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From Sco X-1 to magnetars

Past, present, and future of X-ray studies of neutron stars

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Abstract. A review is made on the 50 years of X-ray study of neutron stars (NSs), with emphasis on results from the series of Japanese satellites, *Hakucho*, *Tenma*, *Ginga*, *ASCA*, *Suzaku*, and MAXI, launched in 1979, 1983, 1987, 1993, 2005, and 2009, respectively. This review covers such topics as; NS diagnostics using X-ray bursts, verification of the concept of standard accretion disks, measurements of magnetic fields of accreting pulsars using electron cyclotron resonances, broad-band studies of magnetars, and study of luminosity-dependent spectral state transitions in low-mass X-ray binaries. Finally, our future with *ASTRO-H* is briefly described.

Key words. Accretion, Accretion Disks – Magnetic Fields – Radiation Mechanisms: Thermal – Stars: neutron – Stars: binaries – X-rays: bursts – X-rays: stars

1. Introduction: 50 Years Ago

The dramatic discovery in 1962 of the cosmic X-ray source, now known as Sco X-1, was followed by its optical identification. As shown in Fig. 1, a blue-excess object was found in June 1966, first in Japan and then in the US, within one of several X-ray error boxes which had been determined using rocket-borne modulation collimators (invented by Prof. M. Oda). This is probably the human being's first sighting of a neutron star (NS), just prior to the discovery of pulsars in 1967.

Since then, the studies of NSs have made a huge progress, thanks to observations in X-ray and radio frequencies, in conjunction with the development of nuclear physics. Figure 2 provides a classification of NSs, where the known major NS populations are indicated. One of our ultimate research goals is to understand the versatility of this figure. Another important aim is to get insight into the dense nuclear matter, and pin down the nuclear equation of state.

2. The Present: *Suzaku* and MAXI

Presently, we are operating in Japan two X-ray missions. One is *Suzaku* (Mitsuda et al. 2007) launched by JAXA in 2005 as the 5th Japanese X-ray satellite. It performs pointing observations, with the X-ray Telescopes and the X-ray Imaging Spectrometer (XIS) working together in the 0.2–10 keV range, as well as the Hard X-ray Detector (HXD) observing in 10–600 keV. Figure 3 compiles wide-band *Suzaku* spectra of various Galactic X-ray sources.

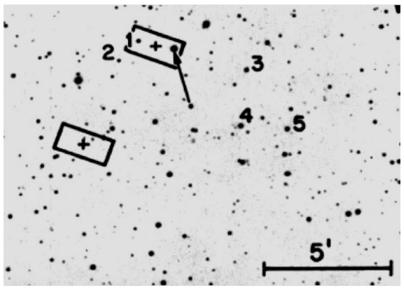

Fig. 1. The optical identification chart of Sco X-1, taken from Sandage et al. (1966).

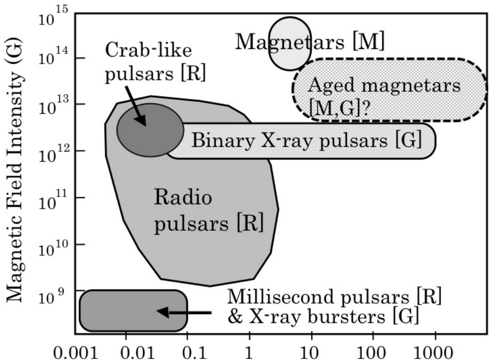

Fig. 2. A classification of NSs, on the plan of rotation periods and magnetic fields. [R], [G], and [M] indicates rotation-powered, gravity-powered, and magnetically-powered ones, respectivey.

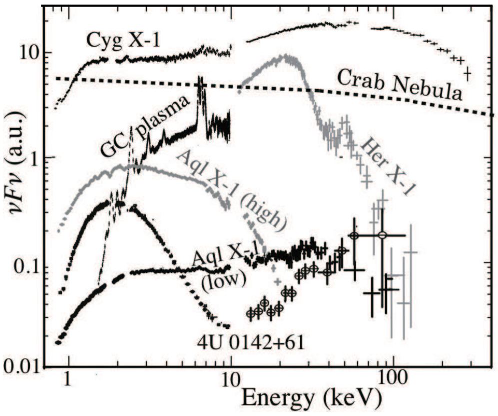

Fig. 3. Wide-band *Suzaku* $\nu F\nu$ spectra of Galactic X-ray sources, including various NS objects.

