SPECIAL FEATURE

Grand unification of neutron stars

Victoria M. Kaspi[1]

Department of Physics, McGill University, Montreal, QC, Canada H3A 2T8

Edited by Neta A. Bahcall, Princeton University, Princeton, NJ, and approved March 4, 2010 (received for review January 22, 2010)

The last decade has shown us that the observational properties of neutron stars are remarkably diverse. From magnetars to rotating radio transients, from radio pulsars to isolated neutron stars, from central compact objects to millisecond pulsars, observational manifestations of neutron stars are surprisingly varied, with most properties totally unpredicted. The challenge is to establish an overarching physical theory of neutron stars and their birth properties that can explain this great diversity. Here I survey the disparate neutron stars classes, describe their properties, and highlight results made possible by the Chandra X-Ray Observatory, in celebration of its 10th anniversary. Finally, I describe the current status of efforts at physical "grand unification" of this wealth of observational phenomena, and comment on possibilities for Chandra's next decade in this field.

pulsars: general | stars: neutron | x-rays: stars

ASTRONOMY

The *Chandra* era has seen the proliferation of a greater variety of possibly distinct observational classes of neutron star than ever before (not even including accreting sources, ignored in this review). With emission spanning the electromagnetic spectrum and radiative properties that span a huge fraction of conceivable phase space, such incredible range and diversity is not only unpredicted, but in many ways astonishing given the perhaps naively simple nature of the neutron star. Collapsed and close cousins to black holes, why should neutron stars exhibit so much "hair?" Indeed, the sheer number of different class names is confusing even within the field. We therefore begin by presenting an introductory census of the currently identified neutron zoo.

The classic young radio pulsars (PSRs) pulse regularly and predictably across the EM spectrum though generally are most observable in the radio band. The PSR prototype is often identified as the Crab pulsar, even though it is far from prototypical of the class, given its unparalleled energy output (10^{38} erg/s), and its magnificent nebula (see Fig. 1). The radio pulsar term is not observationally accurate for the class, as, for example, the Geminga pulsar has all the properties of a radio pulsar except observable radio emission, possibly but not certainly due to unfortunate beaming geometry (1). The term rotation-powered pulsar (RPP) is therefore more cautious and precise: These objects are powered by their loss of rotational energy due to braking by their magnetic fields.

Millisecond pulsars (MSPs), though also rotation powered, have different evolutionary histories, involving long-lived binary systems and a "recycling" accretion episode which spun up the neutron star and quenched its magnetic field (2). In this review, MSPs are a subclass of RPPs and have similar emission properties, although *Fermi* has recently shown that MSPs are surprisingly bright γ-ray sources, suggesting refinements to high-energy emission models are required (3).

The very recently discovered rotating radio transients (RRATs) (4) do not seem to produce observable periodic emission, the defining property of RPPs. Rather, they produce unpredictable sudden short radio bursts, which occur at integral multiples of an underlying periodicity. These may be a subclass of RPPs; this is discussed further below.

Radio emission was long thought to be the hallmark of the nonaccreting neutron star, Geminga notwithstanding. But several different subclasses of generally radio-quiet neutron star have emerged in the *Chandra* era. The isolated neutron stars (INSs; poorly named because most RPPs are also isolated but are not INSs) have as defining properties quasi-thermal x-ray emission with relatively low x-ray luminosity, great proximity, lack of radio counterpart, and relatively long periodicities ($P = 3$–11 s).

Then there are the "drama queens" of the neutron-star population: the magnetars. Magnetars have as their true defining properties occasional huge outbursts of x-rays and soft-gamma rays, as well as luminosities in quiescence that are generally orders of magnitude greater than their spin-down luminosities. Magnetars are thought to be young, isolated neutron stars powered ultimately by the decay of a very large magnetic field. At their worst, magnetars can briefly outshine all other cosmic soft-gamma-ray sources *combined* (5).

The above census would be incomplete without mention of the handful of x-ray bright compact central objects (CCOs), a likely heterogeneous class. They are so named because of their central location in supernova remnants (SNRs), and have otherwise, until very recently, baffling properties.

The challenge of the past decade was—and continues to be—to find a way to unify this variety into a coherent physical picture. What determines whether a neutron star will be born with, for example, magnetar-like properties or as a Crab-like pulsar? What are the branching ratios for the various varieties, and, given estimates of their lifetimes, how many of each are there in the galaxy? Ultimately such questions are fundamental to understanding the fate of massive stars, and the nature of core collapse, while simultaneously relating to a wider variety of interesting high-energy astrophysics, ranging from the equation-of-state of ultradense matter, to the physics of matter in ultrahigh magnetic fields. In this contribution, we review the above observationally defined classes, and consider the status of the progress toward grand unification of neutron stars into a coherent physical understanding of the births and evolution of these objects. Emerging as central to the picture are the stellar surface dipolar magnetic fields (estimated via $B = 3.2 \times 10^{19}(P\dot{P})^{1/2}$ G, where $\dot{P} = dP/dt$) and ages (estimated via the "characteristic age" $\tau \equiv P/2\dot{P}$). We show how observations at x-ray energies are essential to this work, and highlight, as much as space permits, some of the great contributions made by *Chandra* this past decade.

Rotation-Powered Pulsars

RPP rotation periods span the range of 1 ms through 8 s. Their magnetic field strengths range from 10^8 to 9×10^{13} G. Their distribution in P-$\dot{P}$ space is shown in Fig. 2. Those with $P \lesssim 20$ ms and $B \lesssim 10^{10}$ G are usually called MSPs. The x-ray emission from RPPs falls into two broad classes, both of which are generally pulsed and steady (see ref. 6 for a review). First is thermal emission, which itself can be a result of residual cooling following formation in a core-collapse supernova (typically only observable for the first $\sim 10^5$ years or from surface reheating by return currents from the magnetosphere, common for MSPs. Thermal emission has received considerable attention owing to its potential for use in constraining the equation-of-state of dense matter, by compar-

Author contributions: V.M.K. wrote the paper.

