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A detailed analysis of PSR J2021+4026, the first variable gamma-ray pulsar

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Summary. — We present a novel *Fermi*-LAT analysis of PSR J2021+4026, the first variable γ-ray pulsar. With a maximum likelihood fit, we measure variations in the γ-ray flux and spectral parameters of the source on different timescales. We study the evolution of the rotational parameters and test a simple model that relates spin-down variations to jumps in the γ-ray flux. This preliminary work underlines the importance of the variability analysis to understand pulsar magnetospheres.

1. – Introduction

PSR J2021+4026 is a young, radio-quiet γ-ray pulsar ($P \sim 256\,\text{ms}$) lying within the shell of the Gamma Cygni (G 78.2+2.1) supernova remnant. The pulsar was first discovered with the *Fermi* Large-Area Telescope (LAT) [1] using blind periodicity searches [2] and associated with the EGRET source EG J2020+4017. A likely X-ray counterpart was inferred using *Chandra* data [3] and X-ray pulsations were later observed with XMM-*Newton* [4].

Among the more than 250 γ-ray pulsars observed by *Fermi*-LAT(1), PSR J2021+4026 was the first one showing a peculiar state-changing behavior at intervals of a few years. Although several pulsars show glitches, PSR J2021+4026 is unique because its γ-ray flux varies rapidly and simultaneously with its spin-down rate. The first state change (*jump*) was observed in October 2011 [5], when the flux ($F_\gamma \sim 7.9 \times 10^{-10}$ erg cm^{-2} s^{-1}) dropped by ~18% and the spin-down rate ($\dot{P} \sim 5.4 \times 10^{-14}$ s s^{-1}) increased by ~5.6% in a timescale <7 days. After a slow recovery, occurred over ~100 days around December

(1) `https://confluence.slac.stanford.edu/display/GLAMCOG/Public+List+of+LAT-Detected+Gamma-Ray+Pulsars`

2014 [6, 7], a similar jump occurred in February 2018 [8]. The referenced works also pointed out indications of variations in the γ-ray spectral energy distribution (SED).

In this work we performed an advanced maximum likelihood analysis of the most updated *Fermi*-LAT data. We used *Fermitools*([2]), a standard suite released by the *Fermi*-LAT Collaboration. Our purpose is to accurately measure variations in the γ-ray flux and SED across the jumps. We will put the results in the perspective of a change in the geometry of the pulsar magnetosphere.

2. – Methods

The time range of our data covers 12 years from August 5, 2008 to May 26, 2020. The dataset includes all LAT photons of P8R3_SOURCE_V2 event class. We selected events in a region with a radius of 10° around PSR J2021+4026, with zenith angles $z < 90°$ and in the energy range from 100 MeV to 300 GeV. We binned data with 35 logarithmically spaced energy bins (10 bins per decade) and squared angular pixels of size 0°.1. LAT photons are partitioned into four event types (PSF0, PSF1, PSF2, PSF3) based on the quality of the angular reconstruction. Each event type has a different LAT response, hence a likelihood analysis with summed PSF components requires four sets of binned data.

We further divided data in four distinct time intervals, labelled with capital Roman letters, in order to study the spectral variations between different states. These intervals are defined as follows. A: August 5, 2008 (MJD 54683) - October 16, 2011 (MJD 55850). B: October 16, 2011 (MJD 55850) - December 9, 2014 (57000). C: December 9, 2014 (MJD 57000) - February 2, 2018 (MJD 58150). D: February 2, 2018 (MJD 58150) - May 26, 2020 (MJD 58995).

The binned likelihood analysis requires a model of the sky. Our model was built starting from the 4FGL catalog [9] and includes all sources within 20° from PSR J2021+4026. We included templates for the Cygnus Loop and for the Galactic and isotropic diffuse emissions. The SED of PSR J2021+4026 was modeled as $\mathrm{d}N/\mathrm{d}E \propto E^{-\Gamma_1} \exp\left(-bE^{2/3}\right)$. We kept the normalization and the spectral parameters of PSR J2021+4026 free. We freed the normalization of other bright pulsars (PSR J2021+3651, PSR J2032+4027) and extended sources (SNR G 78.2+2.1, Cygnus Cocoon). We also freed the normalization of variable sources within 7°. Finally, we freed the Galactic diffuse emission and fixed the isotropic diffuse emission. We ended up with 23 free parameters.

