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Likely detection of pulsed high-energy γ-rays from millisecond pulsar PSR J0218+4232

L. Kuiper, W. Hermsen

SRON-Utrecht, Sorbonnelaan 2, 3584 CA, Utrecht, The Netherlands

F. Verbunt

Astronomical Institute Utrecht, 3508 TA, Utrecht, The Netherlands

A. Lyne, I. Stairs

University of Manchester, Jodrell Bank, Macclesfield SK11 9DL, UK

D.J. Thompson

Code 661, LHEA, NASA GSFC, Greenbelt, MD 20771, USA

G. Cusumano

IFCAI CNR, Via U.La Malfa 153, I-90146, Palermo, Italy

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. A comparison of the γ-ray profile with the 610 MHz radio profile in absolute phase shows that the two γ- ray pulses coincide with two of the three emission features in the complex radio profile.

1. Introduction

PSR J0218+4232 was discovered by Navarro et al. (1995) as a 2.3 ms radio-pulsar in a two day orbit around a low mass ($\sim 0.2\ M_{\odot}$) white dwarf companion. A striking feature was that the radio-profile appeared complex and very broad.

Targeted observations at soft X-rays (0.1-2.4 keV) with the ROSAT HRI instrument revealed also the pulsed nature in the soft X-ray window: a double

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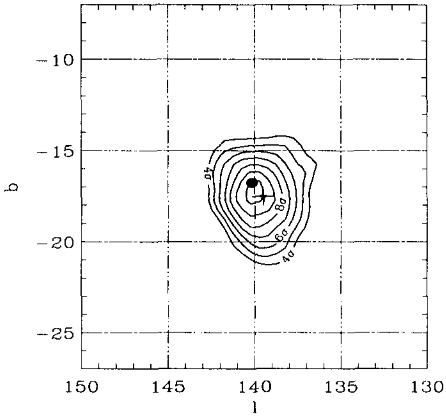

Figure 1. MLR image in galactic coordinates for energies in excess of 100 MeV of the sky region containing 2EG J0220+4228, combining data from 5 separate observations. A detection significance of $\gtrsim 10\sigma$ is reached. The contours start at 4σ in steps of 1σ for 1 degree of freedom. PSR J0218+4232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

peaked lightcurve with a main emission feature phase separated by ~ 0.47 from a second less prominent pulse (Kuiper et al. 1998).

In a recent observation at harder X-rays (1.6-10 keV) with the BSAX MECS instruments the double peaked nature of the X-ray profile was confirmed (Mineo et al. 2000; Nicastro, these proceedings). Spectral analysis showed that the pulsed emission has a very hard spectrum with a power-law photon-index of ~ -0.6.

At high-energy γ-rays the positional coincidence of 2EG J0220+4228 (Thompson et al. 1995) with PSR J0218+4232 was noticed by Verbunt et al. (1996). These authors found also indications for pulsed emission at energies above 100 MeV. In this work all available EGRET observations of PSR J0218+4232 between April 1991 and November 1998 with off-axis angles $< 30°$ have been used to obtain maximum statistics. In the timing analysis we used one single very accurate ephemeris (rms error $85\mu s$) having a validity interval of about 5 years.

2. 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 $0\overset{\circ}{.}5 \times 0\overset{\circ}{.}5$ 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 a $30\overset{\circ}{.}0$ radius around PSR J0218+4232 , by applying a Maximum Likelihood Ratio (MLR) test for the presence of a source at each grid position (for more details see Kuiper et al. 2000).

The MLR-map for energies > 100 MeV is shown in Fig. 1 with superimposed the positions of 2 candidate counterparts, PSR J0218+4232 and 3C66A. The detection significance of the γ-ray source reaches a $\gtrsim 10\sigma$ 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 Fig. 2 for all 3 energy windows.

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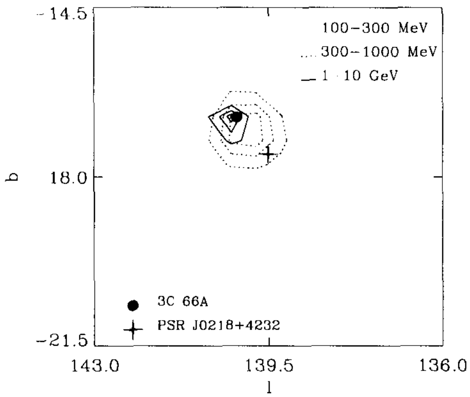

Figure 2. 1, 2 and 3σ location confidence contours of γ-ray source 2EG J0220+4228 in three different broad energy intervals. Between 100-300 MeV 3C66A is located outside the 3σ contour, whereas between 1-10 GeV this is the case for PSR J0218+4232 .

This figure shows that 3C66A is the evident counterpart for the 1-10 GeV window (consistent with the third EGRET catalogue result; Hartman et al. 1999), 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.

3. 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.

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_4^2-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 Fig. 3b). In addition, a pulse phase resolved imaging analysis (see Kuiper et al. 2000) shows that the 100-300 MeV spatial signal is concentrated in the 2 pulses.

A comparison with the X-ray BSAX MECS and ROSAT HRI 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.

Finally, we can compare the 100-1000 MeV lightcurve in absolute phase with the 610 MHz radio profile (Fig. 3a) and find that the 2 γ-pulses coincide with 2 of the 3 radio-pulses within the CGRO absolute timing uncertainty of $\lesssim 100\mu s$.

4. 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 :

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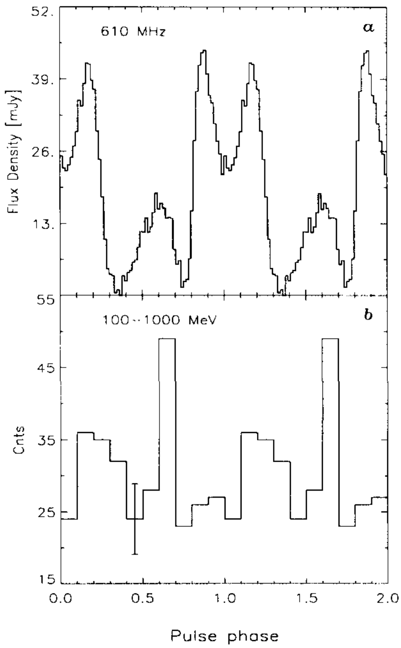

Figure 3. Comparison in absolute time of the radio 610 MHz profile (**a**; Stairs et al. 1999) and the 100-1000 MeV EGRET lightcurve (**b**) of PSR J0218+4232 . A typical error is indicated in the lower panel. Notice the (near) alignment of the 2 high-energy pulses with 2 of the 3 radio-pulses.

- A double-peaked lightcurve in the 100-1000 MeV energy interval with a $\sim 3.5\sigma$ modulation significance.
- The phase separation of the 2 γ-pulses is similar to that at hard X-rays; a comparison in absolute time with the 610 MHz radio-profile shows alignment of the γ 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 2 pulses.

The full analysis and implications of our findings will be presented in detail in Kuiper et al. 2000.

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