The author declares no conflict of interest.

This article is a PNAS Direct Submission.

[1]E-mail: vkaspi@physics.mcgill.ca.

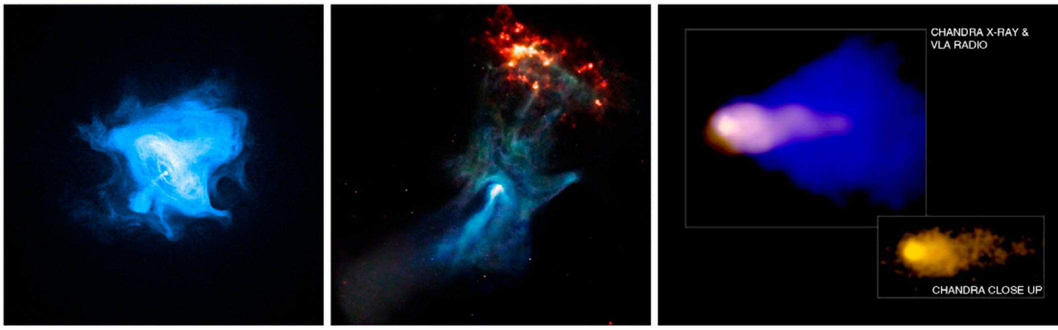

Fig. 1. Three examples of *Chandra*-observed pulsar wind nebulae. (*Left*) The Crab nebula (the image is 5′ across) with its clear toroidal morphology and jet structure (NASA/CXC/SAO/F. Seward et al.). (*Center*) The PSR B1509—58 pulsar wind nebula, nicknamed the "hand of God" (image is 20′ across; NASA/CXC/SAO/P.Slane, et al., Ng et al. in prep.). (*Right*) The "mouse" ram-pressure-confined pulsar wind nebula [1.2′ across; NASA/CXC/SAO/B.Gaensler et al. Radio: NSF/NRAO/VLA; (19)]. These images provide an indication of the variety of structures possible in PWNe.

ing temperatures and luminosities with theoretical cooling curves, accounting for the spectrally distorting impact of the neutron-star atmosphere and also by detailed modeling of x-ray light curves (e.g., ref. 7). For reviews see, for example, refs. 8 or 9. *Chandra* highlights in this area include the detection of a surprisingly low temperature for the pulsar in the young SNR 3C 58 (10), interesting constraints on the equation-of-state from modeling millisecond pulsar thermal emission light curves (7). Major open questions in this area are the nature and impact of the neutron-star atmosphere and whether thermal-emission observations can strongly constrain the equation-of-state of dense matter.

Second is nonthermal, usually power-law emission originating from the magnetosphere, typically more highly pulsed than the thermal component and strongly correlated with the pulsar's spin-down luminosity. The latter is defined as $\dot{E} \equiv 4\pi^2 I\dot{P}/P^3$ where I is the stellar moment of inertia. For a review of magnetospheric emission, see ref. 11, although thinking on this front is currently evolving thanks to recent interesting results from *Fermi* (3). *Chandra's* primary strength in this field is its small background and ability to resolve the point source from its nebular surroundings (see below), allowing superior spectral studies. Major open questions on this subject include how the emission is generated and how is it related to observed nonthermal γ-rays and radio emission.

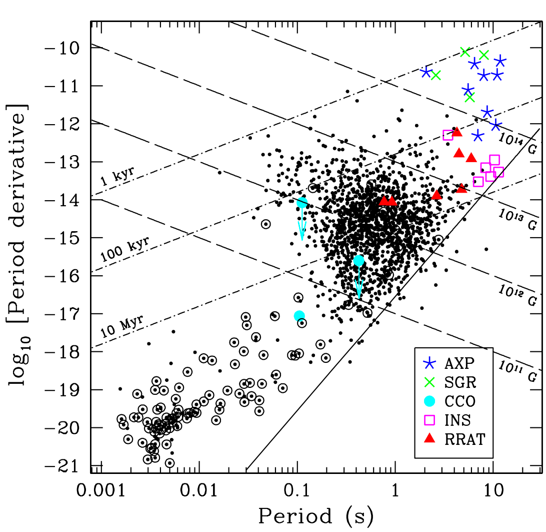

Fig. 2. *P*-$\dot{P}$ diagram for 1,704 objects, including 1674 RPPs (small black dots), 9 AXPs (blue crosses), 5 SGRs (green crosses), 3 CCOs (cyan circles), 6 INSs (magenta squares), and 7 RRATs (red triangles) for which these parameters have been measured. Open circles indicate binary systems. Data from the Australian Telescope National Facility Pulsar Catalog (www.atnf.csiro.au/research/pulsar/psrcat), the McGill SGR/AXP Online Catalog (www.physics.mcgill.ca/pulsar/magnetar/main.html), as well as from refs. 75 and 59. MSPs are RPPs having periods below ~20 ms. Lines of constant *B* (dashed) and τ (dot-dashed) are provided. The solid line is a model death line (see text).

Chandra's great angular resolution means it has been a superb tool for studying RPP surroundings, namely, pulsar wind nebulae (PWNe), the often spectacular result of the confinement of the relativistic pulsar wind by its environment (see ref. 12 for a review). Among *Chandra's* greatest PWN legacies are the discovery of rapid time variability in the Crab and Vela PWNe (see ref. 13 and references therein) as well as of the surprisingly diverse morphologies these objects can have (see Fig. 1 for examples and the aforementioned reviews for more). Detailed modeling of the geometries (14) and emission mechanisms (15) constrain both the properties of the pulsar wind and shock acceleration mechanisms. Important open questions here are the nature and composition of the pulsar wind, specifically whether it consists of only e^+/e^- pairs or also ions (e.g., ref. 16), what are the particle energy distributions, and what is the fraction of energy in particles versus magnetic fields? These have great relevance to our basic understanding of the neutron star as a rapidly rotating magnetic dipole converting rotational kinetic energy into such a powerful particle/field wind. The shock acceleration issues are interesting as well (e.g., ref. 17).

