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Progress on the Knowledge of Neutron Stars and their Magnetic Fields with XMM-Newton

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The talk illustrates the achieved progress in the understanding of neutron stars and their magnetic field with highlight results based on XMM-Newton observations.

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1. Introduction

Neutron stars are classical targets of X-ray observatories and consequently huge expectations accompanied the lunch of the XMM-Newton [1] spacecraft. Contrary to expectations, the spectra of neutron stars were generally found continuum dominated exclusive any spectral features. The situation has changed during the last years as variable spectral features were detected for several neutron stars. These findings allow viewing different magnetic field components of neutron stars. In the following essay we will illustrate the achieved progress with selected highlights resulting from XMM-Newton observations of neutron stars.

2. XMM-Newton

With about 300 refereed papers published each year, XMM-Newton is one of the most successful scientific missions of ESA ever. A summary of the scientific impact can be found in M. Santos-Lleo et al. [2]. A description of the publication statistics can be found in J.-U. Ness et al. [3]. XMM-Newton carries three high throughput X-ray telescopes [4] with an unprecedented effective area. Each telescope has an X-ray CCD camera on its focal plane: one pn camera [5] and two MOS cameras [6]. These cameras comprise the European Photon Imaging Camera (EPIC). In addition XMM-Newton is equipped with two Reflection Grating Spectrometers [7] and an optical monitor [8] for simultaneous X-ray imaging, spectroscopy and UV/optical measurement. The large collecting area and ability to make long uninterrupted exposures provide highly sensitive observations.

The observational potential of XMM-Newton may be illustrated with two examples: There is the first discovery of an evolving dust-scattered X-ray halo around GRB 031203 [9] [10]. The halo appeared as concentric ring-like structures centred on the GRB location and the radii of these structures increased with time. These rings can easily be detected by eye in the pn-images demonstrating the enormous effective area of the X-ray mirrors. A second example is the composite image of the starburst galaxy Messier 82 obtained with the XMM-Newton observatory. The image was created by P. Rodríguez to support the celebration of the International Year of Astronomy as part of the 100 Hours of Astronomy cornerstone project[1]. The image illustrated the scientific potential of simultaneous observation in the optical, UV and X-ray band which allows easily separating galactic populations, star burst activity and hot out-flowing wind.

2.1 Highlights of XMM-Newton observations of neutron stars

A first highlight of observations with XMM-Newton EPIC was the detection of two elongated parallel X-ray tails trailing the pulsar Geminga [11]. These tails are aligned with the neutron stars supersonic motion and show a non-thermal spectrum which is produced by electron-synchrotron emission in the bow shock between the pulsar wind and the surrounding medium. The detection of a pulsar bow shock allows us to gauge the pulsar electron injection energy, the shock magnetic field and constrains the angle between the pulsars motion and the local matter density [11]. The Geminga pulsar shows a 43 eV thermal spectrum from the whole neutron star surface and power-law component above 2 keV [12]. In addition, P. A.Caraveo et al. [12] detected a hot (170 eV)

[1] http://xmm.esac.esa.int/external/xmm_science/gallery/public/level3.php?id=1019

thermal emission from a ∼60-meter-radius spot on the pulsar's surface which is only visible at certain phase intervals. This emission may be coming from polar hot spot(s) as a result of heating from magnetospheric accelerated particles. The X-ray emission characteristics of a second radio-quiet γ-ray pulsar, in CTA 1, can be compared with the findings for Geminga [13]. Phase-resolved spectroscopy was possible for two further bright isolated neutron stars: PSR B0656+14 and PSR B1055-52, which often are compared with Geminga. Their spectra can be described with three components, two blackbody components -a cooler one, possibly originating from the star surface, and a hotter one, coming from a hot spot and a power law [14]. The striking aspect of the phase-resolved phenomenology is the apparent lack of any common phase alignment between the observed modulation patterns for the two blackbody components. These findings do not support standard models of neutron star magnetic field configuration and surface temperature distribution [14].

