

# Magnetars: a short review and some sparse considerations

Paolo Esposito, Nanda Rea and Gian Luca Israel

**Abstract** We currently know about 30 magnetars: seemingly isolated neutron stars whose properties can be (in part) comprehended only acknowledging that they are endowed with magnetic fields of complex morphology and exceptional intensity—at least in some components of the field structure. Although magnetars represent only a small percentage of the known isolated neutron stars, there are almost certainly many more of them, since most magnetars were discovered in transitory phases called *outbursts*, during which they are particularly noticeable. In outburst, in fact, a magnetar can be brighter in X-rays by orders of magnitude and usually emit powerful bursts of hard-X/soft-gamma-ray photons that can be detected almost everywhere in the Galaxy with all-sky monitors such as those on board the Fermi satellite or the Neil Gehrels Swift Observatory. Magnetars command great attention because the large progress that has been made in their understanding is proving fundamental to fathom the whole population of isolated neutron stars, and because, due to their extreme properties, they are relevant for a vast range of different astrophysical topics, from the study of gamma-ray bursts and superluminous supernovae, to ultraluminous X-ray sources, fast radio bursts, and even to sources of gravitational waves. Several excellent reviews with different focuses were published on magnetars in the last few years: among others, Israel and Dall’Osso (2011); Rea and Esposito (2011); Turolla and Esposito (2013); Mereghetti *et al.* (2015); Turolla *et al.*

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(2015); Kaspi and Beloborodov (2017). Here, we quickly recall the history of these sources and travel through the main observational facts, trying to touch some recent and sometimes little-discussed ramifications of magnetars.

## 1 Historical overview

The event at the birth of magnetar studies was the landmark giant flare observed in 1979 from SGR 0526–66 (Mazets *et al.*, 1979; Cline *et al.*, 1980). Nothing alike had been observed before from a pulsar, and the flare was also different from and much brighter than any other gamma-ray burst. The extreme properties of the event forced the astronomer to conceive unusual scenarios. The most appealing one was the existence of a class of neutron stars with super-strong magnetic fields of  $10^{14}$ – $10^{15}$  G (Duncan and Thompson, 1992; Paczynski, 1992). In particular, the word *magnetar* was introduced to designate these objects by Duncan and Thompson (1992). The giant flare and the more common emission of short fainter bursts of these sources were explained by impulsive releases of magnetic energy stored in the neutron star, which could be triggered by fractures in the magnetically stressed crust, perhaps associated to sudden magnetic reconnections in the star’s magnetosphere (Duncan and Thompson, 1992; Thompson and Duncan, 1995, 1996). The handfuls of sources associated to these recurrent hard X-/gamma-ray transients were dubbed soft gamma repeaters (SGRs), to distinguish them from the gamma-ray bursts.

In the same years, another class of X-ray pulsars defying any easy pigeonholing was emerging: the anomalous X-ray pulsars (AXPs; Mereghetti and Stella 1995; van Paradijs *et al.* 1995). They were characterised as persistent X-ray pulsars with periods of a few seconds and owed the adjective ‘anomalous’ to the fact that their X-ray luminosity exceeded that available from spin-down energy loss (while the accretion was ruled out by the lack of any trace of a stellar companion). Thompson and Duncan (1996) noted that except for the emission of short bursts, which had never been observed in AXPs, these sources were very similar to the recently-discovered persistent soft X-rays counterparts of SGRs (Rothschild *et al.*, 1994; Vasisht *et al.*, 1994; Murakami *et al.*, 1994). It was suggested that AXPs could be evolved SGRs, which ended or drastically reduced their explosive activity after having largely depleted their reservoir of magnetic energy, and the opposite possibility, too, was considered: that AXPs might be SGR progenitors in which the magnetic field decay has just begun (e.g. Gavriil *et al.* 2002).

The magnetar hypothesis was arguably the most successful in explaining the salient features of SGRs and AXPs, but some skepticism about the scenario persisted for long, in particular for the AXPs, for which several alternative models could not be excluded (Chatterjee *et al.*, 2000; Mereghetti *et al.*, 2002). The magnetar model really started to become the mainstream when the period derivative of an SGR was measured for the first time (Kouveliotou *et al.*, 1998). Using RossiXTE, it was established that SGR 1806–20 was pulsating at  $P = 7.47$  s and the period was increasing at the rate  $\dot{P} = 2.6 \times 10^{-3}$  s yr $^{-1}$ : with the standard assumption of

a magnetic dipole rotating in vacuum routinely used for standard pulsar, the values correspond to a surface magnetic field of  $B \simeq 3.2 \times 10^{19} \sqrt{P\dot{P}} = 8 \times 10^{14}$  G at the neutron star's equator. Moreover, the release of magnetic energy was necessary to power the X-ray emission of SGR 1806–20, since the spin-down energy loss of the neutron star was two orders of magnitude lower than the observed X-ray luminosity.

Few years later, the detection of SGR-like bursts from the AXP 1E 1048-1–5937 (Gavriil *et al.*, 2002) confirmed the suspect that also AXPs could harbour magnetars. Since then, with the discovery of many new magnetars showing a variegated phenomenology and observations of strong bursting activity and powerful flares from AXPs, as well as prolonged periods of quiescence in once-active SGRs, the AXP–SGR dichotomy seems completely obsolete.

## 2 Observational characteristics

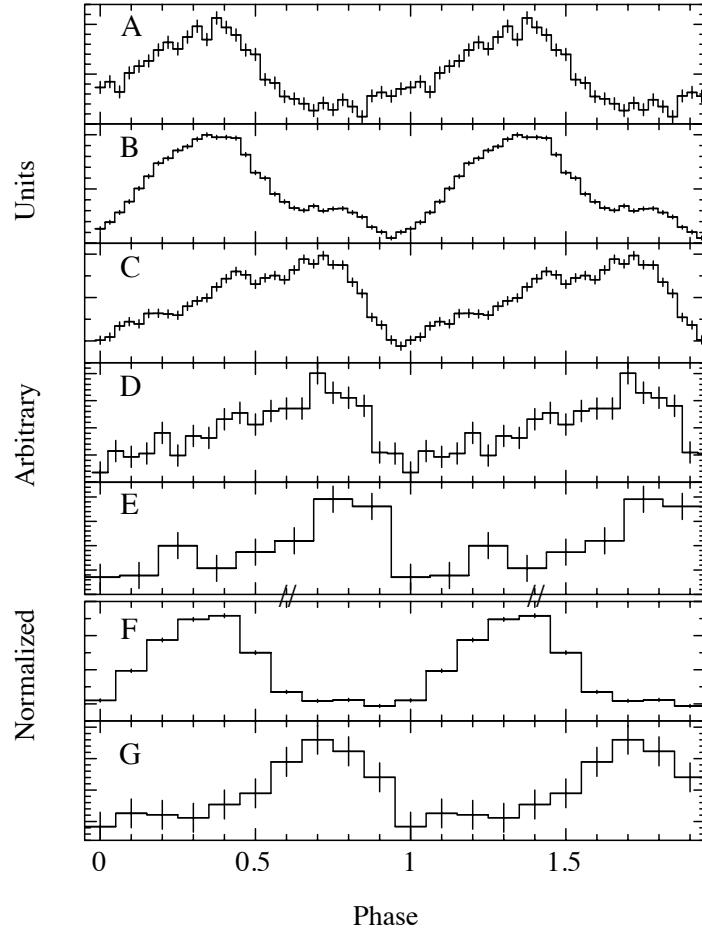
### 2.1 Persistent emission

#### 2.1.1 X-ray emission

The X-ray emission from magnetars is gently modulated at the pulsar spin period, with generally one or two broad sine components and substantial pulsed fractions (the fraction of the flux that changes along the rotation cycle) of 10–30%. The pulse profiles may be energy dependent and may display dramatic changes with time, especially in connection with strong bursting/outbursting activity (see Sect. 2.2). As an example, Fig. 1 shows a multi-epoch and multi-instrument pulse profile of 1RXS J170849.0–400910 (see Götz *et al.*, 2007, for details).

Part of the X-ray luminosity of magnetars in quiescence has a thermal origin and can be fit by a blackbody with temperature  $kT \approx 0.3\text{--}1$  keV, much higher than the typical values for rotation-powered pulsars; magnetar also tend to be more luminous than rotation-powered pulsars of similar characteristic age. Indeed, in magnetars the neutron star surface is believed to be particularly hot because of the extra-heating by the magnetic field decay (e.g. Aguilera *et al.* 2008).

The size of the region of the thermal emission inferred from a blackbody fit is generally much smaller than the surface of the star, possibly suggesting that a single-temperature blackbody is an oversimplification. Substantial anisotropies are indeed expected in the presence of a strong magnetic field in the crust and, since most magnetars are located in the Galactic plane, their spectra are generally heavily absorbed: it is possible that only ‘hot spots’ are detectable in the available X-ray spectra. Small and hot regions are also envisaged to result, rather than from internal heat transfer, from particle bombardment and heat deposition from magnetospheric currents induced by the globally twisted external magnetic field and/or by localised twists. In any case, the thermal emission in magnetars is expected to be significantly distorted by a magnetised atmosphere and also by magnetospheric effects, most



**Fig. 1** Pulse profiles of 1RXS J170849.0–400910, obtained with RossiXTE/PCA (2004 data; panel A: 2.5–4 keV, B: 4–8 keV, C: 8–16 keV, D: 16–32 keV) and INTEGRAL/IBIS (2004 data; panel E, 20–200 keV). Panels F and G show the BeppoSAX MECS (1–10 keV) and PDS (20–200 keV) pulse profiles obtained during a single pointing in 2001. Note that data in panels A to E were folded using an RossiXTE timing solution, while panels F and G using the period measured in the MECS data: the profiles in the two groups are phase-aligned between themselves but not each other. (From Götz *et al.* 2007.)

likely resonant cyclotron scattering onto magnetospheric charges. Since the charged particles populate vast regions of the magnetosphere, with different magnetic field intensities, the scattering produces a hard tail instead than a narrow line or a set of distinct lines and harmonics.

Phenomenologically, in the 0.5–10 keV band magnetar spectra are always well described by the already mentioned blackbody and often one or more additionally harder blackbody or power-law components, the latter with photon index generally

in the range  $\Gamma \sim 2\text{--}4$  (Kaspi and Boydston, 2010; Olausen and Kaspi, 2014). Since in the spectral modelling the (usually large) interstellar absorption, the power-law slope and the blackbody temperature(s) are covariant, it is often difficult to disentangle the components or to tell whether a blackbody or a power-law component is to be preferred. For the magnetar with the lowest absorbing column, CXOU J0100–7211 in the Small Magellanic Cloud, a double-blackbody model provides a much better fit to the data than a blackbody-plus-power-law model (Tiengo *et al.*, 2008). On the other hand, a non-thermal component is certainly present at least in the magnetars detected in the hard-X-ray range.

