

X-ray emission from isolated neutron stars

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Abstract X-ray emission is a common feature of all varieties of isolated neutron stars (INS) and, thanks to the advent of sensitive instruments with good spectroscopic, timing, and imaging capabilities, X-ray observations have become an essential tool in the study of these objects. Non-thermal X-rays from young, energetic radio pulsars have been detected since the beginning of X-ray astronomy, and the long-sought thermal emission from cooling neutron star's surfaces can now be studied in detail in many pulsars spanning different ages, magnetic fields, and, possibly, surface compositions. In addition, other different manifestations of INS have been discovered with X-ray observations. These new classes of high-energy sources, comprising the nearby X-ray Dim Isolated Neutron Stars, the Central Compact Objects in supernova remnants, the Anomalous X-ray Pulsars, and the Soft Gamma-ray Repeaters, now add up to several tens of confirmed members, plus many candidates, and allow us to study a variety of phenomena unobservable in "standard" radio pulsars.

1 Introduction

With more than 1800 detections, rotation powered pulsars (RPP) constitute by far the largest class of isolated neutron stars (INS), despite only one out of ~ 10 radio pulsars is visible because of beaming. Accounting for the selection effects of radio observations, a total population of $\sim 10^6$ RPP is estimated for the whole Galaxy [40]. Observations at gamma-ray energy, where pulsar beaming angles are larger, are now contributing to increase the number of known RPP [1]. About one hundred RPP have been detected also at X-ray energies [7]: they include the youngest and more energetic pulsars (like the Crab), a few older neutron stars at small distances

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(e.g. Vela and Geminga) and several tens of recycled millisecond pulsars (most of which are found in globular clusters [56]).

All kinds of INS, not only the RPP, are X-ray emitters. X-ray observations have been crucial to discover other manifestations of INS, that for various reasons were missed in the standard searches for radio pulsars. The nearby X-ray Dim Isolated Neutron Stars (XDINS), the Central Compact Objects (CCOs) in supernova remnants, the Anomalous X-ray Pulsars (AXPs), and the Soft Gamma-ray Repeaters (SGRs) are examples of these new classes, which, despite totalling only a few tens of sources, are particularly interesting because they offer a different view on a variety of phenomena unobservable in "standard" radio pulsars.

This review is focussed on the main properties of the X-ray emission from these new classes of INS. For an excellent review of the X-ray emission from RPP see [7]. The location on a $P-\dot{P}$ plot diagram of some of the objects discussed here is shown in Fig. 1. The figure also gives lines of constant magnetic field (computed assuming dipole braking, $B = 3.2 \cdot 10^{19} (P \dot{P})^{1/2}$ G), characteristic age ($\tau_c = \frac{1}{2} P / \dot{P}$), and spin-down luminosity ($L_{SD} = I \Omega \dot{\Omega} = 4 \cdot 10^{46} \dot{P} / P^3$ erg s⁻¹).

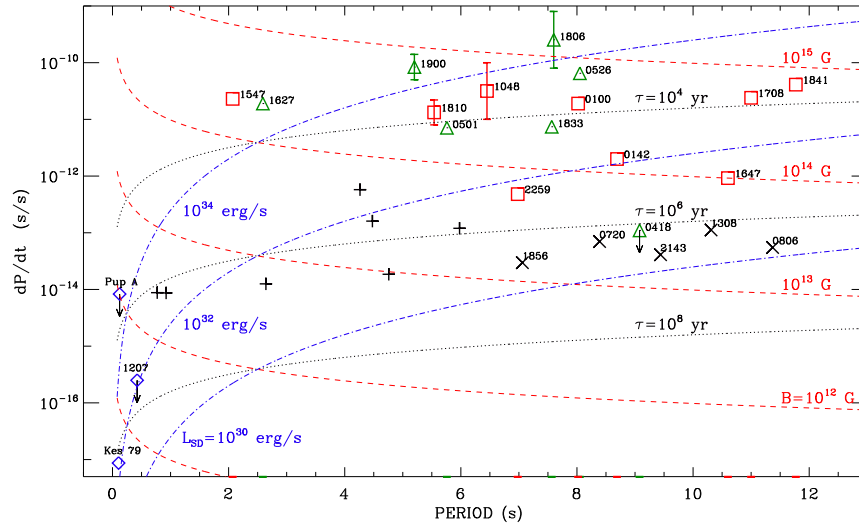


Fig. 1 $P-\dot{P}$ diagram for different classes of INS: XDINS (\times), CCO (\diamond), AXP (squares), SGR (\triangle), RRAT ($+$). The vertical bars indicate the range of \dot{P} variations observed in SGR and AXP. Lines of constant magnetic field (dashed), characteristic age (dotted), and spin-down luminosity (dash-dotted) are also indicated.

2 Origin of the X-ray emission in isolated neutron stars

The X-ray emission observed from INS can be powered by internal heat, rotational energy, accretion, and magnetic field decay. The relative importance of these energy sources, that can also operate at the same time, depends on the age and physical properties of the neutron star.

