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X-ray properties of the mode-switching pulsar PSR B0943+10

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Abstract.
The mode-switching pulsar PSR B0943+10 has been extensively studied in the radio band for many years and, more recently, it has been found to vary also in X-rays, with a flux anticorrelated with the radio emission. Here we review the results of long observations of PSR B0943+10 carried out with *XMM-Newton* and the LOFAR, LWA and Arecibo radio telescopes in 2014. These results support a scenario in which both unpulsed non-thermal emission, likely of magnetospheric origin, and pulsed thermal emission from a small polar cap ($\sim$1500 m^2) with a strong non-dipolar magnetic field ($\sim 10^{14}$ G), are present during both radio modes and vary in intensity in a correlated way.

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1. Introduction

PSR B0943+10 can be considered the prototypical mode-switching radio pulsar. It was soon discovered that its radio emission alternates between two different states: when the pulsar is in B (bursting or bright) mode, its radio emission displays a regular pattern of drifting subpulses, while it is chaotic, and on average fainter, when the pulsar is in the Q (quiescent) mode [1, 2].

Its spin period P=1.1 s and period derivative $\dot{P}$=3.5$\times10^{-15}$ s s^{-1} imply a characteristic age τ=5 Myr, a dipolar surface magnetic field B=4$\times10^{12}$ G, and a spin-down power $\dot{E}_{rot}$=10^{32} erg s^{-1}. The distance of PSR B0943+10, based on its dispersion measure (DM=15.32 pc cm^{-3} [3]) and the Galactic electron density distribution of [4], is $\sim$630 pc. According to the more recent electron density model of [5] the same DM gives instead a distance d=890 pc.

The faint (a few 10^{-15} erg cm^{-2} s^{-1}) X-ray emission of PSR B0943+10 was first detected in 2003 [6], and studied in much more detail thanks to a set of *XMM-Newton* observations carried out in 2011. These observations, providing a useful exposure of about 100 ks, were complemented by simultaneous radio monitoring with LOFAR and the GMRT. This made it possible to analyse separately the X-ray data corresponding to the two radio modes, thus leading to the discovery of X-ray flux variations anticorrelated with the radio modes [7]. In fact, it was found that in the Q-mode, when the radio emission is fainter, the X-ray flux is larger by more than a factor two than in the B-mode.

X-ray pulsations at the rotation period of 1.1 s were detected only in the Q-mode. The X-ray emission during the Q-mode was well described by a blackbody plus power law spectrum, while that of the X-ray fainter B-mode was less constrained: both a single power law and a single blackbody could fit it. The pulsed spectrum (in Q-mode) was found to be a blackbody, consistent in flux and temperature with the blackbody component seen in the total spectrum. Furthermore, the power-law component of the total Q-mode spectrum was consistent, in slope and normalization, with the best fit power-law spectrum of the B-mode. These results led to the suggestion that PSR B0943+10 emits only an unpulsed non-thermal component when it is in B-mode and its higher luminosity in Q-mode is caused by the addition of a 100%-pulsed thermal component [7].

However, since there is evidence from radio data that PSR B0943+10 is a nearly aligned rotator (i.e. small angle between rotation and magnetic axis) and that the line of sight is also close to the rotation axis [8, 9, 10], one would not expect such a large modulation from a hot spot in the polar region. Furthermore, it is unclear what could cause the rapid appearance/disappearance of the pulsed thermal emission when the pulsar switches radio mode. A new longer campaign of simultaneous X-ray and radio observations was therefore carried out in November 2014 in order to clarify these issues. The X-ray observations, performed with the EPIC instrument of the *XMM-Newton* satellite, consisted of seven long pointings ($\sim$16–19 hr each), which, after screening to remove periods of high background, provided a net exposure of $\sim$120 ks during the pulsar Q-mode and $\sim$175 ks during B-mode (for comparison, the previous data consisted of $\sim$50 ks in each mode). Simultaneous radio coverage was provided by using three radio telescopes at different longitudes: the Low-Frequency Array (LOFAR) at 110–190 MHz, the Arecibo telescope at 302–352 MHz, and the Long Wavelength Array (LWA) at 40–80 MHz. Here, we briefly report on the main results obtained in these observations, referring to [11] for more details.