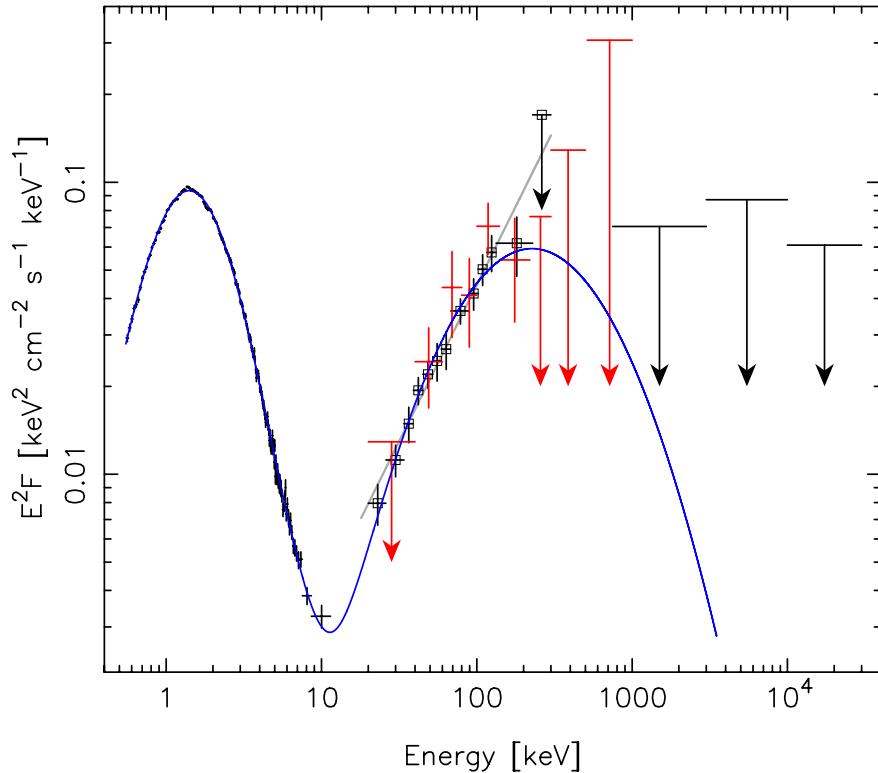
Given the many complications and uncertainties, it is evident that prudence is necessary when drawing physical inferences from the spectral parameters. It is however worth noticing that physical models based on resonant cyclotron scattering (likely, repeated scatterings) of seed thermal photons on mildly relativistic electrons are quite successful in reproducing the general thermal-plus-power-law shape of the continuum and fit the spectra of most magnetars. We refer to Turolla *et al.* (2015) for an overview of the state of the art of these models, their application, and the main open problems.

### 2.1.2 Hard-X-ray emission

In several magnetars, hard X-ray tails with power-law spectra with photon index  $\Gamma \approx 0.5\text{--}2$  (flatter than the soft non thermal components) have been detected with BeppoSAX, RossiXTE, INTEGRAL, Suzaku and NuSTAR extending beyond  $\approx 150\text{ keV}$  (Kuiper *et al.*, 2004, 2006; Götz *et al.*, 2006a, 2007; den Hartog *et al.*, 2008b,a; An *et al.*, 2014; Vogel *et al.*, 2014; Tendulkar *et al.*, 2015; Enoto *et al.*, 2017). Upper limits in the hundreds of keV and MeV regions obtained with CGRO and Fermi indicate that the tails do not extend above  $\approx 500\text{ keV}$  (e.g. den Hartog *et al.*, 2008b; Li *et al.*, 2017). Fig 2 shows the soft-to-hard-X-ray spectrum of 4U 0142+61. Also searches in the GeV and Tev energy bands gave negative results (Li *et al.*, 2017; Aleksić *et al.*, 2013).

The hard components can be variable, but in general their luminosity is comparable with or larger than that measured below 10 keV; also in the sources in which the hard X-ray emission has not been detected, the upper limits do not exclude a substantial contribution to the total luminosity. A peculiar feature of the hard tails is that the pulsed emission has a harder spectrum than the averaged hard X-ray one and also shows phase dependent variations (also morphological changes in the pulse profiles and peak shifts with energy are observed; e.g. den Hartog *et al.* 2008a; Götz *et al.* 2007, see also Fig. 1).

The origin of the hard tails of magnetars is still poorly understood but in general the mechanism suggested, similarly to what proposed for the soft spectra, is the up-scattering on ultra-relativistic electrons with Lorentz factor  $\gamma \gg 1$  (Baring and Harding, 2007; Fernández and Thompson, 2007; Wadiasingh *et al.*, 2018), possibly associated to relativistic outflows near the neutron star Beloborodov (2013b,a).



**Fig. 2** Unabsorbed soft-to-hard-X-ray spectral energy distribution of 4U 0142+61 as observed with XMM-Newton (in black), INTEGRAL/ISGRI (black open squares), INTEGRAL/SPI (red), and CGRO/COMPTEL (black). Down arrows indicate upper limits. See den Hartog *et al.* (2008b, from which the figure was taken) for details on the spectral modelling.

### 2.1.3 Optical or infrared emission

Optical or infrared counterparts have been found for about one-third of the known magnetars (e.g. Israel *et al.* 2004; Mignani 2011). The search is complicated by the intrinsic faintness of magnetars at that wavelengths and by their location in crowded and heavily absorbed regions in the Galactic plane, but in most cases the associations are strengthened by the detection of long-term variability. In three cases, the association is firm because the spin modulation has been detected also in the optical band (4U 0142+61, Kern and Martin 2002; Dhillon *et al.* 2005; 1E 1048.1–5937, Dhillon *et al.* 2009; SGR J0501+4516, Dhillon *et al.* 2011). As anticipated, magnetars are variable also in the infrared/optical range, but it is unclear (possibly because of the lack of adequate multi-wavelength campaigns) whether the changes trace the X-ray flux evolution, as also cases of anti-correlated or simply erratic variations have been reported (Tam *et al.*, 2004; Durant and van Kerkwijk, 2005; Camilo *et al.*, 2007b; Testa *et al.*, 2008; Dhillon *et al.*, 2011).

The magnetar 4U 0142+61 has been detected in both infrared and optical bands and is the one for which the greatest wealth of data is available at these wavelengths (Hulleman *et al.*, 2000, 2004). In near infrared, it shows an excess with respect to the blackbody that fits the optical data; indeed, a multi-temperature (700–1,200 K) thermal model provides a better fit to the data. Wang *et al.* (2006) suggested that the infrared component arises from an extended disk (possibly from supernova fallback) illuminated from the star’s X-rays and passively heated. This interpretation is supported by the correlation observed in this source between the X-ray and infrared emissions (Tam *et al.*, 2004). On the other hand, infrared/optical emission is expected from the inner magnetosphere, a pair-dominated region where the curvature radiation should be able to produce the observed infrared/optical luminosity (Zane *et al.*, 2011). Moreover, a magnetospheric origin would account more easily for the observed optical pulsations, with profiles nearly aligned with those observed at X-rays and displaying similarly broad modulation and large pulsed fraction (20–50%). It is also possible that the infrared and optical emissions have different origins or that the infrared excess in 4U 0142+61 is not well understood. A handful of magnetar has been detected also as pulsating sources at longer wavelength, in the radio band. We give an overview of the properties of magnetars at radio frequencies in Sect. 2.2.3.

## 2.2 *Transient activity*

Magnetars are certainly characterised by an extremely rich observational phenomenology, but this is particularly true when speaking of their transient activity: They display unpredictable and dramatic variations in their emission and timing properties in all the wavelengths at which they are detected, on time scales from milliseconds to months or years, and often with a dynamic range unparalleled by any other embodiment of isolated neutron stars. Their transient radiative events are usually outlined in two main categories: short-duration (ms–minutes) explosive events (giant flares and bursts) and outbursts, in which the X-ray luminosity rises to up to  $\sim 10^3$  times the quiescent level and then decays in weeks to months/years. Perhaps, an outburst more than an event could be considered a ‘syndrome’, in the sense that the flux enhancement is generally accompanied by bursts, spectral changes and timing anomalies, including glitches.

### 2.2.1 Giant flares

Giant flares are the rarest and most energetic events associated with magnetars. They are also the most important, at least historically, as it was the first giant flare, from SGR 0526–66 in the Large Magellanic Cloud on 1979 March 5 (Mazets *et al.*, 1979; Cline *et al.*, 1980), that brought magnetars on the astrophysical scene, provided clear-cut evidence of their neutron-star nature and propensity to produce multiple

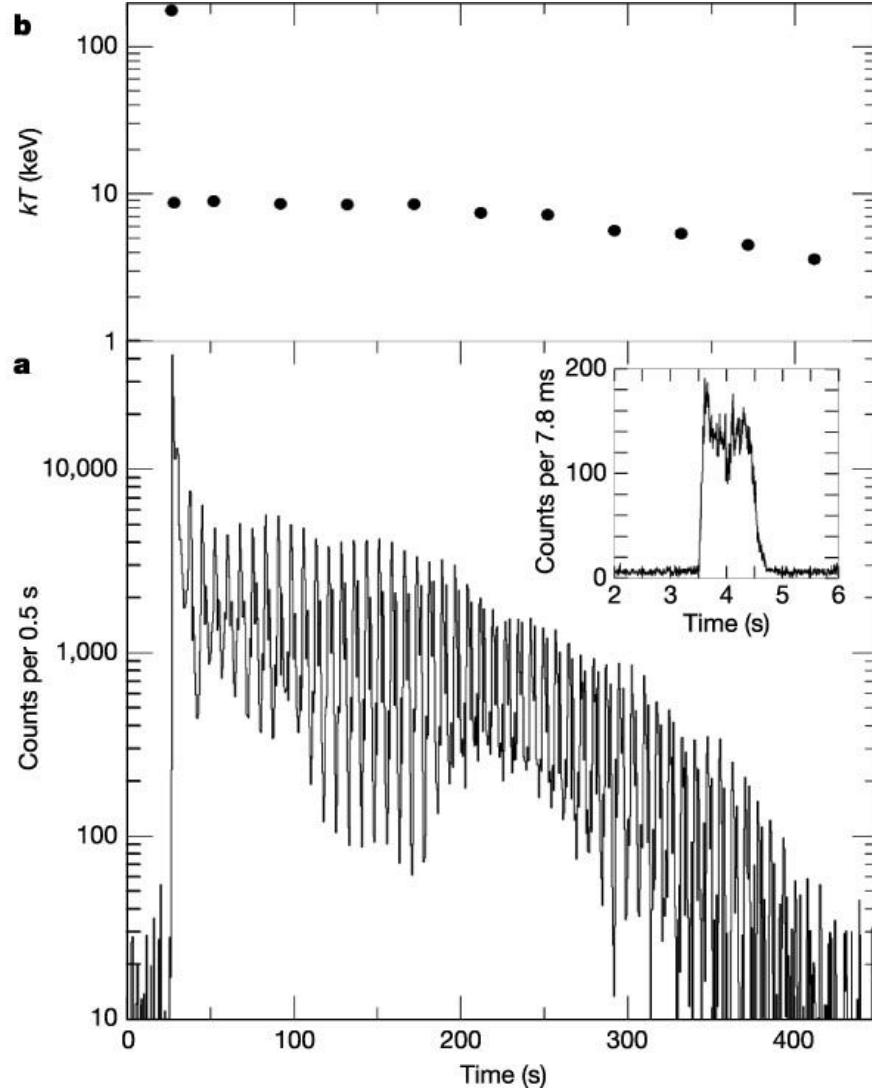
events (at variance with the gamma-ray bursts discovered by the Vela satellites), and prompted—among a multitude of different models (see e.g. Norris *et al.* 1991; Woods and Thompson 2006)—the concept of super-magnetic neutron stars (Paczynski, 1992; Duncan and Thompson, 1992; Thompson and Duncan, 1995). Moreover, they still provide some of the most compelling clues for the presence of magnetic fields of  $10^{14}$  G close to the neutron star surface in magnetars.

A total of three giant flares have been observed. In 1979 from SGR 0526–66, on 1998 August 27 from SGR 1900+14 (Hurley *et al.*, 1999) and on 2004 December 27 from SGR 1806–20 (Hurley *et al.*, 2005; Palmer *et al.*, 2005). It is worth noticing that the three giant flares were emitted from the three first SGPs discovered (but only SGR 0526–66 was discovered because of the event). Since a mere coincidence seems unlikely and a giant flare makes a significant dent in the total magnetic energy pool of a magnetar, a natural explanation would be that those three sources are at the magnetic-activity pinnacle of their life and their frequent bursting activity got them noticed earlier than other magnetars (see also Perna and Pons 2011; Viganò *et al.* 2013).