Neutron stars have internal temperatures of $\sim 10^{11}$ K at birth, that rapidly drop to $\sim 10^9$ K. For the following $\sim 10^5 - 10^6$ years the dominant cooling mechanism is neutrino emission from the star's isothermal core. This leads to surface temperatures of several 10^5 to 10^6 K, with thermal emission peaking in the soft X-ray band. Temperature gradients on the star's surface generally produce observable modulations at the rotation period. Thermal X-ray emission can be observed in INS with ages of $\sim 10^4 - 10^6$ years, provided they are sufficiently close and not too absorbed by the interstellar medium. Older neutron stars are too cool to significantly emit X-rays, while in the youngest pulsars the thermal radiation is difficult to detect because it is outshined by the brighter non-thermal emission. A recent review on the thermal emission from neutron star is given by [171].

Non-thermal emission, that extends over a broad energy range, originates from charged particles accelerated in the NS magnetospheres at the expense of rotational energy (see, e.g., [17]). Non-thermal X-rays are characterized by power-law spectra and strongly anisotropic emission patterns, giving rise to large pulsed fractions. The pulse profiles often show narrow (double) peaks, but in many cases nearly sinusoidal profiles are observed. The most luminous RPP are the Crab and two young pulsars in the Large Magellanic Cloud (the only three pulsars with $L_{SD} > 10^{38}$ erg s $^{-1}$). The efficiency with which the rotational energy is converted to non-thermal luminosity is about 10^{-3} [8, 90], but there is a large dispersion around the average value [130], as expected because of different viewing orientations and, possibly, also other effects. Studies of the $L_X - L_{SD}$ relation with a large sample are complicated by the fact that a significant fraction of the rotational energy loss powers pulsar wind nebulae, which are difficult to disentangle in the more distant and/or fainter objects without adequate spatial resolution.

Accretion is a well established process in X-ray binaries (e.g., [43]). In the lack of a companion star, accreting matter could originate directly from the interstellar medium. However, the relatively large space velocity of neutron stars, and the low density of the interstellar medium, make this process unable to provide sufficiently high luminosities. Alternatively, the matter could be supplied by a debris disk formed by fall-back in the supernova explosion that produced the neutron star. Although this possibility seems more promising, no unambiguous evidence for an INS powered by accretion has been found yet.

The relevance of magnetic energy in powering the emission from neutron stars has been recognized only recently, with the observation of SGRs and AXPs (see [166, 101] for reviews). High magnetic fields ($B \sim 10^{14} - 10^{15}$ G) were first invoked to explain the SGRs and, in particular, the unique properties of the exceptional event of March 5, 1979 from SGR 0526-66 [119, 29]. Objects in which magnetic field decay is the dominant energy source have been named Magnetars. They are particularly

interesting because they offer the unique possibility to study physical processes in magnetic fields of unequalled strength.

3 The X-ray Dim Isolated Neutron Stars

A handful of X-ray sources with large X-ray-to-optical flux ratios, $F_x/F_{opt} \sim 10^4$ – 10^5 , typical of INS, were discovered in the ROSAT satellite All Sky Survey. Their INS nature was confirmed by the measurement of a large proper motion in the brightest source, RX J1856.5–3754 [161], and by the discovery of pulsations at few seconds in other sources [58, 65]. The original members of this class¹ and two new candidates are listed in Table 1. Recent reviews on the XDINS are given in [57, 154].

XDINS have very soft thermal spectra (blackbody temperatures $T_{BB} \sim 40$ – 110 eV), X-ray luminosities $L_X \sim 10^{30}$ – 10^{32} erg s⁻¹, spin periods in the 3–12 s range, faint optical counterparts ($V > 25$), and no radio emission. Period derivatives of the order of 10^{-14} – 10^{-13} s s⁻¹ have been measured for several XDINS through phase connected timing, but in some cases these values are still poorly constrained (see Table 1). The temperatures of XDINS are consistent with neutron stars cooling curves if they have ages of 10^5 – 10^6 years and the effect of their strong magnetic field is taken into account [2]. It is thus generally believed that the XDINS are powered by residual thermal energy.

X-ray sources with such soft spectra can only be observed if the interstellar absorption is small: all the M7 are closer than ~ 0.5 kpc and have $N_H < 4 \cdot 10^{20}$ cm⁻². Their proximity allowed in several cases the measurement of parallax and proper motion showing a distribution of transverse velocities consistent with that of radio pulsars [113]. For these velocities, and typical ISM densities, accretion from the ISM, originally invoked to explain the XDINS emission, cannot provide the observed luminosity. Although the timing parameters give spin-down ages $\tau_c \sim 1$ – 2 million years, the measured spatial velocities and likely birth places in nearby OB associations strongly suggest that their true ages are smaller (see Table 2).

Despite various attempts, none of the XDINS has been detected in the radio band. The most recent upper limits of 0.14 – 5 μ Jy kpc², obtained at 1400 MHz [81], correspond to pulsed luminosities well below those of the faintest observed radio PSRs. However, given the small sample and considering the anticorrelation between beaming aperture angle and pulse period, it cannot be excluded that the lack of radio emission be simply due to unfavorable orientations.

The X-ray light curves of XDINS are nearly sinusoidal, with pulsed fractions, ranging from 1.5% to $\sim 20\%$, and moderate energy dependence. Only in the case of RX J1308.6+2127 two peaks are clearly seen. These properties indicate that we are likely seeing emission from a large fraction of the star’s surface.

