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JD3 – Neutron Stars: Timing in Extreme Environments

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Abstract. The space-time around Neutron Stars is indeed an extreme environment. Whether they are in accreting binary systems, isolated or in non-accreting binaries (perhaps with another Neutron Star), Neutron Stars provide a window onto physical processes not accessible by other means. In particular, the study of their time variability: pulsations, quasi-periodic oscillations, thermonuclear X-ray bursts, flares and giant-flares, pulsar glitches and pulse period variations, constitutes a valuable instrument to unveil those very same physical processes. Here we briefly summarize the most important results presented at Joint Discussion 3 of the XXVII IAU General Assembly.

Keywords. stars: neutron

1. Introduction

Joint Discussion 3 (JD03) was focused on the astronomical systems harboring neutron stars, from isolated and binary radio pulsars to magnetars and accreting X-ray binaries. These systems constitute a unique tool for the study of matter under extreme conditions. Exploring the gravitational wave emission, testing General Relativity in the strong-field regime and the determination of the equation of state of nuclear matter are the major topics.

With the launch of high-energy missions such as XMM-Newton, Chandra, INTEGRAL and Suzaku for energy spectra and RossiXTE for fast time variability, we have made considerable progress in understanding the extreme environment close to compact objects. As a perspective, the future instrumentation for timing analysis, from radio observations to high-energy emissions, have been addressed in this Joint Discussion.

In the three half-day meeting of JD03, a total of 31 oral presentations were given, including six invited, seven solicited and 18 contributed, and about 50 posters were displayed. Four of the invited presentations, which were intended as broad reviews of the subject, are included in this volume. Here, we would like to summarize some of the interesting topics and contributions to the Joint Discussion.

2. Broad iron lines in bright accreting Neutron-Star binaries

A broad iron line, interpreted as a relativistically broadened line from neutral or mildly-ionized iron has been discovered in the X-ray emission of the accreting millisecond X-ray pulsar SAX J1808.4–3658 as observed by XMM-Newton in 2008 (Papitto *et al.* 2009, see Fig. 1, left panel). Relativistic models were fitted to the line: an inner radius of the

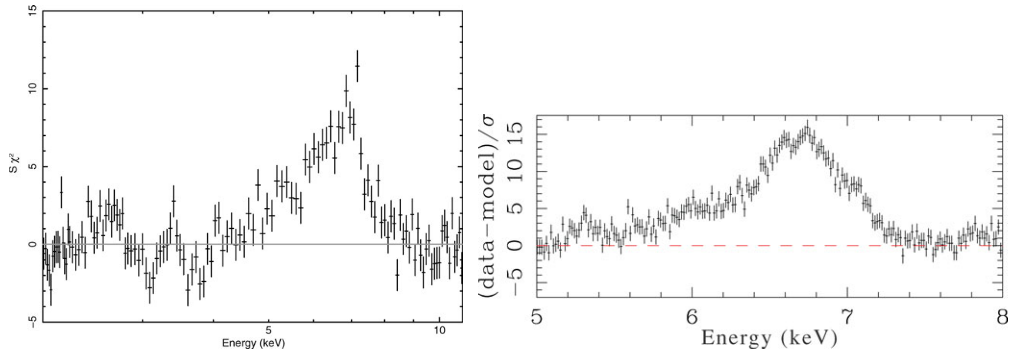

Figure 1. Left: Residuals obtained removing the broad line from the best fit model for the 2008 XMM-Newton observation of SAX J1808.4-3658 (from Papitto *et al.* 2009). Right: similar plot for 4U 1705-44 (from Di Salvo *et al.* 2009).

accretion disk of around 9 gravitational radii was found. For a 1.5 $M_{\odot}$ neutron star, this corresponds to a radius inside the co-rotation radius of the system, which is expected given that pulsations were also observed. A similar line was recently detected by the same group from 4U 1705–44 (Di Salvo *et al.* 2009, see Fig. 1, right panel). Similarly broadened lines were reported by other groups in the recent years: Serpens X-1 (Bhattacharyya & Strohmayer 2007; Cackett *et al.* 2008), 4U 1820–30 and GX 349+2 (Cackett *et al.* 2008) and 4U 1636–53 (Pandel *et al.* 2008), as well as from independent observations of SAX J1808.4–3658 (Cackett *et al.* 2009).