All three giant flares started with a short ( $\sim 0.1$ – $0.2$  s) flash of hard X-rays with peak luminosity  $\gtrsim 10^{44}$ – $10^{45}$  erg s $^{-1}$  ( $\gtrsim 10^{47}$  erg s $^{-1}$  in the case of SGR 1806–20; Hurley *et al.* 2005). The spectrum of this impulsive blaze extends at least to the MeV range and can be described by a blackbody, with initial  $kT$  from  $\approx 30$  to 200 keV (for SGR 0526–66 and SGR 1806–20, respectively). These sudden releases of an immense amount of energy affected in a measurable way (at least for the two most recent events) the Earth’s magnetic field (Mandea and Balasis, 2006) and ionosphere (Inan *et al.*, 1999, 2007). Hurley *et al.* (2005) argued that an extragalactic giant flare as bright as that of SGR 1806–20 could appear at Earth as a short gamma-ray burst up to a distance of several tens of Mpc and therefore magnetar flares might represent a non-negligible fraction of the population of these transients.

After the initial spikes, followed afterglows that were clearly modulated at the rotational period of the neutron stars. The afterglows were much softer than the flash and over a few minutes gradually further softened and faded (Fig. 3). It is extremely interesting that while the luminosity of the three peaks spans 2–3 orders of magnitude, the total energy of the oscillating tail was similar ( $\approx 10^{44}$  erg) in all the events. Since the afterglow is believed to arise from a cloud of photon–pair plasma confined by the star’s magnetic field that cools as the radiation gradually leaks out, this clearly indicates a similar value of the magnetic field in the three magnetars. To trap the fireball, the magnetic pressure must exceed that of the radiation and pairs at the external boundary of the cloud:  $B_{\text{dip}} > 2 \times 10^{14} (E_{\text{fireball}} / (10^{44} \text{ erg}))^{1/2} (\Delta R / (10 \text{ km}))^{-3/2} ((1 + \Delta R / R) / 2)^3$  G, where  $R$  is the stellar radius and  $\Delta R$  the characteristic size of the fireball (Thompson and Duncan, 1995).

In the SGR 1900+14 and SGR 1806–20’s giant flares, observations of transient nebular radio emissions provided evidence for outflows (Frail *et al.*, 1999; Gaensler *et al.*, 2005; Gelfand *et al.*, 2005). For the best-studied case of SGR 1806–20, the minimum energy in the extended radio emission was estimated at  $\approx 10^{43}$  erg, which seems too much to be consistent with pair plasma leaked form the fireball. Indeed, the structure, which was observable for more than a year, is better explained in terms



**Fig. 3** The 2004 December 27 giant flare of SGR 1806–20 as observed by RHESSI (from Hurley *et al.* 2005). Panel a shows the 20–100-keV light curve. The (saturated) spike is at  $\sim 30$  s and the inset shows the profile of a bright burst the preceded the flash by  $\sim 2$  minutes. The modulation at the spin period of SGR 1806–20 (7.5 s) is apparent. Panel b shows the temporal evolution of the spectral temperature.

of an baryon-rich mildly-relativistic ejection interacting with matter surrounding the star (Gelfand *et al.*, 2005; Granot *et al.*, 2006).

The detection of quasi-periodic oscillations (QPOs) in the tails of the giant flares from SGR 0526–66 (with detectors aboard the Prognoz 7 satellite and the Ven-

era 11 and 12 space probes; Barat *et al.* 1983), SGR 1900+14 (Strohmayer and Watts, 2005) and SGR 1806–20 (with RossiXTE and RHESSI; Israel *et al.* 2005; Strohmayer and Watts 2006; Watts and Strohmayer 2006), likely associated to seismic vibrations excited by the powerful explosion, started the field of asteroseismology for neutron stars (see gray box QPOs) and offered a new clue of the presence of a magnetic field  $\gtrsim 10^{14}$  G in magnetars. Vietri *et al.* (2007) observed that for any source there is a maximum rate of variation of the luminosity ( $\Delta L$ ) on a certain timescale ( $\Delta t$ ):  $\Delta L/\Delta t < \eta(2.8 \times 10^{18})/\sigma_T$  erg s $^{-2}$ , where  $\sigma_T$  is the Thomson cross section and  $\eta$  the energy extraction efficiency (Cavallo and Rees, 1978; Fabian, 1979). The 1840-Hz QPO detected in SGR 1806–20 implies a  $\Delta L/\Delta t$  exceeding this limit by a factor larger than  $10/\eta$ . However, a strong magnetic field suppresses the electron-scattering cross section (for one photon polarization mode) below the Thomson's value by a factor  $\propto B^2$  (Herold, 1979, see also van Putten *et al.* 2013). The presence of a magnetic field  $B \gtrsim 2 \times 10^{15}$  G at the surface of SGR 1806–20 would reconcile the QPOs with the luminosity variability limit (Vietri *et al.*, 2007).

### Quasi periodic oscillations and seismology of magnetars

The tail of the 2004 giant flare from SGR 1806–20 displayed clear QPO signals at about 18, 30, 93, 150, 625 and 1840 Hz (Israel *et al.*, 2005; Watts and Strohmayer, 2006). QPOs around frequencies of 28, 54, 84 and 155 Hz were detected in the tail of the 1998 giant flare of SGR 1900+14 (Strohmayer and Watts, 2005), while hints for a signal at  $\sim 43$  Hz were found in the 1979 event from SGR 0526–66 (Barat *et al.*, 1983). Some QPOs were excited simultaneously, others were detected only once in a very narrow time interval, some faded and were re-excited several times. All the detected QPOs are dependent on the phase of the spin period and show large variations of the amplitude with time. Their similarities suggest that the production mechanism is the same and the most obvious responsible are seismic vibrations induced by the giant flares. This is very exciting, as the QPOs provide a window on the neutron-star and magnetic field structures, and even on the dense matter equation of state.

The QPOs, in accordance with early theoretical suggestions (Duncan, 1998), were initially interpreted in terms of torsional shear modes of the neutron star crust. However, it did not take long to realize that neutron stars can sustain many types of oscillation and that the identification of oscillatory modes of magnetars is conceptually (and computationally) extremely challenging because of the magnetic coupling between the crust and the core (Glampedakis *et al.*, 2006; Levin, 2006). Indeed, at the moment, the potential of magnetar asteroseismology is dampened by the high degeneracy because of the many uncertainty associated with the magnetic field and the superfluid state of matter (see for example Levin 2007; Levin and van Hoven 2011; Glampedakis and Jones 2014 for detailed discussions and Turolla *et al.* 2015 for an overview of the current understanding of the field), but also by the

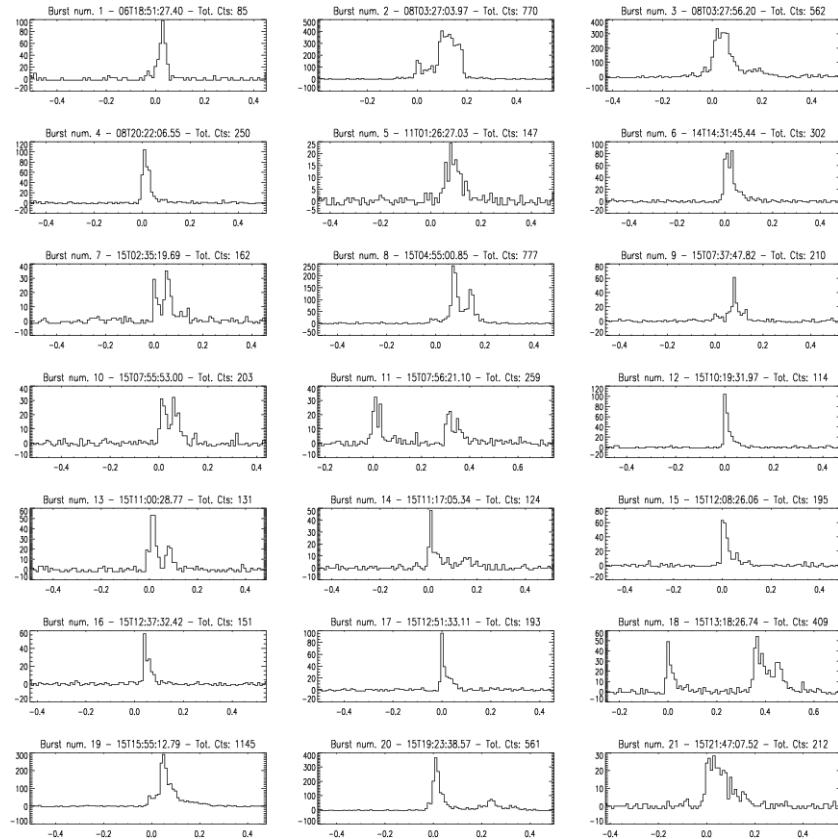
paucity of new data. This motivated searches for QPOs in the more bountiful short bursts. Only one signal, an unusually broad but strong peak at 260 Hz, was identified in a burst, a 0.5-s-long event from 1E 1547.0–5408, while several candidates from  $\sim$ 60 to 130 Hz were found in data sets combining many short bursts (Huppenkothen *et al.*, 2013, 2014b,a). Unfortunately, after the end of the RossiXTE mission and the non selection of LOFT (Feroci *et al.*, 2016) by ESA, the possibility of collecting a large number of photons with good time resolution and without saturation problems in case of exceptional events in the near future seems rather remote.

### 2.2.2 Short bursts

The SGR/magnetar short bursts are the hallmark of magnetars and thousands of them have been recorded and studied, both individually and as samples (Gögüs *et al.*, 2001; Aptekar *et al.*, 2001; Götz *et al.*, 2006b; Israel *et al.*, 2008; van der Horst *et al.*, 2012; Huppenkothen *et al.*, 2015). In the last few years, and in particular since the launch of Swift (which pairs a sensitive hard X-ray instrument with large field of view to an X-ray telescope that provides  $\sim$ arcsec localisation), the short bursts have become the primary channel for the discovery of new magnetars and of the onset of magnetic activity from known sources. The bursting activity is unpredictable: Magnetars usually go through long stretches of quiescence (even decades) that can be interrupted by sparse bursts or by paroxysmal activity, during which hundreds or thousands of events are clustered in days. Or by everything in between.

The impulsive emission of X/gamma ray photons lasts from milliseconds to a few seconds and the peak luminosity is typically in the range  $\approx 10^{36}$ – $10^{43}$  erg s $^{-1}$ . Their profile is usually single-peaked and asymmetric, with a faster rise than decay. Two- or multi-peak bursts are not rare, but since series of bursts can be very rapid, the distinction between single events and multi-peak bursts may be tenuous. Figure 4 shows the light curves of 21 bursts collected from SGR 1806–20 with INTEGRAL in 2003 (from Götz *et al.* 2004).

Some bursts, in general the brightest ('intermediate flares'), can be followed by X-ray tails surviving from minutes to hours. These events resemble the overall shape of the giant flares and their afterglows, except that in some instances the energy in the tail exceed that emitted in the spike (see e.g. Pintore *et al.* 2017). Sometimes these tails show flux modulation at the neutron star spin period, linking directly the afterglow to the neutron star (e.g. to a region of the star surface that was heated by the burst), but a significant fraction of them may be due to (or receive a large contribution from) dust-scattering of the burst emission, in which a fraction of the photons of the burst is re-emitted after reprocessing by clouds/layers of interstellar dust between us and the source (Lenters *et al.*, 2003; Esposito *et al.*, 2007; Gögüs *et al.*, 2011; Pintore *et al.*, 2017). In general, it is possible to disentangle the contri-



**Fig. 4** Light curves of bursts observed from SGR 1806–20 with INTEGRAL in the 15–100 keV range during an active period in 2003. The units of the axes are seconds for the time (x-axis) and counts per bin in the IBIS/ISGRI instrument for the intensity (y-axis); the time bin is 10 ms (from Götz *et al.* 2004).

bution of the delayed dust scattering from that intrinsic to the neutron star only when data sets with a large number of photons and good spatial resolution are available, but sometimes the phenomenon is truly spectacular: see Tiengo *et al.* (2010) for the study of a scattering halo surrounding the magnetar 1E 1547.0–5408 that took the shape of at least three expanding symmetric rings.