A subset of PWNe are the ram-pressure confined variety, showing bow-shock morphology that corresponds with the pulsar's direction of motion through the interstellar medium, e.g., refs. 18 and 19. An example is shown in Fig. 1. These are additionally useful as they provide independent determinations of directions of motion, which are often difficult to determine otherwise, especially for young pulsars. Notably, the first-known PWN around an MSP, a ram-pressure confined structure with morphology in clear agreement with the measured proper motion, was found by *Chandra*, demonstrating unambiguously that MSPs have winds that are similar to those of their slower cousins (20).

From a grand-unification perspective, the properties of RPPs can be seen as the template against which all other classes are compared. Thermal emission, for example, is seen from all the other classes discussed below, demonstrating that it is generic to neutron stars, except the very cool ones for which it is unobservable. By contrast, RPP-type magnetospheric emission is only observable in high spin-down luminosity sources, as are PWNe. When considering any new neutron-star class, in the absence of telltale pulsations, the spectrum is therefore crucial to consider (thermal or nonthermal?) as is the presence or absence of associated nebulosity. This will be a recurring theme in the rest of this paper.

Rotating Radio Transients

Recently, McLaughlin et al. (4) discovered brief radio bursts from galactic sources, but with no directly observed radio periodicities. The number of RRATs is now roughly a dozen and, in practically all cases, an underlying periodicity can be deduced thanks to the phase constancy of the bursts. At first thought to be possibly a truly unique class of neutron star, it now appears most likely that RRATs are just an extreme form of RPP, which have long been recognized as exhibiting sometimes very strong modulation of their radio pulses (21). Indeed several RRATs sit in unremarkable regions of the P-$\dot{P}$ diagram (Fig. 2). Interesting though is the mild evidence for higher-than-average periods and B fields among the RRATs than in the general population, though the numbers are small (Fig. 2). In *Chandra* observations of the relatively high-B RRAT J1819 – 1458 ($B = 5 \times 10^{13}$ G), the source had a thermal x-ray spectrum typical of RPPs of the same age, arguing against any radical physical difference (22). Recently, a small apparently associated PWN was seen in *Chandra* data. It has a somewhat surprisingly high luminosity (though subject to substantial uncertainties), suggesting the presence of a possible additional source of energy beyond rotation power (23). If correct, it would argue for RRATs being somehow physically distinct from RPPs.

Regardless of whether or not RRATs are substantially physically different from RPPs, their discovery is important because it suggests a very large population of neutron stars that were previously missed by radio surveys that looked only for periodicities. This has potentially major implications for the neutron-star birthrate (4, 24).

Magnetars

Magnetars, which traditionally are seen as falling into two classes, the anomalous x-ray pulsars (AXPs) and the soft-gamma repeaters (SGRs), have been studied with practically every modern x-ray telescope, and *Chandra* is no exception. Today these long-P objects are thought to be powered by an intense magnetic field (25, 26), inferred via spin down to be in the range 10^{14}–10^{15} G (see Fig. 2), well above the so-called quantum critical field $B_{\mathrm{QED}} \equiv m_e^2 c^3/\hbar e = 4.4 \times 10^{13}$ G (where QED stands for quantum electrodynamics). For a review of magnetars, see ref. 27. Magnetars have been argued to represent at most ~10% of the neutron-star population, in part because of their apparent association with very massive progenitors, as very strongly demonstrated by the *Chandra* discovery of an AXP in the massive star cluster Westerlund 1 (28). However the discovery of the transient AXP XTE J1810–197 (29) suggests there could be a large, unseen population of quiescent magnetars, which would have important implications for understanding the formation of different types of neutron stars.

Chandra's strengths for magnetar observations have been its spectral resolution, allowing searches for spectral features (none have been found; see refs. 30 and 31), and its angular resolution for searching for associated nebulae (none have been seen, with one possible exception; see ref. 32), and in some cases searching for a proper motion (none have been detected; see refs. 33 and 34). More fruitfully, *Chandra* has provided precise localizations for magnetars, crucial for multiwavelength follow up (e.g., refs. 29 and 35). In addition, *Chandra's* superior viewing windows relative to *XMM* have allowed rapid target-of-opportunity (ToO) observations in response to magnetar outbursts, as triggered, for example, by *RXTE* monitoring. The latter telescope, with its excellent scheduling agility, is ideal for regular snapshot monitoring of magnetars, especially the generally bright AXPs (36–40). However, *RXTE* provides only pulsed fluxes above 2 keV, and spectroscopy of very limited quality in these short observations, hence the need for occasional high-sensitivity focusing telescope observations. For example, *Chandra* ToO observations of AXP 1E 1048.1–5937 revealed a clear correlation between pulsed fraction and flux as well as hardness and flux (see also ref. 41) during the relaxation following this source's 2007 outburst. Such studies constrain models of magnetar outbursts, generally confirming the "twisted magnetosphere" picture (42, 43). Understanding the physics of magnetar outbursts is important not just for studying the behavior of matter in quantum critical magnetic fields, but also for constraining the burst recurrence rate, which is important for constraining the number of magnetars in the Galaxy. *Chandra's* excellent point-source sensitivity has also been important for studying transient magnetars in quiescence (44), showing that they can have a huge dynamic range in flux and be very faint in quiescence, which further emphasizes the possibly large unseen population of quiescent magnetars, important for determining the magnetar birthrate (e.g., ref. 24).

High-B Rotation-Powered Pulsars

A potentially pivotal class of objects are the high-B RPPs. There are now 7 RPPs (including one RRAT, J1819–1458) that have spin down inferred $B > 4 \times 10^{13}$ G, a somewhat arbitrary limit but comparable to B_{QED}, and very close to the lowest B field yet seen in a bona fide magnetar (6×10^{13} G in AXP 1E 2259+586). There is clear overlap between high-B RPPs and magnetars, as is evident in the P-$\dot{P}$ diagram (Fig. 2). There have been multiple efforts to look for magnetar-like emission from high-B RPPs (45–50). The bottom line thus far is that, in spite of very similar spin parameters, the high-B RPPs show x-ray properties that are approximately consistent within uncertainties with those of lower-B RPPs of comparable age (but see ref. 49), though also consistent with spectra of transient magnetars in quiescence (48). The latter point suggested that high-B RPPs could be quiescent magnetars. The radio detections of two transient magnetars lend some support to this idea, although in those cases the radio emission appears temporarily following an outburst, and the radio spectra are distinctly harder than those of most RPPs (51, 52).

