Neutron stars: Observational diversity and evolution

S Safi-Harb
Department of Physics and Astronomy, University of Manitoba, Winnipeg MB R3T 2N2, Canada
E-mail: samar.safi-harb@umanitoba.ca

Abstract. Ever since the discovery of the Crab and Vela pulsars in their respective Supernova Remnants, our understanding of how neutron stars manifest themselves observationally has been dramatically shaped by the surge of discoveries and dedicated studies across the electromagnetic spectrum, particularly in the high-energy band. The growing diversity of neutron stars includes the highly magnetized neutron stars (magnetars) and the Central Compact Objects shining in X-rays and mostly lacking pulsar wind nebulae. These two subclasses of high-energy objects, however, seem to be characterized by anomalously high or anomalously low surface magnetic fields (thus dubbed as ‘magnetars’ and ‘anti-magnetars’, respectively), and have pulsar characteristic ages that are often much offset from their associated SNRs’ ages. In addition, some neutron stars act ‘schizophrenic’ in that they occasionally display properties that seem common to more than one of the defined subclasses.

I review the growing diversity of neutron stars from an observational perspective, then highlight recent and on-going theoretical and observational work attempting to address this diversity, particularly in light of their magnetic field evolution, energy loss mechanisms, and supernova progenitors’ studies.

1. Introduction: Brief history of the neutron stars zoo

This conference celebrates 50 years of neutron stars discovery. Neutron Stars were discovered as Pulsars (PSRs) by Jocelyn Bell and Antony Hewish in 1967 but predicted to exist back in 1934 by Baade and Zwicky, just two years following the discovery of the neutron by Chadwick. It is with the Crab and Vela pulsars discovery in their respective supernova remnants (SNRs) that Baade and Zwicky’s 1934 prediction that supernovae (SNe) make neutron stars was confirmed. The launch of imaging X-ray telescopes, such as Einstein (1980’s), followed by ROSAT and ASCA (1990’s) then by Chandra, XMM-Newton and Suzaku (2000’s), showed us how these rotation-powered pulsars (RPPs) power synchrotron-dominated pulsar wind nebulae (PWNe).

One of the neutron star subclasses introduced in the 1990’s is the ‘anomalous’ X-ray pulsars (AXPs). It was recognized first by Mereghetti & Stella [1] as a new class of X-ray pulsars, since their spectra were much softer than those of accretion-powered pulsars and had no binary companions; furthermore their X-ray luminosity exceeds the energy available from spin-down power, so they can not be powered by rotation. Duncan & Thompson [2] suggested that these are ‘magnetars’, i.e. highly magnetized neutron stars with a magnetic field exceeding the so-called ‘quantum critical field’ value of $B_{\text{QED}} = 2\pi \frac{m_e^2 c^3}{e h} = 4.4 \times 10^{13}$ G. AXPs are now merged with the Soft Gamma-ray Repeaters (SGRs), as bursting high-energy sources whose powerful outbursts are believed to be powered by their magnetic field decay. Dubbed under the
Figure 1. $P$–$\dot{P}$ diagram showing the diversity of neutron stars. Lines of constant dipole magnetic field (solid black) and characteristic age (dashed grey) are shown. The $4.4 \times 10^{13} \, \text{G}$ line corresponds to the QED value of the magnetic field that is traditionally used to separate magnetars from the rotation-powered pulsars. The 3 pulsars shown in cyan (diamond symbol) correspond to the 3 CCOs for which we have a measured $P$ and $\dot{P}$. The 6 starred objects correspond to the 5 HBPs and 1 magnetar associated with a PWN and/or SNR, with the youngest and fastest two being PSR J1846–0258 in Kes 75 and J1119–6127 in G292.2–0.5, both having now displayed magnetar-like activity. The blue triangles correspond to the 3 AXPs + 1 SGR in our Galaxy known to be securely associated with an SNR with known age.

‘Magnetars’ family, these objects are among the most extreme objects known in the universe (see, e.g., [3]).

