Transient Magnetars and Magnetic Field Evolution of Neutron Stars

Teruaki Enoto

The Hakubi Center for Advanced Research and Department of Astronomy,
Kyoto University, Kyoto 606-8302, Japan
E-mail(FS): enoto@kusastro.kyoto-u.ac.jp

Abstract

Accumulating observations of transient activities of magnetized neutron stars have greatly expanded our knowledge of the magnetic field evolution over the neutron star lifetime. In addition to the ordinary transient magnetars characterized by short bursts and large X-ray luminosity variations, low-field magnetars, high-B pulsars, and a compact central object have recently exhibited the similar bursting activity. Despite their superficial observational difference, the diversity of neutron stars is expected to be coherently explained by the evolution of the magnetic field as an overriding parameter. In order to observationally investigate the broadband X-ray spectral evolution of the magnetar class, comprehensive re-analyses were made of all the magnetars observed with Suzaku satellite from 2005 to 2013, combining with early NuSTAR results and with Swift / RXTE monitorings (Enoto et al. 2017). More than nine sources show the hard X-ray power-law radiation above 10 keV, in addition to the well-studied soft thermal component, originating from a stellar surface or vicinity. The X-ray luminosity L_h of the hard component, relative to that of the soft component L_s, is confirmed to follow the correlation to the dipole magnetic field B_d, which results further reinforced our previous suggestions proposed in Enoto et al. 2010. The L_{sd}-L_x diagram of transient sources also implies connections among magnetars, high-B pulsars, and ordinary rotation-powered pulsars, through activation of hidden magnetic components (higher multipole or toroidal field).

Key words: stars: magnetars — stars: magnetic field — stars: neutron — X-rays: stars

1. The Diversity of Magnetized Neutron Stars

Discoveries of new transient magnetars and related families of magnetized neutron stars have greatly expanded our knowledge of magnetic activities and field decay over the neutron star lifetime. Figure 1 is the up-to-date P-$\dot{P}$ diagram (rotation periods P and their derivative $\dot{P}$) of non-accreting isolated neutron stars. This plot clearly shows the diversity, called the "neutron star zoo" (Kaspi 2010; Harding 2013). Majority of this sample is Rotation-Powered Pulsars (RPPs) which electromagnetic radiation is powered by the spin-down luminosity $L_{sd} \propto \dot{P}/P^3$, and usually bright in the radio band. The typical magnetic field of the RPPs is $B \sim 10^{12}$ G derived from their spin periods and derivatives, assuming the magnetic dipole radiation in the vacuum. Above the QED critical field $B_{cr} \equiv 4.4 \times 10^{13}$ G, Soft Gamma Repeaters (SGRs) and Anomalous X-ray Pulsars (AXPs) are collectively called magnetars with extremely strong magnetic fields of $B \sim 10^{14}$–10^{15} G (Thompson & Duncan 1995; Mereghetti 2008; Mereghetti et al. 2015). Their X-ray radiation is believed to be powered by the magnetic energy stored in the stellar interior.

Between the ordinary RPPs and magnetars, there are growing new classes with intermediate magnetic field of $B \sim 10^{13}$–10^{14} G. High-B Pulsars (HBP) are radio emitting pulsars with periods at a few hundred millisecond to a few seconds (Olausen et al. 2013). Magnetic fields of HBPs are stronger than the ordinary RPPs, almost overlapping the magnetar regime in Figure 1. Their X-ray luminosities are usually below L_{sd}, and thus they are classified into the RPPs, at least in a quiescent state. X-ray Isolated Neutron Stars (XINSs) are slowly rotating isolated X-ray objects without radio emission, and thought to be near-by sources (Mereghetti 2011). Magnetic fields of XINSs derived from their pulsations are also stronger than the canonical RPPs, and the stored magnetic energy is thought to affect their hot surface X-ray radiation. Such a strong field was recently supported from a detection of optical polarization from XINS RX J1856.5−3754 (Mignani et al. 2017).