3. The binary pulsar PSR J0737–3039A/B

PSR J0737–3039A/B is a binary system consisting of two radio pulsar with a ∼2.5 hr orbit (Burgay *et al.* 2003; Lyne *et al.* 2004; Kramer & Stairs 2008; Archibald *et al.* 2009). The two pulsars have a period of 23 ms (pulsar A) and 2.8 s (pulsar B). The system is observed almost edge-on, causing eclipses. This system is providing the most stringent constraints on General Relativity in a relatively strong regime, as it yields independent tests for a number of post-keplerian parameters. As time goes on, the measurements become more precise and the limits more stringent. At present, all interval limits on the parameters contain the values expected from General Relativity.

4. γ-ray pulsars

An exciting result from the Fermi γ-ray satellite is the major increase in the discovery of γ-ray pulsars, some of which discovered in γ-rays (see Abdo *et al.* 2009). A graphical summary of the pulsar detections by Fermi can be seen in Fig. 2. The detection of radio-quiet pulsars is particularly important as it shows that γ-rays are emitted in a wider beam than radio emission, favoring models where the high-energy photons are produced in the magnetosphere and not on the polar caps of the neutron star.

5. From accreting binaries to millisecond pulsars

Evolutionary models indicate that neutron-star accreting low-mass X-ray binaries (LMXB) are the progenitors of millisecond radio pulsars, accretion being responsible for their spin-up to fast periods. Indeed, ten years ago the first X-ray millisecond pulsar was discovered in an LMXB, and now a dozen such systems are known.Recently, a

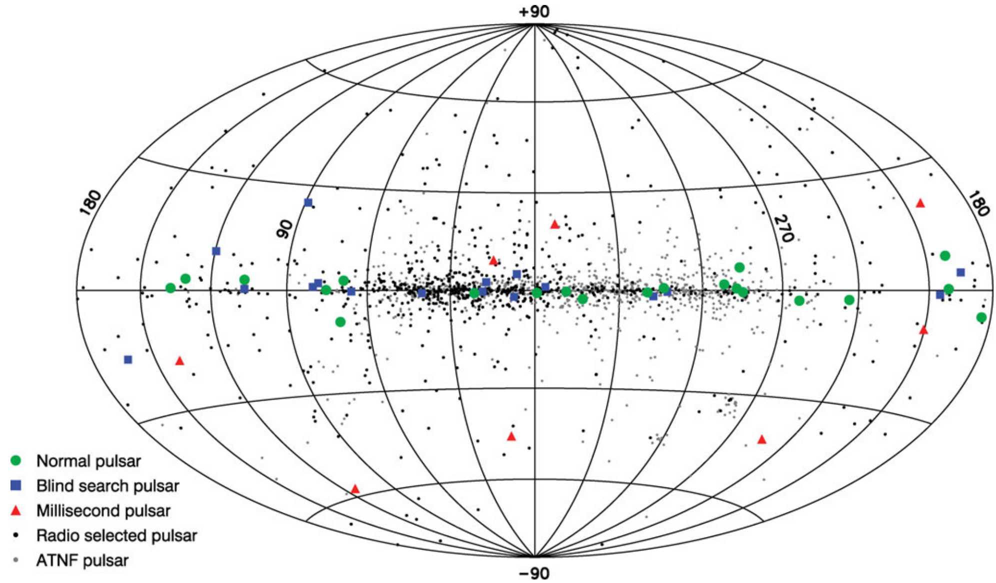

Figure 2. Galactic map of the Fermi pulsar detections (from Abdo *et al.* 2009)

millisecond radio pulsar in a circular binary system was discovered (Archibald *et al.* 2009). While many systems like this are known, optical spectra of this system obtained a decade ago show optical properties consistent with an accreting system: blue continuum, double-peaked emission lines and fast flickering. These properties are not observed today, when the optical spectrum of the companion is consistent with a solar-type star. This strongly suggests that the radio pulsar, PSR J1023+0038, within a decade turned on after an accretion phase stopped, providing compelling evidence for a direct link between these two classes of systems.