In the past decade, other sub-classes of neutron stars have emerged, thanks to sensitive radio and X-ray observations. These subclasses include the X-ray Dim Isolated Neutron Stars (XDINSs) (or the Magnificent Seven [4]), the Rotating Ratio Transients (RRATs [5]), the high-B radio pulsars (HBPs) with $B \geq B_{\text{QED}}$ [6], and the Central Compact Objects (CCOs), typified by the Cas A CCO [7,8]. While we used to treat them as different classes, we are now into the era of unifying these sources thanks to a growing body of observational and theoretical works. This review will highlight these works, focusing on neutron stars with ‘extreme’ magnetic fields (i.e. much smaller or higher than the canonical value of $\sim 10^{12} \, \text{G}$ for the ‘classical’ rotation-powered pulsars) and stressing the fact that their hosting SNRs provide an independent means to address their unification.
2. Pulsars Characteristics and diversity

The diversity of pulsars is connected with their positions on the so-called $P-\dot{P}$ diagram. The period $P$ and period derivative $\dot{P}$ determine their spin-down energy $\dot{E}=I\Omega\dot{\Omega}$ (where $I$ is their moment of inertia and $\Omega=2\pi/P$), their surface dipole field strength (at the magnetic equator) $B=3.2\times10^{19}\left(\dot{P}P\right)^{1/2}\text{G}$, and their characteristic age $\tau_c=P/2\dot{P}$. For some pulsars, the braking index $n=\nu\ddot{\nu}/\dot{\nu}^2$ (where $\nu=1/P$) is measured (e.g., [15]).

Figure 1 shows the $P-\dot{P}$ diagram for the 2,613 currently known pulsars$^1$, revealing the growing diversity of neutron stars, and table 1 summarizes the secure PSR-SNR associations$^2$ for the pulsars with ‘extreme’ magnetic fields. Below we briefly comment on these growing subclasses of neutron stars, and then address the blurring diversity and magnetic field evolution.

2.1. Magnetars and HBPs

There are currently 29 known magnetars (including 6 candidates)$^3$. Magnetars are traditionally discovered as high-energy sources, with no PWNe around them. Only 3 AXPs and 2 SGRs (one of which is an extragalactic pulsar in the LMC SNR N49) are securely associated with SNRs (see figure 2). The High-B Pulsars (HBPs) are a growing class of radio-detected pulsars with an inferred magnetic field close to, or just above, the QED value. We know of approximately a dozen such objects, and they are believed to be powered primarily by rotational energy. The youngest

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$^1$ http://www.atnf.csiro.au/research/pulsar/psrcat (v1.56)

$^2$ http://www.physics.umanitoba.ca/snr/SNRcat (SNRcat)

$^3$ http://www.physics.mcgill.ca/~pulsar/magnetar/main.html
2.2. CCOs

CCOs are X-ray emitting neutron stars found near SNR centres and typified by the compact object in the SNR Cas A (see figure 3). The term CCO was coined by Pavlov et al [7] following the first light Chandra discovery of the object.\(^4\)

There are currently 14 CCOs\(^5\) (including 6 candidates) known in our Galaxy ([8, 19], SNRcat). These objects are X-ray emitters with no optical or radio counterparts, and with no evidence of PWNe surrounding them. X-ray pulsations have been discovered from 3 CCOs (see table 1). Their timing properties imply magnetic fields \(\sim 10^{10} - 10^{11}\) G, much lower than those of the traditional RPPs and magnetars, which led Gotthelf & Halpern [20] to dub them ‘anti-magnetars’. Spectroscopic studies support this interpretation through the discovery of spectral line features interpreted as cyclotron lines from a low \(B\) (e.g., [21–24]) or from modelling their thermal X-ray emission (e.g., [25, 26]).

These objects are also known to be quiet X-ray emitters (except for the ‘CCO’ in RCW 103) with their X-ray emission described by two blackbodies and their X-ray luminosity (ranging from \(\sim 3 \times 10^{32} - 3 \times 10^{34}\) erg s\(^{-1}\)) exceeding their spin-down energy. It is believed that their thermal spectra are derived from residual cooling and partly from accretion of supernova debris (e.g., [20]). One of their intriguing properties is their characteristic ages being orders of magnitude greater than their hosting SNRs’ ages (see table 1 and figure 3).

