Observation of the millisecond pulsar PSR J0218+4232 by EGRET

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Abstract. We report on the likely detection of pulsed high-energy γ-rays from the binary millisecond pulsar PSR J0218+4232 in 100-1000 MeV data from CGRO EGRET. Imaging analysis demonstrates that the highly significant γ-ray source 2EG J0220+4228 ($\sim 10\sigma$) is for energies > 100 MeV positionally consistent with both PSR J0218+4232 and the BL Lac 3C66A . However, above 1 GeV 3C66A is the evident counterpart, whereas between 100 and 300 MeV PSR J0218+4232 is the most likely one. Timing analysis using one ephemeris valid for all EGRET observations yields in the 100-1000 MeV range a double-pulse profile at a $\sim 3.5\sigma$ significance level. The phase separation is similar to the component separation of ~ 0.47 observed at X-rays with ROSAT HRI (0.1-2.4 keV) and BSAX MECS (1.6-10 keV). A comparison in absolute phase of the γ-ray profile with the 610 MHz radio profile shows that the two γ-ray pulses coincide with two of the three emission features in the complex radio profile. The luminosity in high-energy γ-rays appears to amount ~10% of the total pulsar spin-down luminosity.

INTRODUCTION

PSR J0218+4232 is a 2.3 ms radio-pulsar in a two-day orbit around a low mass ($\sim 0.2\ M_{\odot}$) white dwarf companion [5]. A striking feature was that the radio profile appeared complex and very broad.

The pulsar was first detected on positional arguments as a soft X-ray source between 0.1-2.4 keV using ROSAT HRI data, with only indications for a pulsed signal [8]. This stimulated a long targeted observation with the ROSAT HRI instrument establishing also the pulsed nature in the soft X-ray window: a double peaked lightcurve with a main emission feature phase separated by ~ 0.47 from a second less prominent pulse [2].

CP510, *The Fifth Compton Symposium*, edited by M. L. McConnell and J. M. Ryan

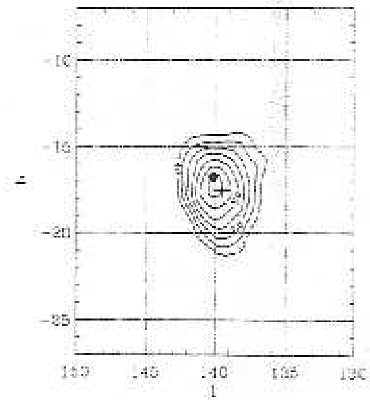

FIGURE 1. MLR image in galactic coordinates for energies in excess of 100 MeV of the sky region containing 2EG J0220+4228, combining data from 5 separate observations. A detection significance of $\geq 10\sigma$ is reached. The contours start at 4σ in steps of 1σ for 1 degree of freedom. PSR J0218+4232 is indicated by a star symbol and 3C66A by a bullet.

In a recent observation at harder X-rays (1.6-10 keV) with the BSAX MECS instruments the double peaked nature with phase separation ~ 0.47 of the X-ray profile was confirmed [4]. Spectral analysis showed that the pulsed emission has a very hard spectrum with a power-law photon-index of ~ -0.6, the hardest pulsar X-ray spectrum reported sofar.

At high-energy (100 MeV - 10 GeV) γ-rays the positional coincidence of the CGRO EGRET source 2EG J0220+4228 [7] with PSR J0218+4232 was noticed by Verbunt et al. [8]. These authors found also indications for pulsed emission at energies above 100 MeV. Since then, PSR J0218+4232 was again twice in the field-of-view of EGRET. In this work all available EGRET observations of PSR J0218+4232 between April 1991 and November 1998 with off-axis angles < 30 deg have been used to obtain maximum statistics. In addition, for the timing analysis we used one single very accurate ephemeris (rms error $85\mu s$) with a validity interval of about 5 years, allowing direct phase folding of all selected events.

IMAGING ANALYSIS

We have combined data from CGRO viewing periods 15, 211, 325, 427 and 728.7/9 and binned the measured γ-ray arrival directions in a galactic 0.5×0.5 grid after applying "standard" EGRET event selections. The measured distribution is compared with an expected model distribution, composed of galactic and extra-galactic diffuse model components and established high-energy γ-ray sources within

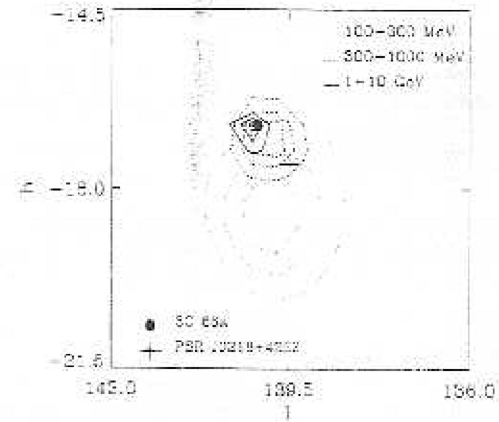

FIGURE 2. 1, 2 and 3σ location confidence contours of γ-ray source 2EG J0220+4228 in three different broad energy intervals. Between 100-300 MeV 3C66A is located outside the 3σ contour, whereas between 1-10 GeV this is the case for PSR J0218+4232

a 30° radius around PSR J0218+4232, by applying a Maximum Likelihood Ratio (MLR) test for the presence of a source at each grid position [3].

