S8-3

Cosmic X-ray Study of the Physics in Strong Magnetic Field and Expectation for Ground Experiments
宇宙Ｘ線の観測による天体の超強磁場現象と地上実験への期待

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Cosmic X-ray observation toward neutron star is a useful method to study the plasma physics in an ultra-strong magnetic field. Accretion-powered X-ray pulsars are now believed to have 10^8 T field around their magnetic pole which field strength is measured via cyclotron resonance scattering features appearing a (quasi) thermal X-ray spectrum. Moreover, X-ray astronomy recently has accumulated evidence that some neutron stars exhibit an extremely strong field of ~10^{11} T. In this talk, we will provide recent observational results and their interpretations.

1. Introduction

Astronomy has provided powerful tools to study the extreme physics since there are many extreme environments in universe, such as a strong gravitational field and high temperature. In particular, X-ray observation of Neutron Stars (NSs) is good plasma diagnosis in strong magnetic fields, exceeding Mega Tesla.

NSs are born after a gravitational collapse of a massive star and believed that their degenerate pressure by neutrons counteracts the force of their gravity. Therefore the radius is very small (~10 km) while the mass is close to Sun. NSs emit electromagnetic radiation in various wavelengths. The radiation has been observed as pulsed emission with their stellar rotation (mainly 0.1 – 10 s). Figure 1 shows the diagram of the rotation period and their derivatives. If we assume the loss of their rotation energy is converted into a magnetic dipole radiation according to a standard pulsar model [2], the magnetic field strength of the NSs can be estimated by the following equation,

$$B = 1.0\ \times 10^{8}\sqrt{\left(\frac{P}{1\ \mathrm{s}}\right)\left(\frac{\dot{P}}{10^{-15}\mathrm{s/s}}\right)}\ \mathrm{T}. \qquad (1)$$

The evaluated fields are shown as blue dashed lines in Figure 1.

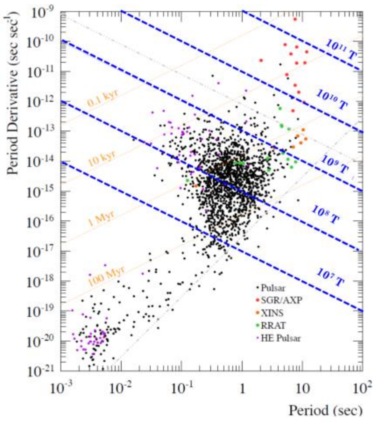

Fig.1. A period and their derivative $(P - \dot{P})$ diagram of neutron stars [1] (http://www.atnf.csiro.au/research/pulsar/psrcat/).

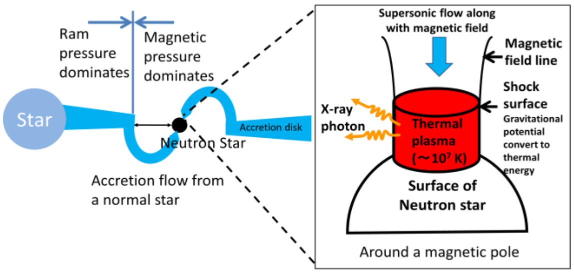

Fig.2. A schematic view of accretion powered pulsar.

2. Accretion Powered Pulsar

An accretion powered pulsar is a magnetized NSs (～10^8 T) orbiting with a normal stellar companion. Figure 2 shows a schematic view of such accretion powered pulsar system. The accreting matter from a normal star is funneled along the magnetic field to the NS poles. Since the gravitational potential of NS is very large, the kinetic energy of the accretion matter is eventually converted to thermal energy (the electron temperature reaches several keV). As a result, the accretion column of thermal plasma is formed around the magnetic pole and emits X-rays photons which are modulated with their spin. The typical spectrum is approximated as power-law in the 5 - 20 keV with a quasi-exponential cutoff at energy ~20 keV. In such an environment, where the strength of the field is greater than the thermal energy of the plasma, a magnetic field effects are dominant in there radiative transfer. For such occasion, there is a clear spectral feature in X-ray spectra called Cyclotron Resonance Scattering Features (CRSFs). CRSF appears at energy of

$$\mathrm{E}_a = \hbar eB/m_e = 11.6(B/10^8\ \mathrm{T})\ \mathrm{keV}. \quad (2)$$