¹ they have been nicknamed “The Magnificent Seven” (M7, hereinafter)

Table 1 Isolated Neutron Stars

Name	P (s)	\dot{P} (s s ⁻¹)	D ^(a) (kpc)	Association	Notes ^(b) and References
XDINS					
RX J0420.0–5022	3.45	-	0.345	-	[59]
RX J0720.4–3125	8.39	7.01 10 ⁻¹⁴	0.36	-	G? [58, 78, 157, 68]
RX J0806.4–4123	11.37	(5.5±3.0) 10 ⁻¹⁴	0.25	-	[59, 77]
RX J1308.6+2127	10.31	1.120 10 ⁻¹³	0.5	-	RBS1223 [65, 74]
RX J1605.3+3249	-	-	0.39	-	RBS1556 [112, 169]
RX J1856.5–3754	7.06	(2.97±0.07) 10 ⁻¹⁴	0.16	-	[161, 151, 156, 158]
RX J2143.0+0654	9.43	(4.1±1.8) 10 ⁻¹⁴	0.43	-	RBS1774 [168, 76]
2XMM J104608.7–594306	-	-	2	-	candidate [127]
RX J1412.9+7922	-	-	3.6	-	candidate, Calvera [137, 140]
CCO					
RX J0822.0–4300	0.122	<8 10 ⁻¹⁵	2.2	Puppis A	[126, 52]
CXOU J085201.4–461753	-	-	1	G266.1–1.2	[123]
1E 1207.4–5209	0.424	<2.5 10 ⁻¹⁶	2	G296.5+10.0	[102, 21, 53]
CXOU J160103.1–513353	-	-	5	G330.2+0.1	[121]
RX J1713.4–3949	-	-	1.3	G347.3–0.5	[87]
CXOU J185238.6+004020	0.105	8.7 10 ⁻¹⁸	7.1	Kes 79	[63, 62]
1E 161348–5055.1	-	-	3.3	RCW 103	T [20]
CXOU J232327.8+584842	-	-	3.4	Cas A	[15, 110, 122]
XMMU J172054.5–372652	-	-	4.5	G350.1–0.3	candidate [44]
XMMU J173203.3–344518	-	-	3.2	G353.6–0.7	candidate [147]
CXOU J181852.0–150213	-	-	8.5	G15.9+0.2	candidate [136]
AXP and SGR					
CXOU J010043.1–721134	8.02	1.9 10 ⁻¹¹	60	SMC	AXP [85, 96, 148]
4U 0142+61	8.69	2 10 ⁻¹²	3.6	-	B, G? [73, 26]
1E 1048.1–5937	6.45	(1–10) 10 ⁻¹¹	8	-	B, G [139, 152, 46, 28]
1E 1547.0–5408	2.07	2.3 10 ⁻¹¹	5	G327.2–0.1	T, B, R [12, 64, 33, 106]
PSR J1622–4950	4.33	1.7 10 ⁻¹¹	9	-	R [88]
CXOU J164710.2–455216	10.6	9.2 10 ⁻¹³	3.9	Westerlund 1	T, B, G [114, 71]
1RXS J170849.0–400910	11.0	2.4 10 ⁻¹¹	5	-	G [141, 72, 18, 27]
XTE J1810–197	5.54	(0.8–2.2) 10 ⁻¹¹	3.1	-	T, B, R [70, 13, 163, 9]
1E 1841–045	11.77	4.1 10 ⁻¹¹	8.5	Kes 73	G [159, 49, 111, 27]
1E 2259+586	6.98	4.8 10 ⁻¹³	4	CTB 109	B, G [39, 80]
AX J1844.8–0256	6.97	-	8.5	G29.6+0.1	candidate, T [160, 142]
SGR 0418+5729	9.1	<1.1 10 ⁻¹³	2	-	T, B [155, 34]
SGR 0501+4516	5.76	7.1 10 ⁻¹²	1.5	-	T, B [131, 4, 30]
SGR 0526–66	8.05	6.5 10 ⁻¹¹	55	LMC, N49	B, GF [95, 93, 149]
SGR 1627–41	2.59	1.9 10 ⁻¹¹	11	-	T, B [165, 103, 37, 32]
SGR 1806–20	7.6	(8–80) 10 ⁻¹¹	8.7	star cluster	B, GF [82, 120, 109, 162]
SGR 1833–0832	7.6	7.4 10 ⁻¹²	10	-	T, B [55, 38]
SGR 1900+14	5.2	(5–14) 10 ⁻¹¹	15	star cluster	B, GF, G? [94, 164, 104]

^(a) in several cases the distances have large uncertainties; the values adopted in the figures of this work are indicated here.

^(b) B = bursts, G = glitches, GF = giant flares, R = radio emission, T = transient

Table 2 Comparison of estimated and spin-down ages of INS

Source	Spin-down age (τ_c)	Estimated age	Method
RX J0720.4–3125	1.9 Myr	$(0.7^{+0.3}_{-0.2})$ Myr	proper motion
RX J1308.6+2127	1.5 Myr	(0.5–1.4) Myr	proper motion
RX J1856.5–3754	3.8 Myr	0.4 Myr	proper motion
1E 1841–045	4.5 kyr	0.5–1 kyr	SNR age
1E 2259+586	230 kyr	(11.7 ± 1.2) kyr	SNR age
SGR 0526–66	2 kyr	5 kyr	SNR age
CXOU J085201.4–461753	>240 kyr	3.7 kyr	SNR age
1E 1207.4–5209	>27 Myr	7 kyr	SNR age
CXOU J185238.6+004020	190 Myr	7 kyr	SNR age

