HIGH-ENERGY OBSERVATIONS OF THE BINARY MILLISECOND PULSAR PSR J0218+4232

L. Kuiper¹, W. Hermsen¹, F. Verbunt², T. Belloni³, A. Lyne⁴

¹) SRON-Utrecht, Sorbonnelaan 2, 3584 CA Utrecht, NL
²) Astronomical Institute, Utrecht University, 3508 TA Utrecht, NL
³) Astronomical Institute "Anton Pannekoek", 1098 SJ Amsterdam, NL
⁴) University of Manchester, NRAL, Jodrell Bank, Cheshire SK11 9DL, UK

ABSTRACT We report the detection of pulsed X-ray emission (4.9σ) from the binary millisecond pulsar PSR J0218+4232 in a 100 ks ROSAT HRI observation. The pulse profile shows a sharp main pulse and an indication for a second weaker pulse at ~ 0.47 phase separation. The pulsed fraction is 37±13%. PSR J0218+4232 was several times in the field of view of the high-energy γ-ray telescope EGRET and a source positionally consistent with the pulsar was detected above 100 MeV. Spatial and timing analyses of EGRET data indicate that the source is probably multiple: Between 0.1 GeV and 1 GeV PSR J0218+4232 is the most likely counterpart, while the BL Lac 3C66A is the best candidate above 1 GeV. If part of the EGRET signal truly belongs to the pulsar, then this would be the first millisecond γ-ray pulsar.

KEYWORDS: millisecond pulsars; PSR J0218+4232; X-rays; Gamma-rays.

1. INTRODUCTION

PSR J0218+4232 was discovered by Navarro et al. (1995) as a highly luminous 2.3 ms radio-pulsar in a 2.0 day orbit around a white dwarf companion. Its unusually broad radio-pulse profile and the indication for radio DC-emission points to a nearly aligned rotator. This is supported by Stairs (1998) who finds a magnetic inclination angle of ~ 10°. At soft X-rays a source positionally consistent with the pulsar was detected in a 22 ks ROSAT HRI observation by Verbunt et al. (1996), who found also indications for pulsed emission. Moreover, these authors noticed that the high-energy (HE) EGRET source 2EG J0220+4228 is positionally consistent with the pulsar and shows indications for pulsed emission for energies above 100 MeV. Here we report the definite detection of pulsed soft X-ray emission from PSR J0218+4232 in a 100 ks ROSAT HRI follow-up observation (see Kuiper et al. 1998) and present the results of a more detailed analysis using additional EGRET data.

2. ROSAT HRI OBSERVATION

The 100 ks ROSAT HRI observation (0.1-2.4 keV) performed in July 1997 yielded a 21σ source consistent in position with the pulsar. A timing analysis using
FIGURE 1: (left) Soft X-ray lightcurve of PSR J0218+4232 from a 100 ks ROSAT HRI observation applying updated pulsar parameters. The modulation significance is $\sim 4.9\sigma$ ($Z^2$-test). The spatially determined background level is shown as a straight dashed line. (right) The 0.3-1 GeV EGRET $\gamma$-ray lightcurve of PSR J0218+4232 combining data from VP 15, 211, 325 and 427 with superposed its Kernel Density Estimator (de Jager et al. 1986). Extrapolated pulsar parameters (Navarro 1995) are used. The modulation is marginally significant ($2.4\sigma$ in a $Z^2$-test). Typical error bars are shown.

the pulsar parameters given in Navarro et al. (1995) extrapolated over a few years yielded a pulsed signal with a $\sim 4.8\sigma$ modulation significance, confirming our earlier indications. The pulse profile consists of a sharp main pulse with an indication for a second weaker pulse at 0.47 phase separation. The pulsed fraction is $37 \pm 13\%$ (see Kuiper et al. 1998). We produced now a new lightcurve through pulse phase folding with an improved pulsar ephemeris, determined by one of us (AL), with a validity interval ranging from MJD 49092 to MJD 50901 ($\sim$ 5 years, covering the epoch of our observation). This is shown in Fig. 1 (left) and the morphology is statistically identical to the lightcurve shown in Kuiper et al. (1998). In Kuiper et al. (1998) we also reported that the large unpulsed component can be explained by emission from a compact nebula with a diameter of $\sim 14''$. It is interesting to note that emission from this source has also been detected at hard X-rays (2-10 keV) by ASCA in a 40 ks observation (Kawai et al. these proceedings). This observation time appeared to be too short to detect the weak pulsed signal.

