Abstract The high-energy sources known as anomalous X-ray pulsars (AXPs) and soft γ-ray repeaters (SGRs) are well explained as magnetars: isolated neutron stars powered by their own magnetic energy. After explaining why it is generally believed that the traditional energy sources at work in other neutron stars (accretion, rotation, residual heat) cannot power the emission of AXPs/SGRs, I review the observational properties of the twenty AXPs/SGRs currently known and describe the main features of the magnetar model. In the last part of this review I discuss the recent discovery of magnetars with low external dipole field and some of the relations between AXPs/SGRs and other classes of isolated neutron stars.

Keywords Neutron stars · Magnetars

1 Introduction

The relevance of magnetic energy in powering the emission from neutron stars (NSs), suggested more than four decades ago [15], has been well established with the discoveries of anomalous X-ray pulsars (AXPs) and soft gamma-ray repeaters (SGRs). These are spinning-down, isolated NSs characterized by the emission of powerful bursts and flares and with luminosities in the soft and hard X-rays greater than their rotational energy loss.

Historically, AXPs and SGRs were divided into two distinct classes reflecting the way they were discovered, but many observations indicate that there are no substantial differences between them. Most AXPs were discovered as bright pulsars in the soft X-ray range (<10 keV) and initially not distinguished from the more numerous population of X-ray binaries powered by accretion. It was then pointed out that their narrow period distribution, long term spin-down, soft X-ray spectrum and faint optical counterparts were at variance with the properties of pulsars in massive binaries [14].

SGRs were instead discovered in the hard X-ray/soft γ-ray range through the observation of bright and short bursts and classified as a subclass of gamma-ray bursts [116], with the notable property of “repeating” from the same sky direction. When the persistent X-ray counterparts of SGRs were identified, it was found that they are pulsating sources very similar to the AXPs.

Even though alternative interpretations have been proposed, the model involving magnetars, i.e. highly magnetized NSs, is the one that most successfully explains the properties of AXPs and SGRs and is currently widely accepted. According to the magnetar model, the emission from these sources is ultimately powered by the energy stored in their strong magnetic fields, which reach B~ $10^{13} - 10^{15}$ G in the magnetosphere, and likely even higher values in the NS interior. This sets them apart from most other NSs which are powered by rotational energy, accretion, or residual heat.

In the last few years it has been realized that the observational distinction between magnetars and other NSs is not as sharp-cut as previously considered and not solely based on the magnetic field intensity. This was already suggested by the existence of some radio pulsars with inferred values of B overlapping those of AXPs/SGRs, but which never showed bursts, flares or other signs of magnetically-powered emission. The recent dis-
covery of NSs that, despite their relatively low external dipole fields, can certainly be classified as AXPs/SGRs based on their outburst properties, indicates that the important discriminant is most likely related to the strength and geometry of the magnetic field in the NS interior, which unfortunately is less prone to direct estimates.

In the first part of this paper I briefly describe why it is believed that the energy sources which are seen to operate in other NSs cannot power the emission of AXPs/SGRs. The two following sections are devoted to the observational properties of these sources (Section 3) and the main features of the magnetar model (Section 4). The discovery and implications of magnetars with low dipole field and possible relations of AXPs/SGRs with other classes of isolated NSs are discussed in the last two sections. For other reviews on these sources see [206, 103, 133, 189].

2 Why a different energy source?

2.1 Rotation

The rotational energy of a NS with spin period $P=2\pi/\Omega$ is $E_{rot}=I\Omega^2/2=2\times10^{46}I_{15}P^{-2}$ erg, where $I=1.45\times10^{45}$ g cm$^2$ is the star moment of inertia. Soon after the discovery of pulsars it was found that their spin periods are increasing, implying a loss rate of rotational energy, $\dot{E}_{\text{rot}}$, sufficiently high to power not only the pulsed radio emission, but also the bright radio/optical/X-ray nebulae observed around the most energetic pulsars. The first striking example was provided by the pulsar PSR B0531+21, whose $\dot{E}_{\text{rot}}=4.6\times10^{38}$ erg s$^{-1}$ matches the total energy output of the surrounding Crab nebula. Most of the spin-down power is lost in a Poynting-dominated wind rather than in beamed photons from the pulsar. Despite the majority of rotation-powered pulsars is observed at radio wavelengths (over 2,000), their energy output in this band is only a very small fraction of $\dot{E}_{\text{rot}}$. The efficiency is higher in the X-ray band, where non-thermal emission is observed in about one hundred pulsars, with an average efficiency $\sim10^{-3}$, but with a large dispersion around this value [158, 119].

At $\gamma$-ray energies the efficiency approaches 100% for middle aged-pulsars (at these high values it is important to specify the solid angle of the radiation beam used in computing the efficiency).

AXPs/SGRs have period derivatives $\dot{P}$ larger than those of radio PSRs, but their long periods lead to values of $\dot{E}_{\text{rot}} \sim 10^{32} - 10^{34}$ erg s$^{-1}$, too small to power their luminosity. This is a robust conclusion, even when luminosity uncertainties deriving from the poorly known distances of some AXPs/SGRs are considered, and it rules out the possibility of interpreting these sources as rotationally powered NSs.

Of course, the energy budget argument to rule out rotation-powered emission does not apply if one assumes that AXPs/SGRs are isolated white dwarfs. Due to its higher moment of inertia, a rotating white dwarf has a spin-down power $10^5 - 10^6$ times larger than that of a NS for the same $P$ and $\dot{P}$ values. This idea was first proposed for 1E2259+586, a 7 s X-ray pulsar at the center of the supernova remnant CTB109 [144], which attracted attention well before the recognition of the AXPs as a separate class of objects [147]. Other authors proposed models for AXPs/SGRs based on white dwarfs [191, 126], but these are challenged by the short spin periods observed in some objects and by the deep upper limits on the optical counterpart of SGR 0418+5729 [37].

2.2 Accretion

Mass accretion is a well-established process in X-ray binaries. The first extra-solar X-ray source, Sco X-1, discovered in the rocket experiment that marked the beginning of X-ray astronomy 50 years ago [62], is an accreting NS [3]. We now know several hundreds accretion-powered NSs in our Galaxy, as well as in other galaxies. All of them are accreting matter provided by their companion stars in binary systems.