In order to enhance the accuracy at energies below 1 GeV, the binned likelihood fit was run applying corrections due to the energy dispersion. We also included likelihood weights, which take account of systematic errors on the diffuse background and are calculated for each event type.

3. – Results and discussion

From the results of the fit to the time intervals A, B, C, and D, we observe a relative flux variation $\Delta F_\gamma / F_\gamma = -15.3 \pm 1.4\%$ at the 2011 jump, $\Delta F_\gamma / F_\gamma = -16.3 \pm 1.4\%$ at the 2018 jump. Changes in the SED (fig. 1) appear to be due to variations in the exponential factor, b, while the power-law index, Γ_1, does not change significantly. Deviations with respect to a constant model (*global*) have significance $>3\sigma$ in A, B and D, while significance is lower (2σ) in C. However, the pre-jump and post-jump SEDs are significantly different (3σ) at both jumps.

([2]) `https://fermi.gsfc.nasa.gov/ssc/data/analysis/documentation/`

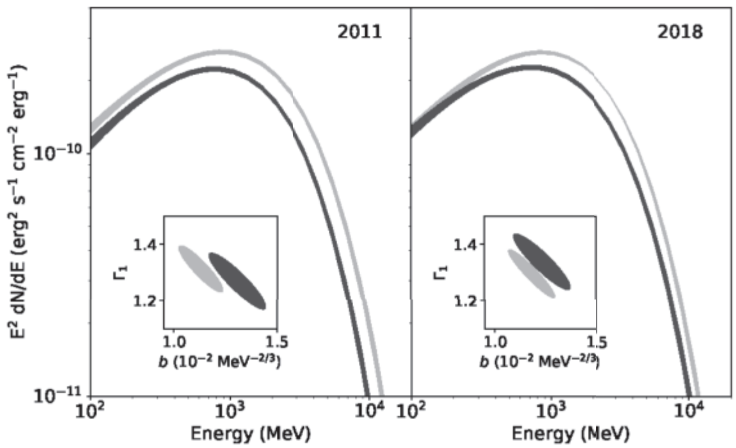

Fig. 1. – Fitted SEDs for the pre-jump (light bands) and post-jump (dark bands) states at the 2011 and 2018 jumps. The bands represent the 3σ credibility intervals from a multivariate Gaussian distribution. The inset panels show the 3σ credibility ellipses around the optimal values of the power-law index, Γ_1, and exponential factor, b.

In order to study short-timescale variations, we also analyzed 30-day and 7-day time intervals. Due to the reduced exposure, we were only able to fit the gamma-ray flux of PSR J2021+4026, fixing the spectral parameters in each state to the values from the global interval. We also performed an H-test [10] and estimated the optimal values of frequency, ν, and spin-down rate, $\dot{\nu}$, on time intervals of 60 days. This way we could relate flux jumps to the corresponding changes in the spin-down evolution (fig. 2). From the mean values and the standard deviations in intervals A, B, C and D we obtained estimates of the relative variations at the jumps: $\Delta F_\gamma/F_\gamma = -16 \pm 6\%$, $\Delta\dot{\nu}/\dot{\nu} = 5 \pm 3\%$ in 2011, $\Delta F_\gamma/F_\gamma = -13 \pm 5\%$, $\Delta\dot{\nu}/\dot{\nu} = 5 \pm 2\%$ in 2018.