As shown in Figure 1, the magnetic field strength of neutron star spans more than seven orders of magnitudes, and different neutron star families show variety of electromagnetic radiation spectra and timing behaviours. However, these distinct manifestations became recently blurred when similar magnetar-like activities

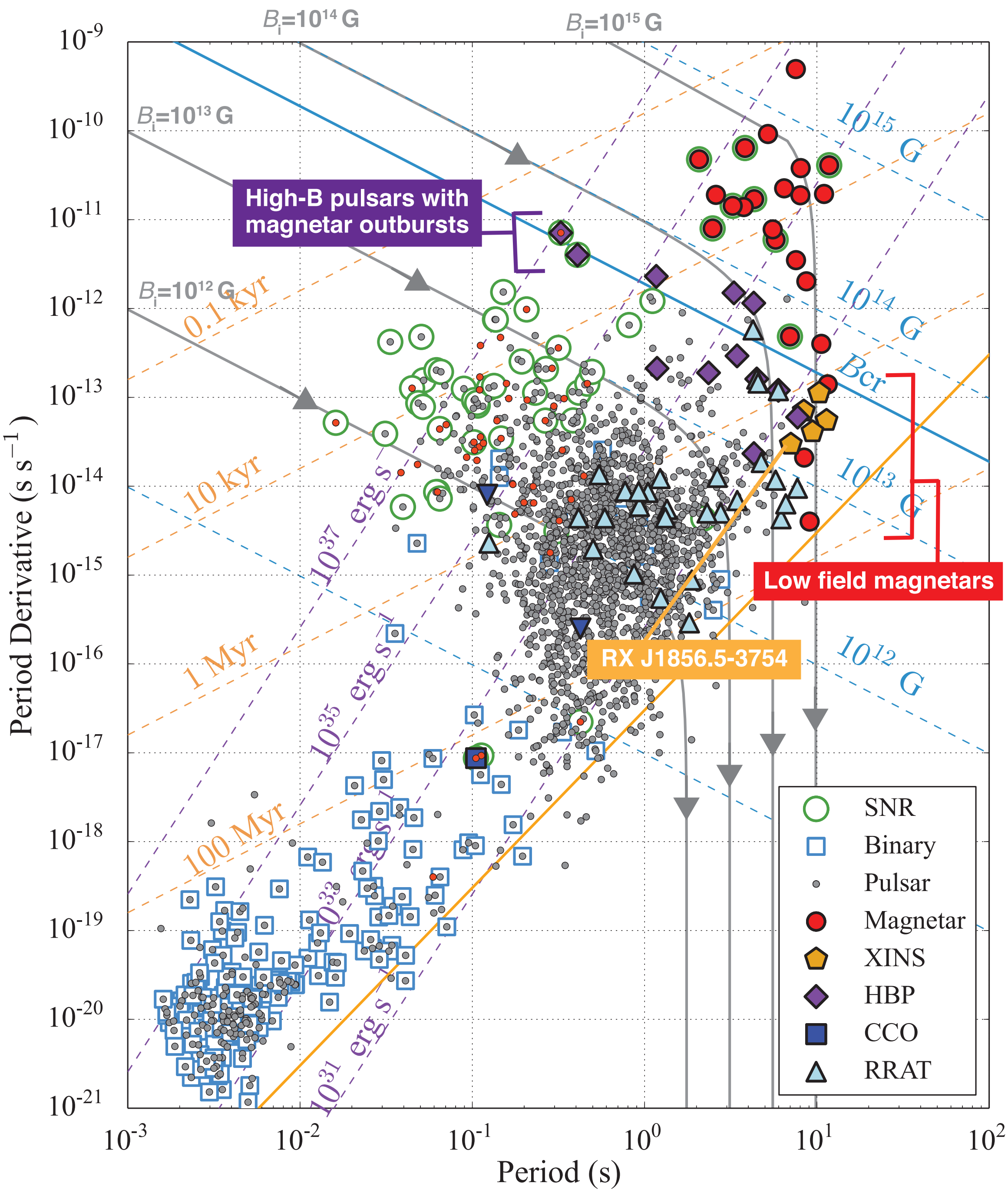

Fig. 1. The P-$\dot{P}$ diagram of various neutron star families as of 2017 January, based on the catalogues or tables (Manchester et al. 2005; Olausen & Kaspi 2014; Mereghetti 2011), including ordinary pulsars (small circles), magnetar (SGRs and AXPs, large red filled circles), X-ray isolated neutron stars (XINSs, orange pendagons), high-B pulsars (HBPs, purple diamonds), central compact objects (CCOs, blue squares), and rotating radio transients (RRATs, lightblue triangles). If a pulsar is associated with a supernova remnant (SNRs) or found in a binary system, they are surrounded by green open circles and blue squares, respectively. The constant spin-down magnetic fields B_d, characteristic ages τ_c, and spin-down luminosity L_{sd} are shown with dashed lines. The QED critical field $B_{cr} = 4.4 \times 10^{13}$ G and the death line are also shown (Harding & Lai 2006). The evolutionary paths are overlaid when assuming the empirical B_d-field decays (see, e.g., Colpi et al. 2000), calculated with some assumptions at different initial magnetic field of $B_i = 10^{12}$, 10^{13}, 10^{14}, and 10^{15} G. Two HBPs with magnetar-like outbursts, three activated low-field magnetars, and XINS RX J1856.5$-$3754 are indicated.

have been reported from different classes (§2.). Furthermore, magnetic field decay and evolution are now believed to be an overriding key parameter, to unify the neutron star zoo (Colpi et al. 2000; Viganò et al. 2013). The magnetic field decay is also supported from an overestimation of the magnetar characteristic age, when comparing between the pulsar characteristic age and supernovae remnant age in the X-ray plasma diagnostics. (Nakano et al. 2015).

2. Transient magnetars and X-ray spectral studies

