Mem. S.A.It. Vol. 90, 204
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Magnetars: neutron stars at the extreme

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Abstract. Magnetars are the strongest magnets we know of. Their X-ray emission is powered by the instabilities and decay of their huge magnetic field ($\sim 10^{14} - 10^{15}$ G). The hallmark of these isolated neutron stars is the unpredictable and variable bursting activity observed in the X-/gamma ray regime and on different time scales (from milliseconds up to tens of seconds). These flaring episodes are often accompanied by enhancements of the persistent X-ray flux, which usually relaxes back to the quiescent level over months to years, the so-called outbursts. Here, I review the observational properties of magnetars, showing a systematic analysis of outbursts and new results in the field. I then finish with some considerations on magnetar-like activity from other classes of neutron stars, recently observed more often.

Key words. Stars: neutron – Stars: magnetars – Stars: magnetic fields – X-rays: bursts

1. Introduction

Historically divided in two classes, the so-called Anomalous X-ray Pulsars (AXPs) and Soft Gamma-ray Repeaters (SGRs) are now believed to be the observational manifestations of the same underlying source: an isolated neutron star endowed with an ultra-strong magnetic field whose decay and instabilities power the emission, hence the name of magnetar (Duncan & Thompson 1992). Several reviews on the topic were published in the last years, e.g., Turolla et al. (2015); Kaspi & Beloborodov (2017); Esposito et al. (2018). Up to now, the magnetar class comprises about 30 members[1]. The discovery rate increased when *Swift* with its Burst Alert Telescope (BAT) and the *Fermi* mission with its Gamma-ray Burst Monitor (GBM) were launched in 2004 and 2008, respectively. These two instruments are designed to monitor the entire sky, being therefore sensitive to bursts regardless of their location. Thus, they have helped to build an unbiased sample of magnetars, selected only for their activity, namely bursting.

All magnetars are confined in the Galactic plane with a scale height of $\sim 20 - 30$ pc, except for SGR 0526–66 and CXOU J0100–7211 that reside in the Magellanic Clouds, and about 1/3 is associated with supernova remnants. Both these characteristics suggest that magnetars are relatively young neutron stars. They display X-ray pulsations with periods in the 0.3 – 12 s interval and relatively large secular spin-down rates ($\dot{P} \sim 10^{-15} - 10^{-11}\ \mathrm{s\,s^{-1}}$). Assuming that they are slowed down by magneto-rotational losses, the surface dipolar magnetic field strength, as inferred from the timing properties, is as high as $\sim 10^{14} - 10^{15}$ G, with the exception of a handful of objects that show a magnetic field in

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[1] 23 confirmed magnetars + 6 candidates; see the online McGill Magnetar Catalog (Olausen & Kaspi 2014).