Some of the X-ray sources now belonging to the AXP group were once believed to be powered by accretion from a binary companion, the most natural explanation at that time, based on analogy with the other X-ray pulsars. However, deep observations in the optical and near infrared (NIR) failed to detect the luminous counterparts expected if these pulsars were in high-mass binaries. Furthermore, X-ray timing studies did...
not show the orbital Doppler shifts expected for binary motion, ruling out also low-mass systems [13,199]. Optical/NIR counterparts have now been firmly identified (on the basis of correlated variability), or proposed (on the basis of accurate positional coincidence) for several AXPs/SGRs. In most cases they are sufficiently faint to rule out normal companion stars and the presence of accretion disks. In three sources (see Table 1) the optical emission is modulated at the period observed at X-rays, implying that it comes from the same rotating object and not from a binary companion.

All these findings strongly indicate that AXPs/SGRs are isolated NSs. They could be powered by accretion only if matter is provided either by the interstellar medium (ISM) or by a disk of fall-back material produced in the supernova explosion from which the NS originated. The former possibility is ruled out because, for typical NS velocities and ISM densities, the resulting accretion rate is too small. Models invoking residual disks around isolated NSs are instead more plausible and represent the most widely discussed alternative to the magnetar interpretation [22,40,187]. In this class of models various mechanisms for the disk formation and different origins for the observed X-ray luminosity have been considered. The interaction with the fossil disk is also invoked to account for the observed long periods and rapid spin-down values. According to [2], who proposed a scenario which unifies the different classes of isolated NSs, the initial properties of a fall-back disk are among the fundamental parameters that determine the fate of a NS.

The main objection to models based on accretion onto isolated NSs is that they cannot easily account for the bursts and flares observed in AXPs/SGRs, thus requiring some additional mechanism and/or energy source to explain these phenomena. One possibility, often considered in so-called “hybrid models”, is that the strong magnetic field powering the bursts is not dipolar, but it is only present in higher order multipoles dominating near the NS surface. They differ from the magnetar model because accretion is invoked to explain the AXPs/SGRs persistent X-ray emission.

2.3 Residual heat

At birth, NSs have internal temperatures of \( \sim 10^{11} \) K at birth, that rapidly drop to \( \sim 10^6 \) K. The dominant cooling mechanism for the following \( \sim 10^5 - 10^6 \) years is neutrino emission from the star’s isothermal core. This leads to surface temperatures of several \( 10^5 \) to \( 10^6 \) K, with emission peaking in the soft X-ray band (see, e.g., [208]). Temperature gradients on the star’s surface modulate the observed flux at the rotation period.

Thermal X-ray emission can be detected in isolated NSs with ages of \( \sim 10^4 - 10^6 \) years, provided they are sufficiently close and the X-rays not too absorbed by the ISM. Older NSs are too cool to significantly emit in the X-rays band, while in the youngest pulsars the thermal radiation is difficult to detect because it is outshined by the brighter non-thermal emission powered by \( \dot{E}_{\text{rot}} \).

There are two relevant observational properties of AXPs/SGRs that cannot be explained resorting only to the NS thermal energy content: (i) the production of a variety of strongly variable and energetic events, ranging from short bursts to giant flares flares, and (ii) the presence of hard tails in the spectra of the persistent emission. Short bursts of hard X-rays, historically the defining characteristics of SGRs, have now been observed in virtually all the AXPs. Their durations (\( \sim 0.01 - 1 \) s), hard spectra (characteristic temperatures \( \sim 30 - 40 \) keV) with little or no spectral evolution, and high peak luminosity (up to \( \sim 10^{42} \) erg s\(^{-1} \)) cannot be explained by the emission of the NS residual heat.

Persistent emission with power-law spectra extending up to hundreds of keV has been discovered with INTEGRAL in several AXPs/SGRs [113,111,71]. The luminosity in these (pulsed) hard tails is a significant fraction of the total energy output from AXPs/SGRs and requires the presence of non-thermal phenomena in their magnetospheres.

2.4 Magnetic energy

As discussed above, the main powering mechanisms\(^6\) at work in other kinds of NSs have problems to explain the properties of AXPs/SGRs. This motivated interest in the alternative proposal of a magnetically-powered emission and led to the development of models based on magnetars [36,176,180].

The magnetic energy of a NS with field \( B_{15}=10^{15} \) G filling its entire volume is \( 3 \times 10^{47} B_{15}^2 \) erg (for a NS radius of 12 km). This is enough to power a luminosity of \( \sim 10^{35} \) erg s\(^{-1} \) for \( \sim 10^5 \) years, a plausible age for AXPs/SGRs, considering their frequent association with supernova remnants (SNRs) or young clusters of massive stars.\(^7\) Slightly higher fields and/or long-lasting episodes with low luminosity (as in transients) make the

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\(^6\) Another energy source is provided by nuclear reactions. This powers the type I bursts observed in many accreting low mass X-binaries. The properties of SGR bursts are very different from those of type I bursts.

\(^7\) The giant flares (section 3.1) in which up to \( \sim 10^{46} \) ergs can be released, are energetically more challenging. This limits the number of such events that a magnetar can emit in its lifetime.
energy budget adequate for all the magnetar candidates observed to date.

There are several pieces of evidence that indicate the presence of a high magnetic field in AXPs/SGRs. The conventional way to estimate the magnetic field of isolated NSs is based on the relation

\[ B_d = 3.2 \times 10^{19} \sqrt{\frac{P}{\dot{P}}} \ G \]  

(1)

which gives the dipolar field as a function of the spin period and its time derivative\(^8\). This relation is based on the simplified and unrealistic assumption that the observed spin-down is caused by the emission of a rotating dipole in vacuum (with orthogonal magnetic and rotation axes). More realistic models of the NS magnetosphere give values within a factor of two from the previous expression (e.g., [169]).