Recently, a major breakthrough occurred. The well-established young, high-B ($B = 4 \times 10^{13}$ G) RPP PSR J1846–0258 at the center of the SNR Kes 75 exhibited a sudden, few-week x-ray outburst in 2006, as detected by *RXTE* monitoring (53). The outburst included a large pulsed flux enhancement, magnetar-like x-ray bursts (53), and, intriguingly, a coincidental unusual spin-up glitch (54). This source had been monitored regularly with *RXTE* since 1999 (55) and had shown no other activity. *Chandra* had observed this source twice: once in 2000 when the RPP was in its usual state and, by amazing coincidence, once in 2006, in the few-week period of activity. These *Chandra* observations showed that the RPP x-ray spectrum softened significantly, with a thermal component emerging from a previously purely power-law spectrum, and that the associated PWN showed likely changes too, though possibly unassociated with the event (53, 56, 57). Overall, this event demonstrates unambiguously a connection between high-B RPPs and magnetars, further supporting the possibility that high-B RPPs could in general be quiescent magnetars, as speculated in ref. 48.

Isolated Neutron Stars

The seven confirmed INSs are characterized, as mentioned earlier, by quasi-thermal x-ray spectra, relative proximity (distances $\lesssim$500 pc), lack of radio or other counterpart, and relatively long spin periods (3–11 s). For past reviews of INSs, see refs. 58, 59. Recently, another possible example of INS was identified, in part thanks to *Chandra* (60, 61). These objects are potentially very interesting for constraining the unknown equation-of-state (EOS) of dense matter, because proper modeling of their x-ray spectra, which are thought to be uncontaminated by magnetospheric processes, could constrain the stellar masses and radii for comparison with different EOS models. Also, INSs may represent an interestingly large fraction of all galactic neutron stars (24). Timing observations of several objects, done in part by *Chandra*, have revealed that they are spinning down regularly, with inferred dipolar surface magnetic fields of typically ~ 1–3×10^{13} G (59, 62) and characteristic ages of ~ 1–4 Myr (see Fig. 2). Such fields are somewhat higher than the typical RPP field. This raises the interesting question of why the closest neutron stars should have preferentially higher B fields.

The favored explanation for INS properties is that they are actually RPPs viewed well off from the radio beam. Their x-ray luminosities are thought to be from initial cooling and they are much less luminous than younger thermally cooling RPPs because of their much larger ages. However, their luminosities are too large for conventional cooling, which suggests an additional source of heating, such as magnetic field decay, which may explain their surprisingly high magnetic fields (discussed further below).

Particularly noteworthy in the INSs are puzzling broad and occasionally time-variable absorption features in their x-ray spectra (63–66). The *Chandra* low-energy transmission grating has contributed significantly to this work (which is also being done using the *XMM* reflection grating spectrometer). The features have been suggested to be proton cyclotron lines, neutral hydrogen transitions, but the time variability is puzzling, suggesting precession (67) or accretion episodes (65). This remains an open issue.

Central Compact Objects

CCOs are neutron-star-like objects at the centers of supernova remnants, but which have puzzling properties which have at some point precluded them from being classified among one of the classes discussed above. Common properties to CCOs are absence both of associated nebulae and of counterparts at other wavelengths.

The poster-child CCO, discovered in the *Chandra* first-light observation, is the central object in the young oxygen-rich supernova remnant Cas A. This mysterious object has been very well studied, especially with *Chandra*. Particularly puzzling is its lack of x-ray periodicity, lack of associated nebulosity, and unusual x-ray spectrum (68–71). Recently, Ho and Heinke (72) suggested that the Cas A CCO has a carbon atmosphere, showing that its *Chandra*-observed spectrum is fit well by such a model, and implies a stellar radius consistent with expectations for a neutron star, in contrast to hydrogen or helium atmosphere models. With the entire surface radiating, the absence of pulsations would not be surprising.

Three other previously mysterious sources classified as CCOs are today, thanks largely to *Chandra*, known to be pulsars with interesting properties. PSR J1852 + 0040 is at the center of the SNR Kes 79 (73, 74). This pulsar, observed only in x-rays, has period 105 ms yet very small spin-down-inferred magnetic field strength, $B = 3.1 \times 10^{10}$ G and large characteristic age, $\tau =$ 192 Myr (75). This age is many orders of magnitude larger than the SNR age, and much older than would be expected for an object of this x-ray luminosity (which greatly exceeds the spin-down luminosity). The B value is also the smallest yet seen in young neutron stars, prompting Halpern and Gotthelf (75) to call this an "antimagnetar." Interestingly, the object sits in a sparsely populated region of the P-$\dot{P}$ diagram (Fig. 2), among mostly recycled binary pulsars. A similar case is the CCO in the SNR PKS 1209–52, 1E 1207.4–5209. Discovered in *ROSAT* observations (76), pulsations were detected at 0.4 s in *Chandra* data (77, 78). Spectral absorption features were seen using *Chandra* (79) and *XMM* (80) but as of yet are not well explained. Interestingly, the source has an unusually small (as yet undetectable) period derivative, implying $B < 3.3 \times 10^{11}$ G and $\tau > 27$ Myr, again, orders of magnitude greater than the SNR age and inconsistent with so large an x-ray luminosity (81). Yet another such low-B CCO is RX J0822–4300 in Puppis A (82). Although its properties are not as well constrained ($B < 9.8 \times 10^{11}$ G), it seems likely to be of similar ilk. Halpern and Gotthelf (75) present a synopsis of other sources they classify as CCOs and argue that these antimagnetars are x-ray bright thanks to residual thermal cooling following formation, with the neutron star having been born spinning slowly (consistent with some recent population synthesis studies, e.g., ref. 83) and with low B. In this case, the origin of the nonuniformity of the surface thermal emission remains puzzling.