A number of models have been used to model the spectral emission of short magnetar bursts, but a single-blackbody model, or a double-blackbody model when broad band data are available (e.g. 1–200 keV), are usually a safe bet (Israel *et al.*, 2008; Israel and Dall’Osso, 2011). The blackbody temperature  $kT$  is typically in the range from  $\sim 2$  to 12 keV and when the double-blackbody decomposition is viable, a bimodal distribution of radii and temperatures takes shape, with a soft blackbody and a hotter ( $\sim 12$  keV) blackbody with smaller surface.

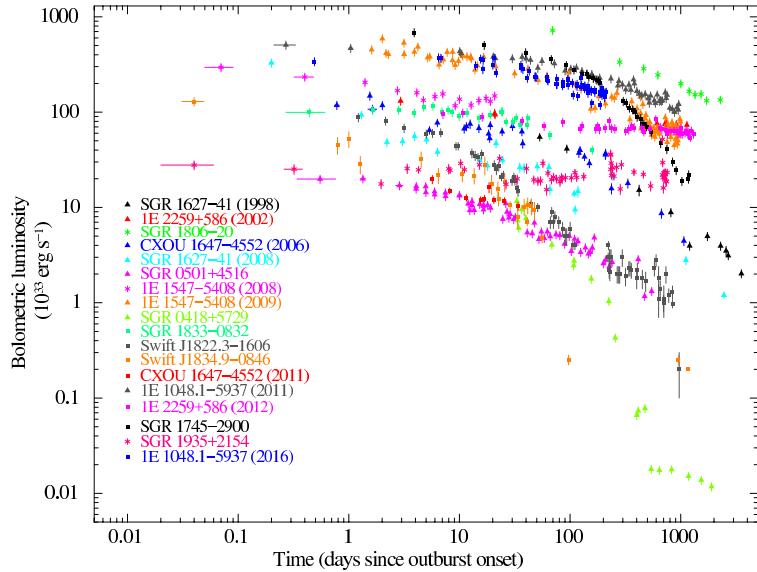
The fluence ( $S$ ) distribution for number ( $N$ ) of bursts usually follows a power-law function  $N(>S) \propto S^{-\alpha}$  over several orders of magnitude, with  $\alpha \sim 0.6\text{--}0.9$ , depending on the sources and the instruments (Görgüş *et al.*, 1999; Görgüş *et al.*, 2000; Aptekar *et al.*, 2001; Götz *et al.*, 2006b). It has been pointed out many times that this behaviour is similar to what observed for earthquakes. The truth is that such distribution is rather ubiquitous in nature and also in artificial and human-influenced systems: classic examples are the sizes of landslides and avalanches, solar flares, forest fires, lunar craters and cities, or the frequency of use of words in human languages (e.g. Newman 2005). As observed by Paizis and Sidoli (2014) for the distribution of hard-X luminosity of supergiant fast X-ray transient, the power-law distribution is characteristic (but not exclusive) of the self-organized criticality systems (Aschwanden, 2013), which inherently and perpetually evolves into a critical state where a minor event can start a chain reaction leading to a catastrophe (Bak and Chen, 1991).

### 2.2.3 Outbursts

In the magnetar world, the term ‘outburst’ is usually used to denote a large enhancement ( $\sim 10\text{--}1000$ ) of the flux that eventually fades away over the course of months or even years (e.g. Rea and Esposito 2011; Coti Zelati *et al.* 2018). A few magnetars have never been observed in outburst, others displayed a single outburst in decades, and some have gone through multiple events. Outbursts, and their onsets in particular, are generally associated to one or more short bursts. It is not clear, however, whether the bursts actually start the outbursts. In fact, the soft X-ray observations that catch a source in an enhanced-flux phase are generally carried out in response of the detection of a burst; on the other hand, for the outbursts discovered serendipitously it is not possible to pinpoint their exact start or exclude that bursts were missed. At any rate, the few cases in which observations were performed fortuitously shortly prior to a burst–outburst combination, indicate that the flux changes are rapid and happen close to the explosive activity, within  $\sim 1\text{--}2$  days (Esposito *et al.*, 2008; Israel *et al.*, 2007; Kennea *et al.*, 2013; Younes *et al.*, 2017b).

The decay pattern is usually complicated, but it often includes an initial rapid decay ( $\lesssim 1$  day; e.g. Woods *et al.* 2004; Esposito *et al.* 2008) and a more extended phase that can be described by power-law or exponential functions. Sudden flux drops and periods of flux stability have also been observed. Figure 5 shows the long-term light curves of all the outbursts discovered up to the end of 2017 and followed with intense and long coverage, mainly using imaging instruments.

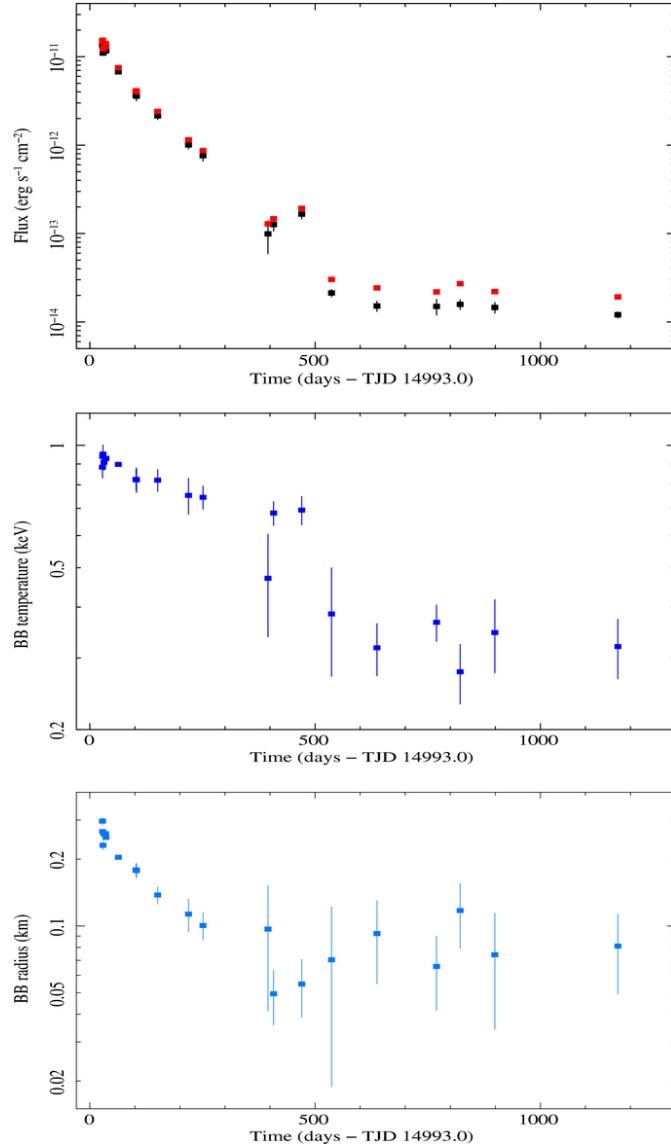
Despite the great variety of behaviours, all outbursts have some common features: At the beginning of the outburst, the X-ray spectrum is harder than in quiescence, and gradually softens as the flux decreases (Fig. 6); The larger the luminosity at the outburst peak, the larger the total energy released during the entire episode (generally in the range  $\approx 10^{41}\text{--}10^{43}$  erg); The larger the total energy of the outburst, the longer the time scale for the relaxation Coti Zelati *et al.* (2018). There is also an anticorrelation between the quiescent X-ray luminosity of a magnetar



**Fig. 5** Light curves of all the outbursts with good observed coverage (from Coti Zelati *et al.* 2018). The luminosities are bolometric (obtained from an extrapolation of the best-fit spectral models in the 0.01–100 keV range).

( $L_{X,q}$ ) and the dynamical range of its outbursts; Coti Zelati *et al.* (2018) found that  $L_{X,\text{peak}}/L_{X,q} \propto L_{X,q}^{-0.7}$ , where  $L_{X,\text{peak}}$  is the maximum X-ray luminosity achieved during the event (see also Pons and Rea 2012). Indeed, several magnetars that could be studied in detail when they were undergoing outbursts, are completely unnoticeable and hardly recognisable as magnetars while in quiescence (or even nondetectable without deep and targeted observations). For this reason, the strategy of the Swift mission (Gehrels *et al.*, 2004) of slewing and pointing its X-ray telescope as soon as possible towards the transient events detected and localized by its wide-field coded-mask detector sensitive to hard X-rays, has proven tremendously successful in discovering new magnetars.

Outbursts are usually accompanied also by changes in the timing properties of the magnetar. The morphology of the pulse profiles, which generally are broad and with one or two main peaks per cycle, can vary dramatically during an outburst, both in shape (as a rule, becoming more complicate when the activity is high) and in pulsed fraction (e.g. Woods *et al.* 2001; Israel *et al.* 2010; Rodríguez Castillo *et al.* 2014; Esposito *et al.* 2010; Dib and Kaspi 2014). During outbursts and in general in period of enhanced activity, magnetars show a more efficient spin-down torque, with variations of a factor up to  $\approx 10$  (e.g. Mereghetti *et al.* 2005; Olausen and Kaspi 2014); the spin-down evolution, however, does not trace or correlate well with the radiative or bursting behaviours (Woods *et al.*, 2007; Younes *et al.*, 2017a). Among



**Fig. 6** Spectral evolution of SGR 0418+5729 with time during the outburst started in 2009 June (the time of the detection of the first burst is MJD 54987.9  $\equiv$  TJD 14987.9). Top panel: flux evolution for the absorbed 0.5–10 keV flux (black), and for the bolometric unabsorbed flux (red). Middle and bottom panels: evolution of the blackbody temperature and radius, calculated at infinity and assuming a distance of 2 kpc (from Rea *et al.* 2013b).

isolated pulsars, magnetars are particularly noisy rotators, and also this aspect is amplified during outbursts (Esposito *et al.*, 2011a; Dib and Kaspi, 2014).

In young radio pulsars ( $\lesssim 10^5$  yr), timing noise has been often suggested to be linked to recovery from glitch events (Hobbs *et al.*, 2010). Magnetars are rather prolific glitchers, comparable to the most frequently glitching radio pulsars, and glitches often happen during outbursts (although in coincidence of some glitches, no X-ray flux enhancements were detected); also, while the amplitude distribution of their glitches peaks on larger  $\Delta v/v$  with respect to the ‘normal’ pulsars, the values observed are in the same range ( $\Delta v/v \sim 10^{-9}\text{--}10^{-5}$ ; Dib *et al.* 2008; Dib and Kaspi 2014). Magnetars glitching behaviour appears to be different in the recovery, which is typically very strong, often resulting in an over-recovery, and in the fact that also *anti-glitches* (that is, episodes of sudden spin down) have been reported. The most eminent anti-glitch candidate was reported for 1E 2259+586 (Archibald *et al.*, 2013), where in less than 4 days, a spin-down of  $\Delta v/v \sim -10^{-7}$  was achieved; the sudden variation was accompanied by a simultaneous short burst and by a small (factor  $\sim 2$ ) but long-lived (months) flux increase. A large ‘braking glitch’ could also have occurred in SGR 1900+14 in an 80-days interval including the epoch of its giant flare (Woods *et al.*, 1999); the observations were however too sparse to tell whether the abnormal increase of the period resulted from a sudden event or from a prolonged period of enhanced spin down.