This feature has been observed as a absorption at several ten keV band from ~20 sources [3,4], which number is about 20% of known accretion powered pulsar. CRSF has appeared sometimes in multiple harmonics (the record is five harmonics from 4U 0115+63) [5]. Using this CRSF diagnosis, accretion powered pulsar is considered as ideal laboratory for plasma physics in a strong magnetic field.

However, there is still some contradiction between observational results and theoretical prediction in profile of CRSFs. For example, many theories predict that there should a fine structure of emission wings caused by incoherent scattering around the absorption feature [6,7], but such a structure has not been observed yet.

To obtain high quality data of the profile, we tried to a deep observation of 4U 1626-67 using *Suzaku* X-ray satellite [8]. Figure 3 shows the results of pulse-resolved spectroscopy. The results show that the CRSF feature at the bright phase is well fitted by typical absorption model. On the other hand, in the dim phase, we find that the feature is better described in terms of an emission rather than absorption. Moreover, the continuum spectrum also changed between the bright and the dim phase [9]. We speculated that the detected emission-line like feature is an emission wing of the cyclotron resonance scattering and that the variation of the continuum is caused by magnetic field effects as the optical depth changes. However, these effects are strongly depend on the geometry of accretion column, density and thermal gradient, and thus the origin is still under discussion.

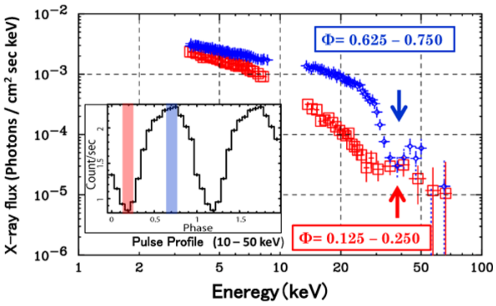

Fig.3. The phase resolved spectra of 4U 1626-67 obtained by *Suzaku* [9].

3.Magnetar

Recent X-ray observations have suggested that some isolated neutron stars are appearing at the upper right corner in Fig.1. Following the estimation of the magnetic field described in the equation (1), they are considered to have extremely strong magnetic field in the $10^{10\text{-}11}$ T. It means that the estimated field strength exceeds the QED critical field strength ($\mathrm{B}_{\mathrm{cr}} = {m_e}^2c^3/\hbar e = 4.4 \times 10^9$ T). The sources are called magnetar in distinction from normal NSs. Evidence for their ultra-strong field also can be seen in different observational properties (bright X-ray luminosity and bursting activity) [10]. The observed persistent X-ray emission from magnetars is composed of thermal emission with its temperature of ~ 0.5 keV and the hard non-thermal tail component emerging above ~10 keV with a hard photon index Γ~1 [11-12]. One of the interpretations of the hard component is photon-splitting caused by QED effects [10]. Moreover, CRSF-like absorption feature has been clearly detected from a one magnetar recently [13]. If the line is a “proton” cyclotron scattering feature, the result would be strong evidence that magnetar is an ideal laboratory to examine the plasma physics in ultra-strong field.

4. Expectation for ground experiments

So far we have outlined the potential of a cosmic X-ray observation for studying plasma physics in extreme magnetic field. However, we would like to emphasize that there is some uncertainties, such as a distance of sources, geometry of the plasma and field. Therefore, if possible, the confirmation of the observational results on a ground experiment is very important to validate theoretical models and understand the extreme field physics including effects of higher-order term of QED.

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