PROCEEDINGS OF SCIENCE

A new mode change in the variable gamma-ray pulsar PSR J2021+4026

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The radio-quiet gamma-ray pulsar PSR J2021+4026 in the Gamma Cygni supernova remnant, is one of the brightest *Fermi*-LAT pulsars. It first drew attentions in October 2011, when it underwent an abrupt drop in its gamma-ray flux, with a simultaneous increase in its spin-down rate. This mode change was followed by a smooth recovery phase around December 2014, then by a similar mode change in February 2018. Being the only variable isolated gamma-ray pulsar observed so far, PSR J2021+4026 has been studied during the whole duration of the *Fermi*-LAT mission and is currently being monitored. We report an updated LAT analysis focusing on the most recent variability event, which occurred in June 2020. In order to characterize the variability of the pulsar, we studied the variations in spectrum, timing and pulse profile in details. We discuss the results using the most recent pulsar models and linking the observed variations to changes in the configuration of the magnetosphere. Monitoring activities on this unique pulsar will help us understand the poorly known mechanisms of variability in gamma-ray emitting neutron stars.

**** 27th European Cosmic Ray Symposium - ECRS ****
**** 25-29 July 2022 ****
**** Nijmegen, the Netherlands ****

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1. Introduction

After 14 years since the launch the *Fermi* mission, the Large Area Telescope (LAT) [1] keeps enhancing our understanding of pulsar physics, having detected more than 270 gamma-ray pulsars[1]. The radio-quiet PSR J2021+4026, or Gamma Cygni pulsar, is a noteworthy *Fermi*-LAT pulsar. It can be found within the radio shell of the Gamma Cygni supernova remnant (G 78.2+2.1), to which it owes its name. A blind search for periodicity [2] first detected pulsations with a period of ~265 ms and associated the pulsar to the EGRET source EG J2020+4017. Later, an X-ray counterpart was discovered with *Chandra* [3], and X-ray pulsations were observed with XMM-*Newton* [4].

PSR J2021+4026 started to draw interest in October 2011, when it underwent a sudden drop in its gamma-ray flux ($F_\gamma \sim 7.9\times10^{-10}$ erg cm^{-2} s^{-1}) by 18% [5]. The variation in the flux was concurrent with an increase in its spin-down rate ($|\dot{f}| \sim 7.9\times10^{-13}$ Hz s^{-1}) by 6%, although no sudden change in the spin frequency was observed. The event occurred over a time scale < 7 days and the pulsar persisted in this state for more then 3 years. A recovery phase, occurred over ~100 days around December 2014, brought the flux and spin-down rate back to the original state [6] [7]. A new mode change, similar to the 2011 event, was observed in February 2018 [8]. The results of previous analyses hinted small variation in the gamma-ray spectrum and pulse profile.

The quasi-periodic switching behavior of PSR J2021+4026 is still unique among *Fermi*-LAT pulsars, and the process producing the mode changes is still being investigated. Previous works managed to point out that the gamma-ray flux variability must be related to changes in the structure of the magnetosphere near the polar caps. This kind of disturbance could in turn be the result of crackings and mass displacements on the crust of the neutron star. Moreover, the observed change in the spin-down rate has been argued with different interpretations, such as the precession of a biaxial star or twisted magnetic field lines. In all cases, the predicted time scales for the mode changes cannot reproduce the observations. Therefore, the nature of PSR J2021+4026 remains unclear.

We report on an updated LAT monitoring activity of PSR J2021+4026 that allowed the detection of a new mode change occurred around June 2020. This work also brings improvement to the spectral analysis compared to our previous report [9]. The manuscript is outlined as follows. In Section 2 we describe our updated *Fermi*-LAT variability analysis and report the results. In Section 3 we discuss the observations, and we make predictions on key parameters for magnetospheric models based on heuristic arguments. Conclusions will follow.

2. Data analysis and results

2.1 Data reduction

The data reduction procedure was performed using the standard *Fermi*-LAT analysis suite, *Fermitools*[2]. The data set used for this analysis includes all LAT photons of P8R3_SOURCE_V2 event class spanning more than 13 years from August 5, 2008 to October 6, 2021. We applied the standard selection cuts for *Fermi*-LAT pulsars: photons were selected within 10° of PSR J2021+4026 with zenith angles $z < 90°$ and in the energy range from 100 MeV to 300 GeV. We

[1] https://confluence.slac.stanford.edu/display/GLAMCOG/Public+List+of+LAT-Detected+Gamma-Ray+Pulsars
[2] https://fermi.gsfc.nasa.gov/ssc/data/analysis/documentation/

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 PSF event types based on the quality of the reconstructed direction. Since each partition corresponds to a different LAT response, we prepared four distinct sets of binned data.