Another magnetar activity associated to X-ray outbursts is the transient pulsed radio emission observed in a few of them. Until the first detection of radio pulses during the outburst of XTE J1810–197 (Camilo *et al.*, 2006), magnetars were (rather staunchly) believed to be radio quiet. Ironically, at the time of its radio activation, XTE J1810–197 was the brightest pulsar of the radio sky, with individual pulses reaching flux density of 10 Jy or more. A few other magnetars were subsequently detected in radio as pulsars: 1E 1547.0–5408 (Camilo *et al.*, 2007a), PSR J1622–4950 (the only magnetar discovered at radio wavelengths so far; Levin *et al.* 2010), and SGR J1745–2900 (Eatough *et al.*, 2013; Rea *et al.*, 2013a). All the detections happened during an X-ray outburst but, interestingly, at least in some cases the radio emission outlived the X-ray flux enhancement (Anderson *et al.*, 2012; Camilo *et al.*, 2016; Scholz *et al.*, 2017). Also, even in periods in which they are overall active in radio, magnetars seem to switch suddenly on and off (Burgay *et al.*, 2009).<sup>1</sup>

Apart from its temporary nature, the pulsed radio emission from magnetars shows in all four sources some clear differences with respect from that of ordinary rotation-powered pulsars (Kramer *et al.*, 2007; Camilo *et al.*, 2008; Levin *et al.*, 2012; Shannon and Johnston, 2013). The radio emission has a very hard spectrum:  $S \propto v^{-0.5}$  or flatter (where  $S$  is the flux density and  $v$  is the frequency), while the typical spectral index of radio pulsars is approximately  $-1.8$  (e.g Seiradakis and Wielebinski 2004). Another peculiar characteristic of magnetar’s pulsed radio emission is the instability of the pulse shape. Most radio pulsars show some pulse-by-pulse variability, but the addition of a few hundred pulses is generally sufficient to attain a

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<sup>1</sup> In this respect, it is interesting to notice that when the radio pulsar PSR J1119–6127 emitted a number of SGR-like bursts and entered an outburst, initially it disappeared as a radio pulsar (Burgay *et al.*, 2016). Furthermore, after the radio reactivation but still during the outburst, Archibald *et al.* (2017) using simultaneous radio and X-ray observations observed that the radio emission shut down in coincidence with the X-ray bursts, with a recovery time of  $\sim 70$  s.

stable pulse profile; more rarely, radio pulsars switches on time scales from minutes to hours between a small number (usually two) of different pulse profiles (Kramer *et al.*, 2006; Lyne *et al.*, 2010). The individual pulses of magnetars have a spiky appearance and stable pulse profiles were never observed (e.g. Kramer *et al.* 2007; Camilo *et al.* 2016); it is therefore unclear whether the profile stabilization would require for magnetars an unprecedented number of pulses or they simply do not have a stable characteristic pulse profile. Finally, high degrees of linear polarization have been measured in magnetars, up to very high frequencies (Camilo *et al.*, 2008; Torne *et al.*, 2017).

### **1E 161348–5055 in RCW 103: The CCO that was not**

Central compact objects in supernova remnants (CCOs) are a small set of isolated neutron stars observed close to centres of young non-plerionic supernova remnants (see De Luca 2017 for a review). CCOs are fairly steady X-ray sources with thermal-like spectra and no counterparts detected at other wavelengths. They owe their redundant designation to the fact that in the years the class emerged, there was not absolute certainty of their neutron-star nature, since no periodic modulations were found in their emission and also searches at radio frequencies failed to detect a pulsar. After numerous deep observations, there is now little doubt that CCOs are indeed neutron stars, and spin periods between 0.1 and 0.5 s and their derivative have been measured in three of them. Interesting, for these sources the inferred dipolar magnetic fields are rather low:  $\sim 10^{10}$ – $10^{11}$  G. This prompted for the CCOs an unifying scenario in which they are either born with weak magnetic fields or with a normal field that has been ‘buried’ beneath the neutron-star surface by a post-supernova stage of hypercritical accretion of fallback matter (Ho, 2011; Viganò and Pons, 2012; Gotthelf *et al.*, 2013). In the latter case, CCOs could in principle have magnetic field in the magnetar range (Viganò and Pons, 2012).

1E 161348–5055 in the 2-kyr-old supernova remnant RCW 103 was one of the CCO prototypes. However, observations of large flux variations (about 2 orders of magnitude) and an unusual spin period of 6.7 h set it apart from CCOs or any other class of isolated pulsars (De Luca *et al.*, 2006). No information or meaningful limit on its magnetic field are available from its rotational parameters (Esposito *et al.*, 2011b), but it is interesting to notice that De Luca *et al.* (2006) discussed as a possible mechanism to slow-down in  $\sim$ 2-kyr a pulsar born with a normal spin period to the rotation rate of 1E 161348–5055 the propeller interaction between an ultra-magnetised neutron star ( $B \sim 10^{14}$ – $10^{15}$  G) and a surrounding supernova fallback debris disk.

A major breakthrough was when, on 2016 June 22, the Swift’s Burst Alert Telescope detected an X-ray burst (see Fig. 7) resembling in all respects those of magnetars from the direction of 1E 161348–5055 (D’Aì *et al.*, 2016; Rea *et al.*, 2016). Its duration was  $\sim$ 10 ms, its luminosity  $\sim 2 \times 10^{39}$  erg s<sup>-1</sup> (15–150 keV), and the spectrum was well described by a blackbody

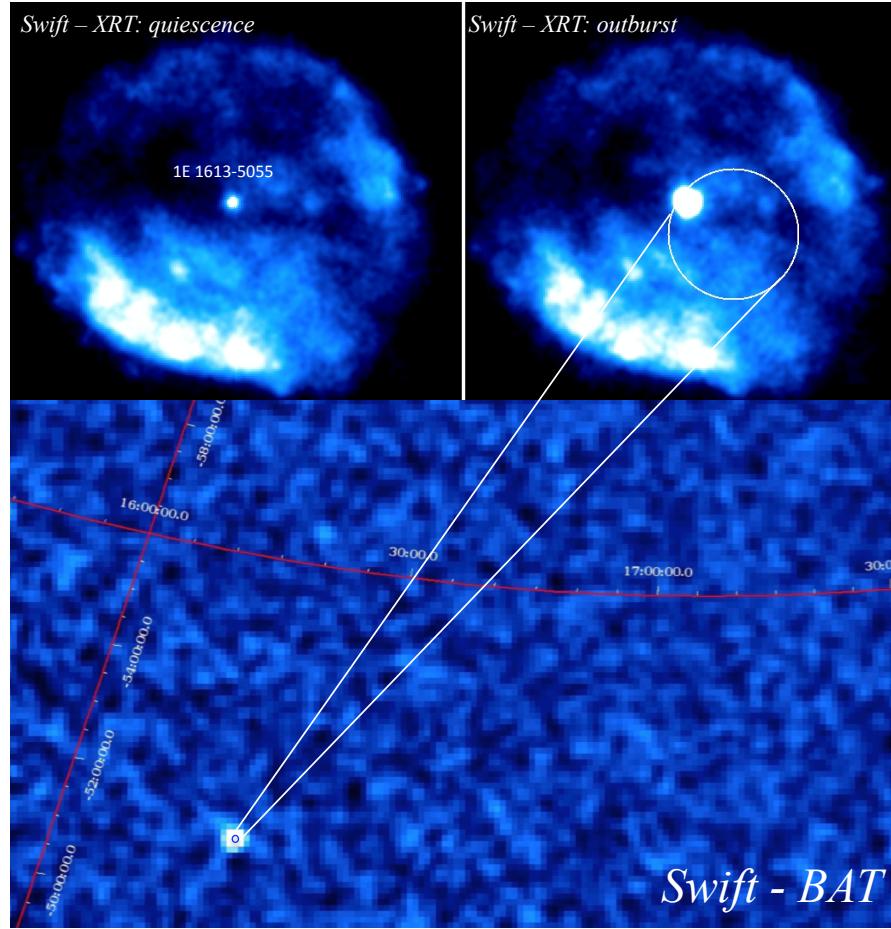
with  $kT \sim 9$  keV. Subsequent follow-up observations with Swift, Chandra and NuSTAR showed that 1E 161348–5055 was undergoing a magnetar-like outburst: Its luminosity was  $\sim 100$  times higher than the level the source had maintained for several years and up at least to the last observation carried out before the burst (about one month earlier); The pulse profile from single-became double-peaked; A hard power-law component was observed up to  $\sim 30$  keV for the first time in its energy spectrum, superimposed to its usual thermal emission (Rea *et al.*, 2016). In the first year from the onset of the outburst, the overall energy emitted was  $\sim 3 \times 10^{42}$  erg (Coti Zelati *et al.*, 2018). Moreover, Hubble observations carried out in the summer of 2016 unveiled at the position of 1E 161348–5055 a faint infrared source that was not detected in older observations (implying a minimum brightening of 1.3 mag) and therefore can be assumed with a high degree of confidence to be the counterpart of the CCO (Tendulkar *et al.*, 2017).

While the features exhibited by 1E 161348–5055 during its outburst match precisely the distinguishing features of magnetars, its 6.7-h period remains puzzling. The infrared observations definitely ruled out any doubt about a binary system but could not confirm or exclude the presence of a fallback disk. Recent modelling of neutron star–debris disk interaction by Ho and Andersson (2017, see also Tong *et al.* 2016) has shown that a disk with mass of  $\approx 10^{-9} M_{\odot}$  could slow the neutron star period from milliseconds down to hours in  $\sim 1$ –3 kyr, if the dipole magnetic field is of  $5 \times 10^{15}$  G. Since the formation and survival of a supernova fallback disk are unclear (Perna *et al.*, 2014), theoretical work is ongoing also on the possibility that the source was slowed down in a relatively short-lived phase of propeller during fallback accretion.

### SGR J1745–2900: The Galactic Centre magnetar

When on 24 April 2013 Swift detected with its X-ray telescope a large flare from the region of Sgr A\* (Degenaar *et al.*, 2013), many minds went to the much anticipated pericenter passage of the object G2, which at the time was expected around mid-2013, and its possible tidal disruption by the Milky Way’s  $4 \times 10^6 M_{\odot}$  black hole (Gillessen *et al.*, 2012, 2013).

Two days later, however, a magnetar-like short burst was detected by the Swift’s coded mask instrument and also a typical magnetar period of 3.8 s was detected, using NuSTAR (Kennea *et al.*, 2013; Mori *et al.*, 2013). The situation was definitely settled when an observation carried out with Chandra (the only X-ray telescope with sufficient angular resolution) showed that a 3.8-s magnetar in outburst, SGR J1745–2900, very close to the position of Sgr A\* (angular separation of  $(2.4 \pm 0.3)$  arcsec) was responsible for all the X-ray luminosity increase measured by Swift ( $\approx 2 \times 10^{35}$  erg s $^{-1}$  at 8.3 kpc, while Sgr A\* was not detected in the same exposure; Rea *et al.* 2013a). (The closest



**Fig. 7** Two Swift-XRT co-added 1–10 keV images of the supernova remnant RCW 103 during the quiescence state of 1E 161348–5055 (from 2011 April 18 to 2016 May 16; exposure time  $\sim 33$  ks; top left) and in outburst (from 2016 June 22 to 2016 July 20; exposure time  $\sim 67$  ks; top right). The white circle is the positional accuracy of the SGR-like burst detected by BAT (bottom), which has a radius of 1.5 arcmin (from Rea *et al.* 2016).

approach of G2 to Sgr A\* actually took place in early 2014; G2 survived and no flaring activity clearly associated to the event was observed; Phifer *et al.* 2013; Pfahl *et al.* 2015; Ponti *et al.* 2015; Plewa *et al.* 2017.) On 28 April 2013, the new magnetar was also detected as a radio pulsar, the one with the highest dispersion measure and rotation measure, suggesting that the source is embedded in the dense and magnetized plasma of the Galactic center (Eatough *et al.*, 2013; Rea *et al.*, 2013a; Bower *et al.*, 2015; Lynch *et al.*, 2015; Torne *et al.*, 2015; Pennucci *et al.*, 2015).

The angular separation between the magnetar and Sgr A\* corresponds to a projected distance of only 0.1 pc, and Rea *et al.* (2013a) estimated that if SGR J1745–2900 was born within 1 pc of Sgr A\*, its probability of being in a bound orbit around the black hole is of  $\sim 90\%$ . Bower *et al.* (2015) measured a transverse velocity of the source relative to Sgr A\* of  $(236 \pm 11) \text{ km s}^{-1}$  and provided further support to the possibility that the magnetar is bound to Sgr A\*. Rea *et al.* (2013a) also noted that the high-energy emission produced by the past activity of the magnetar, passing through the molecular clouds surrounding the Galactic center region, might be responsible for a substantial fraction of the light echoes observed in the Fe fluorescence features.