Presently seven nearby radio-quiet isolated neutron stars discovered in ROSAT data and characterized by thermal X-ray spectra are known [15]. They exhibit very similar properties and despite intensive searches their number remained constant since 2001. XMM-Newton allowed detecting the spin period for RX J1605.3+3249, which was the last member of the sample with unknown spin [16]. The spin-down rate implies a dipolar magnetic field of $B_{dipole}=7.4\times10^{13}$G, which is the highest magnetic field among the group [16]. The X-ray spectra of the group members revealed broad absorption lines which are interpreted as cyclotron resonance absorption lines by protons or heavy ions and/or atomic transitions shifted to X-ray energies by strong magnetic fields [15]. XMM-Newton observations even indicate more complex X-ray spectra with multiple absorption lines. Pulse-phase spectroscopy of the two best studied pulsars, RX J0720.4-3125 and RBS 1223, reveals variations in derived emission temperature and absorption line depth with pulse phase [15]. RX J0720.4-3125 is the most peculiar object among the group, since it shows long-term variations of its spectral and temporal properties on time-scales of years [17]. Considering the latest data sets, the timing behaviour of RX J0720.4-3125 suggests a single sudden event (e.g. a glitch) rather than a cyclic pattern as it should be expected by free precession [18]. .

XMM-Newton performed a long observation of 1E1207.4-5209, where before two absorption features had been detected. G. F. Bignami et al. [19] reported three distinct features, regularly spaced at 0.7, 1.4 and 2.1 keV, plus a fourth feature of lower significance, at 2.8keV in the stars pn spectrum. The features vary in phase with the neutron star's rotation and G. F. Bignami et al. [19] interpreted them as features from resonant cyclotron absorption, implying a magnetic field strength of $B=8\times10^{10}$G, assuming the absorption arises from electrons. K. Mori & C. J. Hailey [20] compared the XMM-Newton X-ray spectrum of 1E1207.4-5209 with different detailed models of neutron star atmospheres. Only oxygen or neon atmospheres at $B\sim10^{12}$G provide self-consistent atmospheric solutions for the obtained spectra. J. P. Halpern & E. V. Gotthelf [21] analysed all archival X-ray timing data from the years 2000-2008 of 1E 1207.4-5209 to measure its dipole magnetic field strength via spin-down. Because most of these observations were not planned for the purpose of phase-coherent timing, the resulting ephemeris is not unique, but is restricted to two comparably good timing solutions that correspond to $B_s=9.9\times10^{10}$G or $B_s=2.4\times10^{11}$G, respectively, assuming dipole spin-down [21]. These solutions strongly support the interpretation by G. F. Bignami et al. [19].

O. Kargaltsev et al. [22] detected absorption features in the XMM-Newton X-ray spectrum of an ordinary rotation-powered radio pulsar, PSR J1740+1000. These findings bridge the gap between the spectra of pulsars and other, more exotic, neutron stars and suggest that the features are more common in the spectra of neutron stars.

The XMM-Newton spectra and spectral changes of several bright dipping low mass X-ray binaries, LMXBs, (EXO 0748-676, XB 1254-690, X 1624-490, MXB 1659-298, 4U 1746-371, XB 1916-053 and 4U 1323-62) were successfully modelled [23], [24]. The spectral changes are explained by an increase in column density and a decrease in the ionization state of a highly-ionized absorber [23], [24]. The complex spectral changes in the X-ray continua observed from the dip sources as a class can be most simply explained primarily by changes in the highly ionized absorbers present in these systems. Especially, there is no need to invoke unusual abundances or partial covering of extended emission regions as proposed before [24].

Supergiant fast X-ray transients are a subclass of supergiant X-ray binaries which are characterized by few-hour-long outbursts reaching luminosities of 10^{36}-10^{37} erg s^{-1}. Alternative scenarios were proposed to explain the outbursts. XMM-Newton observed IGR J18410-0535 for 45 ks. The sources underwent a bright X-ray flare that started about 5 ks after the beginning of the observation and lasted for $\sim$15 ks. This observation provides convincing evidence that the flare was produced by the accretion of matter from a massive clump onto the compact object hosted in this system [25].