2. Results

The larger X-ray count statistics obtained in the 2014 observations, compared to that of the previous data (in particular for the B-mode), made it possible to reveal that the periodic modulation caused by the star's rotation is present also during the B-mode, when the X-ray flux is lower (see figure 1). By comparing the folded light curves obtained before and after T$_{QB}$+ 3 hr (where T$_{QB}$ is the time of the Q-to-B mode transitions), we found some evidence

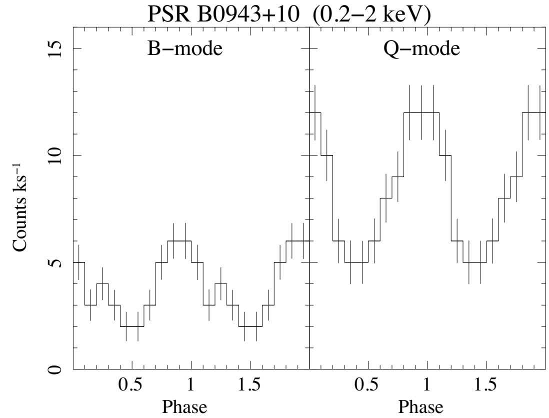

Figure 1. Background-subtracted pulse profiles of PSR B0943+10 in the 0.2-2 keV energy range obtained in the 2014 *XMM-Newton* observations.

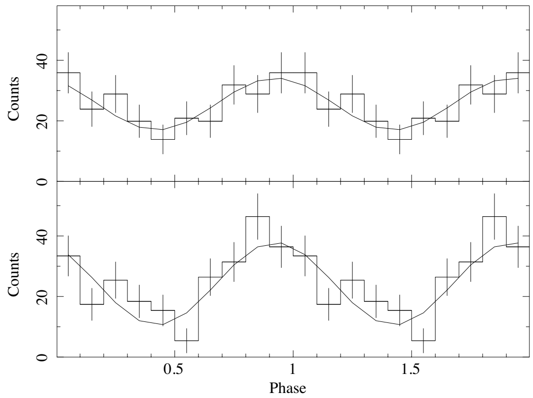

Figure 2. B-mode pulse profiles in the 0.5-2 keV range (background subtracted). Top: initial 3 hr after the Q-to-B transitions. The pulsed fraction is (27±8)%. Bottom: data obtained later than 3 hr after the Q-to-B transitions. The pulsed fraction is (42±8)%.

that the pulsed fraction increases along the B-mode (see figure 2). This possible variation, although only at the $\lesssim 2\sigma$ level, is potentially interesting and might be related to the fact that several properties of the PSR B0943+10 radio emission show an evolution along the B-mode [2, 12, 13, 3]. The possible presence of an increase in the X-ray pulsed fraction is also supported by the failure to detect the B-mode pulsations in the 2011 observations, which covered mostly the first few hours after the Q-to-B mode transitions. Simulations show that, with the count statistics of the 2011 data, the pulsations in B-mode should have been detected at a significance $> 3\sigma$ with a probability of $\sim$50%, if they had the same pulsed fraction measured in 2014.

The spectral analysis confirmed that the Q-mode emission cannot be fit by single component models, as found in [7]. A good fit could be obtained with a blackbody with temperature kT=0.27 keV plus a power law with photon index Γ=2.4, or with the sum of two blackbodies with temperatures kT_1=0.11 keV and kT_2=0.34 keV.

On the other hand, the new data allowed a much better characterization of the B-mode spectrum, which, at variance with the findings of the 2011 observations, could not be fit by a single power law. In fact, a good fit could be obtained either with a single blackbody with temperature kT=0.24 keV, or with the sum of a blackbody and a power law (kT=0.24 keV, Γ=2.3).