Equation (1) yields for the AXPs/SGRs magnetic fields higher than those of typical radio pulsars and up to \( B_d \sim 10^{15} \) G (see Table 2). Although often quoted as the evidence that these objects are magnetars, this argument by itself is rather weak and subject to criticism. For example, other processes, such as the ejection of a wind of relativistic particles, can contribute to the observed torque [79].

Indeed, the evidence for strong magnetic fields powering the AXPs/SGRs, supported by Eq. (1), comes from several concurring observations, of which the most compelling are related to the extreme properties of the giant flares of SGRs. Giant flares start with a short, extremely bright spike, lasting a fraction of a second, during which photons reaching MeV energies are emitted with a hard spectrum. This is followed by a tail with a softer spectrum, lasting several minutes and pulsed at the NS rotation period. The short duration of the initial spikes is consistent with the propagation time of the magnetic instability over the whole NS surface with Alfvén speed [172]. The confinement of the hot plasma responsible for the pulsating tails requires the presence of a strong magnetic field, and sets a lower limit of the order of a few \( 10^{14} \) G on its intensity. Although only three giant flares have been observed, the sources which showed such rare events are, for what concerns all the other properties, undistinguishable from the other SGRs/AXPs.

Other motivations for a high magnetic field come from the short bursts, which have now been detected from almost all AXPs/SGRs. The peak luminosity of the bursts exceed by a few orders of magnitude the Eddington limit for a NS. This is possible because the intense magnetic field affects electron scattering, which becomes strongly anisotropic and dependent on the photon polarization mode. The cross section of the extraordinary mode \((\vec{E} \cdot \vec{B} = 0)\) photons with angular frequency \( \omega \) is reduced by a factor \((\epsilon B/\omega m_e c)^2\) with respect to the Thomson value. As a consequence the radiative flux can exceed the classical Eddington limit in the presence of a strong magnetic field.

Another evidence for very high magnetic fields in SGRs has been pointed out by [192], who considered the high-frequency quasi periodic oscillations (QPOs) observed during the giant flare of SGR 1806–20. The QPOs at 625 and 1840 Hz involved extremely large and rapid luminosity variations, with \( \Delta L/\Delta t \) as large as several \( 10^{43} \) erg s\(^{-2}\). This value exceeds the luminosity-variability limit \( \Delta L/\Delta t < \eta 2 \times 10^{42} \) erg s\(^{-2}\), where \( \eta \) is the efficiency of matter to radiation conversion [21]. The relativistic effects, generally invoked to circumvent this limit (e.g. in blazars and gamma-ray bursts) are unlikely to be at work in the SGR QPO phenomenon. [195] instead propose that the Cavallo-Rees limit does not apply thanks to the reduction in the photon scattering cross section induced by the strong magnetic field. In this way a lower limit of \( \sim 2 \times 10^{15} \) G (10 km/\( R_{NS} \))^3 \((0.1/\eta)^{1/2}\) for the surface magnetic field is derived.

### 3 Observational properties

Twenty confirmed AXPs/SGRs are currently known (Table 1). With the exception of SGR 0526–66 and CXO J0100–7211, which are in the Magellanic Clouds, all of them are Galactic sources distributed at low latitudes in the Galactic plane. Although precise distances are generally not available, their spatial distribution points to typical distances of several kiloparsecs. This is confirmed by the associations with SNRs which have been proposed for several AXPs/SGRs. The most reliable ones, i.e. those of the AXPs/SGRs located at (or close to) the center of the remnant, are indicated in Table 1. Three sources are likely located in clusters of massive stars (marked as MSC in Table 1), suggesting that magnetars are formed in the collapse of very massive stars. The associations with SNRs and young star clusters, as well as their distribution in the Galactic plane, indicate that AXPs/SGRs are relatively young NSs.

AXPs/SGRs have spin periods in the range 2–12 s and positive period derivatives between \( 10^{-12} \) and \( 10^{-10} \) s\(^{-1}\) (Table 2), with few notable exceptions discussed below. Their spin-down is not uniform: they are affected by timing noise and large variations of \( \dot{P} \) on short timescales have been observed in a few cases. Many AXPs/SGRs, for which accurate timing measurements spanning months or years could be obtained,
showed spin-up glitches with values of $\Delta P$ in the same range of those of rotation-powered pulsars, despite their longer periods. The glitches are sometimes associated to changes in the emitted radiation (e.g. bursts, variations in the flux or pulse profile), but there is no simple one-to-one correlation between timing and radiative events. Glitches apparently not associated with bursts and/or flux variations, and vice versa, have been observed [34, 201, 157]. A spin-down glitch (i.e. $\Delta P > 0$, contrary to the usual situation) might have occurred during the August 1998 giant flare of SGR 1900+14 [204], although it is also possible that the observed period change was due to a strong increase in the spin-down before, or immediately after, the flare rather than to a glitch.

Half of the AXPs/SGRs are persistent X-ray sources, i.e. they have always been detected at a nearly constant X-ray luminosity of $\sim 10^{35} - 10^{36}$ erg s$^{-1}$. The other ones, most of which were discovered in the latest years during bright outbursts generally associated to the emission of short bursts, can be classified as transient sources. When bright, their X-ray spectra, luminosity and pulse profile have the same properties seen in the persistent AXPs/SGRs. The decays from the outburst can have different duration and shape and are generally characterized by a spectral softening [159]. In quiescence, luminosities as low as $\sim 10^{31}$ erg s$^{-1}$ have been observed. The outburst duty cycle of transient AXPs/SGRs is still poorly known: multiple out-