Arguably the most bizarre CCO is 1E 161348–5055 in SNR RCW 103. Discovered with *Einstein* (84), this CCO showed no pulsations or a counterpart at other wavelengths. Unusually large variability was reported a decade ago (85) and, more recently, a strong 6.6-h periodicity was seen from the source in an *XMM* observation (86). No infrared counterpart has been detected in spite of deep observations enabled by a precise *Chandra* position (87). The nature of this source is currently unknown, with suggestions ranging from an unusual binary (88, 89) to a neutron star and a fallback disk (90).

Attempts at Unification

In spite of the obviously great diversity in young neutron-star observational x-ray properties, some interesting ideas for grand unification are emerging. A theory of magnetothermal evolution in neutron stars has recently been developed in a series of papers (91–94). Motivated largely by an apparent correlation between inferred B field and surface temperature in a wide range of neutron stars, including RPPs, INSs, and magnetars (91) (but see ref. 50), a model has recently been developed in which thermal evolution and magnetic field decay are inseparable. Temperature affects crustal electrical resistivity, which in turn affects magnetic field evolution, while the decay of the field can produce heat that then affects the temperature evolution. In this model, neutron stars born with large magnetic fields ($>5 \times 10^{13}$ G) show significant field decay, which keeps them hotter longer. The magnetars are the highest B sources in this picture, consistent with observationally inferred fields; the puzzling fact that INSs, in spite of their great proximity, all appear to have high inferred Bs relative to the RPP population is explained nicely as the highest B sources remain hottest, hence most easily detected, longest. A recent attempt at population synthesis modeling of RPPs, INSs, and magnetars using the magnetothermal evolutionary models (95) followed closely a previous analysis of RPPs (83) but found that the populations of RPPs, INSs, and magnetars (though they admit the latter two classes are few in number) can be explained if the birth magnetic field distribution of nascent neutron stars has mean B of $10^{13.25}$ G. This is significantly higher than has been previously thought (83).

If this unification picture is correct, then RPPs, INSs, and magnetars can be roughly understood as having such disparate properties simply because of their different birth magnetic fields and their present ages. Unifying further, RRATs are likely just an extreme form of RPP, with MSPs being binary-recycled RPPs with quenched B fields, as has been believed for many years (2).

The low-B CCOs could be understood in the above picture as being the lowest birth B neutron stars, x-ray bright only because of their true young ages, which are much smaller than their characteristic ages (75). This however presents an interesting quandary. The Kes 79 pulsar (see above) with its small $B = 3.1 \times 10^{10}$ G spins down very slowly. It is widely believed that RPPs, as they spin down, eventually cross a "death line" beyond which their radio emission shuts off, in keeping with the absence of pulsars at long P and small $\dot{P}$ in the P-$\dot{P}$ diagram (Fig. 2). There have been many theory-motivated suggestions for the exact location of the death line which is highly constrained by observations; one possibility is shown in Fig. 2 and is given by $B/P^2 = 0.17 \times 10^{12}$ Gs^{-2} (see ref. 83 and references therein). For the Kes 79 pulsar, in the absence of B-field decay (reasonable for so low a field in the magnetothermal evolutionary model) and assuming dipolar spin down, it will have $P \sim 0.43$ s at death, which will occur in

~3 Gyr. Assuming the other CCOs have similar properties, and noting that their parent SNRs all have ages $\lesssim 7$ kyr, we estimate a birthrate of such low-B objects of ∼0.0004 yr^{-1}. For this birthrate and estimated lifetime, we expect to find $\gtrsim 1 \times 10^6$ of these objects in the galaxy! This is comparable to, or greater than, the expected number of higher-B sources, which though born more often, do not live as long. Yet—and here is the quandary—the Kes 79 pulsar sits in a greatly *underpopulated* region of the P-$\dot{P}$ diagram (see Fig. 2). Selection effects cannot explain this lack of pulsars; only preferentially low radio luminosities could. The latter is consistent with models in which radio luminosity depends on spin-down parameters, as opposed to being only dependent on viewing geometry (see ref. 83).

Next Chandra Decade

There is no shortage of ideas for future tests of the above theory of neutron-star grand unification, and *Chandra* is likely to play a major role. The high-B RPPs are a crossroads class. X-ray observations of these objects, both deep to determine precise spectra and fluxes for comparison with the predictions of magnetothermal evolutionary models, as well as shallow monitoring to permit searches for magnetar-like variations, could be helpful. ToO observations of high-B RPPs at glitch epochs could reveal generic associated magnetar-like behavior, which would be a major breakthrough in our understanding of glitches and, possibly, neutron-star structure (40). Continuing ToO observations of magnetars in outburst will continue to constrain detailed models of magnetars and help understand crucial parameters like outburst recurrence rate, central to understanding how many magnetars there are in the galaxy, hence their birthrate. Continued monitoring of INSs, both to study their intriguing spectra and their variations, as well as their timing properties, is also important. Systematic timing and spectral studies of newly discovered members of any of the classes discussed in this review, particularly CCOs, are clearly very important for making progress, given the paucity of sources in most of the classes. With so many possibilities, the future of this field is very bright. I look forward with high hopes to reading the next *Chandra* decade's neutron-star review.

ACKNOWLEDGMENTS. The author thanks the *Chandra* staff for their dedication, tirelessness, and extreme competence, and acknowledges use of the Australian Telescope National Facility Pulsar Catalog, the McGill AXP/SGR Online Catalog, and thanks Dr. C.-Y. (Stephen) Ng for comments on this paper. The author is grateful for support from the Lorne Trottier Chair in Astrophysics and Cosmology, from a Canada Research Chair, as well as from Natural Sciences and Engineering Research Council of Canada, Le Fonds quebecois de la recherche sur la nature et les technologies, and Canadian Institute for Advanced Research.