It is assumed that neutron stars can develop to millisecond pulsars in LMXBs through accretion of matter and angular momentum from the companion star. The system occurs as bright X-ray emitting LMXB during the accretion phase. When the accretion rate decreases, these binaries host a radio millisecond pulsar whose emission is powered by the rotating magnetic field. A scientific highlight was the detection of the evolutionary link between accretion and rotation-powered millisecond pulsars. A. Papitto et al. [26] observed with XMM-Newton accretion-powered, millisecond X-ray pulsations from the neutron star IGR J18245-2452 that previously was seen as a rotation-powered radio pulsar. Within a few days after a month-long X-ray outburst, radio pulses were again detected demonstrating that the system can swing between the two states on very short timescales.

Through simultaneous observations with XMM-Newton and different radio facilities, W. Hermsen et al. [27] detected synchronous switching in the radio and x-ray emission properties of PSR B0943+10. When the pulsar is in a radio-"bright" mode, the X-rays show only an unpulsed, non-thermal component. Conversely, when the pulsar is in a radio-"quiet" mode, the X-ray luminosity more than doubles and a 100% pulsed thermal component is observed along with the nonthermal component. The finding indicates rapid, global changes in the magnetosphere, which challenge all proposed pulsar emission theories [27].

F. Haberl et al. [28] and V. Hénault-Brunet et al. [29] simultaneously recognized the importance of CXO J012745.97-733256.5. The source is a Be/X-ray binary pulsar near the centre of a supernova remnant, which is located at the outer region of the Small Magellanic Cloud (SMC). The neutron star has a spin period of 1062 s, which is the second longest known in the SMC, and shows a very high spin-down rate. The age of the supernova remnant can be estimated to 10,000 - 25,000 years which is not long enough to spin down the neutron star from a few 10 ms to its current value. This implies that neutron stars in Be/X-ray binaries with long spin periods can be much younger than currently anticipated [28].

RCW 103 is a young (∼2000 years) shelltype supernova remnant, with an X-ray point source very close to its centre. This source, 1E161348-5055, is characterized by unpulsed, soft X-ray emission and no radio or optical counterpart. Based on an XMM-Newton observation A. De Luca et al. [30] detected a strong periodic modulation at 6.67±0.03 hours. The source can either be an X-ray binary, composed of a compact object and a low-mass star in an eccentric orbit, or an isolated neutron star. In the latter case, the combination of its age and period indicate that it is a peculiar magnetar, dramatically slowed down [30]

Anomalous X-ray pulsars and soft gamma-ray repeaters (SGR) emit strong outbursts in soft γ-rays / hard X-rays. It is generally assumed that these bursts can only be caused by a strong magnetic field. Magnetars are neutron stars with a powerful magnetic surface field in the order of 10^{12} to 10^{15}G. Many scientists assume that anomalous X-ray pulsars and SGR are magnetars.

XMM-Newton observed CXOU J164710.2-455216 4.3d prior to and 1.5d subsequent to a 20-ms burst that was detected with Swift. M. P. Muno et al. [31] found that the X-ray luminosity of the pulsar increased by a factor of 100 in the interval between the two XMM-Newton observations, and that its spectrum hardened. In addition, under others, the pulsed count rate increased by a factor of 10 (0.5-8.0 keV). Similar changes have been observed from other magnetars in response to outbursts. M. P. Muno et al. [31] suggests that a plastic deformation of the neutron star crust induced a very slight twist in the external magnetic field, which in turn generated currents in the magnetosphere that were the direct cause of the X-ray outburst.

After nearly a decade of quiescence, the soft gamma-ray repeater SGR 1627-41 emitted a burst on 2008 May 28. A 120 ks long XMM-Newton observation allowed P. Esposito et al. [32] to detect the hitherto unknown pulsations with P=2.594578(6) s and a subsequent Chandra observation allowed to derive the spin-down rate [33], which correspond to a surface dipole magnetic field strength of $B\sim2\times10^{14}$ G. These properties confirm the magnetar nature of the object.