### Table 1

| Location/association | X-rays $>10$ keV | X-rays $<10$ keV | Opt. | NIR | MIR | Radio D (kpc) | $N_H$ (cm$^{-2}$) | References |
|----------------------|-----------------|-----------------|------|-----|-----|--------------|-----------------|-------------|
| 1E 1048.1−5937       | D?              | P               | P    | D   | -   | 6            | 6 $10^{21}$     | [118, 140, 33, 95, 184] |
| 1E 1547.0−5408       | P               | P, T            | -    | D   | -   | 5            | 5 $10^{22}$     | G327.24−0.13 [61, 78, 17, 99, 100, 185] |
| 1E 1841−045          | P               | P               | -    | D?  | -   | 8.5          | 2.3 $10^{24}$   | Kes 73 [194, 113, 175] |
| 1E 2259+586          | -               | P               | -    | D   | D   | 3.2          | 10^{22}         | CIB 109 [140, 85, 101, 106] |
| IRX J1708−4009       | P               | P               | -    | D?  | -   | 3.8          | 1.4 $10^{22}$   | [175, 172, 30, 165] |
| 4U 0142+61           | P               | P               | P    | D   | D   | 3.6          | 5 $10^{24}$     | [140, 31, 86, 105, 197, 164] |
| CXO J0100−7211       | -               | P               | -    | -   | -   | 61           | 6 $10^{20}$     | SMC [115, 182] |
| CXO J1647−4552       | -               | P, T            | -    | -   | -   | 3.9          | 1.3 $10^{22}$   | MSC [145, 94] |
| CXO J1714−3810       | -               | P               | -    | -   | -   | 13.2         | 2.5 $10^{22}$   | CTB 57B [77, 181] |
| PSR J1622−4950       | -               | D, T            | -    | -   | -   | P            | 9               | G533.9+0.0 [117, 5] |
| SGR 0418+5729        | -               | P, T            | -    | -   | -   | 2            | 1.1 $10^{21}$   | [192, 45] |
| SGR 0501+4516        | P               | P, T            | P    | P   | -   | T            | 1.5            | [61, 163, 6, 32, 39] |
| SGR 0526−66          | -               | P               | -    | -   | -   | 55           | 5 $10^{24}$     | LMC, N49 [183] |
| SGR 1627−41          | -               | P, T            | -    | -   | -   | 11           | 9 $10^{24}$     | [205, 48, 42] |
| SGR 1806−20          | D               | P               | -    | D   | T   | 10           | 6 $10^{24}$     | MSC [107, 136, 92] |
| SGR 1833−0832        | -               | P, T            | -    | -   | -   | 10           | 7 $10^{23}$     | [71, 44] |
| SGR 1900+14          | D               | P               | -    | D?  | -   | T            | 15             | 2 $10^{24}$     | MSC [79, 88, 175] |
| Swift J1822−1606     | -               | P, T            | -    | -   | -   | 5            | 2 $10^{24}$     | [122, 141, 162] |
| Swift J1834−0846     | -               | P, T            | -    | -   | -   | 5            | 1.3 $10^{24}$   | W41 [102, 49] |
| XTE J1810−197        | -               | P, T            | D    | -   | P   | 3.1          | 6 $10^{24}$     | [89, 98, 18, 67] |
bursts have been observed only in SGR 1627–41 and 1E 1547.0–5408 [46, 11].

The X-ray spectra of AXPs/SGRs are rather soft below 10 keV and, with only few exceptions, strongly affected by the interstellar absorption at low energy. They are generally fit with two-component models consisting of a blackbody of temperature $kT_{BB} \sim 0.5$ keV plus a power-law (photon index $\Gamma \sim 2$–4) or another blackbody. Many AXPs/SGRs have been detected also in the hard X-ray range, with power-law tails extending up to $\sim 100$–$200$ keV. These hard tails are pulsed, often time-variable, and contribute a significant fraction of the total luminosity. The upper limits in the MeV region require the presence of a spectral cut-off. No detections at higher energies have been reported with $\gamma$-ray satellites (Fermi, AGILE) or ground based Cherenkov telescopes.

Although searches for optical counterparts are difficult due to the high absorption and crowded fields, faint optical and/or NIR counterparts have been identified for several AXPs/SGRs. They have $K$ band magnitudes of $\sim 20$–$22$, which sometimes vary showing either a flux correlation or anti-correlation with the X-rays. Pulsations at the NS spin period have been observed in the optical emission of three sources. In general the optical/NIR fluxes lie above the extrapolation of the blackbody-like X-ray spectra. It should be kept in mind that such fluxes are dependent on the assumed reddening and, therefore, subject to significant uncertainties. A notable exception is provided by SGR 0418+5729 which is located in the Galactic anticenter direction at a relatively high latitude compared to the other AXPs/SGRs (b=+5°). Deep observations with the Hubble Space Telescope provided limits of $\sim 28.6$ and $27.4$ on the magnitudes of its possible counterparts in the $V$ and $J$ band, respectively [32]. These rule out models involving isolated white dwarfs with realistic temperatures.

Detections in the mid infrared (MIR) band have been obtained for 4U 0142+61 at 4.5 and 8 µm [197] and for 1E 2259+586 at 4.5 µm [101] with the Spitzer Space Telescope. They have been interpreted as evidence for a residual disk of debris from the supernova, irradiated and heated by the magnetar’s X-ray flux, but not contributing to the X-ray emission by accretion [9].

Two different phenomena have been observed in AXPs/SGRs at radio wavelengths: variable emission related to the ejection of relativistic matter during giant flares (see Section 3.1) and pulsed emission in XTE J1810–197, 1E 1547.0–5408 and PSR J1622–4950. The fact that these three sources are transients led to the speculation that the mechanisms responsible for the pulsed radio emission in AXPs/SGRs might be related to their transient nature. However, no radio detections of all the other transient AXPs/SGRs have been obtained yet. The pulsed radio emission of AXPs/SGRs is quite different from that of radio pulsars: they show strong variability on daily timescales, their spectra are very flat with $\alpha > 0.5$ (where $S_\nu \propto \nu^\alpha$), and their average pulse profiles change with time [22, 17, 19]. Such differences suggest that the radio emitting regions are more complex than the dipolar open field lines along which the radio emission in normal pulsars is thought to originate. The extremely precise positional measurements affordable through radio interferometry has made it possible to derive proper motions: $13.5 \text{ mas yr}^{-1}$ for XTE J1810–197 [90] and 9 mas yr$^{-1}$ for 1E 1547.0–5408 [20]. For the distances given in Table I the implied transverse velocities are of $190 \text{ km s}^{-1}$ and $230 \text{ km s}^{-1}$, respectively, well in the range of those of radio pulsars.

