Spectral and Temporal Approach to Physics of Neutron Stars

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Astronomical observations of neutron stars provide us an unique approach to investigate the fundamental physics under extreme condition. Degenerate matter inside neutron stars exceeds the nuclear density, and the equation of state of high density matter is observationally constrained via measurements of stellar mass and radius. Neutron stars are also characterized by strong gravity (gravitational redshift $z \sim 0.2$), fast rotation (up to $P \sim 1\,\mathrm{ms}$), and strong magnetic field ($B \sim 10^8\,\mathrm{T}$). Recent progress of X-ray observations further indicates an strongly magnetized subclass of neutron stars, called magnetars[1]. There are accumulating evidence for 2–3 orders of magnitude higher magnetic field than that of canonical neutron stars, with peculiar flare and burst activities interpreted as dissipation of the magnetic energy[2]. Neutron stars are, thus, an ideal laboratory in our universe[3].

We are now about to enter the age of precise astrophysical measurement of neutron stars. The ASTRO-H X-ray observatory[4], expected to be launched in 2015, will realize a ultra-high spectral resolution of $\triangle E \sim 7$ eV in the $\sim$0.3–10 keV band (cf., $\sim$130 eV FHWM at 6 keV of the X-ray CCD onboard *Suzaku*). This will enable us to search for a proton cyclotron feature as direct evidence for the strong field and for a gravitationally-redshifted absorption feature to determine the equation of state of neutron stars. One year after the ASTRO-H, the Neutron star Interior Composition Explorer (NICER)[5] will be attached to the International Space Station (ISS). The NICER project will provide us unprecedented high-timing resolution data of neutron stars with very large photon statistics, and is expected to reveal the equation of state of neutron stars. In addition to these spectral and temporal improvements, polarization is expected to open a new observational window of the X-ray astronomy. The Gravity and Extreme Magnetism Small Explorer (GEMS)[6], the first polarization-dedicated X-ray satellite, was re-proposed in 2014 with a new name.

Prior to the ASTRO-H launch, we have started investigations of scientific topics and possible candidates of observations, and published it as the ASTRO-H White Paper[7]. Hard X-ray from magnetars is listed as one of the good candidates of ASTRO-H[8]. We are also preparing the handbook for the high spectral data handling, called the "Cookbook". As international cooperation for future missions, we have also collaborated with the NICER and X-ray polarimeter groups at NASA Goddard Space Flight Center, mainly contributing to calibration of the NICER X-ray mirror and developments of the X-ray polarimeter[9]. As our collaborative relationship grows, FUture Cooperation is a Key element for the Spectral and Temporal Approach to Physics for neutron stars.

In 2014, we reported a signature of the toroidal field embedded in the magnetar interior[10] from 4U 0142+61 (see Fig 1), and also studied how neutrino emission coupled with the toroidal field affects spin evolution of neutron stars[11]. We studied the magnetic field and accretion mechanism of the slowest rotating X-ray pulsar, 4U 1954+319[12], and iron line emission from the prototypical X-ray pulsar, Herculis X-1 (Her X-1)[13].

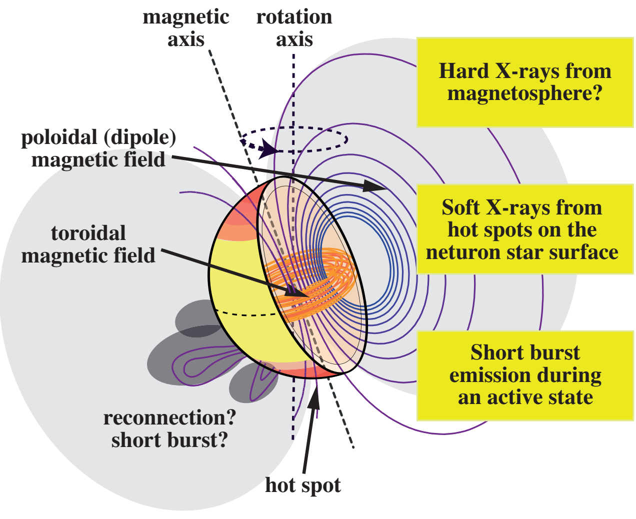

Fig. 1. Schematic view of a magnetar, a subclass of neutron stars with extremely strong magnetic field.

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