XMM-Newton was of fundamental importance to establish low-magnetic-field SGRs. The first object recognized and defining this class was SGR 0418+5729 [34]. N. Rea [35] could also determine the surface dipolar magnetic field of SGR 0418+5729 to $B\simeq6\times10^{12}$G. This measurement confirms the source as the lowest magnetic field magnetar. Two further members of this category could be found: Swift J1822.3-1606 (SGR 1822-1606) [36] and 3XMM J185246.6+003317 [37] [38]. Outburst of low-magnetic-field SGRs could be explained if a strong magnetic field resides in the stellar interior and in multipole components on the surface. N. Tiengo et al. [39] show that the pn spectrum of SGR 0418+5729 has an absorption line which depend strongly on the star's rotational phase. They interpreted the line as a proton cyclotron feature and its energy implies a magnetic field ranging from 2×10^{14}G to more than 10^{15}G. It is interesting to compare the findings for low-magnetic-field SGRs with the proposal by J. E. Trümper et al. [40].

Based on XMM-Newton and Chandra phase-connected timing analysis J. P. Halpern & E. V. Gotthelf [41] were able to determine the spin-down of PSR J1852+0040, which is the central compact object (CCO) in the SNR Kesteven 79. In the dipole spin-down formalism, the found value implies a surface magnetic field strength $Bs=3.1\times10^{10}$G, which is the smallest ever measured magnetic field for a young neutron star, and consistent with being a fossil field. In combination with the upper limits on surface magnetic field for other CCO pulsars, the detection strongly favours the "anti-magnetar" explanation for CCOs low luminosity and lack of magnetospheric activity or synchrotron nebulae [41].

Given the mass and radius constrains for neutron stars, effects of the strong gravity should be observable in the direct vicinity of the stars surface. The theoretical framework of light emission in the strong gravitational field was developed during the last decade, e.g.: [42], [43], [44], [45], [46] or [47].

S. Bhattacharyya & T. E. Strohmayer [48] analysed XMM-Newton data of the LMXB Serpens X-1. The EPIC pn spectra shows that the previously known, broad iron Kα emission line has a significantly skewed structure with a moderately extended red wing. The asymmetric shape of the line strongly supports an inner accretion disk origin of the line. This finding provided for the first time strong evidence of a relativistic line in a neutron star LMXB. O. K. Madej & P. G. Jonker [49] discovered a broad emission feature at $\sim$0.7 keV in the spectra of the ultracompact X-ray binary 4U 1543-624, obtained with the high-resolution spectrographs of the XMM-Newton and Chandra satellites. The donor star in this system is a white dwarf, which transfers oxygen-rich material to the accretor, conceivably a neutron star. The feature is most likely caused by X-rays reflected off the accretion disk in the strong gravitational field close to the accretor [49].

N. A. Webb & D. Barret [50] observed with XMM-Newton three quiescent X-ray binaries in the globular clusters, where the distance is accurately known. The authors used publicly available hydrogen atmosphere models with constant and varying surface gravities to derive the most stringent constraints on the masses (up to 2.4 M_{solar}) and radii ($\sim$8 km) of the neutron stars. The results did allow constraining the equations of state to those which concern normal nucleonic matter and one possible strange quark matter model.

3. Discussion and conclusions

The explanation of "dippers", the low magnetic field magnetars and the anti-magnetar hypothesis for CCOs are the outstanding achievements of the last decade. The many new features, which are now reported from several objects, are most promising to lead to significant progress in the understanding of neutron stars in the next years. Theoretical work as well as more and systematic observations with XMM-Newton and other X-ray observatories are required to fully explore this potential.

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DISCUSSION

PAUL MASON: assuming that there are no problems, what is the expected lifetime of XMM-Newton?

NORBERT SCHARTEL:

The overall status and performance of all the spacecraft elements is excellent. The strongest life-limiting item is fuel which, following the recent introduction of further fuel savings measures (4 reaction wheels), is expected to last until 2028 under the current operations concept.

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