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X-ray studies of the black widow pulsar PSR B1957+20

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Abstract. We report on Chandra observations of the black widow pulsar, PSR B1957+20. Evidence for a binary-phase dependence of the X-ray emission from the pulsar is found with a deep observation. The binary-phase resolved spectral analysis reveals non-thermal X-ray emission of PSR B1957+20, confirming the results of previous studies. This suggests that the X-rays are mostly due to intra-binary shock emission which is strongest when the pulsar wind interacts with the ablated material from the companion star. The geometry of the peak emission is determined in our study. The marginal softening of the spectrum of the non-thermal X-ray tail may indicate that particles injected at the termination shock is dominated by synchrotron cooling.

Keywords. binaries: eclipsing, pulsars: individual (PSR B1957+20)

1. Introduction

The widely accepted scenario for the formation of a millisecond pulsar (MSP) is that an old neutron star has been spun up to millisecond periods in a past accretion phase by mass and angular momentum transfer from a binary late-type companion (Alpar *et al.* 1982). Close binary systems with MSPs are a subject of special interest since they are thought to be the missing link between low-mass X-ray binaries (LMXBs) and isolated MSPs. The discovery of the eclipsing binary pulsar system PSR B1957+20 (Fruchter *et al.* 1988) gave support to this formation scenario.

PSR B1957+20 is in a binary system with a 0.025 $M_\odot$ companion in a 9.16-hr orbital period. It has a spin period of 1.6 ms, the third shortest among all known MSPs. The X-ray emission of PSR B1957+20 is found to be non-thermal dominated and best modeled with a single power-law spectrum, which indicates that the X-rays originate from the shock interaction of the pulsar wind with the wind of the companion star or from the pulsar magnetosphere (Stappers *et al.* 2003, Huang & Becker 2007). A $4-\sigma$ detection of X-ray coherent pulsation was reported by Guillemot *et al.* (2012). In addition, Huang & Becker (2007) found a strong correlation of the pulsar's X-ray flux with its orbital period. However, due to the short exposure we could not know whether the flux modulation was periodic and given the limited photon statistics it was not possible to investigate any spectral variation as a function of orbit phase or to determine the exact geometry of the peak emission. Repeated coverage of the binary orbit in a longer Chandra observation would provide us a better photon statistic and allow us to determine the emission geometry with higher accuracy.

2. Observation and data analysis

A Chandra observation aimed on PSR B1957+20 was performed on 2008 August 15 (ObsID 9088) with an uninterrupted 169-ks exposure. Data reduction and analysis were processed with Chandra Interactive Analysis Observations (CIAO) version 4.3 software and the Chandra Calibration Database (CALDB) version 4.4.1. The level 1 data with background cleaning were used in our study. Data analysis was restricted to the energy range of $0.3 - 8.0$ keV. For the timing and spectral analyses, we extracted the photons from a circular region centered at the radio timing position†, RA(J2000)=$19^h 59^m 36.^s 77$, Dec=$20^\circ 48' 15.'' 12$, with a radius of $2''$.

2.1. *Timing Analysis*

For the timing analysis, we first extracted the photons from the aforementioned circle and translated the photon arrival times to the solar system barycenter by using the CIAO tool *axbary*. The JPL DE200 solar system ephemeris was used for the barycentric correction to ensure consistency with the radio ephemeris.

As the Chandra observation covers over five consecutive binary orbits, by plotting a light curve of the X-ray source counts versus the orbital phase we can confirm that the X-ray flux is not steady with time. We also applied a Kolmogorov-Smirnov (KS) test to the unbinned light curve data in order to have a bin-independent statistical evaluation of the X-ray emission variability. In addition, to search for a modulation of the X-ray flux as a function of orbital phase, we selected X-ray data covering 5 complete and consecutive orbits and then used the radio timing ephemeris of PSR B1957+20 from a pulsar catalog provided by Lucas Guillemot‡ to fold a light curve at the orbital period (see Fig 1 left panel) . Using a χ^2-test, the significance for a flux modulation over the observed orbit was found to be $\sim 99\%$.

2.2. *Spatial Analysis*

Fig. 1 (right panel) shows the Chandra ACIS-S3 image in the energy band 0.3–8 keV of the field around PSR B1957+20. This image was created by using an adaptive smoothing algorithm with a Gaussian kernel of $\sigma < 3$ pixels in order to probe the detailed structure of faint diffuse emission. Both the pulsar and an extended X-ray feature (hereafter the "tail"), protruding from the pulsar position, can be clearly seen in this image. The length of the tail with its orientation to the northeast is about 25 arcsec.