The first spectra of XDINS, obtained with ROSAT, could be well described with blackbody curves. With the better data of XMM and Chandra, significant deviations from this simple model have been detected in most XDINS (the only exception is RX J1856.5–3754 [11]). The features consist of broad absorption lines in the energy range ~ 0.2 – 0.8 keV (see [156, 57] and references therein). Multiple lines, with energy spacings consistent with harmonic ratios, are present in nearly half of the sources. They have been interpreted as proton cyclotron lines or as H and/or He atomic transitions, falling in the soft X-ray range due to the effect of a high magnetic field on the binding energies. Both interpretations require $B \sim 10^{13} - 10^{14}$ G, broadly consistent with the values of 2.5 and $3.4 \cdot 10^{13}$ G derived from the timing parameters of RX J0720.4–3125 and RX J1308.6+2127 assuming dipole braking².

Variability on a time scale of few years was discovered in RX J0720.4–3125 [23], a target regularly observed for XMM calibrations because it was believed to be a constant source. If we exclude AXPs and SGRs, this has been the first INS to show significant changes in its X-ray flux, spectrum and pulse profile. Based on the first observations, it was suggested that the variations had a periodicity of 7.1 ± 0.5 years and could be caused by precession of the neutron star [60]. However, the most recent analysis, which include new observations and take into account the variable phase shifts between hard and soft energy bands, do not support the periodicity [67]. Most of the spectral variation occurred in a relatively short timescale of half a year [157], in coincidence with a possible glitch. A change in the temperature and/or composition of part of the NS surface might have been caused by the energy released in the glitch, or alternatively by a sudden accretion episode.

The other XDINS seem to be constant in flux, but small variations might have been unnoticed since, with the exception of RX J1856.5–3754, they have not been observed very often with sensitive instruments. On the other hand, RX J1856.5–3754

² Note that the lines measure the surface field, which can be higher than the dipole component dominating at large radii and responsible for the spin-down.

is twice as bright as RX J0720.4–3125 and has been observed repeatedly, but no variability has been reported. Interestingly this is the only XDINS without spectral lines [11] and with the smallest pulsed fraction ($\sim 1.5\%$ [151]).

Until recently, attempts to enlarge the XDINS sample had little success. Ongoing searches in the ROSAT Bright Sources Catalogue are reported in [153]. Looking for new INS among the tens of thousands serendipitous XMM and Chandra sources requires a long and difficult multi-wavelength effort, also considering that they are fainter and more distant than the bright M7. One promising source has been selected among XDINS candidates discovered with XMM [127], but its temperature ($kT_{BB}=117$ eV) and estimated luminosity ($\sim 10^{33}$ erg s^{-1}) are larger than those of the M7. The same is true for another candidate, RX J1412.9+7922 [137], for which other interpretations (e.g. a nearby millisecond pulsar) cannot be excluded yet. Its blackbody temperature is $kT_{BB} \sim 200$ eV. A hydrogen atmosphere model ($kT \sim 122$ eV), with a possible emission line at 0.53 keV, gives a better fit to the Chandra data [140]. If the emission comes from the whole star's surface, its distance would be 3.6 kpc, while a smaller emission region and distance should give rise to pulsations. Only the detection of a periodicity could clarify the real nature of these new XDINS candidates.

4 Central Compact Objects in Supernova Remnants

The group of Central Compact Objects (CCOs) consists of several radio quiet X-ray sources located at the center of shell-like SNRs and with high F_x/F_{opt} [124, 19]. The association with SNRs (see Table 1) imply ages at most of a few tens kyrs, and gives the possibility to know their distances. Three CCOs show X-ray pulsations with periods in the 0.1–0.4 s range, consistent with young neutron stars, but with unexpectedly small spin-down rates [51, 62]. The extremely small \dot{P} measured for the CCO in Kes 79 implies a dipole magnetic field of only $3.1 \cdot 10^{10}$ G, while the upper limits for the sources in G296.5+10.0 and Puppis A give $B < 3.3 \cdot 10^{11}$ G and $B < 10^{12}$ G, respectively. The spin-down ages of these three CCOs exceed by orders of magnitude the ages of their associated SNRs (see Table 2), indicating that these INS were probably born with spin periods very close to the current values. It is likely that their relatively long initial spin period and low magnetic field be causally connected. This has led to the "anti-magnetar" nickname for these objects. The three "anti-magnetars" show a variety of different pulse profiles: the CCOs in Kes 79 has a pulsed fraction of $\gtrsim 60\%$, one of the highest among thermally emitting INS [63]. A more standard value of $\lesssim 10\%$ is shown in 1E 1207–5209, but with the peculiarity that most of the pulsation can be attributed to phase variations in the shape of its prominent absorption lines at 0.7, 1.4, 2.1 and possibly 2.8 keV [21]. The pulsations in the Puppis A CCOs eluded an earlier detection because of a phase shift of 180° between nearly sinusoidal profiles in the soft (< 1.2 keV) and hard bands [52].

Most CCOs have thermal-like X-ray emission, with blackbody temperatures in the range ~ 0.2 – 0.5 keV, and no evidence for additional non-thermal components.

The rotational energy loss of the three pulsed COOs is certainly too small to give a detectable contribution to their observed X-rays, assuming a typical efficiency of 10^{-3} . The emission could be due to residual cooling and/or weak accretion from a residual disk.