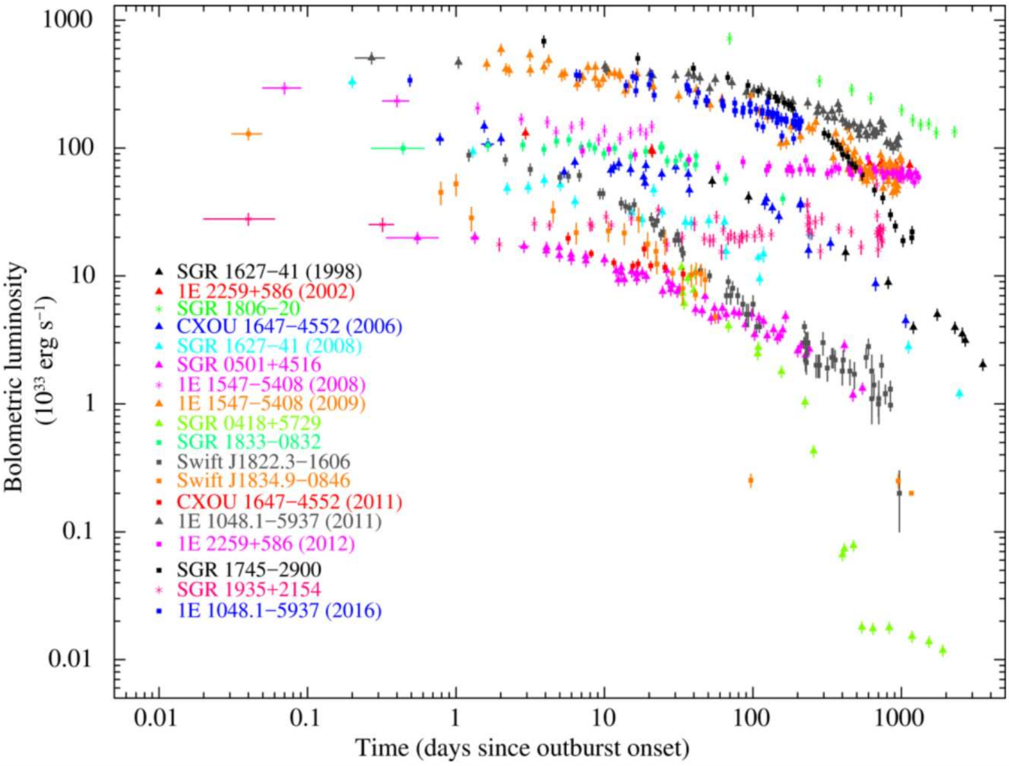

Fig. 1. Light curves of all the outbursts re-analysed by Coti Zelati et al. (2018). The luminosities are bolometric, obtained from an extrapolation of the best-fit spectral models in the 0.01–100 keV.

the range of those of the ordinary radio pulsars ($\sim 10^{12} - 10^{13}$ G; see Turolla & Esposito 2013, for a review). Magnetars are characterized by a X-ray luminosity L_X in the range $\sim 10^{31} - 10^{36}$ erg s^{-1}, generally larger than the rotational energy loss rate. For this reason, their emission is thought to be ultimately powered by the dissipation/instabilities of the extremely high magnetic field rather than its rotation. Magnetars are observed to emit over a broad range, from soft X-rays up to ~ 100 keV (Götz et al. 2006). The soft X-ray emission ($\lesssim$ 10 keV) is well described by a thermal component (a blackbody with temperature $kT \sim 0.3 - 0.9$ keV) plus the inclusion of a second blackbody ($kT \sim 1 - 2$ keV) or a steep power law with photon index $\Gamma \sim 2 - 4$. This decomposition is generally interpreted in a scenario according to which the thermal emission that arises from the hot neutron star surface could be distorted by magnetospheric effects, such as resonant cyclotron scattering (Nobili et al. 2008a,b). The hard X-ray emission can be adequately modelled by a power law flatter than that observed in the soft X-ray band ($\Gamma \sim 0.5 - 2$). It is modulated at the magnetar spin period and its luminosity is comparable or higher than that measured in the 0.3 – 10 keV energy interval. The mechanism at the origin of these hard tails is still under debate. A possible explanation invokes resonant scattering of thermal photons on a population of highly relativistic electrons threaded in the magnetosphere (Baring & Harding 2008).

2. Flaring activity

The hallmark of this class of isolated neutron stars is the unpredictable and variable bursting activity in the X-/gamma ray band, which encompasses a wide interval of time scales and luminosities. In particular, three kind of events have been observed.

The *giant flares* are the most powerful phenomena. Detected only three times so far, they reached a peak luminosity $\geqslant 10^{44}$ – 10^{45} erg s^{-1}. All three events started with an initial spike of 0.1 – 0.2 s duration, followed by a tail modulated at the magnetar spin period (see e.g., Hurley et al. 1999). The *intermediate bursts* last $\sim$ 1 – 40 s and have a peak luminosity of $\sim 10^{41}$ – 10^{43} erg s^{-1}. They are characterised by an abrupt onset and usually show thermal spectra (see e.g., Israel et al. 2008). Finally, the *short bursts* are the most common events, with duration from milliseconds to few seconds and peak luminosity of $\sim 10^{39}$ – 10^{41} erg s^{-1}. They can come in storms or occur sporadically and represents the most effective tool to identify new magnetars (see e.g., Woods et al. 2004).