SGR J1745–2900 is proving to be an important probe for the compact object population and the interstellar medium in the Galactic center, but is also exhibiting an interesting behaviour as a magnetar. About 3.5 years after the outset of the outburst, it has not reached the quiescent/pre-outburst luminosity level yet (Coti Zelati *et al.*, 2017). Its spectral evolution is difficult to reconcile with crustal cooling models, while a continuous particle bombardment from returning currents of the neutron star surface better explain the data. In this hypothesis, both temperature and size of the region at the footprint point of the bundle of current-carrying field lines decrease, as the magnetospheric twist gradually dissipates and the rate of particles impacting the surface consequently declines (Coti Zelati *et al.*, 2015, 2017).

### 2.3 Magnetar formation

The generation of magnetar-like magnetic fields from the progenitor star is still a debated and relatively open problem. All along, preliminary calculations have shown that the effects of a turbulent dynamo amplification occurring in a newly born neutron stars can indeed result in a magnetic field of up to a few  $10^{17} \text{ G}$ . This dynamo effect is expected to operate only in the first  $\sim 10 \text{ s}$  after the supernova explosion of the massive progenitor, and if the proto-neutron star is born with sufficiently small rotational periods (of the order of 1–2 ms). The resulting amplified magnetic fields are expected to have a strong multipolar structure and toroidal component (Duncan & Thompson 1992, Thompson & Duncan 1993). This formation scenario predicts two main observational consequences: (a) magnetars should have large kick velocities, of the order of  $10^3 \text{ km s}^{-1}$  and (b) their associated supernovae should be more energetic than ordinary core collapse-supernovae, because of the additional rotational energy loss of such fast spinning proto-neutron star.

However, this additional energy loss is not observed in the supernova remnants surrounding magnetars (Vink and Kuiper, 2006; Martin *et al.*, 2014), nor a large kick velocity is observed in the few cases where this could be measured. In particular, measured magnetar proper motions are  $v = 212 \pm 35 \text{ km s}^{-1}$  for XTE J1810–197

(Helfand *et al.*, 2007),  $v = 280 \pm 130 \text{ km s}^{-1}$  for 1E 1547–5408 (Deller *et al.*, 2012),  $v = 157 \pm 17 \text{ km s}^{-1}$  for 1E 2259+586 and  $v = 102 \pm 26 \text{ km s}^{-1}$  for 4U 0142+61 (Tendulkar *et al.*, 2013), while candidate proper motion velocities are  $v = 350 \pm 100 \text{ km s}^{-1}$  for SGR 1806–20 and  $v = 130 \pm 30 \text{ km s}^{-1}$  for SGR 1900+14 (Tendulkar *et al.*, 2012). All these values are well within the typical radio pulsar distribution (see also the gray box on the Galactic Centre magnetar SGR 1745–2900).

The fact that the former predictions did not seem to be fulfilled is however not sufficient to dismiss the dynamo formation mechanism (for example, about the lack of evidence for a particularly energetic supernova, Dall’Osso *et al.* 2009 noted that most of the rotational energy of a proto-neutron star with internal toroidal field  $\approx 10^{16} \text{ G}$  should be released through gravitational waves, without supplying substantial additional energy to the ejecta), but it has lent some support to other formation scenarios. One alternative theory is based on magnetic flux conservation arguments and postulates that the distribution of field strengths in neutron stars simply reflects that of their progenitors. In this fossil field scenario, magnetars would be the descendant of the massive stars with the highest magnetic fields (Ferrario and Wickramasinghe, 2006). Counter-arguments have been put forward also in this scenario by Spruit (2008), who argued that the number of highly magnetic massive stars with  $B \gtrsim 1 \text{ kG}$  is not sufficient to explain the magnetar population. Furthermore, even assuming that most of the magnetic flux is indeed conserved, magnetic fields higher than  $10^{14} \text{ G}$  seem unattainable.

Recent surveys of very massive stars have shown how in our Galaxy massive stars tend to be in binaries (Sana *et al.*, 2006). Furthermore, a detailed radial velocity survey of Westerlund 1, an open cluster of very massive stars which contains a magnetar, CXOU J164710.2–455216, have discovered the possible companion massive star that might have resulted by the disruption of a massive binary progenitor (Clark *et al.* 2014; see Section 2.6 for more details). All these results are pointing to a further element in magnetar formation: the evolution in a binary system of massive stars. The binary scenario might overcome the problem of the spin down by the core–envelope coupling. In particular, both mass transfer and stellar merger in compact binaries may lead to substantial spin-up of the mass-gainer (or of the remnant of the merger), favoring the amplification of the magnetic field via dynamo effects (Langer, 2012). Recent simulations have shown that gamma-ray bursts and hyper-luminous supernovae can indeed be powered by recently formed millisecond magnetar (Metzger *et al.*, 2011), although no direct or sound observational evidence of the existence of such fast spinning and strongly magnetic neutron stars has been collected thus far.

## 2.4 Magnetic field evolution and the neutron star bestiary

The evolution of magnetic fields in neutron stars has been extensively studied by a number of authors in the past. In the neutron star solid crust, the field evolves under the influence of the Lorentz force (causing the Hall drift) and the Joule effect (re-

sponsible for Ohmic dissipation). The evolution in the liquid core is very uncertain. In the core, soon after the neutron star birth (from hours to days) protons undergo a transition to a type-II superconducting phase (Baym *et al.*, 1969), in which the magnetic field is confined to tiny flux tubes surrounded by nonmagnetized matter. The dynamics of those flux tubes, likely coupled to the motion of superfluid neutron vortices, is a complex problem that makes the magnetic field evolution in the core formally difficult to tackle (see Elfritz *et al.* 2016). Most works (e.g. Goldreich and Reisenegger, 1992; Geppert and Rheinhardt, 2002, 2006; Pons *et al.*, 2007, 2009; Gonzalez and Reisenegger, 2010; Viganò *et al.*, 2013) considered mainly the magnetic evolution in the solid crust, a  $\sim$ 1-km-thick lattice of ions, where the electrical conduction is governed by electrons.

The magnetic field evolution in a neutron star is strictly coupled to its thermal evolution. In fact, the magnetic field influences the heating rate and, secondarily, affects the rate of a few neutrino processes; on the other side, the conduction of heat becomes anisotropic in the presence of a strong magnetic field. The simultaneous study of the magnetic and temperature evolutions (*magneto-thermal evolution*) was started by Pons and Geppert (2007) and Aguilera *et al.* (2008) with simplifying assumptions, and later implemented in two-dimensional simulations of the fully coupled magneto-thermal evolution in Pons *et al.* (2009), but including only the Ohmic dissipation. More recently, Viganò and Pons (2012) presented the first two-dimensional magneto-thermal code able to manage arbitrarily large magnetic field intensities while self-consistently including the Hall term throughout the entire evolution.

The magneto-thermal evolution in the lifetime of the neutron star is governed by the Hall induction equation, for the magnetic evolution:

$$\frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \left\{ \frac{c^2}{4\pi\sigma} [\nabla \times (e^v \mathbf{B}) - \omega_B \tau_e (\nabla \times (e^v \mathbf{B})) \times \mathbf{B}/B] \right\},$$

where  $\sigma$  is the electrical conductivity,  $e^v$  is the lapse function that accounts for redshift corrections, and  $\omega_B \tau_e = B\sigma/en_e c$  is the magnetization parameter ( $\omega_B = eB/m_e^* c$  is the gyration frequency of electrons,  $n_e$  is the electron number density, and  $\tau_e$  and  $m_e^*$  are the relaxation time and effective mass of electrons),

and the cooling, or energy-balance, equation for the thermal evolution of the crust:

$$c_v \frac{\partial T}{\partial t} + \nabla \cdot (-\hat{\kappa} \cdot \nabla T) = -Q_v + Q_j,$$

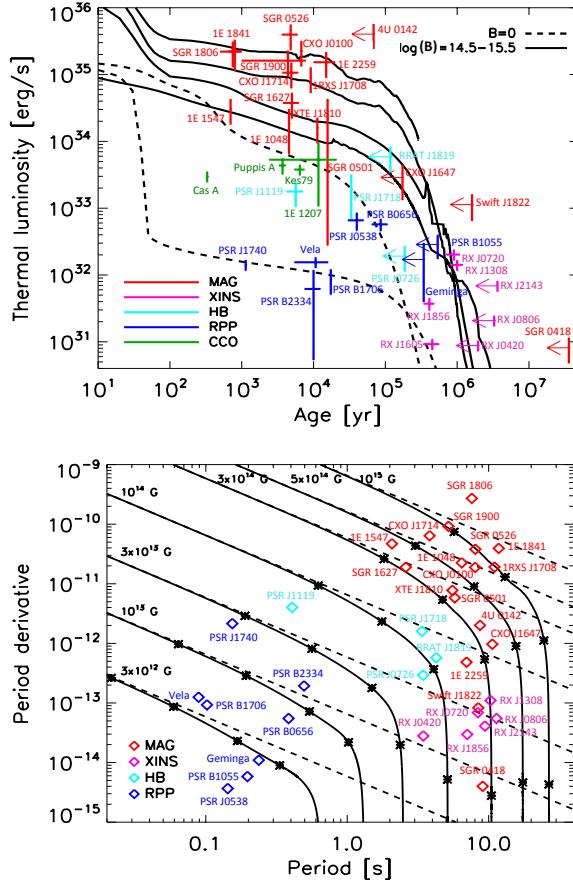
where  $c_v(T, \rho)$  is the specific heat (mainly driven by the neutrons),  $\hat{\kappa}(T, \rho)$  is the thermal and electrical conductivity, and  $Q_v(T, \rho)$  are the neutrino emissivities, and all these quantities depend on the temperature ( $T$ ) and density ( $\rho$ ).

For low temperatures ( $T \lesssim 10^8$  K) or strong magnetic fields,  $\omega_B \tau_e \gg 1$ , the evolution is Hall-dominated. For high temperatures (large resistivity) or weak fields,

$\omega_B \tau_e \ll 1$ , we have instead what is called the *dissipative regime*.

During the past decades, the study of the neutron star field decay, thanks to the continual comparison between theoretical modelling and observations, proved to be fundamental for the understanding of the secular evolutions of pulsars. In particular, recent advances in the magneto-thermal evolutionary models and the availability of deep X-ray observations of many thermally emitting isolated neutron stars, allowed a significant improvement towards the unification of the “bestiary” of different classes of isolated neutron stars (see e.g. Kaspi, 2010; Kaspi and Kramer, 2016, for an overview of the different observational manifestations of neutron stars). The sample of detected neutron stars with thermal emission consist of about 40 sources, ranging from magnetars, X-ray dim isolated neutron stars, and central compact objects, to rotational-powered pulsars and ‘high- $B$ ’ pulsars (Viganò *et al.*, 2013). Figure 8 (upper panel) shows the thermal luminosity of all these neutron stars as a function of the age together with several cooling curves for magnetic fields in the range of  $3 \times 10^{14}$ – $3 \times 10^{15}$  G and for two envelope compositions, hydrogen and iron, as computed by Viganò *et al.* (2013). Note that for young neutron stars ( $t < 100$  kyr, still in the neutrino cooling era), light-elements envelopes are able to maintain a higher luminosity (up to an order of magnitude) than iron envelopes. The inspection of a range of theoretical models, as well as observations, has shown that the magnetic field has little effect on the luminosity for ‘weakly’ magnetized neutron stars with  $B < 10^{13}$  G. These objects, of which the radio pulsars are the most notable representatives, have thermal luminosities that are compatible with those predicted by standard non-magnetic cooling models. Overall, the magneto-thermal simulations can broadly reproduce the observed X-ray luminosities for a range of initial magnetic field strengths, envelope compositions, and neutron star masses. As the neutron stars age and become colder, they also spin down, primarily due to dipolar radiation losses. In the absence of field decay, pulsars should follow linear tracks in the  $P$ – $\dot{P}$  diagram (see dashed lines in the lower panel of Fig. 8). However, when magnetic field dissipation is taken into account, evolutionary tracks in the  $P$ – $\dot{P}$  diagram bend down (Fig. 8).

