We present XMM-Newton MOS imaging and PN timing data of the millisecond pulsar PSR J0218+4232. We confirm the previously detected pulsations of PSR J0218+4232 and we show that the folded lightcurve is dependent on energy. We present the broad band (0.2-10.0 keV) spectrum of this millisecond pulsar, as well as the spectra of: the pulsed emission, the individual pulses, the interpulse and the non-pulsed region and we compare our results with previous data from Rosat, BeppoSAX and Chandra. We discuss the results of the spectral fitting in the context of recent pulsar models.


Introduction

Pulsars show two different types of X-ray pulsations: soft pulsed emission with blackbody spectra where the emission is from the neutron star surface, such as cooling emission from the whole surface as a relic of the neutron star’s birth and/or the emission from a heated region, most likely the polar cap; or pulsed emission with narrow pulses and hard power law spectra, where it is thought that the emission arises from the magnetosphere [see e.g.][for further discussion]sait97,kuip98,taka01. Therefore detecting not only a pulsation, but also determining the form of the pulse profile, could help to identify the underlying emission mechanism and detection of the polar cap thermal radiation would allow us to discriminate between various models of pulsars and study the properties of neutron star surface layers zavl02,pavl97,zavl98. Many millisecond pulsars (MSPs) such as PSR B1821-24 [e.g.][sait97 and PSR B1937+21 [e.g.][taka01, like many ordinary pulsars, show X-ray pulsations and have been observed to emit X-ray spectra that are well fitted by a hard power law. In contrast, it has been proposed that the millisecond pulsar PSR J0437-4715 emits thermal radiation from hot polar caps zavl98,zavl02.

The radio source J0218+4232 has been known for many years dwar90,hale93 although it was first confirmed to be a millisecond pulsar by nava95, using radio observations made with the Lovell telescope in 1993. A pulse period of 2.3 ms was determined. nava95 also showed that this luminous pulsar $[L_{400} > 2700 \text{ mJy kpc}^2]$ where $L_{400}$ is the luminosity at 400 MHz nava95 is in orbit with a low mass white dwarf ($0.2 M_\odot$), with an orbital period of about two days. From the dispersion measure a lower limit on the distance of 5.7 kpc was derived.

verb96 showed evidence for PSR J0218+4232 at high energies, both in X-rays using ROSAT and $\gamma$-rays, using EGRET, the High-Energy Gamma-Ray Telescope aboard the Compton Gamma-Ray Observatory (CGRO). They also presented some indication of pulsation in both energy domains. kuip00 provided stronger evidence for the detection of pulsed $\gamma$-ray emission from PSR J0218+4232, also using EGRET data. kuip98 presented further evidence for the X-ray pulsation at the radio pulse period using 98 ks of ROSAT data. They also likened the sharp pulses to those of PSR B1821-24 and the Crab pulsar, which indicates a magnetospheric origin of the pulsed X-ray emission. They also estimated that almost two thirds of the soft X-ray (0.1-2.4 keV) emission is non-pulsed, where nava95 also stated that a large fraction of the radio emission is not pulsing. Lead them to the conclusion that PSR J0218+4232 is an aligned rotator. This was further supported by stai99, using polarimetric radio observations.

BeppoSAX observations of PSR J0218+4232 mine00 provided detailed information on the pulsar’s temporal and spectral emission properties (1.6-10 keV). They showed that pulse 1 [lying at $\phi=0.8$, in][mine00 is much stronger than pulse 2 (lying at $\phi=0.3$) in the 1.6-4 keV energy band, but that pulse 2 is much stronger than pulse 1 in the 4-10 keV energy band. Also at the higher energy no non-pulsed component was apparent above the background level. They determined a very hard power law fit, photon index = $0.61\pm0.32$, to the pulsed part of the spectrum, with a fixed column density of $5\times10^{20} \text{ cm}^{-2}$ [sec][verb96, which gave a flux of $4.1\times10^{-13} \text{ ergs cm}^{-2} \text{ s}^{-1}$ (2-10 keV). The measured spectral indices of pulse 1 and pulse 2 were $0.84\pm0.35$ and $0.42\pm0.36$. The total spectrum was well fitted by a power law, with a photon index of $0.94\pm0.22$ and they found a flux of $4.3\times10^{-13} \text{ ergs cm}^{-2} \text{ s}^{-1}$ (2-10 keV). kuip02 showed that the non-pulsed spectrum of
PSR J0218+4232 has a softer spectrum than the pulsed emission, using 73 ks of Chandra data. Recently, kuip02, kuip02b presented multiwavelength (radio, X- and γ-ray) pulse profiles of PSR J0218+4232. They found that the two X- and γ-ray pulses are aligned and that the X-ray pulses are also aligned with two of the three radio pulses. This is a very interesting result as multiwavelength emission can help to discriminate between the different theoretical models proposed to describe the nature of millisecond pulsars, such as the polar cap models [see] and references therein [hard02] and the outer gap models [see] and references therein [chen00], and thus trace the origin of the emission. For example, in polar cap scenarios, γ-ray pulses should be accompanied by X-ray pulses at the same phase and with similar shapes [ruda99].