The bursts often announce that the source has entered an active phase, commonly referred to as *outburst* (see Rea & Esposito 2011, for an observational review). During an outburst, the persistent X-ray flux suddenly increases up to three orders of magnitude higher than the quiescent level. Then, it usually relaxes back to the pre-outburst level on time scales spanning from weeks to months/years (see Fig. 1). The outbursts are accompanied by a spectral hardening, which corresponds to an increase of the blackbody temperature and/or the appearance of a hot blackbody component beside the cold one related to the emission from the neutron star surface. In some cases, a transient not-thermal hard power law tail is detectable (Enoto et al. 2017). Moreover, these events are often followed by timing anomalies, such as glitches or pulse profile changes, and give an opportunity to search for pulsed radio emission (detected in four cases so far) and infrared/optical counterparts.

It is believed that outbursts are caused by heat deposition in a restricted area of the magnetar surface, however the mechanism responsible for their activation is still poorly understood. They are most likely triggered by magnetic stresses in localized regions of the crust that are able to deform part of it in a plastic way. Then, the plastic flows convert mechanically the magnetic energy into heat (Beloborodov & Levin 2014; Beloborodov & Li 2016). A fraction of the deposited heat is conducted up to the surface layers and radiated, producing a delayed thermal afterglow emission. Furthermore, the crustal displacements implant a strong external magnetic twist, in the form of a bundle of current-carrying closed field lines. An additional source of heating is provided by the impact of the currents flowing along the twist and hitting the surface of the magnetar (Beloborodov & Thompson 2007; Beloborodov 2009). As the energy supply from the star interior is progressively depleted, the bundle must decay to support its own currents. Both mechanisms – internal and external – are most likely at work during an outburst.

3. Magnetar-like activity from non-canonical magnetars

Recently, we observed magnetar-like activity from sources that are not classified as magnetars. These discoveries demonstrate how magnetar magnetic fields may be present in other classes of isolated neutron stars.

3.1. X-ray dim isolated neutron stars

X-ray dim isolated neutron stars (XDINSs) are seven radio-quiet, nearby ($\lesssim 500$ pc), thermally emitting neutron stars that rotate slower ($P \sim 3$ – 11 s) and have higher inferred surface dipolar magnetic fields ($B_{dip} \sim 10^{13}$ G) than the bulk of the radio pulsars (see Turolla 2009, for a review).

According to the most recent magneto-thermal models (Viganò et al. 2013), XDINSs are likely to be the descendants of magnetars. Moreover, the discovery of two phase-dependent spectral features in two low-field magnetars (Tiengo et al. 2013; Rodríguez Castillo et al. 2016) drove the motivation of the work of Borghese et al. (2015, 2017). They performed a systematic search for similar spectral features in the XDINSs to find evidence for a magnetar (nondipolar) magnetic field. Through the inspection of energy versus phase normalized images and a detailed pulse-phase spectroscopy, they investigated the presence of narrow, absorption spectral features that can vary along the rotational phase. This investigation led to the discovery of such features, present in only 20% of the rotation cycle, in the X-ray spectra of two XDINSs. Owing to the narrow width and the strong dependence on the rotational phase, these spectral lines are likely due to proton resonant cyclotron absorption/scattering in a confined magnetic loop close to the stellar surface. The line energy was $\sim$ 750 keV, corresponding to a magnetic field strength of about 5 times higher than the dipolar surface component inferred from the timing parameters.

These findings provide evidence that XDINSs can be endowed with a nondipolar magnetic field strong enough to displace the crust and power bursting activities, eventually. More generally, these discoveries support the idea that the magnetic field of highly magnetized neutron stars is indeed complex, with substantial deviations from a pure dipole on small scales, and strengthen the evolutionary link between XDINSs and magnetars.