The MLR-map for energies > 100 MeV is shown in Figure 1 with superimposed the positions of 2 candidate counterparts, PSR J0218+4232 and 3C66A. The detection significance of the γ-ray source reaches a $\geq 10\sigma$ level. The number of counts (> 100 MeV) assigned to this excess is ~ 230. We also produced MLR-maps in the broad "standard" EGRET differential energy windows: 100-300 MeV, 300-1000 MeV and 1-10 GeV. The resulting location confidence contours of the γ-ray source are shown in Figure 2 for all 3 energy windows.

This figure shows that 3C66A is the evident counterpart for the 1-10 GeV window (consistent with the third EGRET catalogue result [1]), whereas PSR J0218+4232 is the most likely counterpart for the 100-300 MeV window. Between 300 and 1000 MeV both sources contribute to the excess.

TIMING ANALYSIS

For the timing analysis we have selected events in a circular aperture around the PSR J0218+4232 position with an energy dependent extraction radius. This radius has been determined a priori from a signal-to-noise optimization study taking into account the energy dependent point source distribution and the best fit total sky background model as derived in the imaging analysis.

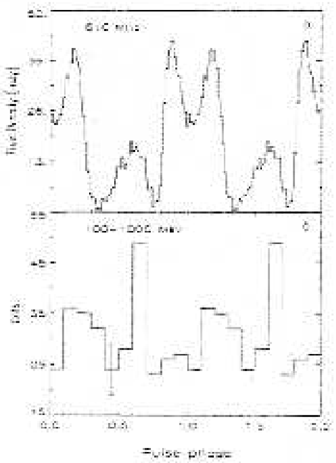

FIGURE 3. Comparison in absolute time of the radio 610 MHz profile (a [6]) and the 100-1000 MeV EGRET lightcurve (b) of PSR J0218+4232. The EGRET lightcurve deviates from a flat distribution at the $\sim 3.5\sigma$ significance level. A typical error is indicated in the lower panel. Notice the (near) alignment of the 2 high-energy pulses with 2 of the 3 radio-pulses.

We folded the barycentric arrival times of 100-1000 MeV events with the pulsar timing parameters from one single ephemeris taking into account the binary nature of the system. We obtained a 3.5σ signal in a Z_1^2-test and the lightcurve showed one prominent pulse between phases 0.6 and 0.7 following a broader less prominent pulse between phases 0.1 and 0.4 (see Figure 3b). Phase folding of events with energies above 1 GeV gives a statistically flat light curve. Moreover, a pulse phase resolved imaging analysis [3] shows that the 100-300 MeV spatial signal is concentrated in the phase intervals of the 2 pulses. This reinforces the conclusion drawn in the imaging analysis that 3C66A is the dominant counterpart of the high-energy EGRET source above 1 GeV, and PSR J0218+4232 below 300 MeV.

A comparison with the X-ray BSAX MECS [4] and ROSAT HRI [2] lightcurves shows that the phase separation of the pulses in the γ-ray lightcurve is similar to the separation of ~ 0.47 found at X-rays. The large uncertainties in the absolute timing of the X-ray profiles does sofar not allow conclusions on the absolute phases of the X-ray and γ-ray pulses.

However, we can compare in absolute phase the 100-1000 MeV lightcurve with the 610 MHz radio profile (Figure 3a) and find that the 2 γ-ray pulses coincide with 2 of the 3 radio-pulses within the absolute timing uncertainty of the radio Jodrell Bank observations and of CGRO (the latter $\leq 100\mu s$).

SUMMARY

This study shows that we obtained good circumstantial evidence for the first detection of high-energy γ-rays from a millisecond pulsar, PSR J0218+4232 :

- A double-peaked lightcurve in the 100-1000 MeV energy interval with a $\sim 3.5\sigma$ modulation significance.
- The phase separation between the 2 γ-ray pulses is similar to that at hard X-rays ($\sim$0.47); a comparison in absolute time with the 610 MHz radio-profile shows alignment of the γ-ray pulses with 2 of the 3 radio pulses.
- Between 100 and 300 MeV the EGRET source position is consistent with PSR J0218+4232 with the signal concentrated in the phase intervals of the 2 pulses. Above 1 GeV the BL Lac 3C66A is in the sky map the evident counterpart, and, consistently, no pulsed signal is found in the timing analysis for energies above 1 GeV.

Finally, we confirm the earlier indications [8], that the energy loss in γ-rays corresponds to $\sim$10% of the total pulsar spin-down luminosity.

The full analysis and implications of our findings will be presented in detail in a forthcoming paper [3].

REFERENCES

1. Hartman R.C., Bertsch D.L., Bloom S.D., et al., *ApJS* **123**, 79 (1999).
2. Kuiper L., Hermsen W., Verbunt F., et al., *A&A* **336**, 545 (1998).
3. Kuiper L., Hermsen W., Verbunt F., et al., *A&A*, in preparation (2000).
4. Mineo T., Cusumano G., Kuiper L., et al., *A&A*, submitted (2000).
5. Navarro J., de Bruyn A.G., Frail D.A., et al., *ApJ* **455**, L55 (1995).
6. Stairs I.H., Thorsett S.E., Camilo F., *ApJS* **123**, 627 (1999).
7. Thompson D.J., Bertsch D.L., Dingus B.L., et al., *ApJS* **101**, 259 (1995).
8. Verbunt F., Kuiper L., Belloni T., et al., *A&A* **311**, L9 (1996).