6. Future missions I: ASTROSAT

The near future for X-ray timing relies on the Indian mission ASTROSAT. This satellite, due to be launched in late 2010, will feature a number of astronomical instruments. In addition to an UV telescope, a soft X-ray telescope, a high-energy CdZnTe high-energy detector and an All-Sky Monitor, a large high-pressure collimated proportional counter will be available (see Fig. 3, left panel). This instrument, the LAXPC, will cover the energy range 3–100 keV with an effective area of $\sim$6000 cm^2 at 5 keV, comparable to that of the RXTE/PCA, but much higher above 10 keV (see Fig. 3, right panel). This instrument will take over the heritage of the RXTE/PCA and, thanks to its larger area at high energies, will open a new window on fast-timing phenomena from accreting binaries.

7. Future missions II: the Advanced X-ray Timing Array (AXTAR)

While ASTROSAT is expected to be operative in the near future, AXTAR is still at the stage of mission concept. It is a dedicated satellite for sub-millisecond timing of bright Galactic sources (Chakrabarty *et al.* 2008, see Fig. 4). Its main instrument is collimated Silicon detector covering the energy range 2–50 keV with a large collecting area (8 square meters). Such an instrument would provide a much larger number of photons, allowing to explore in much more detail the known signals and to discover weaker ones. The

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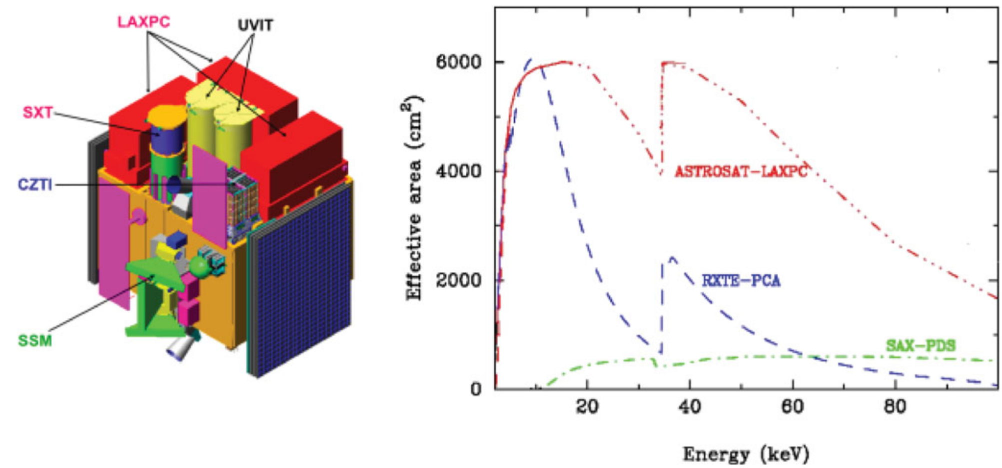

Figure 3. Left: The ASTROSAT payload. Right: The effective area curves for the ASTROSAT LAXPC in comparison to those of the RXTE/PCA and the BeppoSAX/PDS. From Chakrabarty *et al.* 2008. From `http://meghnad.iucaa.ernet.in/ãstrosat/`.