Comparing observations and theoretical modelling of the neutron star magneto-thermal evolution, considering both the luminosity and the rotational period properties, we can gather that objects like the traditional rotation-powered radio pulsars were born with magnetic fields in the range of a few  $10^{12}$ – $10^{13}$  G. When they cool and slow down, they eventually become invisible in both the radio and the X-ray bands, and hence they lack observable counterparts. On the other hand, pulsars born with fields exceeding the  $10^{14}$  G, will be observed now as young magnetars or high- $B$  pulsars (depending on the strength and the configuration of the field at birth), and have as descendants the objects known as X-ray dim isolated neutron stars. These simulations point to evolutionary connections (some of which have been suspected for long) between apparently different groups of pulsars: Most likely, they are all essentially the same kind of objects, but they were born with different magnetic field strength and geometry, and are observed at different evolutionary stages of their life.



**Fig. 8** Top: Comparison between observational data and theoretical cooling curves. The thermal luminosity was evaluated for each source using the best estimated distance available and ages were estimated from kinematic measurements, when available, or as the characteristic age derived from the timing parameters (in this case, an arrow was used for objects older than 10 kyr, for which the characteristic age is considered an upper limit on the real age and not a reasonable approximation). Dashed lines are non-magnetic cooling curves, the upper with  $M = 1.10 M_\odot$  and a light-element envelope, and the lower with  $M = 1.76 M_\odot$  and an iron envelope. The magneto-thermal evolutionary tracks (solid lines) were computed for magnetic fields in the range  $B = 3 \times 10^{14} - 3 \times 10^{15}$  G and both iron and light-element (upper) envelopes. Bottom: Evolutionary tracks in the  $P-\dot{P}$  diagram for a 1.4- $M_\odot$  neutron star with  $B_p^0 = 3 \times 10^{12}, 10^{13}, 3 \times 10^{13}, 10^{14}, 3 \times 10^{14}$ , and  $10^{15}$  G. Asterisks mark the real ages  $t = 10^3, 10^4, 10^5, 5 \times 10^5$  yr, while dashed lines show the tracks followed in absence of magnetic field decay. (Adapted from Viganò *et al.* 2013.)

## 2.5 Low- $B$ magnetars and high- $B$ pulsars

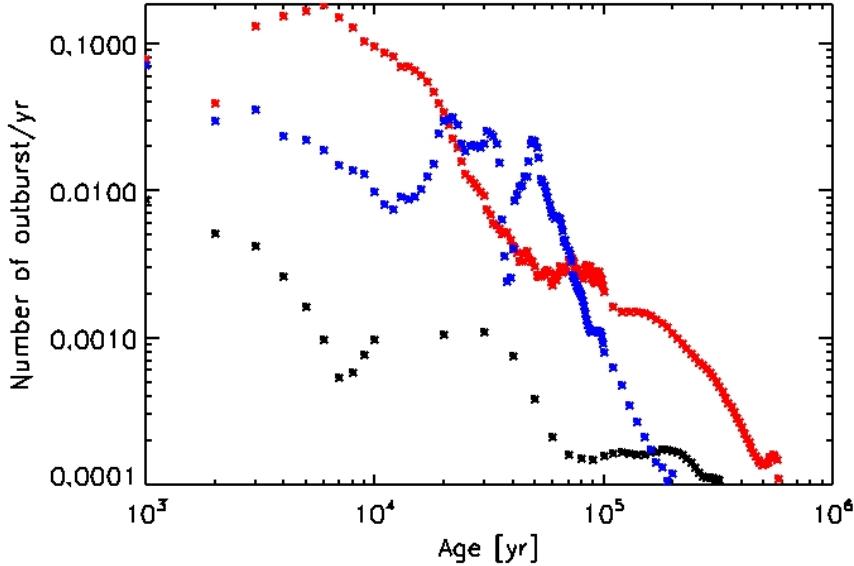
Recently, the long standing belief that magnetars must posses supercritical magnetic fields<sup>2</sup> has been challenged by the discovery of full-fledged magnetars with a dipole magnetic field well in the range of ordinary radio pulsars: SGR 0418+5729, Swift J1822.3–1606, and 3XMM J1852+0033 (Rea *et al.* 2010, 2012, 2014; see Turolla and Esposito 2013 for a review). Those three magnetars are in fact not dissimilar from the other members of the class, except for the strength of the dipole magnetic field  $B_p$  estimated from the spin parameters, in the range  $(0.6\text{--}4) \times 10^{13}$  G. Furthermore, this results also in a large characteristic age of  $>10^6$  yr, two or three orders of magnitudes larger than the typical magnetar ages, suggesting that these low-field magnetars might be old objects. The small number of detected bursts (with comparatively low energetics) and the low persistent luminosity in quiescence have been taken as further hints that these might be worn-out magnetars, approaching the end of their active life (Turolla *et al.*, 2011). The ‘old magnetar’ scenario sounds appealing since it offers an interpretation of the low-magnetic-field magnetars within an already well established framework, validating the magnetar model also for (surface) field strengths quite far away from those of canonical SGR/AXPs.

The crucial issue is whether a relatively low dipolar field is consistent with the starquake models, in which the primary cause of the outbursts is an internal deposition of energy following a crust failure once the magnetically induced shear stress exceeds a critical value. The magnetic stress needed to break the crust is strongly dependent on the density (it is much easier to break the outer crust than the inner crust); moreover, the crust thickness grows as the temperature drops with age. Detailed calculations show that a local magnetic field of  $\approx 2 \times 10^{15}$  G should be necessary to break the crust, but closer to the surface of the crust, due to the smaller density, magnetic fields as low as  $\sim 10^{14}$  G may lead to crust fractures (Gourgouliatos and Cumming, 2015; Lander *et al.*, 2015). At any rate, the minimum requirement seems to be around  $10^{14}$  G. So, can (and how) aged, cold and low-magnetic-field magnetars still produce bursts and outbursts? This depends on the internal toroidal component of its magnetic field. For this reason, objects with similar dipolar magnetic field strength as inferred from their period and period derivative can display very different behaviours. In general the toroidal component of the magnetic field is unmeasurable in a pulsar (but see the gray box for SGR 0418+5729), but this reasoning help us understanding and explaining the populations of active magnetars, low-magnetic-field magnetars, and high- $B$  pulsars. A rough prediction of the expected outburst rate for different initial magnetic field configurations and life stages is given for standard assumptions in Fig. 9. For an object similar to SGR 0418+5729, a rate of  $\approx 10^{-3}$  starquakes  $\text{yr}^{-1}$  is expected (Perna and Pons, 2011; Viganò *et al.*, 2013). Assuming that there are about  $10^4$  neutron stars in the Galaxy with similar age, and that a (very approximatively) 10% of them were born as magnetars, a naive extrapolation of this event rate to the whole neutron star population leads to the occurrence of  $\sim 1$  low-

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<sup>2</sup> The electron quantum critical magnetic field  $B_Q = m_e^2 c^2 / (\hbar e) \simeq 4.4 \times 10^{13}$  G was traditionally considered the threshold above which magnetars could be found.

magnetic-field-magnetar outburst per year. Therefore, we expect that more and more objects of this class will be discovered in the upcoming years. Similarly, we can anticipate some magnetar-like events from only-sporadically-active sources labelled as belonging to other classes of isolated neutron stars, as perhaps shown by the outbursts of PSR J1846–0258 and PSR J1119–6127 (Gavriil *et al.*, 2008; Archibald *et al.*, 2016; Göögüs *et al.*, 2016).



**Fig. 9** Outburst rate as a function of time for neutron stars with different magnetic field configurations and strength:  $B_p^0 = 3 \times 10^{14}$  G in black,  $B_p^0 = 10^{15}$  G in red, and in blue  $B_p^0 = 10^{14}$  G but with an initial strong toroidal field of  $B_t^0 = 5 \times 10^{15}$  G (from Viganò *et al.*, 2013).

#### An energy-dependant absorption line in the cornerstone low-magnetic-field magnetar: SGR 0418+5729

The most searched-for indicator of the magnetic field strength in neutron stars are cyclotron features in their spectra. The cyclotron energy for a particle of charge and mass  $e$  and  $m$  is  $E_{\text{cycl}} = 11.6(m_e/m)/(1+z) B_{12} \text{ keV}$ , where  $z \approx 0.8$  is the gravitational redshift,  $m_e$  is the mass of the electron, and  $B_{12}$  is the magnetic field in units of  $10^{12}$  G. For magnetic fields of  $\approx 10^{14}$  G, magnetospheric protons can produce cyclotron lines in the soft X-ray range .

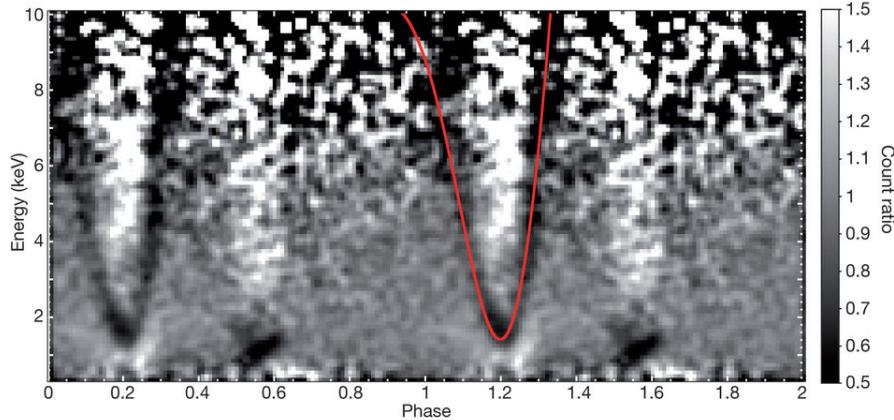
The most convincing of such features in a magnetar was reported by Tiengo *et al.* (2013), who observed a phase-dependent absorption feature in the spec-

trum of the low-magnetic-field magnetar SGR 0418+5729 during its 2009 outburst (Esposito *et al.*, 2010; Rea *et al.*, 2013b). The feature was more prominent in a deep XMM–Newton observation but was present also in data collected with RossiXTE and Swift (Tiengo *et al.*, 2013, see also Esposito *et al.* 2010). The line energy was varying between  $\sim 1$  and 5 keV in approximately one-fifth of the rotation cycle (Fig. 10), corresponding to magnetic field strength values of  $10^{14}$  to  $10^{15}$  G if due to protons (Tiengo *et al.* 2013 devised a toy model in which the cyclotron line is due to thermal photons crossing protons localised in a magnetic loop with magnetic field of  $10^{14}$ – $10^{15}$  G close to the surface of the star). An electron cyclotron feature is indeed implausible, as the electrons, considered the dipole magnetic field of  $B_p \simeq 6 \times 10^{12}$  G, should be confined in a small volume at a few stellar radii from the neutron star surface (while the alternative explanation in terms of atomic transition lines is ruled out by the variability of the line energy with the spin phase). If the feature is really a proton cyclotron line, it demonstrates in SGR 0418+5729 the presence of nondipolar magnetic field components strong enough to break the neutron star crust and give rise to magnetar outbursts.

Rodríguez Castillo *et al.* (2016) reported the presence of a similar feature in Swift J1822.3–1606, the magnetar with the second lower magnetic field ( $B_p \sim (1\text{--}3) \times 10^{13}$  G Olausen and Kaspi 2014; Scholz *et al.* 2012), again indicating the presence of localised magnetic fields of  $10^{14}$ – $10^{15}$  G. Interestingly, spectral features with analogous characteristics have been detected also in two X-ray dim isolated neutron stars, RX J0720.4–3125. and RX J1308.6+2127 (Borghese *et al.*, 2015, 2017); in these cases, the magnetic fields deduced in the hypothesis of a proton cyclotron line are of  $\sim 2 \times 10^{14}$  G, in both cases around 5 times the values inferred from the spin parameters.

