

Japan Academy Prize to:

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for “Study of Strong Magnetic Fields of
 Neutron Stars by means of X-Ray Observa-
 tions”

***Outline of the work:***

Neutron stars, each weighing about 1.4 times the Sun and only about 10 km in radius, are the densest of all the celestial objects existing in the Universe. They consist almost solely of neutrons, of which the degeneracy pressure competes with the gravity. Among these exotic objects, those with strong magnetic fields and rapid rotation emit periodic electromagnetic radiation over the widest frequency range from radio waves to gamma-rays. They are called pulsars.

Using the Japanese cosmic X-ray satellites *Ginga*, *ASCA*, and *Suzaku*, Dr. Kazuo Makishima and his collaborators have been exploring the world frontier of observational studies of X-ray pulsars. Their abundant achievements include the following highlights of particular importance.

Pulsars are classified into three types according to their energy sources: rotation-powered ones like the Crab pulsar, accretion-driven objects in binary systems (the majority of X-ray pulsars), and those powered by magnetic energies (often called magnetars). Canonical value of $\sim 10^8$ T is thought to characterize the magnetic fields of the first two classes, while magnetars are considered to have super-strong fields of 10^{10-11} T.

Under strong magnetic fields, electrons exhibit quantized energies called Landau levels, and their transitions among these levels produce, in their radiation spectra, absorption features known as electron cyclotron resonance lines. When the field strength is about 10^8 T, these features appear right in the X-ray energies. In the 1990s, Dr. Makishima used the *Ginga Observatory* to successfully discover these lines from 7 X-ray pulsars, and later he contributed to four more discoveries using the currently operating *Suzaku*. These 11 objects make up a majority of the altogether 18 X-ray pulsars from which the electron cyclotron resonance lines have ever been detected. Since all these lines appeared in an energy range of 10-50 keV, the magnetic fields strengths of these neutron stars are inferred to cluster in a narrow range of $(1-4) \times 10^8$ T (Makishima *et al.* 1990). This fact in turn means that (1) these dense stars are born with relatively similar magnetic field strengths, and (2) their fields do not decay significantly in 10^8 years (typical ages of these binary systems). These results argued against a popular view in the 1990s, that the magnetic fields of neutron stars should decay with time.

Further reinforcing these results using *ASCA* as well, Dr. Makishima has proposed a novel explanation, that the intense magnetic fields of neutron stars can be a manifestation of nuclear ferromagnetism, realized when the magnetic moments of constituent neutrons align parallel to one another (Makishima *et al.* 1999).

As the next step, Dr. Makishima, using *Suzaku*, leads the study of magnetars (the 3rd class) which are considered to harbor even stronger magnetic fields reaching 10^{10-11} T. Under such an extraordinary condition, the Landau level separations of electrons become larger than their rest-mass energy, predicting various exotic quantum electro-dynamical (QED) phenomena to take place. In fact, Dr. Makishima, in collaboration with Dr. Enoto and several others, pointed out that an enigmatic hard X-ray component that characterizes the X-ray

spectra of magnetars is produced by a QED effect known as “photon splitting” process (Enoto, Nakazawa, Makishima *et al.* 2010).

While the above-quoted field intensities of magnetars, 10^{10-11} T, refer to their dipole fields extending outside the stars, Dr. Makishima recently discovered convincing evidence that even stronger toroidal (donut-shaped) magnetic fields are hidden inside them. When his team observed the magnetar 4U 0142+61 with *Suzaku*, they found that its hard X-ray pulses (with a period of 8.69 sec) are phase-modulated by about ± 0.7 sec, with a long period of about 15 hours (No such effects were observed in soft X-ray pulses.). Dr. Makishima proposed that this intriguing phase modulation is explained as free precession of a neutron star that is deformed into a slightly prolate shape. This deformation corresponds to a tiny deviation of the ratio of the moments of inertia from unity (only 1/6200). This deformation, though small, requires the presence of an ultra-strong toroidal field of the order of 10^{12} T inside this densest object. These novel results have been published in *Physical Review Letters* (Makishima *et al.* 2014), which was picked up by the American Physical Society, in its *Synopsis*, as “an exceptional research”.

Recently, Dr. Makishima and his collaborators have discovered a very similar effect from a second magnetar, 1E 1547-54. In this case, the phases of its hard X-ray pulses are periodically modulated as well, with a period of about 18,000 times its pulse period of 2.1 seconds. Thus, the free precession, and hence the axial deformation by ultra-strong internal magnetic field, might be common features of magnetars. The formation of such a toroidal-dominated magnetic field configuration is predicted by theoretical studies of core-collapse supernovae (e.g. Kotake *et al.* 2004; Braithwaite 2009).

These outstanding achievements by Dr. Makishima, as described above, are considered to deepen our understanding not only of the formation and evolution of neutron stars, but also of the equation of state of nuclear matter and quantum many-body problems.

List of publications

1. Papers on Strongly-Magnetized Neutron Stars

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