\(^4\) In a footnote referring to the Cas A compact object, Pavlov et al [7] state: ‘According to the convention recommended by the Chandra Science Center, this source should be named CXO 3232327.9+584842. We use the abbreviation CCO for brevity.’

\(^5\) the total would be 15 CCOs if we include the variable X-ray source 1E 161348–5055 in RCW 103.
2.3. Diversity blurred

A growing body of observational and theoretical work has emerged blurring this apparent diversity: (1) The discovery of magnetar-like outbursts accompanied by spectral changes from the rotation-powered HBP J1846–0258 in the SNR Kes 75 [13, 27, 28] and more recently from the older HBP J1119–6127 in the SNR G292.2–0.5 [29–31] (2) The discovery of transient radio emission from magnetars (e.g., [32]) commonly discovered as high-energy objects. (3) The discovery of low-\(B\) magnetars, i.e. with \(B < B_{QED}\), through their bursting activity [33–35] (4) The discovery of magnetar-like activity from 1E 161348–5055 [36, 37], the variable central X-ray source in the SNR RCW 103, classified by some authors as a CCO. (5) The discovery of PWNe (which are characteristic of RPPs) around the magnetar, Swift J1834.9–0846 [38] and the HBP J1119–6127 [39–41] which, as mentioned above, recently revealed itself as a magnetar – see figure 1.

The thermal X-ray luminosities of some of the HBPs and magnetars are systematically higher than those of the traditional radio pulsars, suggesting that magnetic fields affect their X-ray emission. Using 2D simulations of the fully-coupled evolution of both temperature and magnetic field in neutron stars, Viganò et al [42] unified the phenomenological diversity of magnetars, HBPs and isolated nearby neutron stars by varying their initial magnetic field, mass and envelope composition. Furthermore, the magnetic field topology was argued to play a key role in the observed properties of the bursting activity of neutron stars. Perna & Pons [43] showed that the toroidal component, particularly its strength with respect to the poloidal component, plays a significant role in the frequency of the bursting activity and its dependence on the age of the system. In addition, the role of fallback disks around young isolated neutron stars has been highlighted by Alpar et al [44] to unify different classes of neutron stars.

3. SNRs associations shedding light on magnetic field evolution

Generally it is assumed that neutron stars lose energy by spinning down due to the emission of magneto-dipole radiation. However, this simple model does not describe the neutron star population for the following reasons. First, it predicts a braking index \(n = 3\), which has not been observed in young neutron stars; most of the measured indices are smaller than 3 (e.g., [15]). Second, the pulsars securely associated with SNRs show a remarkable disparity between their characteristic age and the SNR age, in some cases differing by several orders of magnitude (especially for the CCOs). Under the standard assumption of constant magnetic field, we have:

\[ P_0 = P \left[ 1 - (n - 1) \tau \frac{P}{\dot{P}} \right]^{\frac{1}{n-1}}. \]

Replacing \( \tau \) with the SNR age (table 1), we are generally unable to explain the observed braking indices and enforce the SNR’s age to be equal to the PSR’s age with a constant \( n \) (see, e.g., figure 2 in [45]). Rogers & Safi-Harb [45, 46] addressed magnetic field evolution focusing on the diverse population of neutron stars with ‘anomalous’ magnetic fields (i.e. much higher or lower than the canonical value of \(10^{12}\) Gauss). These objects include the AXPs, SGRs, HBPs and CCOs securely associated with SNRs of known ages and listed in table 1.