3.1 Bursts and flares

AXPs/SGRs are characterized by highly variable radiative phenomena spanning a wide range of time scales and luminosities: from the short bursts of soft $\gamma$-rays, which led to the discovery of the SGRs, to the extremely energetic giant flares, observed to date in only three sources, SGR 0526–66 (March 5, 1979; [130]), SGR 1900+14 (August 27, 1998; [87]), and SGR 1806–20 (December 27, 2004; [151, 137]).

The typical short bursts have peak luminosity of $10^{38}$–$10^{42}$ erg s$^{-1}$ and durations in the range $\sim 0.01$–1 s, with a lognormal distribution peaking at $\sim 0.1$ s. They usually consist of single (or a few) pulses with fast rise time and slower decay. The bursts can occur sporadically, separated by long time periods, or in groups of tens or hundreds concentrated in a few hours. The periods of high bursting activity are often associated to enhancements of the persistent emission (outbursts) of transient AXPs/SGRs, but there are also cases in which only one or a few isolated bursts have been observed, both in transient and persistent sources. The bursts fluences span the range from a few $10^{-10}$ to $10^{-4}$ erg cm$^{-2}$, and follow a power law distribution [74, 85]. The burst spectra in the hard X-ray range (above $\sim 15$ keV) are well fit by optically thin thermal bremsstrahlung models with temperature $kT \sim 30$–$40$ keV. When also lower energy data are included, a model consisting of the sum of two blackbody functions, with temperatures $kT_1 \sim 2$–$4$ keV and $kT_2 \sim 8$–$12$ keV, provides a better description of the burst spectra [51, 149, 47, 100].

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9 See [31] for a different interpretation in terms of an accretion-based model.
Giant flares involve the sudden release of an enormous amount of energy (\(\sim (2-200) \times 10^{44}\) ergs) and have unique spectral and timing signatures: they start with a short hard spike followed by a longer pulsating tail. Their properties indicate that a large fraction of the energy escapes directly as a relativistically expanding electron/positron plasma, while the rest is gradually radiated away by a thermal fireball magnetically trapped in the NS magnetosphere which gives rise to the pulsating tail. Other features that can be present in giant flares are a precursor burst and long lasting afterglows at radio (see below) and soft \(\gamma\)-rays \[137\].

The initial spikes of hard radiation reach a peak luminosity \[L_{\gamma}\] larger than \(4 \times 10^{44}\) erg s\(^{-1}\) (up to \(\sim 10^{47}\) erg s\(^{-1}\) for SGR 1806–20) and their spectrum, with characteristic temperature of hundreds of keV, is much harder than that of short bursts. The initial spikes are characterized by rise time smaller than a few milliseconds and duration of a few tenths of seconds. A complex, structured profile has been observed in the initial spike of the 2004 giant flare of SGR 1806–20 \[174, 168\].

The pulsating tails of giant flares display a strong evolution of the flux, timing and spectral properties. They have optically thin bremsstrahlung spectra with temperatures of a few tens of keV, but in the two most recent and better observed giant flares a combination of cooling thermal components and power laws extending into the MeV region was required \[74, 13, 54\]. The decaying light curves, lasting several minutes, are strongly modulated at the NS rotation period and show complex pulse profiles which evolve with time.

Despite the energy emitted in the initial spike of SGR 1806–20 was larger than that of the other sources, the energy in the pulsating tails was roughly of the same order (\(\sim 10^{44}\) ergs) for the three giant flares. Since the tail emission originates from the fraction of the initial energy that remains trapped in the NS magnetosphere, forming an optically thick photon-pair plasma \[176\], this indicates that the magnetic field in the three sources is similar. In fact the amount of energy that can be confined in this way is determined by the magnetic field strength, which is thus inferred to be of several \(10^{14}\) G in these three magnetars.

Quasi periodic oscillations (QPOs) were discovered in the giant flare of SGR 1806–20 \[93\]. This prompted a re-analysis of the data available for the previous giant flares and the same phenomenon was found in SGR 1900+14 \[171\]. The QPOs appear at frequencies in the range \(\sim 20-150\) Hz (and also at 625 and 1840 Hz for SGR 1806–20) for different time intervals during the tails of the giant flares, and are often correlated with specific phases of the spin-period. They have been attributed to seismic vibrations in the NS solid crust or to Alfvén oscillations in the fluid core (see, e.g., \[198\] and references therein). Their study could provide constraints on the NS internal structure.

Transient radio emission was detected after the giant flares of SGR 1900+14 and SGR 1806–20 \[52, 53\]. The properties of the SGR 1806–20 radio emission could be studied in detail for more than one year. The proper motion of the radio blob indicates an anisotropic ejection of relativistic matter in a solid angle of \(\sim 0.5-1\) sterad. Other parameters could be estimated by modelling the source expansion and flux temporal evolution. Although jet models with different physical and geometrical details can fit the data equally well, all of them show evidence for an anisotropic ejection of \(10^{24}\)–\(10^{25}\) g of mildly relativistic matter associated to the giant flare \[16, 73\].

A few strong flares, involving less energy than the giant flares, but definitely brighter and much rarer than the normal short bursts, have also been seen in a few sources. The strongest of these “intermediate” flares was observed on April 18, 2001 from SGR 1900+14 \[108, 74\]. It lasted about 40 s and showed pulsations at the NS rotation period, as in the tails of giant flares, but it lacked an initial spike. Particularly strong bursts have also been observed, for example in SGR 1627–41 \[127\] and in 1E 1547.0–5408 \[138\]. It is possible that all these bursts and/or flares can be explained by the same physical process, involving a large distribution of energies \[142\]. It seems, however, that the giant flares, especially due to the peculiar properties of their initial spikes, are a different phenomenon.