2.3. *Spectral Analysis*

Assuming that the X-ray emission originates from the intra-binary shock or the pulsar's magnetosphere (Stappers *et al.* 2003, Huang & Becker 2007, Guillemot *et al.* 2012), we expect the radiation to be synchrotron. To test this hypothesis, we fitted the spectrum with an absorbed power-law model (PL). Unexpectedly, a single PL model cannot provide any statistically acceptable description of the observed spectrum. We also tested whether a single blackbody (BB) model, a double PL model, a PL+BB, a MEKAL, a thermal bremsstrahlung (TB), a MEKAL+PL, and a PL+TB model can provide an appropriate modeling of the data. We found those models cannot yield a better or an acceptable description. Therefore, we suspect a dependence of the X-ray spectrum of PSR B1957+20 on its orbital phase due to the variability observed in its X-ray flux level which seems to correlate with its orbital period.

† from the ATNF Pulsar Catalogue
‡ ftp://www.cenbg.in2p3.fr/astropart/lucas/report/1959+2048.html

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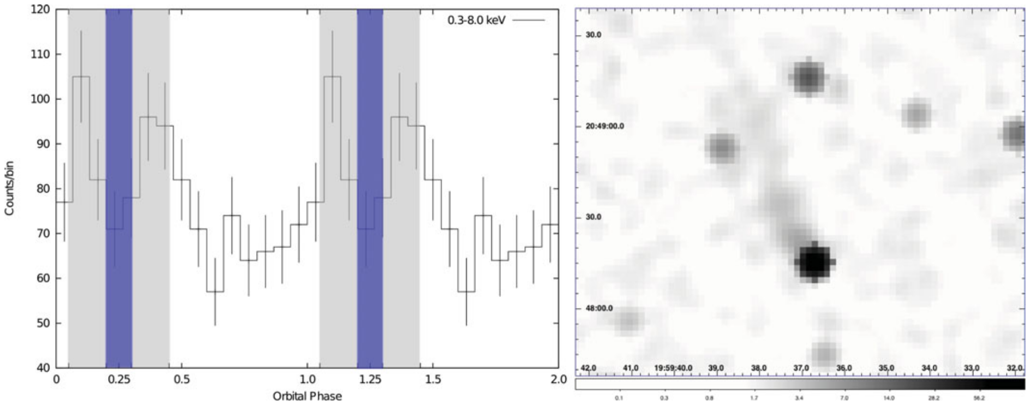

Figure 1. *Left:* A folded light curve at the orbital period. The blue shaded regions mark the radio eclipse of the black widow pulsar. *Right:* Chandra ACIS-S3 image in the energy band 0.3–8 keV of PSR B1957+20 smoothed with an adaptive Gaussian filter.

To investigate whether the X-ray spectral behavior of PSR B1957+20 varies across the orbit, we analysed the X-ray spectra within the orbital phase of $\phi = 0.05 - 0.45$ which covers the eclipsing region and outside the aforementioned region ($\phi = 0.45 - 1.05$) separately. We found that the binary-phase resolved spectral analysis reveals a non-thermal emission nature of the detected X-rays and each of the observed spectra can be well described by a single PL model with different photon indices, which indicates that its spectral behavior is orbital dependent.

We selected a box of $16'' \times 6''$ with an orientation along the proper motion direction as the region of the X-ray tail of PSR B1957+20 and found an absorbed single PL model fits the X-ray spectrum of the tail well, which implies that the X-ray emission originates from the pulsar interaction with the ambient medium. A softening of the spectrum of the X-ray tail as a function of the distance from the pulsar is expected if synchrotron cooling of the particles injected at the termination shock is dominated. For the purpose of investigating the possible spectral variation, we performed a spatially-resolved spectral analysis using two separate extraction regions along the tail. An indication for such a spectral variation was found in this study.

3. Summary and conclusion

We have searched for the orbital modulation of the X-ray emission from PSR B1957+20. Analysing the data with a χ^2-test and a K-S test revealed a marginal intra-orbital flux modulation, which suggests that the non-thermal X-rays from PSR B1957+20 are mostly due to intra-shock emission at the interface between the pulsar wind and the ablated material from the companion star. The pulsar wind electrons and positrons are accelerated and randomized by the shock and emit the X-rays via the synchrotron process.

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