3.1. Magnetic Field Decay

Magnetic field decay has been invoked to describe the evolution of AXPs and SGRs (e.g., [47–49]). Magnetic field decay channels depend on a variety of effects including Ohmic dissipation, ambipolar diffusion and the Hall drift. While for the low-\(B\) pulsars with ages \(\sim 10–100\) kyr the Ohmic dissipation is expected to dominate the magnetic field evolution, for magnetar-strength-\(B\) pulsars, the Hall effect provides the dominant mechanism for the field evolution on timescales comparable to their associated SNR ages.
Table 1. Pulsars with very high or very low magnetic field securely associated with SNRs with known ages.

| Pulsar (SNR)                    | $P$  | $B \times 10^{13}$ G | $\tau$ (kyr) | $\tau_{\text{SNR}}$ (kyr) |
|---------------------------------|------|----------------------|--------------|--------------------------|
| AXP 1E 1841–045 (Kes 73)        | 11.79| 70.3                 | 4.57         | 0.75–2.10                |
| AXP 1E 2259+586 (CTB 109)       | 6.98 | 5.9                  | 230          | 10.0–16.0                |
| CXOU J171405.7–381031 (CTB 37B)| 3.83 | 50                   | 0.95         | 0.35–3.15                |
| SGR 0526–66 (N49)               | 8.05 | 56                   | 3.36         | < 4.80                   |
| SGR 1627–41 (G337.0–0.1)        | 2.59 | 22                   | 2.2          | < 5.0                    |
| HBP J1846–0258 (Kes 75)         | 0.3265| 4.9                 | 0.73         | 0.90–4.30                |
| HBP J1119–6127 (G292.2–0.5)     | 0.408| 4.1                  | 1.61         | 4.20–7.10                |
| RX J0822.0–4300 (Puppis A)      | 0.113| $3.27 \times 10^{-4}$ | 193          | 3.70–5.20                |
| CXOU J185238.6+004020 (Kes 79)  | 0.105| $3.05 \times 10^{-3}$ | $1.92 \times 10^5$ | 5.40–7.50        |
| 1E 1207.4–5209 (PKS 1209–51/52) | 0.424| $9.83 \times 10^{-3}$ | $3.02 \times 10^5$ | 2.00–20.0        |

3.2. Magnetic field growth

The hypothesis of fallback accretion goes back decades ago [50–52]. The submergence of the magnetic field due to fallback accretion has been explored by a number of authors (e.g., [53,54]), and revived recently [45,46,55–61] for the following reasons: (1) $n<3$ (see Section 3.3); (2) timing of CCOs giving low surface $B \sim 10^{10}–10^{11}$ G; (3) spectroscopic evidence for low surface magnetic field, as found, e.g., for the CCOs in Cas A, PKS 1209–51/52, and Puppis A; (4) the highly modulated pulsed signal in Kes 79’s CCO implying a much higher internal magnetic field. This all supports growing evidence for the submerged field scenario due to fallback accretion.

3.3. Empirical model for magnetic field evolution

In Rogers & Safi-Harb [45,46], both magnetic field growth and decay are described within the same basic framework, using empirical models for magnetic field evolution developed for various classes of neutron stars. In this approach the braking index is time-dependent: $n = 3 - 4\tau f_D/f_G$, where the function $f_j(t)$ carries the time-dependence of the field. Thus, field decay gives $n > 3$ since $f_D < 0$, and field growth gives $n < 3$ since $f_G > 0$. The sample shown in table 1 (plus other RPPs with a measured braking index) gives solutions to the field evolution in neutron stars, some of which are shown in figure 4 (see [45] and figure 5 therein for a more detailed and complete description of the sample and fits considered). Magnetic field growth has been used to fit the 3 CCOs (cyan), the 2 SGRs (red) and the HBP J1846–0258 in Kes 75 (green). AXPs have been fit with magnetic field decay models highlighted by the grey area in figure 4 [47]. It is worth noting that the time evolution of the CCOs’ characteristic age explains the apparent large discrepancy between the pulsars’ ages (appearing very old) and the ages of the associated young SNRs. In particular, for the three systems shown, the PSR and SNR ages match at times $\geq 10^{4.5}$ yr, by which time the SNR would have mostly dissipated. Therefore, the characteristic age for these pulsars does not reflect their true age as long as they are within their SNRs. This property, along with their inferred low asymptotic field strength, lead to the suggestion that CCOs could be ancestors of old isolated radio pulsars as long as they overcome the accretion phase (which would explain their X-ray dominant emission) and their surface field grows to the critical limit required for radio emission. The late time evolution of the CCOs may also link them to the class of objects known as XDINS: radio-quiet X-ray pulsars with long periods and no apparent SNR associations, with some of these objects having magnetic fields $\geq 10^{13}$ G, similar to the HBPs.
4. SN progenitors
The diversity of neutron stars can be related to the diversity in SNe types resulting from core-collapse SNe (e.g., [62–64]).