2.2 Model

We built a model of the gamma-ray sky including sources from the latest *Fermi*-LAT catalog (4FGL-DR3) [10] selected within 20° of PSR J2021+4026Ẇe also included templates for the Galactic and isotropic diffuse emissions. We modeled the gamma-ray spectrum of PSR J2021+4026 as

$$\frac{dN}{dE} \propto \begin{cases} \left(\frac{E}{E_0}\right)^{\gamma_0 - \frac{d}{2}\ln\frac{E}{E_0} - \frac{db}{6}\ln^2\frac{E}{E_0} - \frac{db^2}{24}\ln^3\frac{E}{E_0}} & \text{if } \left|b\ln\frac{E}{E_0}\right| < e^{-2} \\ \left(\frac{E}{E_0}\right)^{\gamma_0 + \frac{d}{b}} \exp\left[\frac{d}{b^2}\left(1 - \left(\frac{E}{E_0}\right)^b\right)\right] & \text{otherwise} \end{cases} \tag{1}$$

with E_0 = 2 GeV. This function was introduced in 4FGL-DR3 to reduce the correlation between spectral parameters, allowing to fit the exponential term of the model with no fixed parameters. Therefore, in our analysis all parameters except E_0 were initially set free. We also freed the normalization of other two bright pulsars, PSR J2021+3651 and PSR J2032+4027, and of the extended sources associated to SNR G 78.2+2.1. Although no other pulsar in the field shows variability, there are extragalactic sources with reported flaring behavior. In order to reduce the external contribution to flux changes, we freed the normalization of all variable point sources within 7°. Finally, we freed the Galactic diffuse emission and fixed the isotropic diffuse emission. The total number of free parameters is 23.

2.3 Flux and timing monitoring

Our study is based on a binned maximum likelihood analysis with summed PSF components. The accuracy at energies below 1 GeV was improved by adding 2 extra energy bins in order to take account of the energy dispersion. Moreover, our pipeline included the computation of likelihood weights for each event type to reduce systematic errors on the diffuse background. As a preliminary step, we ran the analysis on the full dataset. This produced a global model of the region, valid over the whole 13 years of data, which was used as input to the following analysis.

Flux monitoring was performed by dividing the data set in intervals of 30 days. The binned analysis was run on each interval, but due to the reduced exposure only the gamma-ray flux of the sources was kept free, while spectral parameters were fixed to the values of the global model. The obtained time series revealed an increase in F_γ some time around mid 2020, which we identified as the recovery from the 2018 flux drop. In order to better locate the event in time, we parameterized the time series as follows:

$$F_\gamma(t) = \begin{cases} F_0 & \text{if } t < t_0 \\ F_0 + \frac{F_1 - F_0}{t_1 - t_0}(t - t_0) & \text{if } t_0 \le t < t_1 \\ F_1 & \text{if } t \ge t_1 \end{cases} \tag{2}$$

We reduced the time window to the last 3 years and 8 months of the time series, i.e. after the 2018, and fitted the function to the points (Figure 1). The results show that the event is centered

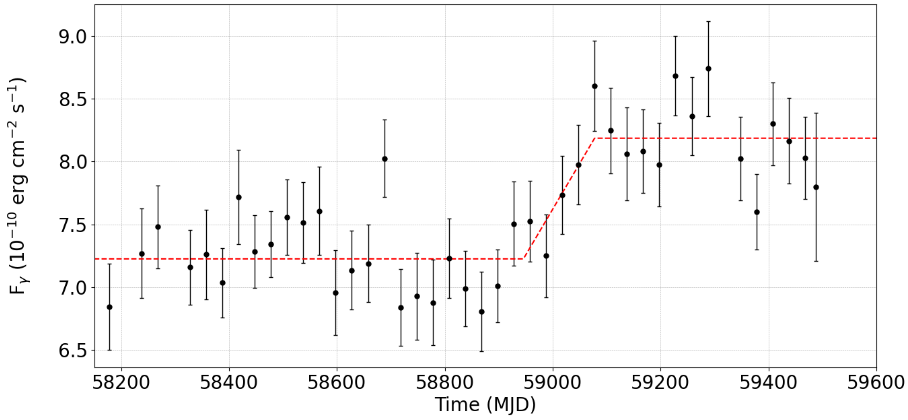

Figure 1: Energy flux of PSR J2021+4026 between February 2018 and October 2021. Error bars were obtained with binned likelihood fits to 30-day intervals. The red dashed line indicate the best fit function.

around June 10, 2020, and that the flux rises by ~12% over ~100 days. Although these numbers are consistent with the 2014 recovery, we were expecting the new event around April 2021. In fact, the previous observations suggested an interval of about 3 years and 2 months between subsequent mode changes. Therefore, we can conclude that the cadence of the events is not regular.