Some of magnetars suddenly exhibit a large X-ray enhancement, called "outbursts". In an early phase of X-ray outbursts, sporadic short bursts are radiated with X-ray luminosities exceeding the canonical Eddington limit (Nakagawa et al. 2007; Enoto et al. 2009; Enoto et al. 2012). These transient magnetic activities, detected mainly from the Swift satellite, increased the number of magnetars (see a review, for example, Rea & Esposito 2011). The power-law distribution of short bursts fluence is suggested to show statistical similarity to the solar flare and seismology on the Earth (Gutenberg-Richter, e.g., Nakagawa et al. 2007). Based on this statistical similarity, the persistent emission is proposed to be composed of accumulation of un-resolved micro short bursts (Nakagawa et al. 2009, but see also, Enoto et al. 2012).

Figure 2 summarizes the observed X-ray luminosities L_x of the persistent emission, compared with their spin-down luminosity L_{sd}. In the canonical understanding, the persistently bright magnetar L_x exceeds L_{sd}, while L_x of the ordinary RPPs stays below L_{sd}. However, transient magnetars exhibit intermediate property between these two classes. One example is a fast rotating ($P \sim 2$ s) faint AXP 1E 1547.0−5408 which was observed with Suzaku within a week after the onset of the 2009 outburst (Enoto et al. 2010), and another follow-up observation was further performed one year later (Iwahashi et al. 2013) with regular Swift monitorings. At an early phase, L_x becomes comparable to those of persistently bright sources, whereas L_x is decreasing back to a quiescence, close to the region of ordinary RPPs (Figure 2). As shown in this source, some of HBPs or XINSs are dormant magnetars or magnetar descendent.

This view is further reinforced by discoveries of transient magnetar-like activities of three low-field magnetars (LFMs) and two HBPs. So far, there are at least three LFMs known; SGR 0418+5729 (Rea et al. 2013), Swift J1822.3−1606 (Rea et al. 2012), and 3XMM J185246.6+003317 (Rea et al. 2014). Their B_d strength is comparable to ordinary RPPs (e.g., $B_d \sim 6 \times 10^{12}$ G for SGR 0418+5729), while the magnetar-like outburst and short burst activities have been reported. The detection of absorption feature from activated SGR 0418+5729 in soft X-rays, interpreted as