3.2. High-*B* radio pulsars

If the strong magnetic field is the engine of the magnetar X-ray variability, it is natural to think that sources with magnetar-strength fields might display similar behaviours. The prof came in 2006, when the rotation-powered pulsar PSR J1846–0258 underwent a X-ray brightening by a factor of > 20 associated with several magnetar-like bursts (Gavriil et al. 2008). The source has a dipolar magnetic field moderately higher than the rest of the rotation-powered pulsar population ($\sim 5 \times 10^{13}$ G).

Another event supporting a link between high-*B* pulsars and magnetars took place recently. The pulsar PSR J1119–6127 experienced a X-ray flux enhancement by a factor of $\sim$ 200, heralded by short, bright bursts (Archibald et al. 2016). Radio observations performed few days after the outburst onset did not detect pulsed radio emission from the source, which turned on as a radio pulsar again after $\sim$ 10 days from the initial outburst activation. Archibald et al. (2017) present simultaneous X-ray and radio observations of PSR J1119–6127, performed during a period of magnetar-like bursts about one month after the outburst onset. The rotationally powered radio emission was not detected in coincidence with the X-ray bursts.

3.3. The central source of RCW 103

1E 161348–5055 (1E), located close to the center of the supernova remnant RCW 103, was considered one of the prototypes of the central compact object (CCO) class. CCOs are steady X-ray source with thermal-like spectra and no counterpart at other wavelengths (see De Luca 2017, for a review).

Remarkable features were observed in 1E, setting it apart from the CCOs: an unusual spin period of 6.67 h and observations of flux variability (about 2 orders of magnitude). Recently, a new event shed light on the nature of this source. On 2016 June 22, a short ($\sim$ 10 ms) magnetar-like burst of hard X-rays from the direction of 1E triggered *Swift* BAT (see Fig. 2; D'Aì et al. 2016; Rea et al. 2016). The burst light curve shows a double-peaked profile with a luminosity of $\sim 2 \times 10^{39}$ erg s^{-1}. Follow-up observations with *Swift*, *Chandra* and *NuSTAR* showed that 1E was experiencing a magnetar-like outburst: the flux was a factor $\sim$ 100 higher than the quiescent level; the pulse profile became double-peaked from single-peaked; a hard component was detected up to $\sim$ 30 keV for the first time (well modelled by a power law with $\Gamma \sim 1.2$; Rea et al. 2016). One year after the outburst onset, the broadband spectrum softened and the pulse profile exhibited a simpler morphology (Borghese et al. 2019). All the aspects caught by these observations match with the features of a magnetar in outburst. However, the periodicity of 6.67 h makes 1E unique among the known magnetars. A very efficient braking mechanism is required to slow down the source in $\sim$ 2 kyr from its birth period at the currently measured value. Most models consider a propeller interaction with a fall-back disk that can provide an additional spin-down torque besides that due to dipole radiation (see e.g., Ho & Andersson 2017).