XMM-Newton combines the spectral capabilities of ROSAT (0.1-2.5 keV) and the BeppoSAX MECS (2-10 keV), which, when coupled with the XMM-Newton’s sensitivity, gives us unparalleled spectral information from low to high energies. We have thus used XMM-Newton to observe the millisecond pulsar PSR J0218+4232 to show the evolution of the pulsed profile from low energies (0.4-1.6 keV) to high energies (up to 12 keV). We present spectra of the pulsar as a whole and both the pulsed and non-pulsed components and we draw some conclusions about the nature of the emission from PSR J0218+4232.

Observations and data reduction

PSR J0218+4232 was observed by XMM-Newton on 2002 February 11-12. The observations spanned 37.2 ks (MOS cameras) and 36 ks (PN camera), but a soft proton flare affected 17 ks of the MOS exposure and 16.5 ks of the PN exposure. The MOS data were reduced using Version 5.3.3 of the XMM-Newton SAS (Science Analysis Software). However, for the PN data we took advantage of the development track version of the SAS. Improvements have been made to the OAL (ODF (Observation Data File) access layer) task (version 3.106) to correct for spurious and wrong time values, premature increments, random jumps and blocks of frames stemming from different quadrants in the timing data in the PN auxiliary file, as well as correcting properly for the onboard delays [kirs03]. Using this version, our timing solution improved (see Sect. sec:pntiming).

We employed the MOS cameras in the full frame mode, using a thin filter [see] [turn01]. The MOS data were reduced using ‘emchain’ with ‘embadpixfind’ to detect the bad pixels. The event lists were filtered, so that 0-12 of the predefined patterns (single, double, triple, and quadruple pixel events) were retained and the high background periods were identified by defining a count rate threshold above the low background rate and the periods of higher background counts were then flagged in the event list. We also filtered in energy. We used the energy range 0.2-10.0 keV, as recommended in the document ‘EPIC Status of Calibration and Data Analysis’ [kirs02]. The event lists from the two MOS cameras were merged, to increase the signal-to-noise.

The PN camera was also used with a thin filter, but in timing mode which has a timing resolution of 30µs [stru01]. The PN data were reduced using the ‘epchain’ of the SAS. Again the event lists were filtered, so that 0-4 of the predefined patterns (single and double events) were retained, as these have the best energy calibration and we filtered in energy. The document ‘EPIC Status of Calibration and Data Analysis’ [kirs02] recommends use of PN timing data above 0.5 keV, to avoid increased noise. We used, in general, the data between 0.6-12.0 keV as this had the best signal-to-noise, although we have also tried to exploit the data in the 0.4-0.6 keV band (see Sect. sec:pntiming). The on-board event times expressed in the local satellite frame were subsequently converted to Barycentric Dynamical Time, using the SAS task ‘barycen’ and the coordinates derived from 6.5 years of radio timing measurements, as given in kuip02.

Timing analysis sec:pntiming

In the PN timing mode, all the two-dimensional spatial information is collapsed into a single dimension (x-direction). We extracted the pulsar data using a rectangular region centered on the pulsar.

We corrected the data for the orbital motion of the pulsar and the data were folded on the radio ephemeris given in kuip02. We verified that the corrections made to the timing data with the development version of the SAS are indeed correct. We tested frequencies at and around the expected frequency. We used a χ² test to determine the frequency at which the pulse profile was the strongest. We found the largest peak in the χ² versus change in frequency from the expected frequency at ∆ν = 2 ×10⁻⁶s⁻¹, see Fig. fig:chisquare. This is well inside the resolution of this dataset (∼1/Tobs), which is 3 ×10⁻⁵s⁻¹, thus we can conclude that the data reduction and analysis made to the dataset are reliable. The folded lightcurve (0.6-12 keV), data folded on the radio frequency, counts versus phase, is shown in Fig. fig:folded. This lightcurve is very similar to the lightcurve presented by kuip02, where both pulses can be found at approximately the same phase [within the timing uncertainties of Chandra and XMM-Newton] [kuip02, tenn01, kirs03]. Fitting the two pulses with
two Lorentzians and a background [in a similar way to][1]kuip02, we find a pulse separation of $\phi = 0.491 \pm 0.022$ (90% confidence limit), consistent with previous results e.g. kuip98, mine00 and kuip02. The FWHM of the pulses are $\delta \phi_1 = 0.112 \pm 0.038$ for the pulse centred at phase $\phi_1 = 0.242 \pm 0.008$ and $\delta \phi_2 = 0.121 \pm 0.056$ for the pulse centred at $\phi_2 = 0.733 \pm 0.014$. These values are also consistent with the values presented in kuip02. Fitting the pulses with two Gaussians or fitting the pulses separately gives a similar result.

Figure [width=8cm]fig1.ps $\chi^2_\nu$ versus change in frequency from the expected pulsation frequency (shown as the solid vertical line at $\Delta \nu = 0.0$), calculated with the ephemeris of kuip02. See Sect. sec:pntiming for details. fig:chisquare