When data of good statistical quality are available, single-temperature blackbody spectra do not provide acceptable fits. Better fits are obtained with the sum of two blackbodies with kT_1 in the range 0.16–0.4 keV and $kT_2 \sim 2 kT_1$. This simple model can be thought as a first approximation of a non-uniform temperature distribution. The hotter blackbody is energetically significant: the bolometric luminosities of the two components are in the ratio $L_2/L_1 \sim 0.2\text{--}0.7$. The two-blackbody model implies small X-ray emitting areas ($R_1 \sim 0.4\text{--}4$ km, $R_2 \sim 0.06\text{--}0.8$ km), which are difficult to explain in weakly magnetized neutron stars. The situation does not significantly change if atmosphere models, which give lower temperatures and larger radii, are used instead of the blackbody fits.

It is unclear whether also the CCOs with unknown spin period can be interpreted as "anti-magnetars". The lack of pulsar wind nebulae and of radio/gamma emission suggests that also these COOs have a small L_{SD} , but this can result equally well from a small \dot{P} or from a long spin period. Thus it cannot be excluded that CCOs constitute a heterogeneous class comprising objects of different kinds. The source at the center of the ~ 330 years old Cas A SNR is one of the most studied CCOs. It has a very soft spectrum and most spectral fits, with a variety of thermal models, indicate an emitting area smaller than the whole surface of a neutron star. No pulsations have been detected, down to quite stringent limits [110, 122, 62], but an anti-magnetar interpretation remains plausible, considering the possibility of an unfavorable orientation and the variety of pulsed fractions seen in other INS.

On the other hand, the CCO in RCW 103, with a clear periodicity at 6.67 hours and long term variations spanning more than two orders of magnitude [20], has unique properties requiring an ad-hoc explanation. The periodicity, if interpreted as an orbital motion, suggests a low mass binary [20, 10], but the deep optical limits pose severe constraints on the companion star [22]. Models involving magnetars, isolated or in a synchronous binary, and fall-back disks have also been proposed [129, 89].

5 The Magnetar candidates: Anomalous X-ray Pulsars and Soft Gamma-ray Repeaters

Anomalous X-ray Pulsars (AXPs) and Soft Gamma-Ray Repeaters (SGRs) are spinning-down pulsars characterized by a luminosity in the soft and hard X-rays larger than their available rotational energy loss and by the emission of bursts and flares.

The first AXPs, discovered as bright pulsars in the soft X-ray range (< 10 keV), were initially classified as X-ray binaries powered by accretion. Further X-ray data, coupled to deep searches for optical/IR counterparts, revealed their different nature

[108]. In particular, these observations showed that the narrow period distribution, long-term spin-down, and soft spectrum of the AXPs were at variance with the properties of the larger population of pulsars in massive binaries. Furthermore, no signs of binary companions could be found in the AXPs [107].

The SGRs were instead discovered through the detection of bright and short bursts in the hard X-ray/soft gamma-ray range, and initially considered a particular subclass of gamma-ray bursts [86, 5], with the notable property of “repeating” from the same sky direction. When accurate localizations became available, it was possible to identify the X-ray counterparts of SGRs, finding that they are pulsating sources very similar to the AXPs.

Although historically divided in two classes, many similarities indicate that AXPs and SGRs are probably the same kind of astrophysical objects (see [166, 79, 101] for reviews). The most successful model to explain AXPs and SGRs involves highly magnetized neutron stars, or “magnetars” [29, 144, 145], but other possibilities have been proposed, e.g., models based on INS accreting from residual disks [16, 125, 3, 31], or different kinds of quark stars [167, 69, 118, 14].

Magnetars differ from the normal pulsars, not only for their higher field intensity, but also because their magnetosphere is not dipolar. It is believed to consist of a twisted dipole, i.e. a field with a significant azimuthal component. This causes the presence of large-scale currents with high charge density flowing in the magnetosphere and affecting the emerging spectra by resonant scattering.

At energy below 10 keV, the X-ray spectra of AXP and SGRs have been traditionally described with a two-components model consisting of a power-law plus a blackbody with $kT_{BB} \sim 0.5$ keV. The steepness of the power-law component (especially in the AXPs, photon index $\sim 3-4$) requires N_H values higher than those independently estimated in other ways and leads to overestimate the flux of the near infrared and optical counterparts (unless a drastic, and possibly un-physical, spectral cut-off is invoked). This problem is solved by adopting a two-blackbody model, that gives equally good fits [61]. XMM observations of CXOU J010043.1–721134 in the Small Magellanic Cloud, less affected by the interstellar absorption than the Galactic AXPs/SGRs, have clearly demonstrated that the power-law plus blackbody model can be rejected with high confidence, while a good fit to the soft X-ray spectrum is obtained with the sum of two blackbodies [148].

Magnetars have been detected also in the hard X-ray range ($\gtrsim 20$ keV), with INTEGRAL and RXTE. Hard power-law tails, extending to ~ 150 keV, have been seen both in AXPs [84, 25, 24] and SGRs [105, 54, 36, 131]. The hard X-ray emission is pulsed, and gives a luminosity comparable to, and in some cases higher than, that in the soft X-ray band.