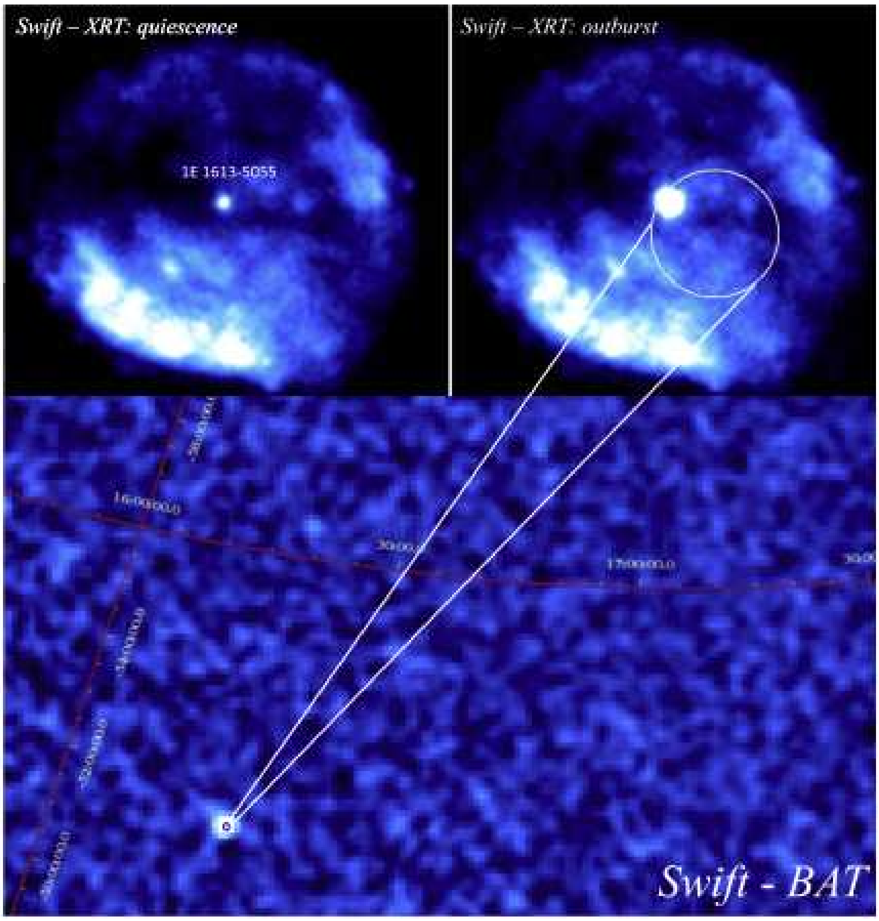

Fig. 2. Two *Swift*-XRT co-added 1–10 keV images of the SNR RCW 103 during the quiescence state of 1E 161348–5055 (from 2011 April 18 to 2016 May 16; exposure time ~ 66 ks; top left) and outburst (from 2016 June 22 to 2016 July 20; exposure time ~ 67 ks; top right). The white circle is the positional accuracy of the detected magnetar-like burst, which has a radius of 1.5 arcmin. From Rea et al. (2016).

4. Magnetar Outburst Online Catalog

Coti Zelati et al. (2018) performed a systematic and homogeneous analysis of the spectral properties for 23 outbursts (from the very first active phases throughout their decays) from 14 magnetars, the two above-mentioned high-*B* radio pulsars and 1E using all the available data acquired by the *Swift*, *Chandra* and *XMM-Newton* X-ray observatories, as well as data collected in a handful of observations by the instruments aboard *BeppoSAX*, *ROSAT* and *RXTE*. This sums up to about 1100 observations (from 1998 to 2017) for a total exposure time of more than 12 Ms.

A systematic study is required to model the outburst cooling curves in a consistent way and unveil possible correlations among different parameters. An anticorrelation between the quiescent X-ray luminosity and the luminosity increase during outburst was found, suggesting the existence of a limiting luminosity of $\sim 10^{36}$ erg s^{-1} for the outburst regardless of the quiescent level. This also means that we observe large flux enhancements only in faint quiescent sources. Moreover, a larger luminosity at the outburst peak translates into a larger amount of energy released during the outburst, and the more energetic outbursts are the also those with a longer overall duration.

All these results are presented in the *Magnetar Outburst Online Catalog* (`http://magnetars.ice.csic.es`), an interactive database where the user can plot any combination of parameters (e.g., maximum luminosity, decay time scales and energy released), and download the data.

5. Conclusions

In the last decades, magnetars have become more and more popular among the community. Given that a huge magnetic field offers an easy way to solve both observational and theoretical problems, magnetars are being employed to explain several astrophysical phenomena, such as fast radio bursts, ultra-luminous X-ray sources, superluminous supernovae, and gravitational waves. Moreover, magnetars seem to be the key objects to understand the intriguing diversity in the neutron star world. It has been discovered that radio pulsar and isolated neutron neutron stars, such as the puzzling source in the supernova remnant RCW 103, can behave like magnetars. For this reason, it may be more appropriate to speak about magnetar-like activity than a magnetar class.

Acknowledgements. I warmly thank the SOC and the LOC for organizing a very interesting meeting and for the invitation to speak.

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