 2013, *MNRAS*, 434, 123
Younes, G. *et al.*, 2016 *ApJ*, 824, 138
Zhu, W. W., Kaspi, V. M., McLaughlin, M. A., Pavlov, G. G., Ng, C.-Y., Manchester, R. N, Gaensler, B. M., & Woods, P. M. 2011 *ApJ*, 734, 44

https://doi.org/10.1017/S1743921317010390 Published online by Cambridge University Press