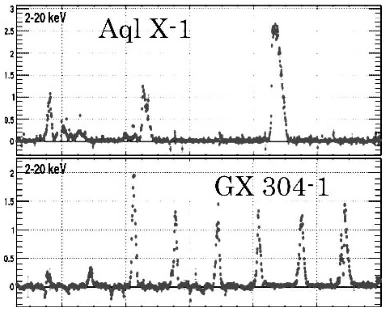

Fig. 4. MAXI light curves of two NS recurrent transients, covering 3 years from 2009 August.

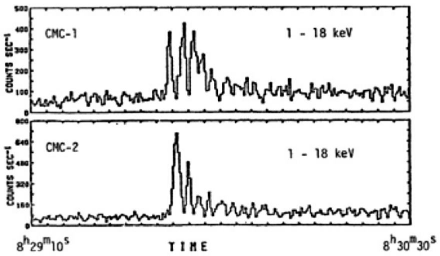

Fig. 5. The first X-ray burst detected by *Hakucho*, from 4U 1608-52. Outputs from the two counters are oppositely ("push-pull") modulated. Their sum gave light curves, while their difference burst positions.

MAXI (Monitor of All-sky X-ray Image) (Matsukoka et al. 2009) is an all-sky monitor experiment, launched in 2009 June into the JAXA's Japan Experimental Module comprising the International Space Station. As exemplified in Fig. 4, it provides continuous 3-band light curves in 2–20 keV. Its "wide but shallow" capability is ideally complementary to the "deep but narrow" property of *Suzaku*.

3. *Hakucho* (1979)

Let us look back in the history. The first Japanese X-ray satellite *Hakucho*, launched in 1979, carried a pair or modulation collimators. As shown in Fig. 5, we used it to observe X-ray bursts (thermonuclear flashes) from LMXBs (low mass X-ray binaries; binaries of weak-field NSs and low-mass stars). Using *Hakucho*, we thus discovered 8 new X-ray burst sources.

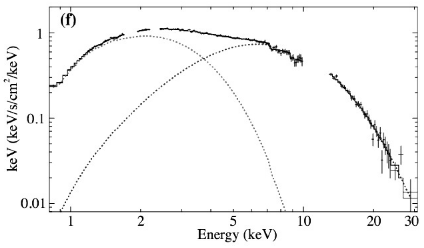

Fig. 6. An $\nu F\nu$ spectrum of the LMXB Aql X-1, acquired with *Suzaku* in the soft state (see Fig. 3). It is fitted with a softer disk BB and a weakly Comptonized BB (Sakurai et al. 2012).

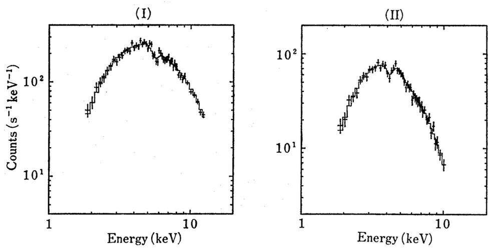

Fig. 7. *Tenma* spectra of two X-ray bursts from 4U 1636-53, wherein a hint of redshifted Fe-K absorption line is visible (Waki et al. 1984).

Applying the Stefan-Boltzmann law to fluxes and colors of the detected bursts, the NSs in many LMXBs were confirmed to have a radius of ~ 10 km, as theoretically predicted. Invoking the Eddington limit argument, we also revealed that the distance to the Galactic center is shorter, ~ 8 kpc (Inoue et al. 1981), than the 10 kpc then believed.

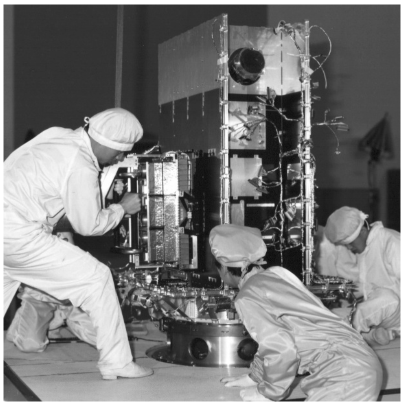

Fig. 8. One of 8 proportional counters comprising the LAC experiment is being mounted on *Ginga*. The person at the middle is the present author.