It was suggested [6] that a shift in the magnetic inclination angle, α, as a consequence of a glitch could produce changes in spin-down rate and luminosity. A numerical solution of the equations for magnetohydrodynamics in a force-free magnetosphere [11] gives a formula for the γ-ray spin-down luminosity: $L_{\rm sd} \propto \nu^4\ (1+\sin^2\alpha)$. By setting $L_{\rm sd} = \dot{E}_{\rm rot}$ we get $\Delta\dot{\nu}/\dot{\nu} = \sin 2\alpha\ \Delta\alpha\ (1+\sin^2\alpha)^{-1}$. Assuming a pre-jump inclination angle $\alpha = 63°$, obtained from a model of the magnetosphere [6], and the spin-down variation we measured, $\Delta\dot{\nu}/\dot{\nu} = 5 \pm 2\%$, we get $\Delta\alpha = 6 \pm 2°$ and $\Delta L_{\rm sd}/L_{\rm sd} = 5.0 \pm 1.7\%$. The latter value is not consistent with the measured relative flux variations, indicating that this simple model is not sufficient to describe the behavior of the pulsar. More sophisticated models [12] produce detailed magnetospheric structures, though only in the stationary case. However, we could search hints about the dynamics of the variations by fitting these models to the observed γ-ray emission in the different states.

The importance of PSR J2021+4026 is due to the uniqueness of its time evolution. For this reason we are monitoring and analyzing its γ-ray flux continuously: this fine investigation will lead us to a deeper knowledge of the physics of pulsar magnetospheres.

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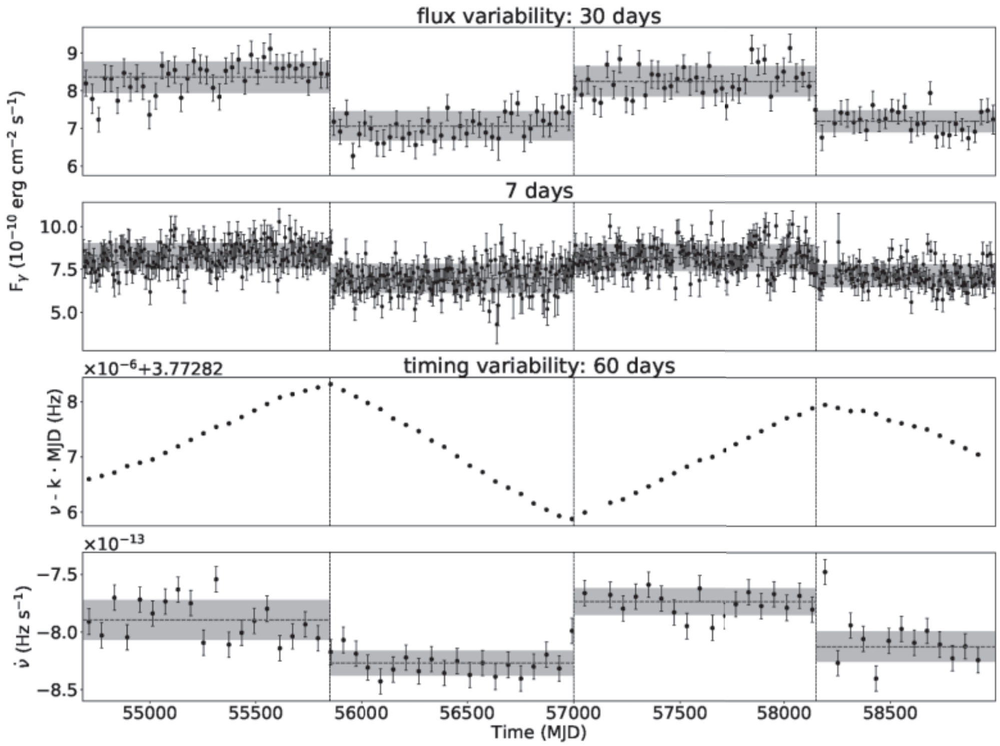

Fig. 2. – Energy flux and timing parameters of PSR J2021+4026 in the time range from August 5, 2008 to May 26, 2020. Rather than the frequency, $\nu - k \cdot \mathrm{MJD}$ is reported, where $k = 6.844 \times 10^{-8}$ Hz day^{-1} is a global spin-down rate obtained from a χ^2 fit. Horizontal dashed lines and shaded bands represent the mean values and the 1σ confidence bands in the time intervals A, B, C and D. Vertical dashed lines indicate the boundaries of the time intervals.

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