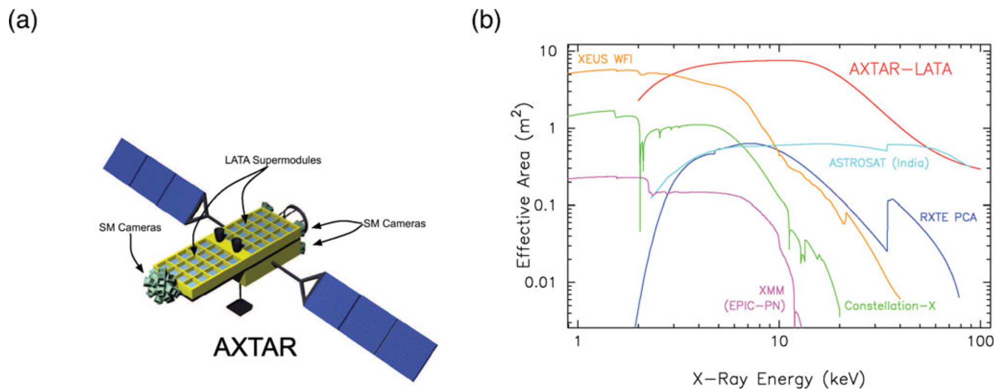

Figure 4. Left: A sketch of the AXTAR mission concept. Right: The effective area curves for AXTAR in comparison to those of other timing-capable instruments. From Chakrabarty *et al.* 2008.

main goals of the mission are to obtain measurements of general-relativistic effects in the strong field regime and to put constraint on the equation of state of neutron matter. In addition to the main large instrument with large collecting area, an all-sky monitor will ensure that a good dense monitoring of the bright X-ray sky is available for triggers and for following the long-term evolution of selected sources.

8. Future missions III: IXO

The largest endeavor of the X-ray community at the moment is IXO, the International X-Ray Observatory. This mission is currently under review by NASA, ESA and JAXA, and if accepted would fly sometime after 2017.

In its current design, IXO will carry 5 instruments on board: A Wide-Field Imager with intermediate (CCD-like) spectral resolution, a Narrow-Field Imager with high spectral resolution (using micro-calorimeters), a High-Time Resolution Spectrograph (HTRS), an X-ray polarimeter and a Grating spectrograph. The mission will cover the $0.10 - 12keV$

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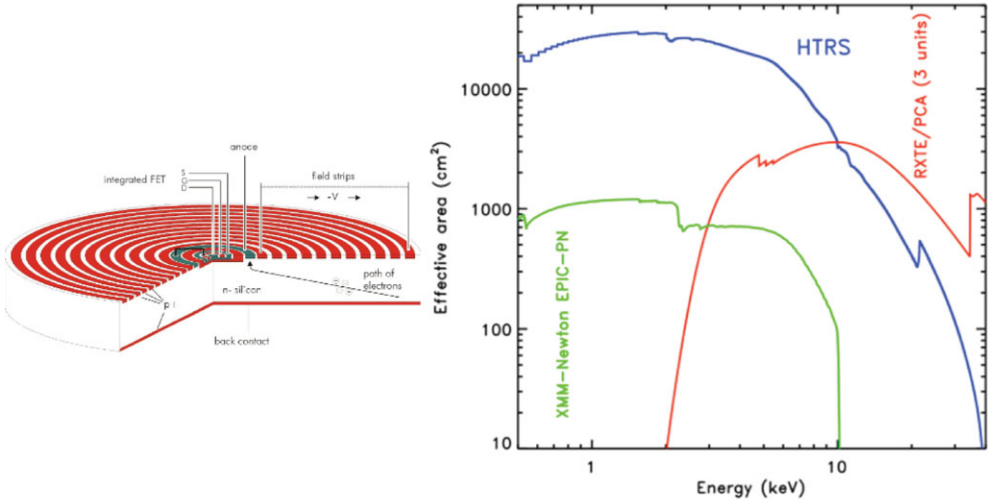

Figure 5. A schematic representation of one of the silicon-drift detectors that will be used in the HTRS (left), and the effective area of the combination of HTRS and IXO telescope in comparison with XMM-Newton and RossiXTE (right).

energy band, with a possible extension up to 40 keV. The current design anticipates 3 m^2 at 1.25 keV, 0.65 m^2 at 6 keV, and 150 cm^2 at 30 keV.

The main instrument on board IXO for timing is the HTRS (Barret *et al.* 2008). This instrument will consist of an array of silicon-drift detectors to collect the X-rays focused by the mirrors, with a spectral resolution of $\sim$ 150 eV, a time resolution of 10 μs, and a count rate capability of 10^6 counts/s (equivalent to about 5 Crabs) with less than 10% deadtime (see Fig. 5). The main science goals are to study strong gravity around neutron stars and black holes, and to constrain the neutron-star equation of state.

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