4. *Tenma* (1984)

Our 2nd mission *Tenma*, launched in 1983, carried the Gas Scintillation Proportional Counter developed in-house. Using it, we discovered that *persistent* spectra of luminous ($\gtrsim$ 0.1 times the Eddington limit) LMXBs can be described by the sum of two spectral components (Mitsuda et al. 1984); a softer one from a "standard" accretion disk (Shakura & Sunyaev 1973), and a harder blackbody (BB) from the NS surface. This was reinforced by subsequent missions, including *RXTE* (Takahashi et al. 2011). A *Suzaku* result on the LMXB Aql X-1 in its outburst, shown in Fig. 6, confirms the *Tenma* view over the broadest energy band.

Another intriguing *Tenma* result is the possible detection of absorption lines in X-ray burst spectra from a few LMXBs, as reproduced in Fig. 7. If they are interpreted as gravitationally-redshifted Fe-K absorption lines, these NSs are inferred to have a very high mass-to-radius ratio. However, this phenomenon has not been reconfirmed by the following missions, and still remains open. More convincing detections of these features would be vital to the nuclear equation of state.

5. *Ginga* (1987)

With an improved capability of the M-3SII launch vehicle, and an extensive international collaboration with British and US groups, the 3rd mission, *Ginga*, became significantly more powerful. With a broad-band (2–30 keV) sensitivity, the Large Area Counter (LAC) (Turner et al. 1989) experiment on *Ginga* yielded a series of novel results on the X-ray sky, both Galactic and beyond.

Following the balloon and *HEAO-1* works (Trümpner et al. 1978; White et al. 1983), we discovered/confirmed, with the *Ginga* LAC, electron cyclotron resonance scattering features (CRSFs) in the spectra of some ten X-ray pulsars (Makishima et al. 1999); e.g., 4U 1538−52 (Clark et al. 1990) and X0331+53 (Makishima et al. 1990), at resonance energies of 22 keV and 28 keV, respectively. These were followed by further CRSF detections with *BeppoSAX* (Santangelo et al. 1999b), *RXTE*, and *Suzaku* (see §7, and Her X-1 in Fig. 3). Up to the 4th harmonic features were detected from 4U 0115+63 (Santangelo et al. 1999a).

Calculations of the CRSF features are an important subject (Schönherr et al. 2007). Empirically, as described in Makishima et al. (1999) and in Fig. 9, the Lorentzian-type formula for classical cyclotron resonance, including higher harmonics, can well describe the feature, when the continuum is represented by so-callee NPEX model. The Gaussian modeling of CRSFs is usually less successful.

Since the CRSF energy is given as $E_a = 11.6 \times B_{12}$ keV where B_{12} is the surface magnetic field (MF), B, in 10^{12} G, these CRSF detections yield the MF distribution of Fig. 10 when combined with other measurements. The result cannot be easily reconciled with the idea of MF decay which was popular till the 1990's. Instead, we propose that the NS magnetism is a manifestation of nuclear ferromagnetism caused by quantum spin alignment of neutrons (Makishima et al. 1999). This hypothesis is attaining some theoretical support.

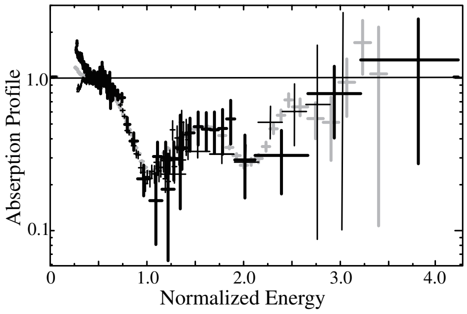

Fig. 9. CRSF profiles of three X-ray pulsars; Her X-1 (Enoto et al. 2008, thin black) and A0535+26 (Terada et al. 2006, thick black) both with *Suzaku*, and X0331+53 (gray) with *RXTE* (Nakajima et al. 2010). After individually modeling the continua by NPEX models, and normalizing the energy to respective CRSF energies, the CRSF profiles of the 3 pulsars can be reproduced by nearly the same Lorentzian-type CRSF parameters.

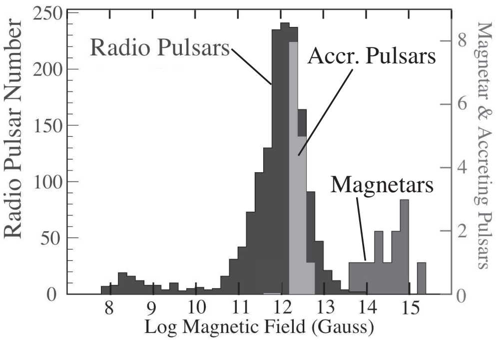

Fig. 10. The distribution of surface (poloidal) MFs of radio pulsars (ordinate to the left), and of accreting pulsars and magnetars (right ordinate). The results on accreting pulsars are based on the CRSF measurements, while the rest on the "period and period-derivative" method.