4.1. Magnetar progenitors
Which stars make magnetars? Two scenarios of interest have been proposed in the literature. (1) The proto-neutron star model where the neutron star is born with a few milliseconds period [2], which predicts that the initial kinetic energy of the supernova would be reflected in a super-energetic hosting SNR. However, studies of magnetar SNRs and HBP SNRs (albeit limited to a very small sample and subject to low-resolution, CCD-type, X-ray spectroscopy) yield a ‘typical’ kinetic energy of the order of a few \( \times 10^{50} \)–\( 10^{51} \) ergs (e.g., [14, 65]). Furthermore, the inferred ratio of initial to current spin-period (\( P_0/P \)) for the magnetars and HBPs is not much smaller than 1, unlike what is predicted by the proto-neutron star model. (2) The fossil field hypothesis where magnetars are born from the most massive, most magnetic, main-sequence stars [66]. Studies of magnetar SNRs point towards massive progenitors (see, e.g., [67]), supporting the fossil field hypothesis. However, this is not conclusive given that a few other studies point to lower mass progenitors [68, 69].

4.2. CCOs’ progenitors
Progenitor studies have been performed on the CCOs-hosting SNRs: Cas A, Puppis A, Kes 79, RCW 103 and RX J1713.7–3946. It is interesting to note that these studies point to progenitor masses around 20 \( M_\odot \) (although inconclusively). Below we summarize these studies.

- Cas A, the youngest historical type SN in our Galaxy, harbours the CCO CXOU J232327.9+584842. It is commonly believed that Cas A results from a SN Iib event with a progenitor mass of \( \sim 15–25 \ M_\odot \) and may have lost its H envelope to binary interaction (e.g., [70]), although a slightly higher mass (up to \( \sim 30 \ M_\odot \)) progenitor has been also discussed in the literature (e.g., [71]).
- Puppis A is a \( \sim 4.5 \) kyr-old SNR harbouring the 112 ms CCO RX J0822–4300. Spatially resolved spectroscopic studies of SNR ejecta using Suzaku, Chandra and XMM-Newton point to a 15–25 \( M_\odot \) progenitor [72, 73].

Figure 4. Pulsar age versus SNR age shown with evolutionary tracks for evolving magnetic fields in PSR–SNR pairs. The solid black diagonal line corresponds to equal PSR and SNR ages. The colours/symbols match those used in figure 1, with the cyan, red and green curves showing field growth fits to 3 CCOs, 2 SGRs and 1 HBP, respectively. See §3.3 for details.
• Kes 79 is a ∼5 kyr-old SNR harbouring the CCO CXOU J185238.6+004020 (PSR J1852+0040). A multi-wavelength study, together with an X-ray spectroscopic study of the ejecta compared to nucleosynthesis model yields, suggest a 15–20 $M_\odot$ progenitor [17]).

• RX J1713.7–3946 (G347.7–0.5) is a ∼1–2 kyr-old SNR harbouring the CCO 1WGA J1713.4–3949. The measured metal abundance ratios suggest that the progenitor star was a relatively low-mass star ($\lesssim 20 M_\odot$). However, based on the inferred blast wave velocity of ∼6,000 km/s which is considered fast for such a core-collapse SNR, Katsuda et al [74] propose that RX J1713.7–3946 results from a SN Ib/c and that its progenitor is a member of an interacting binary.

• RCW 103 is a ∼2 kyr-old SNR hosting near its centre the unusual CCO 1E 161348–5055 which had been recently proposed to be a magnetar [36,37]. Comparison of the ejecta abundances inferred from X-ray spectra with supernova nucleosynthesis yields models suggests a progenitor mass of ∼18–20 $M_\odot$ [75].