Considerable effort is ongoing in the analysis and interpretation of the AXPs and SGRs spectra, in order to progress from purely phenomenological fits to more physical models. The presence of a relatively dense plasma in magnetospheres with a twisted configuration [146] is expected to affect the emergent spectrum through resonant cyclotron scattering (RCS) of the thermal photons emitted by the underlying neutron star’s surface. A simplified model, based on a semi-analytical treatment of these effects [92], has been systematically applied to several magnetar candidates

[133]. This showed that at $E < 10$ keV the RCS model can replace the blackbody plus power-law model (in most sources an additional power-law is still required to fit the hard X-ray tails). More realistic 3-D simulations have also been performed to compute the magnetar's spectral models [41, 117, 116] and quite successfully applied to the spectra of several magnetar candidates [170].

Two possibilities have been proposed to explain the high-energy tails in the context of the twisted magnetosphere model [143]: bremsstrahlung from a thin turbulent layer of the star's surface heated to $kT \sim 100$ keV by magnetospheric currents and synchrotron emission from mildly relativistic pairs produced at a height of ~ 100 km above the neutron star. Compton up-scattering of soft thermal photons, emitted from the star surface, by relativistic electrons threaded in the magnetosphere has also been considered [66, 47, 6].

Compared to all the other INS, AXPs and SGRs stand apart for their striking variability properties. I refer not only to the short bursts and (giant) flares, but also to the so called "persistent" emission, which for historically bright sources varies around 10^{36} erg s^{-1} , while for newly-discovered transients has been seen to span up to five orders of magnitude. About half of the AXPs/SGRs have been always seen at relatively high flux levels since the time of their discovery. They were thought to be steady sources, but, as more sensitive imaging observations became available, it appeared that variations of $\sim 50\%$ on timescales from days to months are quite common. Long term variations are sometimes correlated with changes in the spin-down properties. This is not unexpected in the magnetar model involving variations in the magnetospheric twist angle. For example, the luminosity variations, the correlation between spectral hardness and spin-down rate, and the increase in the bursting activity observed before the 2004 giant flare of SGR 1806–20 [109] are consistent with

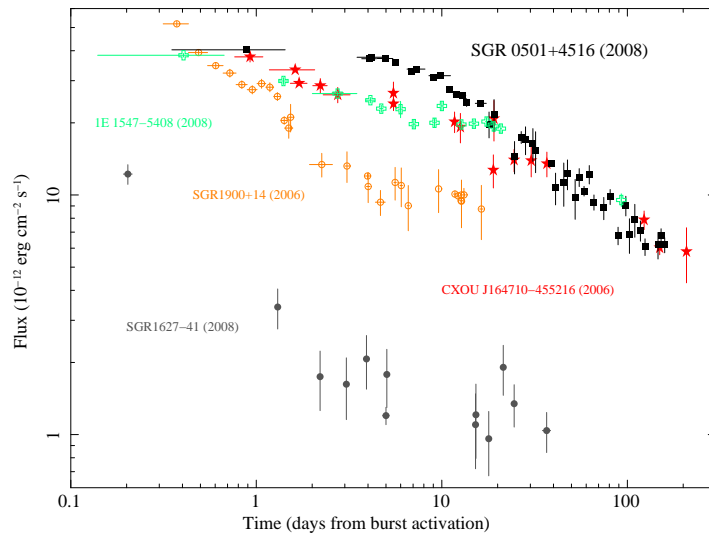


Fig. 2 X-ray light curves of outburst decays observed in several AXPs and SGRs (from [131]).

a gradually increasing magnetospheric twist angle. This gives rise to a larger optical depth for resonant scattering (causing a hardening of the X-ray spectrum), a higher rate of crustal fractures (responsible for the bursts), and a faster spin-down (because of the larger fraction of field lines that open out across the speed of light cylinder). The spectral softening and the decrease in the flux and spin-down rate observed after the giant flare [132, 150] are also consistent with this picture, suggesting a twist angle reduction as consequence of the global magnetic rearrangement following the giant flare.

The first transient AXP, XTE J1810–197, was serendipitously discovered during the decay phase of an outburst in 2003 [70]. Comparison of the highest observed luminosity with archival data, showing a faint soft source with $L_x \sim 10^{33} \text{ erg s}^{-1}$, indicated a dynamic range of two orders of magnitude. Several other transient AXP/SGR have been discovered after XTE J1810–197 (see Table 1). When bright, their spectral and timing properties are similar to those of the persistent sources. During their low (or “quiescent”) states they have luminosity of $\sim 10^{32} \text{ erg s}^{-1}$ and soft thermal spectra, that make them similar to the CCOs.

Transient AXPs/SGRs now outnumber the persistent members of the class, and their number will certainly increase in the future. It is difficult to estimate how many AXP/SGRs are present in the Galaxy, because the duty cycle of transient magnetars is poorly known. At least two sources have shown more than one outburst (SGR 1627–41 in 1998 and in 2008 [35]; 1E 1547.0–5408 in Summer 2007 [64] and 2008–2009 [106]), but other events might have been missed. In fact the rate of discoveries of new transients has increased in the latest years, thanks to the presence of satellites with large field of view and continuous sky monitoring, like Fermi and Swift. These new data revealed a variety of behaviors for what concerns the outburst evolution of the different sources, as shown by the examples plotted in Fig. 2. Poorly sampled light curves can be roughly described by power-law decays with a variety of slopes, while the well sampled light curves show that the time decay is initially steeper and flattens after about one day. This could indicate the presence of two different mechanisms operating on different timescales, e.g. dissipation of magnetospheric currents followed by cooling of the star’s crust. Re-brightenings, or “bumps”, superimposed on the decaying trends have also been observed, for example in SGR 1900+14 [42].