## 2.6 Magnetars in binary systems

It is not clear whether magnetar exist in binary systems but, although it is possible that magnetars to form have to sacrifice the companion, binarity may be an important ingredient for the production of magnetars for at least two reasons. Firstly, if magnetars descend from particularly massive stars ( $\gtrsim 20 M_\odot$ ), the binary interaction may prevent the formation of a black hole instead of a neutron star. Secondly, in the case the magnetic fields of magnetars are formed through dynamo amplification, even if magnetars form from stars with lower masses, a binary system may help the stellar core to maintain the angular momentum necessary for the dynamo mechanisms. On the other hand, in the fossil field scenario, in which the neutron star magnetic field reflects that of the stellar precursor, progenitors belonging to binary systems may be disfavoured, since magnetic hot stars in compact binary systems are very rare (Neiner *et al.*, 2015).



**Fig. 10** Normalised energy-versus-phase ‘spectral image’ of SGR 0418+5729. It was obtained from the XMM–Newton data binning the source photons into 100 phase bins and 100-eV-width energy channels and normalising the counts first by the phase-averaged energy spectrum and then by the pulse profile (normalised to the average count rate). The red line shown for one of the cycles represents the proton cyclotron model of Tiengo *et al.* (2013, from which the image was taken) and highlights the V-shaped absorption feature.

Both scenarios for the origin of magnetar magnetic field require a very massive progenitor, heavier than  $\sim 20 M_{\odot}$ . For the fossil field, because there seems to be in main sequence stars a trend of stronger magnetic fields with larger masses (Ferrario and Wickramasinghe 2008 and references therein). In the dynamo hypothesis, because to produce neutron stars rotating fast enough to generate a magnetar field via  $\alpha\text{-}\omega$  dynamo, a star more massive than  $\sim 20\text{--}35 M_{\odot}$  star is necessary (Heger *et al.*, 2005). There are also observational facts that favour very massive stars as the magnetar precursors. Considering the spatial distribution of the known magnetars, it has been noted that their height on the Galactic plane is smaller than that of OB stars. This suggests that they were produced by the most massive O stars (Olausen and Kaspi, 2014). Furthermore, there are some tentative associations of magnetars with massive star clusters.

In the most convincing case, CXOU J164710.2–455216 in Westerlund 1, the young age of the cluster ( $\sim 4$  Myr) implies a progenitor with minimum mass of  $\sim 40 M_{\odot}$  (Muno *et al.*, 2006).<sup>3</sup> To allow such a massive star to produce a neutron star, Clark *et al.* (2014) suggested a binary with  $(41 + 35) M_{\odot}$  stars and an orbital period shorter than 8 days.<sup>4</sup> The idea is that the binary interaction drives the pri-

<sup>3</sup> For the progenitor of SGR 1900+14, a lower mass of  $\sim 17 M_{\odot}$  has been inferred, suggesting that magnetars could form from stars with a wide spectrum of initial masses (Clark *et al.*, 2008; Davies *et al.*, 2009).

<sup>4</sup> They also found a candidate for the other member of the pre-supernova system: Wd1–5, a  $\sim 9 M_{\odot}$  runaway star that is escaping the cluster at high velocity and has a peculiar carbon excess that may be due to the binary evolution.

mary in a Wolf–Rayet star that through its powerful stellar winds loses mass to the point that the formation of a neutron star is possible. The star also avoids the supergiant stage, during which the core would lose angular momentum because of the core–envelope coupling.

Observationally, the presence of magnetars is often invoked in high-mass X-ray binaries (e.g. Bozzo *et al.*, 2008) and in particular for some persistent Be systems with long-spin-period ( $\gtrsim 1000$  s) neutron stars. The issue is that, according to the standard picture, after a short propeller phase, the neutron star enters the accretor stage and its spin period quickly settles at an equilibrium value. To have an equilibrium period longer than 1000 s, the neutron star dipole field must be  $\gtrsim 10^{14}$  G (Davies and Pringle, 1981). This is unless the accretion rate is very low, but it would be orders of magnitude below the rate necessary to account for the luminosity of these persistent Be X-ray binary systems, hence the puzzle. However, in the recent model of quasi-spherical settling accretion in wind-fed high-mass X-ray binaries by Shakura *et al.* (2012), the equilibrium period can be of  $\sim 1000$  s even for ‘ordinary’ magnetic fields of  $\sim 10^{12}$ – $10^{13}$  G and acceptable accretion rates. The model has been applied successfully in populations studies and to model samples and singles sources (e.g. Chashkina and Popov, 2012; Li *et al.*, 2016), including the slowest known accreting pulsar, in the high-mass X-ray binary system AX J1910.7+0917 (spin period of 36.2 ks; Sidoli *et al.*, 2017).

There is however an exception, the Be X-ray binary SXP 1062 in the Small Magellanic Cloud, which has a spin period of 1062 s and is robustly associated to a supernova remnant with kinematic age of  $(2\text{--}4) \times 10^4$  yr (Hénault-Brunet *et al.* 2012; Haberl *et al.* 2012 propose an even younger age using a temperature–size relationship). In fact, for typical values of magnetic field and accretion rate, it would have been impossible for the neutron star to enter the propeller stage and become an accretor within the time constraint of a few  $\times 10^4$  yr dictated by the age of the supernova remnant. After considering several possible scenarios, Popov and Turolla (2012) proposed a neutron star born with an initial magnetic field of  $\gtrsim 10^{14}$  G that then decayed to a present value of  $\sim 10^{13}$  G (derived in the assumption that the star is rotating close to the equilibrium period).

Magnetars are increasingly popular also in the field of ultraluminous X-ray sources (ULXs). These sources—a few hundreds of them are known—are observed in off-nucleus regions of nearby galaxies at X-ray luminosities exceeding a few  $10^{39}$  erg s $^{-1}$  (Kaaret *et al.*, 2017). Since this threshold for isotropic luminosity is larger than the Eddington limit for spherical accretion of fully ionized hydrogen onto a  $\sim 10\text{-}M_\odot$  compact object (a scale value of the black holes of stellar origin observed in our Galaxy), ULXs were considered the observational manifestation of massive black holes of stellar origin ( $\lesssim 80\text{--}100\text{ }M_\odot$ ) and, the brightest ones in particular, promising candidates of intermediate-mass black holes of  $10^3\text{--}10^5\text{ }M_\odot$  (Miller and Colbert, 2004). For these reason, the recent discovery in three ULXs (M82 X-2, NGC 5907 ULX, and NGC 7793 P13) of pulsars with spin periods from 0.4 to 1.4 s has been a blow, showing both that some ULXs (even in the high side of their luminosity distribution) may host neutron stars and that neutron stars can achieve extreme super-Eddington luminosities (Bachetti *et al.*, 2014; Israel *et al.*, 2017a,b).

The most luminous of the bunch, NGC 5907 ULX, which has a period of  $\sim 1.1$  s, was observed at a maximum X-ray luminosity of  $\sim 10^{41}$  erg s $^{-1}$ , more than 500 times the Eddington limit for a  $1.4 M_{\odot}$  neutron star (Israel *et al.*, 2017a). In principle, a neutron star with a magnetic field of  $\gtrsim 10^{15}$  G could attain such a super-Eddington luminosity (Dall’Osso *et al.*, 2015; Mushtukov *et al.*, 2015), since the magnetic field reduces the electron scattering cross section (see also Sect. 2.2.1). However, this explanation is not viable in the cases of NGC 5907 ULX and NGC 7793 P13, because such a huge magnetic field coupled with the rapid spinning of the star would inhibit the accretion via the propeller mechanisms. A possible solution proposed by Israel *et al.* (2017a) is that the magnetic field is indeed of a few  $10^{14}$  G at the neutron star surface, but is dominated ( $\sim 90\%$ ) by multipolar components, which vanish rapidly with the distance, so that at the magnetospheric radius ( $\approx 100$  neutron star radii) the magnetic field is virtually the dipolar one, low enough for the accretion to proceed. It is interesting to note that this hypothesis does not require for the neutron star only a superstrong magnetic field (a purely dipolar magnetic field would not work), but a complex magnetic field configuration similar to that envisaged for magnetars.

Finally, there is a peculiar binary source in which the presence of an ultra-magnetized neutron star has been suggested not as a wildcard to explain its properties, but because it actually showed one of the specific characteristics of magnetars: LS I +61°303. It is one of the few gamma-ray (TeV) binaries (Dubus, 2013) and is in a orbit of 27 days with a  $10-15 M_{\odot}$  Be star. LS I +61°303 is also a periodic (27 d) and variable radio source (it is often referred to as a *microquasar*) and, since no direct evidence for the presence of a neutron star has been obtained so far (for example, pulsations, mass limits or thermonuclear bursts), the nature of its compact object is still debated. In 2008, Swift triggered on a short, SGR-like burst from LS I +61°303. With a duration of  $\sim 0.2-0.3$  s, a blackbody spectrum with temperature of 7.5 keV, and luminosity of  $\sim 2 \times 10^{37}$  erg s $^{-1}$ , the event had the characteristics of a magnetar burst (Torres *et al.*, 2012). A second magnetar-like burst was detected again by Swift in 2012 (Burrows *et al.*, 2012). Torres *et al.* (2012) discussed the implication of the presence of a magnetar in LS I +61°303 and showed that it would be compatible with the properties of the source.

### 3 Final remarks

Until about a decade or little more ago, magnetars were regarded as a sort of astrophysical oddities and only comparatively few small groups of astronomers were interested in them. In recent times however, a number of surprising observational discoveries connected more strictly magnetars to the other classes of neutron stars and made them hard to be ignored by the large community studying pulsars at different wavelengths. In fact, it has been discovered that magnetars can be radio pulsars and also that ‘ordinary’ X-ray and radio pulsars, as well as other sources, such as the peculiar neutron star in the supernova remnant RCW 103, can behave like magnetars, showing the whole array of magnetar activity: bursts, outbursts, dramatic and

abrupt pulse profile changes and other timing anomalies. We have also learnt that magnetars can populate unexpected regions of the  $P-\dot{P}$  diagram, with dipole magnetic fields measured from the rotation parameters that are comparable to or lower than those of the radio pulsars, disguising at the same time much stronger nondipolar magnetic field components. On the other hand, there are mounting evidences that magnetar (nondipolar) magnetic fields may be present also in other classes of isolated and binary neutron stars; in the future, they might manifest magnetar behaviour. Summarising, episodes of magnetar activity and their frequency seem to be related to the total magnetic energy stored in the internal field of a neutron star but, while a huge tank of this energy is typically associated to the pulsars in the upright corner of the  $P-\dot{P}$  diagram, the external dipolar magnetic field inferred from the spin period and the slow-down rate is not necessarily a good proxy for it. For this reason, maybe it would be more appropriate to speak of magnetar-like activity (or ‘magnetic restlessness’) in neutron stars rather than of magnetars.

Perhaps even more importantly, magnetars are proving to be key objects in understanding the puzzling observational diversity among the different classes of isolated neutron stars. After all, neutron stars are relatively simply, collapsed, objects, presumably all governed by the same equation of state: Why do they come in so many flavours? Theoretical progresses, chiefly about the complexity and the evolution of their magnetic field, are paving the way to a unifying view, in which the age, the different magnetic field strength and geometry at birth, and few other pivotal parameters, such as the mass and the chemical composition of the envelope, can explain the neutron star diversity.

Magnetars are being increasingly invoked in a variety of astrophysical sources and phenomena, from high-mass X-ray binaries and ULXs, to gamma-ray bursts, superluminous supernovae, fast radio bursts, sources of gravitational waves, and many others. While in some cases they are used in a lighthearted way as jacks-of-all-trades, because a huge magnetic field offers an easy way to solve an observational or theoretical problem, magnetar are finally receiving the attention they deserve. This will trigger more and more observational and theoretical efforts which, together with new forthcoming powerful and innovative instruments, such as CTA, SKA, Athena+, X-ray polarimeters, space interferometers, and giant optical telescopes, are bound to deliver many important and surprising discoveries. Magnetars enthusiasts are well positioned to enjoy the next few decades.

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