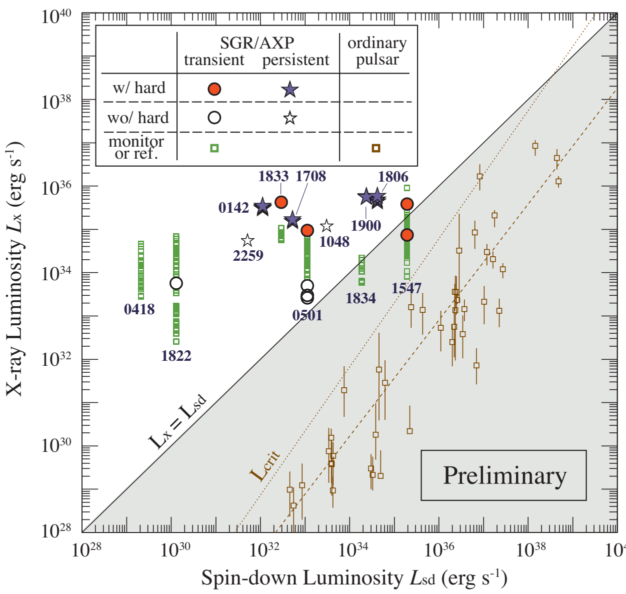

Fig. 2. The L_{sd}-L_x diagram, modified from Enoto et al. 2017 (see also Shibata et al. 2016). The ordinary RPPs (brown square symbols) can be powered by the rotational energy ($L_x < L_{sd}$), while persistently bright magnetars (star symbols) stay in the $L_x > L_{sd}$ regime. Transient magnetars (circle symbols or green squares) are intermediate objects between the above two classes, since L_x is highly variable, and sometimes crossing L_{sd} during a decaying phase of X-ray outbursts.

proton cyclotron resonance, indicates the surface magnetic field is much stronger than B_d (Tiengo et al. 2013). We also searched absorption feature for some persistently bright magnetars with Suzaku, but we only put upper-limits on the equivalent width of absorption (Miyazaki et al. 2016). As another example, two HBP, PSR J1846−0258 and PSR J1119−6127, also exhibited transient magnetar activities in 2006 and 2016, respectively (Archibald et al. 2016). Such a transient activity is expected to originated from hidden magnetic field components, for example, higher multipoles on a stellar surface, or the toroidal field in a stellar interior. Usually, only the surface dipole magnetic field B_d is measurable from P and $\dot{P}$, while the internal toroidal field was thought to be difficult to be observationally identified. However, signatures for the free precession were reported from two magnetars 4U 0142+61 and 1E 1547.0−5408 (Makishima et al. 2014; Makishima et al. 2016). These are interpreted as the deformation of a neutron star due to the internal strong toroidal field.

All these magnetic activities suggest the magnetic field decay is a key to unify the different classes of highly mangetized neutron stars. Since the Suzaku satellite (Mitsuda et al. 2007), operated from 2005 until 2015, had the broad-band coverage (0.2–600 keV) using the X-ray Imaging Spectrometer (XIS, Koyama et al. 2007) and the Hard X-ray Detector (HXD, Takahashi et al. 2007; Kokubun et al. 2007), the soft-thermal surface radiation and hard X-ray magnetospheric emission (Kuiper et al. 2006) of magnetars were simultaneously observed. We previously reported that the X-ray luminosity L_h of the hard component, relative to that of the soft component L_s, follows the positive correlation to the dipole magnetic field B_d (Enoto et al. 2010). Using all the magnetars observed with Suzaku satellite from 2005 to 2013, we performed comprehensive re-analyses of them, combining with early NuSTAR results and with Swift / RXTE monitorings (Enoto et al. 2017), and re-confirmed the previous result. This indicates that the magnetar broadband spectra is also governed primarily by the dipole magnetic field intensity B_d.