1. Halpern JP, Holt SS (1992) Discovery of soft x-ray pulsations from the γ-ray source Geminga. *Nature* 357:222–224.
2. Bhattacharya D, van den Heuvel EPJ (1991) Formation and evolution of binary and millisecond radio pulsars. *Phys Rep* 203:1–124.
3. Abdo AA, et al. (2009) A population of gamma-ray millisecond pulsars seen with the Fermi large area telescope. *Science* 325:848–852.
4. McLaughlin MA, et al. (2006) Transient radio bursts from rotating neutron stars. *Nature* 439:817–820.
5. Hurley K, et al. (2005) An exceptionally bright flare from SGR 1806-20 and the origins of short-duration γ-ray bursts. *Nature* 434:1098–1103.
6. Kaspi VM, Roberts MSE, Harding AK (2006) *Compact Stellar X-ray Sources*, eds WHG Lewin and M van der Klis (Cambridge Univ Press, Cambridge, UK), pp 279–340.
7. Bogdanov S, Grindlay JE, Rybicki GB (2008) Thermal x-rays from millisecond pulsars: Constraining the fundamental properties of neutron stars. *Astrophys J* 689:407–415.
8. Yakovlev DG, Pethick CJ (2004) Neutron star cooling. *Annu Rev Astron Astr* 42:169–210.
9. Zavlin VE (2007) Thermal emission from isolated neutron stars: theoretical and observational aspects. *Astrophys Space Sci* 357:181–209.
10. Slane P, Helfand DJ, Murray SS (2002) New constraints on neutron star cooling from Chandra observations of 3C 58. *Astrophys J Lett* 571:L45–L49.
11. Harding A (2009) Pulsar high-energy emission from the polar cap and slot gap. *Astrophys Space Sci* 357:521–542.
12. Gaensler BM, Slane PO (2006) The evolution and structure of pulsar wind nebulae. *Annu Rev Astron Astr* 44:17.
13. Weisskopf MC, Karovska M, Pavlov GG, Zavlin VE, Clarke T (2007) Chandra observations of neutron stars: An overview. *Astrophys Space Sci* 308:151–160.
14. Ng C, Romani RW (2008) Fitting pulsar wind Tori. II. Error analysis and applications. *Astrophys J* 673:411–417.
15. Bucciantini N (2008) Modeling pulsar wind nebulae. *Adv Space Res* 41:491–502.
16. Amato E, Arons J (2006) Heating and nonthermal particle acceleration in relativistic, transverse magnetosonic shock waves in proton-electron-positron plasmas. *Astrophys J* 653:325–338.
17. Sironi L, Spitkovsky A (2009) Particle acceleration in relativistic magnetized collisionless pair shocks: Dependence of shock acceleration on magnetic obliquity. *Astrophys J* 698:1523–1549.
18. Kaspi VM, Gotthelf EV, Gaensler BM, Lyutikov M (2001) X-ray detection of pulsar PSR B1757-24 and its nebular tail. *Astrophys J Lett* 562:L163–L166.
19. Gaensler BM, et al. (2004) The mouse that soared: High-resolution x-ray imaging of the pulsar-powered bow shock G359.23-0.82. *Astrophys J* 616:383–402.
20. Stappers BW, Gaensler BM, Kaspi VM, van der Klis M, Lewin WHG (2003) An x-ray nebula associated with the millisecond pulsar b1957 + 20. *Science* 299:1372–1374.
21. Weltevrede P, Stappers BW, Rankin JM, Wright GAE (2006) Is Pulsar B0656 + 14 a very nearby rotating radio transient?. *Astrophys J* 645:L149–L152.
22. Reynolds SP, et al. (2006) Discovery of the x-ray counterpart to the rotating radio transient J1819-1458. *Astrophys J* 639:L71–L74.
23. Rea N, et al. (2009) Discovery of extended x-ray emission around the highly magnetic RRAT J1819-1458. *Astrophys J* 703:L41–L45.
24. Keane EF, Kramer M (2008) On the birthrates of Galactic neutron stars. *Mon Not R Astron Soc* 391:2009–2016.
25. Thompson C, Duncan RC (1995) The soft gamma repeaters as very strongly magnetized neutron stars—i. Radiative mechanism for outbursts. *Mon Not R Astron Soc* 275:255–300.
26. Thompson C, Duncan RC (1996) The soft gamma repeaters as very strongly magnetized neutron stars. ii. Quiescent neutrino, x-ray, and alfven wave emission. *Astrophys J* 473:322–342.
27. Woods PM, Thompson C (2006) *Compact Stellar X-Ray Sources*, eds WHG Lewin and M van der Klis (Cambridge Univ Press, Cambridge, UK), pp 547–586.
28. Muno MP, et al. (2006) A neutron star with a massive progenitor in Westerlund 1. *Astrophys J* 636:L41–L44.
29. Ibrahim AI, et al. (2004) Discovery of a transient magnetar: XTE J1810-197. *Astrophys J* 609:L21–L24.
30. Patel SK, et al. (2001) Chandra observations of the anomalous x-ray pulsar 1E 2259 + 586. *Astrophys J* 563:L45–L48.
31. Juett AM, Marshall HL, Chakrabarty D, Schulz NS (2002) Chandra high-resolution spectrum of the anomalous x-ray pulsar 4U 0142 + 61. *Astrophys J* 568:L31–L34.
32. Vink J, Bamba A (2009) The discovery of a pulsar wind nebula around the magnetar candidate AXP 1E1547.0-5408. *Astrophys J* 707:L148–L152.
33. DeLuca A, Caraveo PA, Esposito P, Hurley K (2009) Chandra astrometry sets a tight upper limit to the proper motion of SGR 1900 + 14. *Astrophys J* 692:158–161.
34. Kaplan DL, Chatterjee S, Hales CA, Gaensler BM, Slane PO (2009) Constraining the proper motions of two magnetars. *Astron J* 137:354–366.
35. Wachter S, et al. (2004) Precise localization of the soft gamma repeater SGR 1627-41 and the anomalous x-ray pulsar AXP 1E1841-045 with Chandra. *Astrophys J* 615:887–896.
36. Kaspi VM, Chakrabarty D, Steinberger J (1999) Phase-coherent timing of two anomalous x-ray pulsars. *Astrophys J* 525:L33–L36.
37. Kaspi VM, Gavriil FP, Chakrabarty D, Lackey JR, Muno MP (2001) Long-term RXTE monitoring of the anomalous x-ray pulsar 1e 1048.1-5973. *Astrophys J* 558:253–262.
38. Gavriil FP, Kaspi VM (2002) Long-term rossi x-ray timing explorer monitoring of anomalous x-ray pulsars. *Astrophys J* 567:1067–1076.
39. Dib R, Kaspi VM, Gavriil FP (2007) 10 years of rxte monitoring of anomalous x-ray pulsar 4U 0142 + 61: Long-term variability. *Astrophys J* 666:1152–1164.
40. Dib R, Kaspi VM, Gavriil FP (2008) Glitches in anomalous x-ray pulsars. *Astrophys J* 673:1044–1061.
41. Tiengo A, et al. (2005) Three XMM-Newton observations of the anomalous x-ray pulsar 1E 1048.1-5937: Long term variations in spectrum and pulsed fraction. *Astron Astrophys* 437:997–1005.
42. Thompson C, Lyutikov M, Kulkarni SR (2002) Electrodynamics of magnetars: Implications for the persistent x-ray emission and spin-down of the soft gamma repeaters and anomalous x-ray pulsars. *Astrophys J* 574:332–355.
43. Thompson C, Beloborodov AM (2005) High-energy emission from magnetars. *Astrophys J* 634:565–569.
44. Tam CR, Kaspi VM, Gaensler BM, Gotthelf EV (2006) Chandra monitoring of the candidate anomalous x-ray pulsar AX J1845.0-0258. *Astrophys J* 652:548–553.
45. Pivovaroff M, Kaspi VM, Camilo F (2000) X-ray observations of the high magnetic field radio pulsar PSR J1814-1744. *Astrophys J* 535:379–384.
46. McLaughlin MA, et al. (2003) PSR J1847-0130: A radio pulsar with magnetar spin characteristics. *Astrophys J* 591:L135–L138.
47. Gonzalez ME, Kaspi VM, Lyne AG, Pivovaroff MJ (2004) An XMM-Newton observation of the high magnetic field radio pulsar PSR B0154 + 61. *Astrophys J* 610:L37–L40.
48. Kaspi VM, McLaughlin MA (2005) Chandra x-ray detection of the high-magnetic-field radio pulsar PSR J1718-3718. *Astrophys J* 618:L41–L44.
49. Gonzalez ME, Kaspi VM, Camilo F, Gaensler BM, Pivovaroff MJ (2005) Unusual pulsed x-ray emission from the young, high magnetic field pulsar PSR J1119-6127. *Astrophys J* 630:489–494.