3. EGRET OBSERVATIONS

PSR J0218+4232 was several times in the field of view of the HE $\gamma$-ray telescope EGRET and a $5.4\sigma$ source, 2EG J0220+4228, positionally consistent with the pulsar was detected above 100 MeV in the data from viewing periods (VP) 15 and 211 (Thompson et al. 1995). This source was tentatively identified by e.g. Dingus et al.
FIGURE 2. EGRET images for energies above 100 MeV: (a) Total, (b) “Pulsed” and (c) “Unpulsed”. The contours start at a 3σ detection significance level (1 degree of freedom) in steps of 1σ. PSR J0218+4232 is indicated by a + sign and 3C66A by a × sign.

(1996) with the BL Lac 3C66A based on its positional coincidence. Verbunt et al. (1996) showed that indications in the timing analyses make also PSR J0218+4232 a potential counterpart. In this paper we have combined EGRET data from more VP’s, 15, 211, 325 and 427, and confirmed the source detection at a ∼ 6σ significance level for energies above 100 MeV. Timing analyses similar to those presented in Verbunt et al. (1996) have been performed using this enlarged dataset and again indications for pulsed emission were found at significance levels between 2.5−3σ for energies above 100 MeV adopting the extrapolated pulsar parameters presented in Navarro et al. (1995). The new 0.3-1 GeV lightcurve is shown in Fig. 1 (right). The modulation is marginally significant, 2.4σ in a $Z^2_4$-test. Based on this lightcurve we tentatively defined a “pulsed” interval as the combination of the phase ranges 0.08-0.24 and 0.42-0.52. We also produced images in broad EGRET energy intervals, 0.1-0.3, 0.3-1, 1-10 GeV and the integral band > 100 MeV selecting the events further on their pulse phase. The maps for energies above 100 MeV in the “Total” (no pulse phase selection), “Pulsed” and “Unpulsed” (complement of “pulsed”) phase windows are shown in Fig. 2 and the near“ON/OFF” effect indicates that the signal is largely confined to the “pulsed” interval suggesting an association with the pulsar. This “ON/OFF” effect is even more pronounced for the differential interval 0.3-1 GeV, but between 1-10 GeV this is absent and the most likely counterpart in this energy range is 3C66A (see Fig. 3 (right), confirmed by Hartman et al. 1998). Below 1 GeV PSR J0218+4232 appears to be the most likely candidate both on account of the spatial (see Fig. 3 left) and timing results.

4. DISCUSSION

We have clearly detected pulsed emission from PSR J0218+4232 at soft X-rays (0.1-2.4 keV). The sharp pulses point to a magnetospheric origin and the most likely
FIGURE 3 (left) Location confidence contours for the excess for energies above 100 MeV with the small 1-10 GeV contribution from 3C66A “subtracted”. PSR J0218+4232 (+) is the most likely candidate although some emission from 3C66A below 1 GeV can not be excluded. (right) The same, but now for the 1-10 GeV band. PSR J0218+4232 (+) is located outside the 3σ contour, while 3C66A (×) is consistent with the excess.

production site is near the light cylinder, where the magnetic field strength $B_{lc}$ is comparable to that of the Crab pulsar. The millisecond pulsars PSR B1821-24 and PSR B1937+21 (Kawai et al. these proceedings), both ranked in the top 5 in a $B_{lc}$-ordered scheme, show also sharp X-ray pulses and their spectra appear non-thermal suggesting also a magnetospheric origin near the light cylinder. If the indications for pulsed emission from PSR J0218+4232 at high energy $\gamma$-rays turn out to be genuine then this would be the first ms-pulsar detected above 100 MeV. According to Sturner & Dermer (1994) PSR J0218+4232 should be sufficiently luminous to be detected at HE $\gamma$-rays, if these are produced in an “outer gap” near the light cylinder. Moreover, in a simple spindown-flux ranked scheme, sofar very successful in selecting promising $\gamma$-ray pulsars, PSR J0218+4232 can be found in the top 40, just below the established $\gamma$-ray pulsar PSR B1055-52. A 3-week EGRET observation scheduled for October 1998 might establish the timing signature at HE $\gamma$-rays and approved observations with SAX and AXAF will disclose detailed properties of the pulsar and the extended/DC source.

REFERENCES
Dingus, B.L., Bertsch, D.L., Digel, S.W., et al., 1996, ApJ 467, 589
Hartman, R.C., et al., 1998, ApJS in press (3rd EGRET catalogue)
de Jager, O.C., Swanepeol, J.W.H., Raubenheimer, B.C., et al., A&A 170, 187
Kuiper, L., Hermes, W., Verbunt, F., et al., 1998, A&A 336, 545
Navarro, J., de Bruyn, A. G., Frail, D. A., et al., 1995, ApJ 455,L55
Stairs, I. H., 1998, Thesis Princeton University
Sturner, S., Dermer, C., 1994, A&A 281, 314
Thompson, D.J., Bertsch, D.L., Dingus, B.L., et al., 1995, ApJS 101, 259
Verbunt, F., Kuiper, L., Belloni, T., et al., 1996, A&A 311,L9