4 The magnetar model

Strongly magnetized NSs can form if they are born with initial spin period \(P_0\) shorter than the overturn time of \(\sim 3-10\) ms of the convection driven by the high neutrino luminosity \(L_\nu > 10^{52}\) erg s\(^{-1}\) \[38\]. The efficient dynamo resulting in this case can generate magnetic fields as high as \(3 \times 10^{17}\) (\(P_0/1\) ms\(^{-1}\) G. Rapid neutrino cooling in the proto-NS is essential in driving the strong turbulent convection which amplifies the seed field. Such a dynamo operates only for a few seconds, but, in principle, it can generate fields as high as \(10^{16}\) G, most likely with a multipolar structure and with a strong toroidal component, in the NS interior \[180, 23\].

An alternative formation scenario has also been proposed, according to which magnetars would be the descendent of the stars with the highest magnetic fields. The wide distribution of field intensities in magnetic white dwarfs has been attributed to the spread in the

\[10\] Here and in the following we quote luminosities for isotropic emission.
magnetic fields of their progenitors and a similar situation could apply to NSs. The possible association of some AXPs/SGRs with clusters of massive stars seems to indicate that they descend from stars of mass above . However, evidence for a lower mass progenitor has been derived for SGR 1900+14. Independent on the origin of their strong field, young magnetars undergo rapid spin-down due to magnetic dipole radiation and particle wind losses. Rotation periods of several seconds are reached in a few thousands years, explaining why no magnetars are observed at short periods.

Magnetic field decay provides a source of internal heating which can play an important role in the X-ray emission from the surface of magnetars. This internal heating source yields a surface temperature higher than that of a cooling NS of the same age and smaller magnetic field. The enhanced thermal conductivity in the strongly magnetized envelope contributes to raise the surface temperature. The decay of the magnetic field is in turn affected by the NS temperature evolution, which makes it difficult to derive a self-consistent, complete and realistic model. Simulations in 2-D have been performed for the case in which the magnetic field is sustained by currents in the NS crust. They indicate that systematically higher surface temperatures are obtained for NSs with strong internal toroidal fields.

The evolution of the internal field deforms the NS crust contributing to the persistent X-ray emission through low level seismic activity and storing magneto/elastic energy which becomes available to power bursts and flares when the crust cracks. Alfvén waves in the magnetosphere accelerate charged particles leading to Comptonization and bombardment of the surface. A first attempt to derive the overall bursting properties of magnetars, taking into account the magneto/thermal evolution of the poloidal and toroidal internal field components, indicates significant differences in the energetics and recurrence time as the magnetar evolves. Objects with a lower toroidal field are generally less active. The frequency of the bursts decreases with age and, to a lesser extent, also their energy. Interestingly, sporadic bursts are predicted for magnetic fields as low as a few $10^{12}$ G.

A twisted magnetosphere ($B_0 \neq 0$) supports currents much larger than the Goldreich-Julian current flowing along open field lines in normal pulsars. An electron/positron corona is formed in the closed magnetosphere, consisting of flux tubes anchored on both ends to the NS surface. The currents are carried by charges extracted from the NS surface and pairs produced along the flux tubes. The strong flow of charged particles provides an additional source of heating for the star surface and gives rise to a significant optical depth for resonant cyclotron scattering in the magnetosphere. Repeated scattering of the thermal photons emitted at the star surface can produce the power-law components observed in the spectra of AXPs/SGRs.

Most of the models developed to derive the spectral and timing evolution properties of magnetars considered globally twisted magnetospheres, but it is more likely that the twist is imparted only to a small bundle

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### Table 2: Main properties of the AXPs and SGRs.

| Period | P | B | Flux | $L_X$ | Notes | References |
|--------|---|---|------|-------|-------|------------|
| (s)    | (10^{-11} s^{-1}) | (10^{14} G) | [2–10 keV] | [0.5–10 keV] |        |            |
| I1E0241.1–5957 | 6.45 | 1–10 | 2.6–8.1 | 0.5–4 | 0.9–7 | B,G | 132, 184, 59, 35 |
| I1E547.0–5408 | 2.07 | 2.3 | 2.2 | 0.03–9 | ~0.01–4 | B,G | 63, 138, 11, 112 |
| I1E1841–045 | 11.77 | 4.1 | 7 | 1.6 | 4 | B,G | 66, 143, 34, 114, 120 |
| I1E2259+586 | 6.98 | 0.048 | 0.6 | 1–4 | 2–7 | B,G | 201, 60, 104 |
| I1RXS J1708–4009 | 11.0 | 2.4 | 5.2 | 2–3 | 1.5–2.5 | G | 165, 96, 24, 34 |
| 4U0124+61 | 8.69 | 0.2 | 1.3 | 6–7 | 3 | B,G? | 97, 36, 104, 55, 57 |
| I1E0100–7211 | 8.02 | 1.9 | 4 | 0.013 | 2 | G | 115, 131, 182 |
| I1E0146–4552 | 10.6 | <0.04 | <0.7 | 0.01–4 | 0.007–1 | B,G? | 136, 200, 4 |
| I1E7147–3810 | 3.82 | 6.4 | 5 | 0.14 | ~1 | - | 77, 75, 166 |
| PSR J1622–4950 | 4.33 | 1.7 | 2.7 | 0.003–0.14 | ~0.01–40 | - | 5 |
| SGR 0418+5729 | 9.1 | 0.0004 | 0.06 | 0.002–3 | ~10^{-4}–20 | B | 162, 45 |
| SGR 0501+4516 | 5.7 | 0.7 | 2 | 0.13–4 | ~0.01–0.25 | B | 163, 38 |
| SGR 0526–66 | 8.05 | 4 | 5.7 | 0.05 | ~10 | F,B | 130, 128, 183 |
| SGR 1627–41 | 2.59 | 1.9 | 2.2 | 0.006–1.2 | ~0.01–2 | B | 134, 48, 42 |
| SGR 1806–20 | 7.6 | 8–80 | 8–25 | 1–3 | 2–6 | F,B | 151, 143, 202 |
| SGR 1833–0832 | 7.56 | 0.28 | 1.5 | <0.004–0.4 | <0.01–1 | B | 71, 44 |
| SGR 1900+14 | 5.2 | 5–14 | 5.1–8.6 | 0.4–1 | 2–5 | F,B,G? | 139, 204, 135 |
| Swift J1822–1606 | 8.44 | 0.03 | 0.5 | 0.008–25 | 0.002–10 | B | 161, 167 |
| Swift J1834–0846 | 2.48 | 0.8 | 1.4 | <0.0004–3 | <10^{-4} | B | 102, 49 |
| XTE J1810–179 | 5.54 | 0.8–2.2 | 2.1–3.5 | 0.05–8 | 0.008–1.3 | B | 47, 203, 12 |
of field lines. How the magnetic energy is dissipated in an untwisting magnetosphere has been studied in detail by [10], who derived expressions for the resulting luminosity evolution. Most of the energy is dissipated as thermal radiation in the footprints of a bundle of twisted lines which are heated by the accelerated magnetospheric particles. The magnetosphere gradually untwists through the expansion of a potential region which causes a reduction in the area of these hot spots. The small emitting surfaces inferred from the blackbody fits of transient AXPs/SGRs are consistent with this scenario.