One of remaining big mysteries is a mechanism to make various types of highly mangetized neutron star. Recently, a Compact Central Object (CCO) 1E 161348−5055 at the centre of the supernova remnant RCW 103 showed the magnetar-like activity. In addition, another mechanism to make a magnetized neutron star, Accretion-Induced Collapse (AIC), is suggested from X-ray observations of symbiotic X-ray binaries (Enoto et al. 2014). These remaining questions are expected to be answered by future X-ray missions. In early 2017, Neutron star Interior Composition ExploreR (NICER) is planned to be launched by Space X Falcon 9 and to be attached to the International Space Station (ISS) (Arzoumanian et al. 2014). The primary goal is to determine the equation of state of high density matter inside neutron stars via precise measurement of neutron star radii, whereas magnetars and highly mangetized neutron stars are also one of the main targets, especially for transient sources.

Acknowledge

I gratefully acknowledge S. Takeshige for his supporting of compiling catalogues and references to make figures in this proceeding. I also thank my collaborators for our discussion of results presented here, K. Makishima, S. Shibata, T. Kitaguchi, Y. Suwa, T. Uchide, S. Kisaka, T. Nakano, H. Murakami, Y. Nakagawa, K. Gendreau, Z. Arzoumanian, T. Okajima, T. Mihara, W. Iwakiri, and T. Tamagawa. T. E. was supported by Kakenhi 15H00845 and 16H02198.

References

Archibald, R. F., Kaspi, V. M., Tendulkar, S. P., & Scholz, P. 2016, ApJL, 829, L21

Arzoumanian, Z., et al. 2014, SPIE Proc., 9144, 914420

Colpi, M., et al., 2000, ApJL, 529, L29

Enoto, T., Nakagawa, Y. E., et al. 2009, ApJL, 693, L122

Enoto, T., et al. 2010, PASJ, 62, 475

Enoto, T., et al. 2010, ApJL, 722, L162

Enoto, T., Makishima, K., et al. 2011, PASJ, 63, 387

Enoto, T., et al., 2012, MNRAS, 427, 2824

Enoto, T., Sasano, M., et al. 2014, ApJ, 786, 127

Enoto, T., et al. 2017, ApJ, submitted

Harding, A. K., & Lai, D. 2006, Reports on Progress in Physics, 69, 2631

Iwahashi, T., Enoto, T., et al. 2013, PASJ, 65, 52

Kaspi, V. M. 2010, Proc. Nat. Acad. Science, 107, 7147

Kokubun, M., et al. 2007, PASJ, 59, 53

Koyama, K., et al. 2007, PASJ, 59, 23

Kuiper, L., Hermsen, W., et al., 2006, ApJ, 645, 556

Harding, A. K. 2013, Frontiers of Physics, 8, 679

Manchester, R. N., et al., 2005, The Astronomical Journal,, 129, 1993

Makishima, K., Enoto, et al. 2014, Physical Review Letters, 112, 171102

Makishima, K., Enoto, et al. 2016, PASJ, 68, S12

Mereghetti, S. 2008, The Astronomy and Astrophysics Review, 15, 225

Mereghetti, S. 2011, Astrophysics and Space Science Proceedings, 21, 345

Mereghetti, S., et al., 2015, Space Science Reviews, 191, 315

Mignani, R. P., et al. 2017, MNRAS, 465, 492

Mitsuda, K., et al. 2007, PASJ, 59, 1

Miyazaki, N., et al., 2016, PASJ, 68, 100

Nakagawa, Y. E., et al. 2007, PASJ, 59, 653

Nakagawa, Y. E., et al., 2009, PASJ, 61, 109

Nakano, T., et al. 2015, PASJ, 67, 9

Olausen, S. A., Zhu, W. W., et al. 2013, ApJ, 764, 1

Olausen, S. A., & Kaspi, V. M. 2014, ApJS, 212, 6

Rea, N., & Esposito, P. 2011, ASSP, 21, 247

Rea, N., et al. 2012, ApJ, 754, 27

Rea, N.,et al. 2013, ApJ, 770, 65

Rea, N., et al., 2014, ApJL, 781, L17

Shibata, S., et al., 2016, ApJ, 833, 59

Takahashi, et al. 2007, PASJ, 59, 35

Tiengo, A., et al. 2013, Nature, 500, 312

Thompson, C., et al., 1995, MNRAS, 275, 255

Viganò, D., et al. 2013, MNRAS, 434, 123