4.3. The Crab

Going back to the ‘poster’ outcome of a core-collapse SN, the Crab’s progenitor is known to be an ∼8–10 $M_\odot$ progenitor star. However, it has a low visible mass of ∼5 $M_\odot$ and a small kinetic energy of <10$^{50}$ erg for a young core-collapse SNR. Two scenarios have been discussed: (1) a massive undetected shell beyond the visible PWN [76], (2) an electron-capture SN, an endothermic reaction of electrons captured in an O-Ne-Mg core of a super AGB star with a low energy (∼10$^{50}$ erg) explosion [77].

This puzzle has been most recently addressed with the Hitomi X-ray satellite [78]. One of the science goals for Hitomi was to search for thermal X-ray emission from the synchrotron-dominated SNRs, thanks to its unprecedented spectral resolution and sensitivity to the thermal X-ray emission with the Soft X-ray Spectrometer. A brief observation took place just before the end of the Hitomi mission [79]. The gate valve was still closed, which hampered the sensitivity below 2 keV. While no thermal X-rays were detected, as in previous dedicated searches (e.g., with Chandra [80]), a more constrained upper limit on the X-ray emitting plasma has been established with Hitomi and past Chandra and XMM-Newton studies. Furthermore, while a low-energy supernova explosion has been favoured [81,82], a higher energy Fe core-collapse explosion could not be ruled out but implies, depending on the environment, a very stringent upper limit on the ambient density or mass loss rate [79].

5. Future prospects

Despite significant advances in neutron stars physics in the past 50 years, many questions remain to be answered. We hope the answers will be obtained with the planned X-ray missions.

• The sample of PSR-SNR associations has been limited by sensitivity and resolution. Furthermore, the X-ray emission from CCO descendants and old radio pulsars would benefit from deep X-ray observations and/or a sensitive X-ray survey. The upcoming eRosita X-ray satellite (Germany/Russia), expected to be launched in 2018, will allow us to expand our sample and probe the X-ray emission from the different classes of neutron stars.

• To date, we do not have braking index measurement of magnetars (SGRs and AXPs) and other neutron stars subclasses, and most measurements done to-date point to an index $n<3$. Timing studies of the different classes of neutron stars is needed to shed light on their braking indices, which in turn addresses magnetic field evolution. The recently launched ASTROSAT (India/Canada), NICER (NASA), and the HXMT (China) X-ray satellites will provide a new window into timing studies of pulsars.
• X-ray polarimetry is still lacking in the field, but is crucial as it provides a direct measurement of the neutron star’s magnetic field and sheds light on its topology (particularly for the magnetars and PWNe). XPE (ESA), IXPE (NASA) and XTP (China) are currently being planned for the near future.

• High-resolution X-ray spectroscopy is needed to (a) provide an accurate measurement of SNR ages, (b) probe SN progenitors and (c) provide a direct measurement of the neutron star’s magnetic field. Powerfully demonstrated by the glimpse of the Hitomi satellite on a few targets before its loss, high-resolution X-ray spectroscopy is now planned for the X-ray recovery mission (XARM, JAXA/NASA; 2021 timescale) and in the more distant future for Athena (ESA; 2028 timescale) and Lynx (NASA; beyond 2030).