An alternative possibility to explain the transient magnetars involves the fast deposition of energy deep in the NS crust [123]. This could result, for example, from a sudden fracture driven by magnetic stresses and would induce a heating of the surface. Since the subsequent thermal evolution depends primarily on the properties of the outer crust and on the depth of the energy deposition, a modelling of the outburst decays might provide some information on the star structure. However, the transients observed up to now are far from showing a uniform picture [159]. Furthermore, the systematic and statistical spectral uncertainties affecting the observations often prevent a simple comparison with the predictions of the models, as shown, e.g., by the case of SGR 1627−41 [134]. Recent theoretical work suggests that the maximum luminosity observable in an outburst is limited to \( \sim 10^{36} \text{ erg s}^{-1} \), independent on the amount of energy released in the crust [157]. This is due to the self-regulating effect resulting from the strong temperature-dependence of neutrino emission and might explain why persistently bright AXPs/SGRs do not undergo outbursts, but change their luminosity by, at most, a factor of a few.

It is clear that the giant flares must be powered by magnetic energy, but how this exactly occurs and where the energy is accumulated before being released remain open questions. The two main scenarios which have been considered involve either the build-up of elastic energy in the crust, which finally causes a large-scale fracture [17d, 178], or the gradual injection of energy in the magnetosphere, which is released when an instability produces a rearrangement of the field [124, 63, 207]. In the first class of models the flare occurs when the tensile strength of the crust is exceed, while in magnetospheric models it is more difficult to determine which is the triggering process that can explain the extremely rapid energy release. More data will certainly help to answer these questions, but the extremely rare and completely unpredictable nature of these events limit the observational progress.

5 Magnetars with low external field

Until recently the known AXP/SGR with the lowest magnetic field (as given by Eq. 1) was 1E2259+586 with \( B_d=6\times10^{13} \text{ G} \), only slightly larger than the quantum critical field, \( B_{QED} = \frac{\hbar c}{e} = 4.4\times10^{15} \text{ G} \). This pulsar, despite its value of \( B_d \) smaller than that of all the other magnetar candidates, was the first AXP to show the strong bursting activity previously believed to be a prerogative of SGRs [104].

In June 2009 the new transient SGR 0418+5729 was discovered through the detection of two short bursts seen by different satellites [192, 45]. Pulsations at 9.1 s were soon found in its X-ray emission, but despite an extensive monitoring of the outburst decay in the following months, no significant \( \dot{P} \) could be measured. This was quite unexpected because the fast spin-down rates of all the other transient AXPs/SGRs were always evident after only a few days of observations. The upper limit of \( \dot{P}<6\times10^{-15} \text{ s}^{-1} \) obtained after two years implied \( B_d<7.5\times10^{12} \text{ G} \) [160], an unprecedented value for a source showing all the typical characteristics of a magnetar. Only recently, thanks to a phase-coherent timing analysis of all the observations of SGR 0418+5729 spanning more than three years, it has been possible to measure its small spin-down of \((4\pm1)\times10^{-15} \text{ s}^{-1}\) [162], which translates into a field \( B_d=6\times10^{12} \text{ G} \).

A similar situation occurred for another transient, Swift J1822−1606 [122], discovered in July 2011 through the detection of several bursts, while a timing analysis of more than six years of data of CXO J1647−4552 led to revise its previously reported \( \dot{P} \) into an upper limit [4]. The dipole moments inferred for these two sources imply surface fields of \( B_d=5\times10^{13} \text{ G} \) and \( B_d<7\times10^{13} \text{ G} \), respectively. They are not as low as that of SGR 0418+5729, but still below that of the bulk of “traditional” AXPs/SGRs and in the range of fields inferred for a non-negligible number of rotation-powered radio pulsars.

These findings indicate that a high magnetic dipole moment is not a mandatory condition for a magnetar. Indeed what really matters to power the magnetar activity and emission is the strength of the internal field, and in particular of its toroidal component which is responsible for the NS crust deformation/cracking and

\[^{11}B_{QED}\] is the magnetic field for which the energy of the first Landau level of the electron equals its rest mass. It was often regarded as the boundary between normal pulsars and magnetars, although there is no real physical reason or threshold effect to motivate this.

\[^{12}\] Two isolated bursts were detected in October and November 2001 from 1E1048.1−5937 [54], but 1E2259+586 in June 2002 emitted more than 80 bursts in 4 hours, associated to an increase of the persistent flux and a glitch.
for imparting twists to the external magnetosphere. It is also likely that the magnetosphere is not dipolar but contains a significant contribution from higher order multipoles, which increase the field close to the star surface, but fall-off rapidly with radius and do not contribute to the spin-down.

It has been suggested that objects like SGR 0418+5729 are old magnetars, in which a substantial decay of the magnetic field has occurred. An initial configuration with internal toroidal field of a few $10^{16}$ G and external dipole of $B_d=2.5 \times 10^{14}$ G can reproduce the observed properties of SGR 0418+5729 in the context of a magneto-thermal evolution with field decay $\tau_B=5 \times 10^{13}$ years. A weaker initial $B_d$ would not spin-down the pulsar to the currently observed long period. An immediate consequence of the external field decay is that the characteristic age, defined as $\tau_c=P/2\dot{P}$, greatly overestimates the true age of the magnetar, which in the above model is of the order of $\sim 10^6$ years.