For the timing monitoring we selected photons within 1° of the pulsar and divided the full data set in 60-day intervals. We performed an H-test [11] on each interval and produced time series for f and $\dot{f}$. Unlike the other events, all consistent with a relative change in $\dot{f}$ of ~5%, the 2020 mode change is less evident and appears to be delayed by a few months with respect to the flux change. Figure 2 provides an overall view on all the mode changes observed so far.

2.4 Spectral variability

For the spectral variability analysis we defined a set of longer intervals according to the estimated dates of the mode changes, 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) - June 10, 2020 (MJD 59010). E: June 10, 2020 (MJD 59010) - October 6, 2021 (MJD 59493). Dates were taken from the literature for all events except the latest.

We ran the binned likelihood analysis on each interval separately, keeping all the spectral parameters free to vary. This was not possible our previous report due to a different choice of the spectral model [9]. Therefore, it represents an improvement in our capability of characterizing spectral variations. The results of our analysis (Figure 3) show indications of changes in the power-law index, γ_0. In particular, the spectrum appears softer when the pulsar is is the low-flux state, with $\Delta\gamma_0/\gamma_0 \sim 5\%$. Anyway, the significance of the variation is $\sim 3\sigma$ only at the 2011 mode change, while it's lower for the other events. No change can be observed in the parameters d and b.

2.5 Pulse profile variability

The pulsations of PSR J2021+4026 show two main peaks, with a peak separation ~ 0.5 in phase and a significant inter-peak emission. The off-pulse constant emission is bright and comparable to