50. Zhu W, Kaspi VM, Gonzalez ME, Lyne AG (2009) Xmm-Newton X-ray detection of the high-magnetic-field radio pulsar PSR B1916 + 14. *Astrophys J* 704:1321–1326.
51. Camilo F, et al. (2006) Transient pulsed radio emission from a magnetar. *Nature* 442:892–895.
52. Camilo F, Ransom SM, Halpern JP, Reynolds J (2007) 1E 1547.0-5408: A radio-emitting magnetar with a rotation period of 2 seconds. *Astrophys J* 666:L93–L96.
53. Gavriil FP, et al. (2008) Magnetar-Like Emission from the Young Pulsar in Kes 75. *Science* 319:1802.
54. Livingstone MA, Kaspi VM, Gavriil FP (2010) Timing behavior of the magnetically active rotation-powered pulsar in the supernova remnant Kestevan 75. *Astrophys J* 710:1710–1717.
55. Livingstone MA, Kaspi VM, Gotthelf EV, Kuiper L (2006) A braking index for the young, high magnetic field, rotation-powered pulsar in Kesteven 75. *Astrophys J* 647:1286–1292.
56. Kumar HS, Safi-Harb S (2008) Variability of the high magnetic field x-ray pulsar PSR J1846-0258 associated with the supernova remnant Kes 75 as revealed by the Chandra X-Ray Observatory. *Astrophys J* 678:L43–L46.
57. Ng C, Slane PO, Gaensler BM, Hughes JP (2008) Deep Chandra observation of the pulsar wind nebula powered by pulsar PSR J1846-0258 in the supernova remnant Kes 75. *Astrophys J* 686:508–519.
58. Haberl F (2007) The magnificent seven: Magnetic fields and surface temperature distributions. *Astrophys Space Sci* 181–190.
59. Kaplan DL, van Kerkwijk MH (2009) Constraining the spin-down of the nearby isolated neutron star RX J0806.4-4123, and implications for the population of nearby neutron stars. *Astrophys J* 705:798–808.
60. Rutledge RE, Fox DB, Shevchuk AH (2008) Discovery of an Isolated compact object at high galactic latitude. *Astrophys J* 672:1137–1143.
61. Shevchuk ASH, Fox DB, Rutledge RE (2009) Chandra observations of 1RXS J141256.0 + 792204 (Calvera). *Astrophys J* 705:391–397.
62. Kaplan DL, van Kerkwijk MH (2005) A coherent timing solution for the nearby isolated neutron star RX J1308.6 + 2127/RBS 1223. *Astrophys J* 635:L65–L68.
63. Haberl F, Zavlin VE, Trüper J, Burwitz V (2004) A phase-dependent absorption line in the spectrum of the x-ray pulsar RX j0720.4-3125. *Astron Astrophys* 419:1077–1085 arXiv: astro-ph/0312413.
64. Zane S, et al. (2005) XMM-Newton detection of pulsations and a spectral feature in the x-ray emission of the isolated neutron star 1RXS J214303.7 + 065419/RBS 1774. *Astrophys J* 627:397–403.
65. van Kerkwijk MH, Kaplan DL, Pavlov GG, Mori K (2007) Spectral and rotational changes in the isolated neutron star RX J0720.4-3125. *Astrophys J* 659:L149–L152.
66. Hambaryan V, Neuhäuser R, Haberl F, Hohle MM, Schwope AD (2009) XMM-Newton RGS spectrum of RX J0720.4-3125: An absorption feature at 0.57 keV. *Astron Astrophys* 497:L9–L12.
67. Haberl F, et al. (2006) Evidence for precession of the isolated neutron star RX J0720.4-3125. *Astron Astrophys* 451:L17–L21.
68. Pavlov GG, Zavlin VE, Aschenbach B, Truemper J, Sanwal D (1999) The compact central object in Cas A: A neutron star with hot polar caps or a black hole?. *Astrophys J* 531: L53–L56.
69. Chakrabarty D, Pivovaroff MJ, Hernquist LE, Heyl JS, Narayan R (2001) The central x-ray point source in Cassiopeia A. *Astrophys J* 548:800–810.
70. Mereghetti S, Tiengo A, Israel GL (2002) The x-ray source at the center of the Cassiopeia A supernova remnant. *Astrophys J* 569:275–279.
71. Pavlov GG, Luna GJM (2009) A Dedicated Chandra ACIS observation of the central compact object in the Cassiopeia A supernova remnant. *Astrophys J* 703:910–921.