6 Is there evidence for magnetic activity in other classes of NSs?

As shown by the sources discussed in the previous section, a high dipole field is not a necessary condition for the onset of magnetar activity. This leads to the interesting possibility that NSs with “normal” magnetic field values, as estimated with Eq. (1), might show signatures of magnetar-like behavior, such as, e.g., bursts or other kinds of variability. Indeed some examples of this have been found in recent years, pointing to a closer connection and possible evolutionary links among different classes of isolated NSs.

The 0.3 s pulsar PSR J1846–0258, at the center of the Kes 75 SNR, was considered a rotation-powered radio pulsar. About one fifth of the radio pulsars with measured $\dot{P}$ have $B_d$ values larger than that of SGR 0418+5729. This population could well harbor other “hidden” magnetars, possibly showing weak and sporadic bursting activity (hence difficult to detect).

Magnetically-driven activity can manifest itself also through plastic deformations of the crust which appear as long term variations in the (thermal) emission from the star surface, rather than as abrupt bursts. A possible example has been observed in the 8.4 s X-ray pulsar RX J0720.4–3125, which showed spectral variability on a time scale of few years. Most of the variation occurred in a relatively short timescale of half a year, in coincidence with a possible glitch.

This source belongs to the small group of X-ray Dim Isolated NSs (XDINS) discovered with the ROSAT satellite (see, e.g., [188] for a review). XDINS have very soft thermal spectra (blackbody temperatures $T_{BB} \sim 40$–110 eV), X–ray luminosities $L_X \sim 10^{30}$–$10^{34}$ erg s$^{-1}$, spin periods in the 3–12 s range, faint optical counterparts ($V>25$), and no detectable radio emission. Their magnetic fields, inferred either from Eq. (1) for the few XDINS with measured $\dot{P}$ or from the absorption lines present in their spectra, are of the order of $10^{13}$–$10^{14}$ G. It is possible that the XDINS are old magnetars ($\sim 10^5$–$10^6$ years), in which most of the magnetic energy has been dissipated and whose X-ray emission is now powered by the residual thermal energy. Their temperature is consistent with theoretical cooling curves if the effects of stronger initial fields are taken into account [1, 154, 156].

Another example of long term variation which might be related to magnetic activity, is provided by the 0.4 s X-ray pulsar RX J0822–4300, located in the Puppis A SNR. XMM-Newton observations showed that the centroid energy of an emission line visible in its X-ray spectrum decreased from 0.8 keV in 2001 to 0.73 keV in 2009-2010. RX J0822–4300 belongs to a small group of sources known as Central Compact Objects (CCOs). These are X-ray sources with thermal-like X-ray emission ($kT_{BB}\sim 0.2$–0.5 keV) located at the center of shell-like SNRs and with high ratios of X-ray-to-optical flux, typical of isolated NSs. CCOs are not detected in the radio band, are not surrounded by pulsar wind nebulae and do not show any evidence for non-thermal components in their X-ray spectra (see, e.g., [26], for a review). The CCOs properties suggested an interpretation in terms of isolated NSs with small values of $E_{rot}$, despite the young age inferred from their associated SNRs. This has been confirmed for three CCOs in which pulsations have been detected.
have periods in the 0.1–0.4 s range, and exceptionally small spin-down rates \( \dot{P}_{\text{d}} = 6 \times 10^{-17} \text{s s}^{-1} \), yielding \( B_{\text{d}} = 3 \times 10^{10} \text{G} \), \( B_{\text{d}} = 9.8 \times 10^{10} \text{G} \) and \( B_{\text{d}} = 2.9 \times 10^{10} \text{G} \), for the sources in Kes 79, G296.5+10.0 and Puppis A, respectively. These NS were probably born with spin periods very close to the current values and it is likely that their relatively long initial spin period and low magnetic field be causally connected. Alternatively, CCOs might have been born with a higher field which was then buried beneath the NS surface by the accretion of fall back material after the supernova explosion. Depending on the amount of accreted matter and on the properties of the NS crust and core, the reemergence of the field can take place on a large range of timescales, from a few thousand to several billion years \( \approx 10^{13} \text{yr} \). The presence of a strong buried field can help to explain the gradients in the surface temperature responsible for the large pulsed fractions and/or phase-dependent spectral properties of CCOs, which are otherwise difficult to understand for their low values of \( B_{\text{d}} \). The variability in the X-ray spectral feature of RX J0822–4300, if related to magnetic activity, supports this connection between CCOs and AXPs/SGRs.

Finally, it is worth mentioning the Swift/BAT detection of two short SGR-like bursts from the direction of the peculiar X-ray/radio/\( \gamma \)-ray source LS I +61\(^{\circ} \)303 \( \times 10^{15} \text{G} \). This is one of the very few X-ray binaries detected at GeV/TeV energies. It is composed of a Be type star and a compact object, which is likely a NS (although this cannot be confirmed since no pulsations have been detected and the possibility of a black hole companion has also been considered).

### 7 Conclusions

The success of the magnetar model in explaining the properties of AXPs/SGRs indicates the existence of NSs with magnetic fields of \( \sim 10^{15} \text{G} \). Their extremely energetic flares yield the highest radiation fluxes which reach the Earth from outside the Solar System, often causing measurable effects on the atmosphere \( 91 \), \( 147 \). Exciting results have been obtained in the study of AXPs/SGRs in the latest years, contributing to change our vision of the population of NSs in the Galaxy.

Magnetars are relevant also in other astrophysical contexts which have not been discussed here. These include, for example, the supernova explosions, the production of gamma-ray bursts, the acceleration ultrahigh-energy cosmic rays, the production of neutrinos, and the emission of gravitational waves (see, e.g., \( 153 \)). Being the only places in the Universe in which we can observe and study physical processes in magnetic fields of such extreme intensity, AXPs/SGRs will certainly remain among the most interesting astrophysical objects for theoretical studies and for observations with the experimental facilities that will become available in the coming years.

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