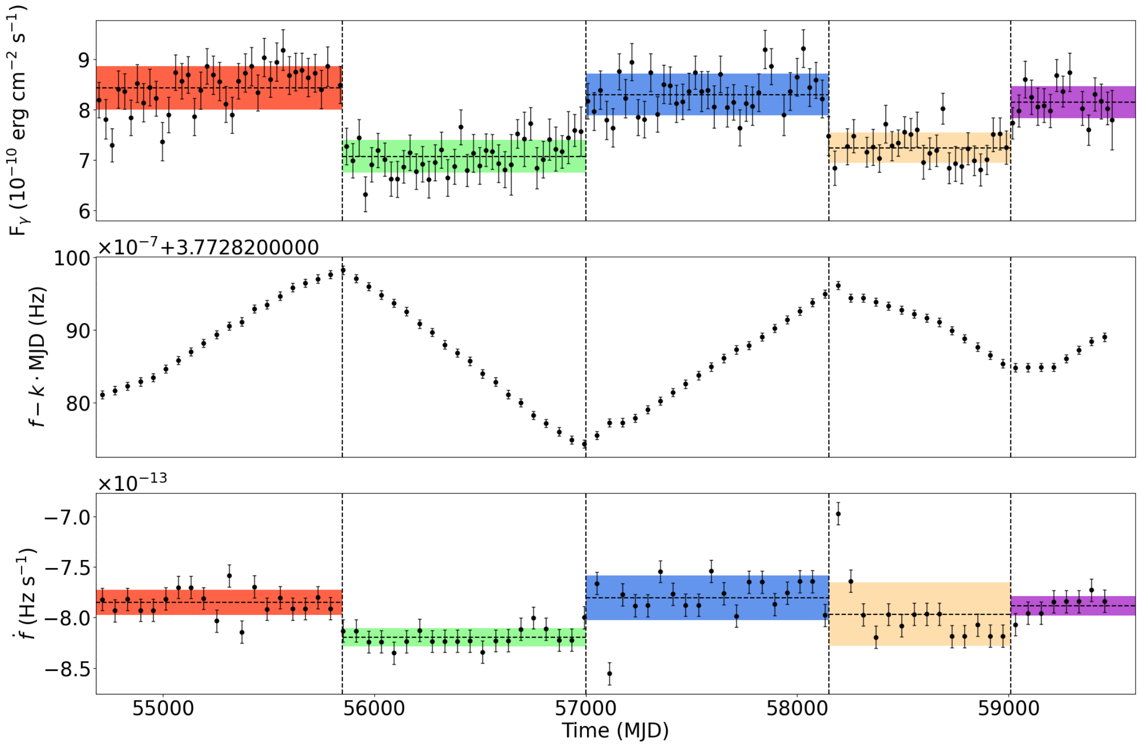

Figure 2: Energy flux and optimal timing parameters of PSR J2021+4026 in the time range from August 5, 2008 to October 6, 2021. Rather than the frequency, $f - k{\cdot}\mathrm{MJD}$ is reported, with $k = 6.847{\times}10^{-8}$ Hz day^{-1}, where k is an average spin-down rate obtained from a χ^2 fit. Horizontal dashed lines and colored bands represent the mean values and the 1σ confidence bands in the time intervals A (red), B (green), C (blue), D (orange) and E (purple) defined in Section 2.4. Vertical dashed lines indicate the boundaries of the time intervals.

the pulsed component. Consequently, we defined a model for the profile including two Gaussian peaks, a Gaussian bridge emission and a constant component. We performed an unbinned maximum likelihood fit to the pulse profile of PSR J2021+4026 with the purpose of studying variations across the mode changes. We analyzed the four time intervals defined in Section 2.4 separately. We included photon probabilities computed using a spatial model of the LAT source: this allowed us to estimate the background emission and to achieve a more accurate estimate of the parameters.

Our preliminary results highlight significant variations in the ratio between the pulsed component and the off-pulse constant emission. In particular, the unpulsed fraction is always more prominent when the gamma-ray flux is high, and it can be up to 4 times higher with respect to the low flux state. The positions of the peaks and their relative amplitudes do not appear to change. On the other hand, there are hints of changes in the width of the highest peak, although this is still only a weak indication.

3. Discussion

State switching is not an unknown phenomenon in pulsars astrophysics, and in fact it has been observed in radio pulsars. In particular, a small family of young radio pulsars has been