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References
[1] Mereghetti S and Stella L 1995 ApJ (Letters) 442 L17
[2] Duncan R C and Thompson C 1992 ApJ (Letters) 392 L9
[3] Turolla R, Zane S and Watts A L 2015 Reports on Progress in Physics 78 116901 Preprint astro-ph/1507.02924
[4] Haberl F 2004 Memorie della Societ´a Astronomica Italiana 75 454 Preprint astro-ph/0401075
[5] McLaughlin M et al 2006 Nature 439 817
[6] Ng C-Y and Kaspi V M 2011 Astrophysics of Neutron Stars: A Conference in Honor of M Ali Alpar vol 1379, ed G¨o˘g¨u¸s et al (AIP Conf. Proc.) p 60 Preprint astro-ph/1010.4592
[7] Pavlov G G, Zavlin V E, Aschenbach B, Tr¨umper J and Sanwal D 2000 ApJ (Letters) 531 L53
[8] Gotthelf E V, Halpern J P and Alford J 2013 ApJ 765 58
[9] Sasaki M, Plucinsky P P, Gaetz T J, Smith R K, Edgar R J and Slane P O 2004 ApJ 617 322
[10] Kumar H, Safi-Harb S, Slane P O and Gotthelf E V 2014 ApJ 781 41
[11] Kulkarni S et al 2003 ApJ 585 948
[12] Esposito P et al 2009 ApJ (Letters) 690 L105
[13] Kumar H and Safi-Harb S 2008 ApJ (Letters) 678 L43
[14] Kumar H, Safi-Harb S and Gonzalez M E 2012 ApJ 754 96
[15] Espinoza C M 2013 Neutron Stars and Pulsars: Challenges and Opportunities after 80 years vol 291, ed J van Leeuwen (IAU Symp. Proc.) p 195 Preprint astro-ph/1211.5276
[16] Petre R, Becker C M and Winkler P F 1996 ApJ (Letters) 465 L43
[17] Zhou P, Chen Y, Safi-Harb S, Zhou X, Sun M, Zhang Z-Y and Zhang G-Y 2016 ApJ 831 192
[18] Huang U et al 2004 ApJ (Letters) 615 L117
[19] Pavlov G G, Sanwal D and Teter M A 2004 Young Neutron Stars and Their Environments vol 218, ed F Camilo and B M Gaensler (IAU Symp. Proc.) p 239 Preprint astro-ph/0311526
[20] Gotthelf E V and Halpern J P 2008 40 Years of Pulsars: Millisecond Pulsars, Magnetars and More vol 983, ed C Bassa et al (AIP Conf. Series) p 320 Preprint astro-ph/0711.1554
[21] Sanwal D, Pavlov G G, Zavlin V E and Teter, M A 2002 ApJ (Letters) 574 L61
[22] Bignami G F, Caraveo P A, De Luca A and Mereghetti S 2003 Nature 423 725
[23] DeLuca A et al 2012 MNRAS (Letters) 421 L72
[24] Gotthelf E V and Halpern J P 2009 ApJ 695 (Letters) L35
[25] Ho W C G and Heinke C O 2009 Nature 462 71
[26] Suleimanov V S, Klochkov D, Pavlov G G and Werner K 2014. ApJ Supplement Series 210 13
[27] Gavriil F P, Gonzalez M E, Gotthelf E V et al 2008 Science 319 1802
[28] Ng C-Y, Slane P O, Gaensler B M and Hughes J P 2008 ApJ 686 508
[29] Vousnes G, Kouveliotou C and Roberts P 2016 GCN 19736
[30] Kennea J A et al 2016 ATel 9274
[31] Göğüs E et al 2016 ApJ 829 L25
[32] Camilo F et al 2006 Nature 442 892
[33] Rea N et al 2010 Science 330 944
[34] Scholz P, Ng C-Y, Livingstone M A, Kaspi V M, Cumming A and Archibald R F 2012 ApJ 761 66
[35] Zhou P, Chen Y, Li X-D, Safi-Harb S, Mendez M, Terada Y, Sun W and Ge M-Y 2014 ApJ (Letters) 781 L16
[36] D’Ai A et al 2016 MNRAS 463 2394
[37] Rea N, Borghese A, Esposito P, et al 2016 ApJ (Letters) 828 L13
[38] Younes G et al 2016 ApJ 824 L38