72. Ho WCG, Heinke CO (2009) A neutron star with a carbon atmosphere in the Cassiopeia A supernova remnant. *Nature* 462:71–73.
73. Gotthelf EV, Halpern JP, Seward FD (2005) Discovery of a 105 ms x-ray pulsar in Kesteven 79: On the nature of compact central objects in supernova remnants. *Astrophys J* 627:390–396.
74. Halpern JP, Gotthelf EV, Camilo F, Seward FD (2007) X-ray timing of PSR J1852 + 0040 in Kesteven 79: Evidence of neutron stars weakly magnetized at birth. *Astrophys J* 665:1304–1310.
75. Halpern JP, Gotthelf EV (2010) Spin-down measurement of PSR J1852 + 0040 in Kesteven 79: Central compact objects as anti-magnetars. *Astrophys J* 709:436–446.
76. Helfand DJ, Becker RH (1984) Observation of stellar remnants from recent supernovae. *Nature* 307:215–221.
77. Zavlin VE, Pavlov GG, Sanwal D, Trümper J (2000) Discovery of 424 millisecond pulsations from the radio-quiet neutron star in the supernova remnant PKS 1209-51/52. *Astrophys J* 540:L25–L28.
78. Pavlov GG, Zavlin VE, Sanwal D, Trümper J (2002) 1E 1207.4-5209: The puzzling pulsar at the center of the supernova remnant PKS 1209-51/52. *Astrophys J* 569:L95–L98.
79. Sanwal D, Pavlov GG, Zavlin VE, Teter MA (2002) Discovery of absorption features in the x-ray spectrum of an isolated neutron star. *Astrophys J* 574:L61–L64.
80. De Luca A, et al. (2004) Xmm-newton and vlt observations of the isolated neutron star 1E1207.4-5209. *Astron Astrophys* 418:625–637.
81. Gotthelf EV, Halpern JP (2007) Precise timing of the x-ray pulsar 1E 1207.4-5209: A steady neutron star weakly magnetized at birth. *Astrophys J* 664:L35–L38.
82. Gotthelf EV, Halpern JP (2009) Discovery of a 112 ms x-ray pulsar in Puppis A: Further evidence of neutron stars weakly magnetized at birth. *Astrophys J* 695:L35–L39.
83. Faucher-Giguère C.-A, Kaspi VM (2006) Birth and evolution of isolated radio pulsars. *Astrophys J* 643:332–355.
84. Tuohy I, Garmire G (1980) Discovery of a compact x-ray source at the center of the supernova remnant RCW 103. *Astrophys J* 239:107.
85. Gotthelf EV, Petre R, Vasisht G (1999) X-ray variability from the compact source in the supernova remnant RCW 103. *Astrophys J* 514:L107–L110.
86. De Luca A, Caraveo PA, Mereghetti S, Tiengo A, Bignami GF (2006) A long-period, violently variable x-ray source in a young supernova remnant. *Science* 313:814–817.
87. De Luca A, et al. (2008) Deep infrared observations of the puzzling central x-ray source in RCW 103. *Astrophys J* 682:1185–1194.
88. Pizzolato F, Colpi M, De Luca A, Mereghetti S, Tiengo A (2008) 1E 161348-5055 in the supernova remnant RCW 103: A magnetar in a young low-mass binary system?. *Astrophys J* 681:530–542.
89. Bhadkamkar H, Ghosh P (2009) Young pre-low-mass X-ray binaries in the propeller phase. Nature of the 6.7-h periodic x-ray source 1E 161348-5055 in RCW 103. *Astron Astrophys* 506:1297–1307.
90. Li X (2007) The nature of the compact x-ray source in supernova remnant RCW 103. *Astrophys J* 666:L81–L84.
91. Pons JA, Link B, Miralles JA, Geppert U (2007) Evidence for heating of neutron stars by magnetic-field decay. *Phys Rev Lett* 98(7):071101.
92. Aguilera DN, Pons JA, Miralles JA (2008) 2D Cooling of magnetized neutron stars. *Astron Astrophys* 486:255–271.
93. Aguilera DN, Pons JA, Miralles JA (2008) The impact of magnetic field on the thermal evolution of neutron stars. *Astrophys J* 673:L167–L170.
94. Pons JA, Miralles JA, Geppert U (2009) Magneto-thermal evolution of neutron stars. *Astron Astrophys* 496:207–216.
95. Popov SB, Pons JA, Miralles JA, Boldin PA, Posselt B (2010) Population synthesis studies of isolated neutron stars with magnetic field decay. *Mon Not R Astron Soc* 401:2675–2686.