The observation of outburst decays, and, more in general, of the spectral and flux variability of transient AXPs/SGRs, has the potential to greatly advance our understanding of neutron stars. For example, detailed studies of the long term spectral evolution have been reported for XTE J1810–197 [50, 9]. However some caveats should be remembered when interpreting the observational data. Often the observations have a poor and irregular time sampling, especially in the initial and possibly more variable phases, and/or are obtained with different instruments. This reduces the possibility of determining correlations between the different energy ranges in a robust way. At late times, when the fluxes are small, spectral uncertainties can be significant, also in view of the bolometric corrections required by the high interstellar absorption. Furthermore, the observed fluxes most likely result from the superposition of various physical components with different variability behaviors and

difficult to disentangle. Part of these problems will be reduced when broad-band, sensitive instruments able to react in a short time to the discovery of new transient events will become available.

6 Rotating Radio Transients

New techniques of analysis for transient radio signals, applied to data of the Parkes Multibeam Survey, have led to the discovery of Rotating Radio Transients (RRATs) [99]: neutron stars which emit short (2-30 ms) radio pulses at intervals of minutes to hours. Their rotation periods, ranging from 0.4 to 7 s, have been inferred from the largest common divisors of the time intervals between bursts. RRATs are probably a large galactic population, that remained undiscovered for a long time due to lack of adequate radio searches, but their relation to other classes of INS is unclear (see [97] for a review).

The radio properties of RRATs show analogies with those observed in some peculiar radio RPP, and they might represent extreme cases of some of these phenomena. On the other hand, their long rotation periods, and the fact that transient radio emission has been observed in a couple of AXPs [13, 12], suggest a possible relation with magnetars. The period derivatives, determined to date for only $\sim 6-7$ of the nearly twenty known RRATs [98], indicate magnetic fields above 10^{13} G only in about half of the cases (see Fig. 1).

PSR J1819–1458 is the only RRAT that has been detected at X-ray energies [135]. It has a luminosity of $\sim(2-5) 10^{33}$ erg s^{-1} (for $d=3.6$ kpc) and its X-ray emission is pulsed at the rotation period of 4.26 s. The light curve is nearly sinusoidal, with a pulsed fraction of about 35%. The spectrum, well fit by a blackbody ($T_{BB} \sim 0.14$ keV) plus a possible feature around 1 keV [100], indicates that the emission is of thermal origin (the luminosity is subject to the distance uncertainty, but most likely larger than $L_{SD}=3 10^{32}$ erg s^{-1}). A Chandra observation has shown evidence for diffuse X-ray emission surrounding PSR J1819–1458 [134]. If this nebula is powered by the rotational energy of the RRAT, an efficiency of $\sim 20\%$, much higher than that of all the other pulsar wind nebulae, is required. This discrepancy could be reduced by a smaller distance, or by invoking a shock caused by a large spatial velocity of PSR J1819–1458, but the possibility that magnetic energy contributes to power the observed diffuse emission has also been proposed [134].

X-ray upper limits at a level much smaller than the flux of PSR J1819–1458 have been reported for other two RRATs [75]. If the X-ray emission from RRATs is simply due to cooling, this could be caused by a larger age of these two objects (their spin-down ages are 0.4 and 0.8 Myr, compared to $\tau_{SD}=0.1$ Myr for PSR J1819–1458). However, the significant uncertainties on distance and absorption prevent a firm conclusion.

Table 3 Rotation Powered Pulsars with $B > 4 \cdot 10^{13}$ G.

Name	Period (s)	\dot{P} (s s ⁻¹)	B (G)	L_x (erg s ⁻¹)
J1847–0130	6.7	$1.3 \cdot 10^{-12}$	$9.4 \cdot 10^{13}$	$< 5 \cdot 10^{33}$
J1718–3718	3.4	$1.6 \cdot 10^{-12}$	$7.4 \cdot 10^{13}$	$6 \cdot 10^{33}$
J1814–1744	4.0	$7.5 \cdot 10^{-13}$	$5.5 \cdot 10^{13}$	$< 2 \cdot 10^{33}$
J1734–3333	1.2	$2.3 \cdot 10^{-12}$	$5.2 \cdot 10^{13}$	–
J1846–0258	0.3	$7.1 \cdot 10^{-12}$	$4.9 \cdot 10^{13}$	$4 \cdot 10^{34}$ in SNR Kes 75
J1119–6127	0.4	$4.0 \cdot 10^{-12}$	$4.1 \cdot 10^{13}$	$3 \cdot 10^{33}$ in SNR G292.2–0.5

7 Rotation-powered pulsars with high magnetic field

Table 3 lists all the RPP for which the timing parameters indicate a dipolar field greater than, or close to, the quantum critical value $B_c = \frac{m^2 c^3}{\hbar e} = 4.4 \cdot 10^{13}$ G. Most of them have spin periods of a few seconds and in the P- \dot{P} diagram lie in the same region of the AXPs/SGRs. However, these four pulsars do not show magnetar characteristics, such as the production of bursts/flares or particularly strong and variable emission. In fact their X-ray luminosity is smaller than L_{SD} [128], as expected for standard RPP.