[39] Gonzalez M E and Sasi-Harb S 2003 ApJ (Letters) 591 L143
[40] Sasi-Harb S and Kumar H 2008 ApJ 684 532
[41] Blumer H, Sasi-Harb S and McLaughlin M 2017 ApJ (Letters) 850 L18 Preprint astro-ph/1711.01600
[42] Viganò D, Rea N, Pons J A, Aguilera D N and Miralles J A 2013 MNRAS 434 123
[43] Perna R and Pons J A 2011 ApJ (Letters) 727 L51
[44] Alpar M A, Çalışkan, Ş and Ertan U 2013 Feeding Compact Objects: Accretion on All Scales vol 290, ed C M Zhang et al (IAU Symp. Proc.) p 93 Preprint astro-ph/1211.4721
[45] Rogers A and Sasi-Harb S 2017 MNRAS 465 383
[46] Rogers A and Sasi-Harb S 2016 MNRAS 457 1180
[47] Nakano T et al 2015 PASJ 67 9
[48] Dall’Osso S et al 2012 MNRAS 422 2878
[49] Colpi M, Geppert U and Page D 2000 ApJ (Letters) 529 L29
[50] Colgate S A 1971 ApJ 163 221
[51] Zel’dovich Y B, Ivanova L N and Nadezhdin D K 1972 AZh 49 253
[52] Chevalier R A 1989 ApJ 346 847
[53] Muslimov A and Page D 1995 ApJ (Letters) 440 L77
[54] Geppert U, Page D and Zannias T 1999 A&A 345 487
[55] Ho W C G 2011 MNRAS 414 2567
[56] Ho W C G 2015 MNRAS 452 845
[57] Popov S B and Turolla R 2012 Electromagnetic Radiation from Pulsars and Magnetars vol 466, ed W Lewandowski et al (San Francisco: Astron. Soc. Pacific) p 191 Preprint astro-ph/1206.2819
[58] Bernal C G, Lee W H and Page D 2010 RMxAA 46 309
[59] Bernal C G, Page D and Lee W H 2013 ApJ 770 106
[60] Igusheva A P, Elfritz J G and Popov S B 2016 MNRAS 462 3698
[61] Eksi K Y 2017 MNRAS 469 1974
[62] Chevalier R A 2005 ApJ 619 839
[63] Milisavljev I D and Fesen R 2017 Preprint astro-ph/1701.00891
[64] Patnaude D and Badenes C 2017 Preprint astro-ph/1702.03228
[65] Vink J 2008 AdSpR 41 503
[66] Ferrario L and Wickramasinghe D 2008 MNRAS (Letters) 389 L66
[67] Sasi-Harb S and Kumar H 2013 Neutron Stars and Pulsars: Challenges and Opportunities after 80 years vol 291, ed J van Leeuwen (IAU Symp. Proc.) p 480 Preprint astro-ph/1210.5261
[68] Borkowski K and Reynolds S P 2017 ApJ 846 13
[69] Davies et al 2009 ApJ 707 844
[70] Young P A, Fryer C L, Hungerford A et al 2006 ApJ 640 89
[71] Pérez-Rendón B, García-Segura G and Langer N 2009 A&A 506 1249
[72] Katsuda S et al 2012 ApJ 757 49
[73] Hwang U, Petre R and Flanagan K 2008 ApJ 676 378
[74] Katsuda S et al 2015 ApJ 814 29
[75] Frank K A, Burrows D N and Park, S 2015 ApJ 810 113
[76] Chevalier R A 1977 Supernovae, Astro. and Space Science Library vol 66, ed D. Schramm (Dordrecht: Springer)
[77] Nomoto K, Sugimoto D, Sparks W M, Fesen, R A, Gull T R and Miyaji S 1982 Nature 299 803
[78] Takahashi T et al 2014 SPIE 9144 25 Preprint astro-ph/1412.1356
[79] Hitomi collaboration 2017 PASJ in press Preprint astro-ph/1707.00054
[80] Seward F D, Gorenstein P and Smith R K 2006 ApJ 636 873
[81] Smith N 2013 MNRAS 434 102
[82] Yang H and Chevalier R A 2015 ApJ 806 153
[83] Ferrand G and Sasi-Harb S 2012 AdSpR 49 1313 (SNRcat)
[84] Manchester R N, Hobbs, G B, Teoh, A and Hobbs M 2006 AJ, 129, 1993

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