6. *ASCA* (1993)

Carrying onboard four high-throughput X-ray mirrors developed under a US-Japan collaboration, the 4th Japanese X-ray mission, *ASCA* (Tanaka et al. 1994), for the first time enabled X-ray imaging up to 10 keV and innovated the cosmic X-ray research. As shown in Fig. 11, the four focal planes were equipped with two CCD cameras (XIS) based on another US-Japan collaboration, and two Gas Imaging Spectrometer (GIS) sensors we developed (Ohahsi et al. 1996; Makishima et al. 1996). The XIS enabled high-resolution spectroscopy, while the GIS provided a wider field of view and a higher time resolution.

A wide range of *ASCA* results, both Galactic and extra-Galactic, include the identifications of enigmatic "soft gamma repeaters", SGR 1806−20 (Murakami et al. 1994) and SGR 1900+14 (Hurley et al. 1999), with pulsating Galactic persistent X-ray sources, most likely a kind of NSs. These results, enabled by the large dynamic range and fine time resolution available with the GIS, significantly reinforced the emerging concept, that these objects and "anomalous X-ray pulsars" together form a new class of NSs called magnetars (Thompson

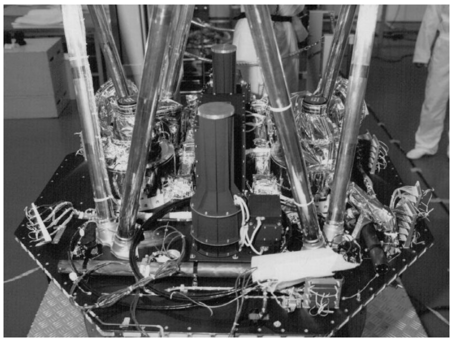

Fig. 11. The focal plane of *ASCA*. The two black cylindrical objects are the GIS sensors.

& Duncan 1995). As represented by a clustering at $B = 10^{14-15}$ G in Fig. 10, they are thought to have ultra-strong MFs exceeding the critical value of $B = 4.4 \times 10^{14}$ G, and to emit their X-rays (both persistent and bursts) by somehow dissipating their huge magnetic energies into radiation (Thompson & Duncan 1995; Enoto et al. 2010).

7. *Suzaku* (2005) again

Having been through the history, we are back again to the present, and would like to describe some novel *Suzaku* results on NSs.

The HXD (Takahashi et al. 2007; Kokubun et al. 2007) onboard *Suzaku* has allowed detections of new CRSFs, from A1118−61 (Suchy et al. 2011) and GX304−1 (Yamamoto et al. 2012) both at ∼ 55 keV, and GRO J1008−57 at ∼ 80 keV (Atel #4759). The latter two were successfully triggered by MAXI alerts. Also, the 2nd harmonic feature was detected from Her X-1 at ∼ 70 keV (Fig. 3, Fig. 9) (Enoto et al. 2008), and a possible cyclotron emission line from 4U 1626−67 (Iwakiri et al. 2012). Thus, the 50–100 keV energy range, i.e., $B = (4-8) \times 10^{12}$ G, is being explored, but those above ∼ 100 keV ($B > 10^{13}$ G) are still waiting to be investigated with *ASTRO-H*.

The XIS and HXD onboard *Suzaku* form an ideal combination for broad-band spectroscopy of magnetars. As revealed in Fig. 12, their spectra were found to all consist of two components (Enoto et al. 2010); the long-known soft thermal emission often described by a two-temperature BB (Nagawa et al. 2009), and the enigmatic hard-tail component discovered with *INTEGRAL* (Kuiper et al. 2006). This two-component nature applies to the spectra of both their persistent emission and weak short bursts (Nagawa et al. 2011; Enoto et al. 2012).

As clearly seen in Fig. 12, the hard component of magnetars becomes *weaker* (relative to the soft component), but *harder*, with their age. When combined with the unusually hard slope, this suggests that the hard component is emitted by some exotic mechanism. One promising idea is that positrons produced in their mangtenosphere annihilate on the stellar surface, and the resulting 511 keV photons repeatedly "split" into two as the strong MF acts as a virtual photon (Enoto et al. 2010). *ASTRO-H* will allow us to detect the expected sharp spectral cutoff above 511 keV.

There is an interesting possibility (Nakano et al. 2012) that Type II supernovae produce as many magnetars as the ordinary magnetic NSs.