Very interesting results were obtained by applying a 3-D maximum likelihood analysis (ML) [14] to *simultaneously* derive the spectra of the pulsed and unpulsed emission. The findings of [7] for the Q-mode were confirmed: the pulsed flux is thermal, being well fit by a blackbody (kT=0.29 keV) but not by a power-law. The opposite is true for the unpulsed flux, which can be fit by a power-law (Γ=2.5) and not by a blackbody. The blackbody describing the pulsed emission and the power law describing the unpulsed emission are consistent with the two components used to fit the total spectrum of the Q-mode. The situation is not so well constrained for the B-mode, where, both for the pulsed and unpulsed emissions, it was impossible to distinguish between a power law and a blackbody, which gave equally good fits.

It is reasonable to assume that the spectral components in the B-mode are the same as in the

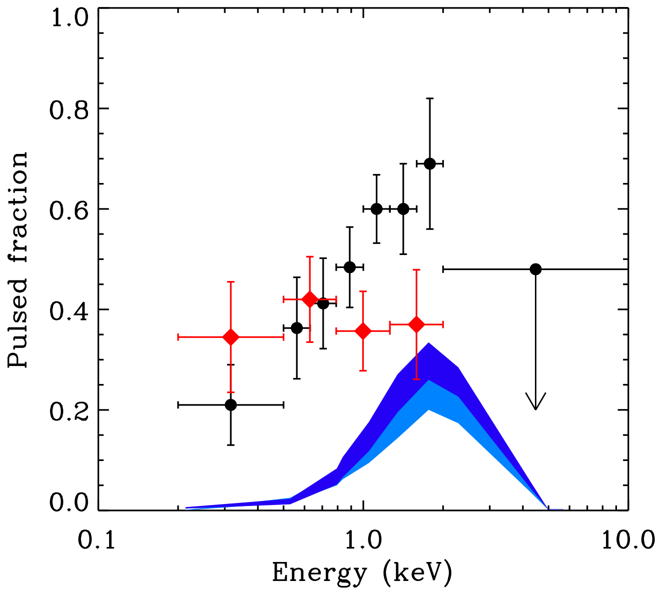

Figure 3. X-ray pulsed fraction as function of energy for the Q-mode (black dots) and for the B-mode (red squares). The blue regions show the values expected for the polar cap emission computed with model atmospheres of different temperatures (light blue kT=0.25 keV, dark blue kT=0.14 keV, see [11] for details) for the most likely ranges [10] of the angles between the magnetic and rotation axis ($10° < \xi < 15°$) and between the rotation axis and the line of sight ($5° < \chi < 10°$).

Q-mode, i.e. the thermal emission is pulsed and the non-thermal is non-pulsed. The opposite situation (thermal unpulsed plus non-thermal pulsed emission), although statistically consistent with the data, is more difficult to interpret physically. In fact, a significant and finely-tuned change in both spectral components would be required when the pulsar switches between the different radio modes.

These results are illustrated in figure 4, where the spectra obtained with the 3-D ML for the pulsed (red) and unpulsed (blue) components are compared with those derived for the total emission (black).

3. Discussion

The above results strongly suggest that PSR B0943+10 emits a combination of thermal and non-thermal X-rays in both radio modes. The X-ray flux variation, anticorrelated with that in the radio band, involves both spectral components and, quite surprisingly, the pulsations are due to the thermal component.

The best-fit temperature of the thermal component in the Q-mode is ~30% higher than that of the B-mode. Thus the flux variation can, in principle, be explained only by the temperature change of a fixed emitting area. However, the temperatures and emitting areas derived by the