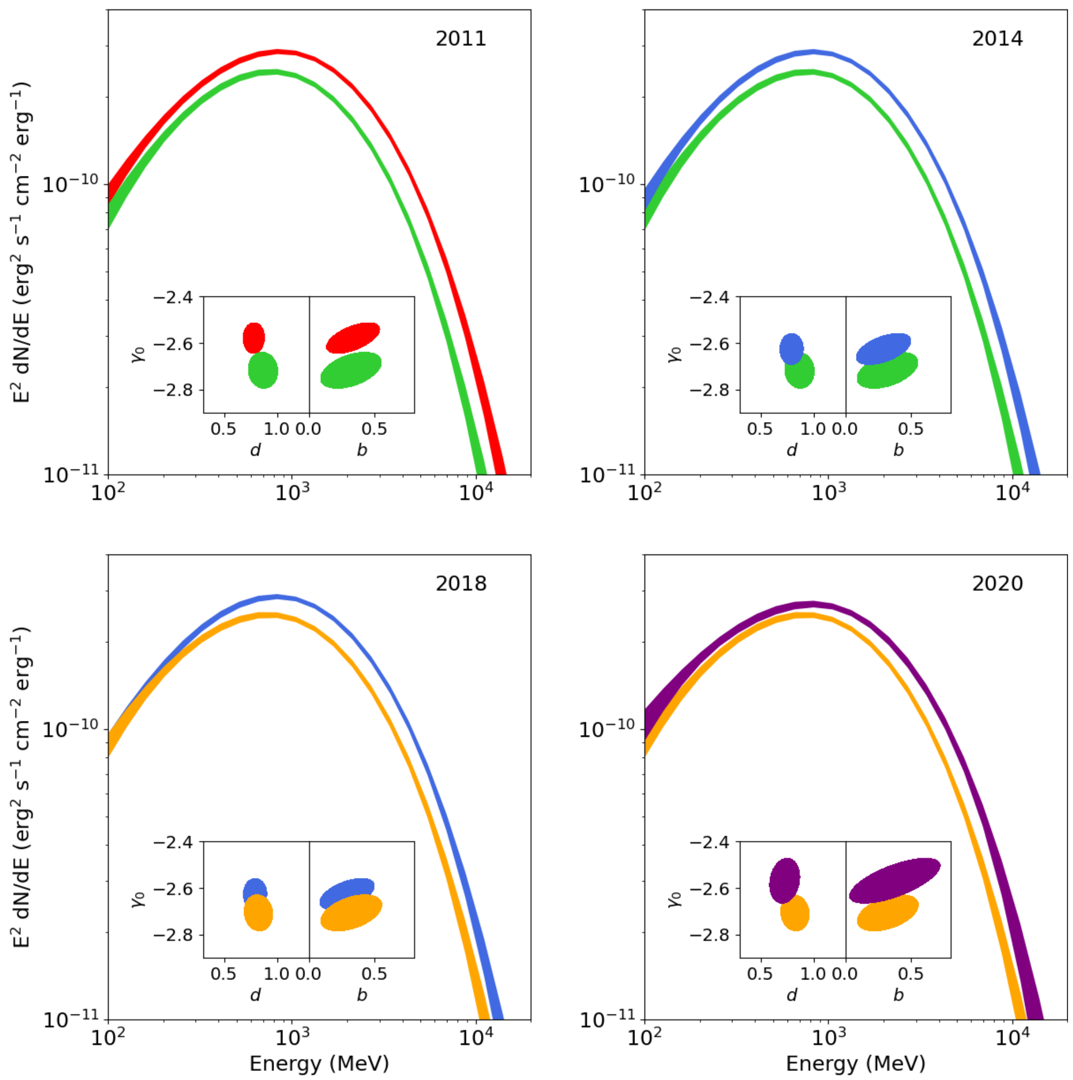

Figure 3: Fitted spectra of PSR J2021+4026 in intervals A (red), B (green), C (blue), D (orange) and E (purple) at the four mode changes. The bands represent the 3σ credibility intervals from a multivariate Gaussian distribution. The inset panels show the 3σ credibility ellipses around the optimal values of the spectral parameters.

seen switching between discrete spin-down states [12]. In these individuals the spin-down rate is correlated to changes in the radio profile, sometimes leading to extreme nulling events. Two of these pulsars, PSR J2043+2740 and PSR J0922+0638, have also been detected by *Fermi*-LAT, but no hints of gamma-ray variability have yet been observed. If there are any changes in the LAT light curve, we may be unable to detect them due to the low gamma-ray flux. On the other hand, PSR J2021+4026 has evident mode changes in the gamma rays but no radio counterpart. Therefore, there are currently no observational results linking radio intermittence with gamma-ray mode changes. It is thus clear how observing concurrent variability in multiple wavelegths would represent a key achievement in studying the state-switching phenomenon in young pulsars.

Fermi-LAT has observed variability in other classes of pulsars. For example, the binary millisecond pulsar PSR J1023+0038 has shown an evident mode-changing behavior [13]. In particular, in 2013 an increase in its gamma-ray flux was observed concurrently with a radio disappearance. This event was interpreted as a transition between a rotation-powered state and an accretion-powered state due to the presence of a binary companion. Anyway, this model does not apply to PSR J2021+4026, which is young and isolated. Therefore, the origin of its mode changes must lie elsewhere.

Purely heuristic considerations may help us outline a theoretical interpretation for PSR J2021+4026. For instance, the correlation of the flux drop with an increase in the spin-down rate suggests that the gamma-ray variability must be linked to changes in the whole magnetospheric structure. Movements of masses at the neutron start surface, i.e. starquakes, could rearrange the geometry of the magnetic field lines, allowing us to see a different emission region with lower gamma-ray efficiency. The varying spectral hardness, and in particular the peak of the spectrum shifting towards lower energies, can be interpreted assuming a resistive magnetosphere. In fact, we can link the ∼5% relative change in $\dot{f}$ to an 8% increase in the conductivity [14]. This in turn implies an 8% increase in the pair multiplicity and a comparable decrease in the electric field, which ultimately produces a decrease in the gamma-ray flux [15]. Unfortunately, it's not easy to get more quantitative results, and we can only expect that numerical simulations would reproduce the observed 12% drop in the gamma-ray flux.

4. Conclusions

We have reported on an updated monitoring activity of the variable gamma-ray pulsar PSR J2021+4026 with *Fermi*-LAT. We observed a new mode change located around June 2020, and we identified it as the recovery after the 2018 flux drop. A detailed analysis of the spectral variability showed indications of a spectral softening at the mode changes. A best fit to the pulse profile revealed evident changes in the off-peak fraction of the emission. We stress how the continuous monitoring of PSR J2021+4026 and further study of its emission properties are powerful tools to probe the nature of this unique source, and to investigate the phenomenon of variability in gamma-ray pulsars.

Acknowledgments

The *Fermi*-LAT Collaboration acknowledges support for LAT development, operation and data analysis from NASA and DOE (United States), CEA/Irfu and IN2P3/CNRS (France), ASI and INFN (Italy), MEXT, KEK, and JAXA (Japan), and the K.A. Wallenberg Foundation, the Swedish Research Council and the National Space Board (Sweden). Science analysis support in the operations phase from INAF (Italy) and CNES (France) is also gratefully acknowledged. This work performed in part under DOE Contract DE-AC02-76SF00515.

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