Another novel *Suzaku* plus MAXI result on NSs is investigation of the low/hard state of LMXBs. A dramatic spectral change was observed from Aql X-1 (Fig. 3, Fig. 4), associated with its state transition from the high/soft to the low/hard states. In contrast to the high/soft spectrum in Fig. 6, its low/hard spectrum (Fig. 3) is reproduced by emission from a truncated disk, plus a strongly Comptonized BB; the Comptonizing corona is identified with an optically-thin spherical accretion flow, forming inside the truncated disk (Sakurai et al. 2012). Furthermore, at luminosities $\lesssim 10^{36}$ erg s^{-1}, the BB emitting radius on the NS surface was found to start decreasing from ∼ 10 km, down to ∼ 3 km at ∼ 10^{34} erg s^{-1} involving a rapid luminosity decrease. This can be explained by emergence of a small magnetosphere, followed by accretion suppression due to propeller effects (Matsukoka & Asai 2003). With *ASTRO-H*, we may detect coherent fast pulsations from these objects, and determine their masses.

8. *ASTRO-H*

In collaboration with NASA, ESA, SRON, and several other institutions, we are constructing

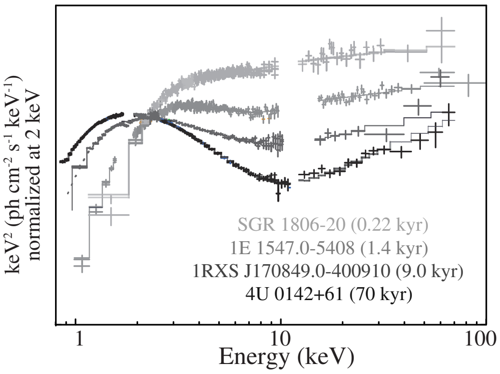

Fig. 12. *Suzaku* $\nu F \nu$ spectra of four magnetars, normalized at 2 keV, fitted by an empirical two-component model (Enoto et al. 2010). Their characteristic ages are given in parenthesis.

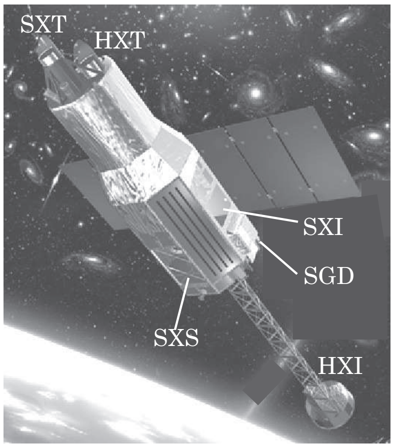

Fig. 13. An artist's impression of *ASTRO-H*.

ASTRO-H (Takahashi et al. 2012), a powerful successor to *Suzaku*, to be launched in 2015 by the JAXA's H-2A rocket. As illustrated in Fig. 13, it weighs 2.7 tons, and has a length of 14 m, and carries two focusing optics systems; the Soft X-ray Telescope (SXT), and the Hard X-ray Telescope (HXT). The SXT, with a focal length of 5.6 m, utilizes two units of nested thin-foil Wolter-I mirrors, both working in 0.3–12 keV. One of them focuses on an X-ray CCD camera called the Soft X-ray Imager (SXI), while the other on the innovative X-ray calorimeter array, or the Soft X-ray Spectrometer (SXS), with an energy resolution of $\lesssim$ 7 eV at 6 keV. The HXT consists of two sets of identical "Super Mirrors", reflective up to ~ 80 keV, with a focal length of 12 m. They form images on two units of the Hard X-ray Imager (HXI) which utilize Si and CdTe strip detectors. In addition, we have the Soft Gamma-ray Detector (SGD), working in the 60–500 keV range using Compton kinematics. The HXI and SGD are descendants of the *Suzaku* HXD, and use sophisticated active shields made of BGO scintillators.

Based on the long and rich history of NS investigation with the predecessor missions, we hope to explore the following new NS science with *ASTRO-H*.

1. Search 100–200 keV regions of some classes of X-ray pulsars for CRSFs (§ 5), to discover NSs with $B \gtrsim 10^{13}$ G.
2. Verify the photon splitting hypothesis (§ 7) of magnetars, and search the Galactic plane for aged magnetars that may lurk therein.
3. Better constrain the nuclear equation of state, by detecting redshifted Fe-K lines (§ 4) and coherent LMXB pulsations (§ 7).
4. Probe surface conditions of NSs, and get insight into the dense nuclear matter.

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