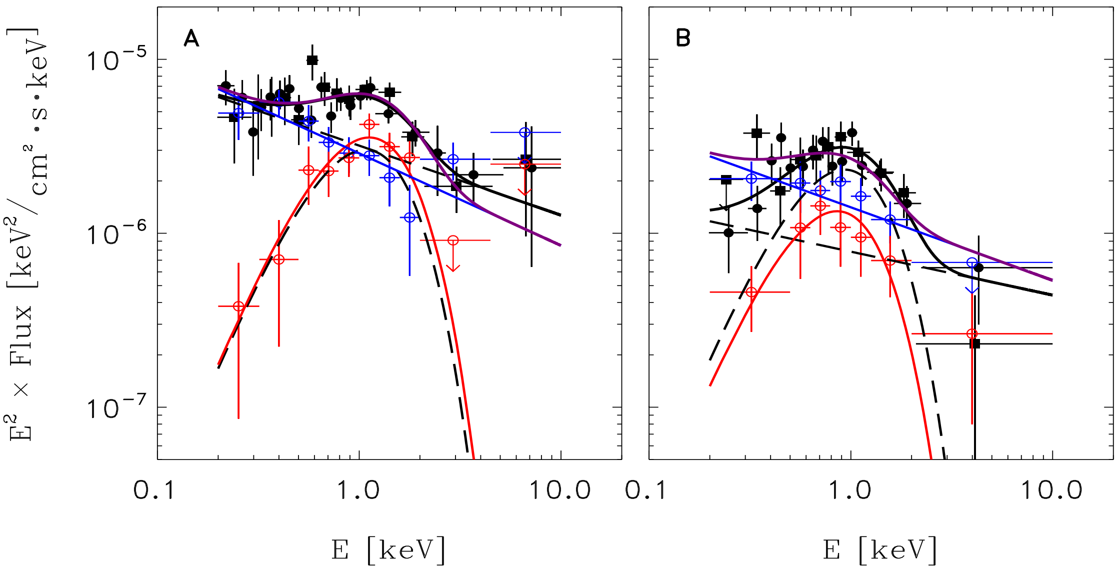

Figure 4. Spectra of the Q-mode (left panel) and B-mode (right panel) obtained in the 2014 observations of PSR B0943+10. All the spectra have been derived with a Maximum Likelihood analysis, which gives the best sensitivity for faint X-ray sources [7]. Black lines and points refer to the spectra of the total (i.e. pulsed plus unpulsed) emission (circles = pn, squares = sum of the two MOS; the solid lines are the best-fit blackbody plus power law models, while the dashed lines indicate the individual components). The red and blue points and lines refer to the spectra simultaneously derived for the pulsed and non-pulsed components (see [11, 14] for details). Blue indicates the unpulsed component (best-fit with a single power-law) and red indicates the pulsed component (best-fit with a single blackbody). Note that, in both modes, the sum of the blue and red lines (indicated in purple) is fully consistent with the solid black line.

fits are strongly correlated and, as shown in figure 5, it is also possible that an area variation is entirely (or partially) responsible for the difference in flux between the two modes.

In any case, it is clear that the thermally-emitting area is a small fraction of the star surface, as expected for an old pulsar like PSR B0943+10, in which only the magnetic polar caps are heated by backward-accelerated magnetospheric particles, while the bulk of the surface has cooled below detectability in the X-ray band. Even with the upward revised distance of 890 pc, the projected emitting area derived from the blackbody fits is smaller than that expected for the polar cap defined by the last open field lines of a dipolar field ($A \sim \pi R_{pc}^2 = \frac{2\pi^2 R^3}{cP} = 1.3 \times 10^5$ m^2, for a star radius $R = 13$ km).

The flux of the unpulsed power-law increases by a factor $\sim$2 from the B- to the Q-mode, while that of the pulsed blackbody increases by a factor $\sim$3. The flux correlation between the thermal and non-thermal X-rays is not surprising in the framework of the Vacuum Gap models [15, 16, 17, 18] in which the pairs are produced relatively close to the star surface and the accelerated particles are responsible both for the non-thermal emission in the magnetosphere and for the heating of the polar regions through return currents. On the other hand, Space Charge Limited Flow models with particles leaving freely the star surface (e.g. [19, 20]), predict the pair-creation front much higher in the magnetosphere. Since in this case only a few percent