The situation is quite different for the young PSR J1846–0258, located in the supernova remnant Kes 75. In this 0.3 s pulsar, the high inferred B derives from its large \dot{P} , the highest of all RPPs. Its spin-down luminosity of $8 \cdot 10^{36}$ erg s⁻¹ is certainly sufficient to power the X-ray emission observed from the pulsar, $L_X = 2.6 \cdot 10^{34}$ (d/6 kpc)² erg s⁻¹, and from the associated pulsar wind nebula, $L_{PWN} = 1.4 \cdot 10^{35}$ (d/6 kpc)² erg s⁻¹ [115]. Thus the discovery of magnetar-like activity from PSR J1846–0258 was quite surprising, because this pulsars was considered a *bona-fide* RPP, despite the lack of a radio detection (easily explained as due to an unfavorable orientation). Four short bursts from PSR J1846–0258 were seen with RXTE on May 31, 2006 [45]. The onset of the bursting activity was coincident with a large spin-up glitch and with the beginning of an enhancement in the pulsed X-ray flux which lasted about one month [91]. Spectral and flux variations associated with this event were seen also in the hard X-ray range [83].

PSR J1119–6127 [48, 138], has timing parameters very similar to those of PSR J1846–0258, and, like the latter, it is located in a young SNR (G 292.2–0.5) and is surrounded by a pulsar wind nebula. Its X-ray emission shows a large pulsed fraction and a spectrum consisting of a thermal-like component with temperature $kT_{BB} \sim 0.2$ keV and a hard power-law. The strong thermal emission, quite remarkable for a young pulsar, might be the result of some recent magnetar-like activity, similar to that observed in PSR J1846–0258. It would be important to monitor this pulsar, and other RPP with similar parameters, to look for bursts.

8 Conclusions

X-ray observations have revealed an unexpected variety of manifestations of INS. The thermal components in these objects span more than four orders of magnitude in luminosity (see Fig. 3), with a dependence on temperature broadly consistent with the blackbody relation $L \propto T^4$ for objects of similar size. The observed spectral and timing properties indicate that different energy sources, besides the obvious cooling of the primeval internal heat, are at play in powering such thermal-like components.

The effects of a strong and dynamic magnetic field are especially evident in the paroxysmic behavior of SGRs and AXPs, but it is also possible that the variability observed in the XDIN RX J0720.4–3125 be due to changes in the magnetic field configuration, and certainly the magnetic field plays an important role in the thermal evolution of INS. This is well demonstrated by the relatively high surface temperatures of XDINS. It is now clear that at least a fraction of the enigmatic CCOs are young pulsars with very weak magnetic fields. However, also in these sources, localized regions of stronger field might be present and be responsible for the small emitting areas inferred from the spectral fits.

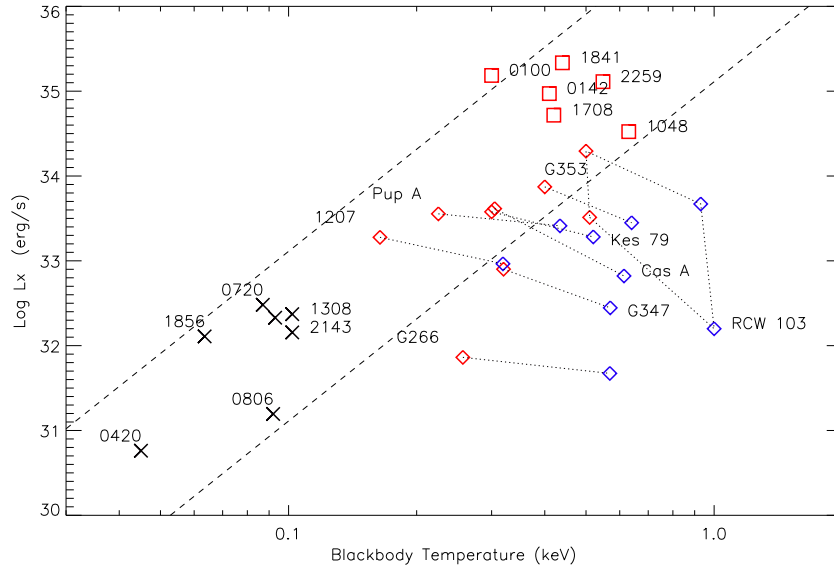


Fig. 3 Temperature-Luminosity diagram for different classes of INS (XDINS (\times), CCO (\diamond), persistent AXP (squares)). For the sake of uniformity, all the temperatures are from blackbody fits (model atmospheres generally yield values smaller by a factor $\sim 2-3$). For the CCO the luminosities and temperatures of the two-blackbody fits are indicated. For RCW 103 the figure shows two intensity states. In AXPs the contribution to the luminosity from the power-law spectral components are neglected. The lines indicate the blackbody relations for emitting radii of 1 km and 10 km.

The magnetar-like behavior of PSR J1846–0258, together with the recent discovery of PSR J1622–4950 [88], the first "radio-selected" magnetar, point to a closer connection between radio pulsars and magnetars than previously thought. It is also noteworthy that SGR 0418+5729, one of the most recently discovered SGRs, has an inferred (dipolar) field smaller than $\sim 3 \cdot 10^{13}$ G.

The data collected in the latest years, besides enlarging the sample of INS, are leading to recognize objects with "intermediate" properties. While this makes the boundaries between the different INS classes less well defined, it gives the prospects of unifying in a global coherent picture all the varieties of INS manifestations.

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