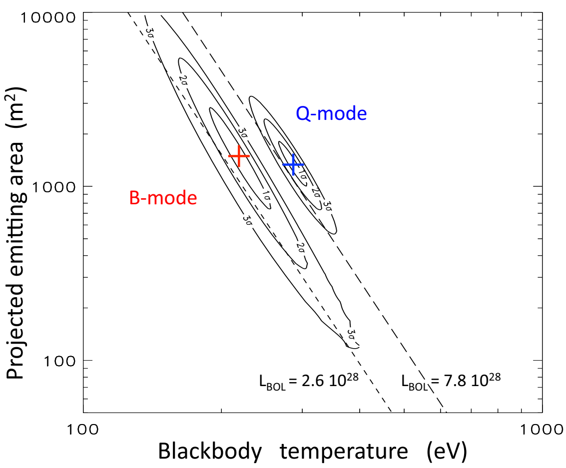

Figure 5. Error regions of the parameters derived for the thermal emission of PSR B0943+10 in the B- and Q-modes. The crosses indicate the best fit values of blackbody temperature and projected emitting area, while the contours show the corresponding uncertainty regions (1, 2, and 3σ c.l.). The dashed lines indicate values of the bolometric luminosities (in erg s^{-1}) of the polar cap, corrected for the (small) projection effect and assuming d=630 pc.

of the return particles might reach the surface, one would not naturally expect a correlation beteween the thermal and non-thermal emission.

The high pulsed fraction of the thermal X-ray component (figure 3) is rather puzzling considering the geometry of PSR B0943+10 derived from radio observations [8, 10, 3]. Although one should remember that such estimates are subject to model dependent uncertainties, there is a broad consensus that PSR B0943+10 is a nearly aligned rotator seen approximately pole-on. Therefore, the polar cap hot spot should not produce strongly pulsed X-rays, unless the emission is significantly beamed, e.g. due to magnetic effects. Another possibility that has been proposed to solve this puzzle is that of an offset magnetic dipole [21].

4. Conclusions

Extensive radio observations of the prototypical mode-switching pulsar PSR B0943+10, carried out for more than 40 years, have provided a wealth of information and a detailed knowledge of its complex phenomenology. However, the cause of the mode-switching in radio pulsars remains unknown. Thanks to the high sensitivity of the *XMM-Newton* satellite, it has now become possible to supplement the radio studies with a high-energy view, which might help to understand better this phenomenon. In this respect it is useful to obtain X-ray observations of similar objects. So far, this has been done for PSR B1822–09 and PSR B0823+26.

PSR B1822–09 is younger ($\tau = 0.2$ Myr) and more energetic ($\dot{E}_{rot} = 4.6 \times 10^{33}$ erg s^{-1}) than PSR B0943+10 and is believed to be a nearly orthogonal rotator [22, 23]. Differently from PSR B0943+10, its mode changes occur very frequently, with average mode durations of only a few minutes. t was extensively observed with *XMM-Newton* (200 ks of exposure) in 2013–2014, but no evidence for X-ray variations was found [14]. Its spectrum was well fit by two blackbodies with temperatures $kT_1 = 0.08$ keV, $kT_2 = 0.19$ keV and emitting radii $R_1 = 2$ km, $R_2 = 100$ m. Both the hotter and the cooler blackbody components seem to contribute to the X-ray pulsations, which are present in both radio modes. The apparent lack of X-ray changes related to the radio-modes could be due to the short duration of the modes in PSR B1822–09. This could arise, e.g., if the timescale for the X-ray variation is longer than the mode duration.

However, this seems to be in contradiction with the recent X-ray observations of PSR B0823+26 [24], in which a high X-ray state lasting only 6 minutes has been seen. This pulsar has timing parameters very similar to those of PSR B0943+10 (P=0.5 s, $\dot{P}$=1.7×10^{-15} s s^{-1}) and it also shows a Bright and a Quiet radio mode [25], but, contrary to PSR B0943+10, the X-ray flux is higher during the B-mode [24].

It thus appears that the multiwavelength picture that is emerging from the observations of these three pulsars is rather heterogeneous and further X-ray observations of these and other mode-switching pulsars are required to advance. Unfortunately, most mode-switching radio pulsars are relatively old and not very energetic. This means that they are too faint for detailed studies in the X-ray range with the current facilities. Future X-ray satellites with a large effective area will be essential to provide high quality data, provided they have adequate timing capabilities and good sensitivity also in the soft range below ∼1–2 keV, where the emission from old pulsars dominates.

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