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The gamma-ray pulsar in the Gamma Cygni supernova remnant

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Summary. — We report updated results on PSR J2021+4026, based on the latest data collected by the *Fermi* Large Area Telescope. This pulsar was discovered using blind search techniques in the error box of the EGRET source 3EG J2020+4017 in the Gamma Cygni supernova remnant (SNR G78.2+2.1). This source is located in a quite complex region, mainly because of the highly structured diffuse Galactic background. Since its discovery in gamma rays no other pulsed counterparts for PSR J2021+4026 have been found at other wavelengths (*e.g.*, radio), and this could put important constraints on its emission characteristics. We present recent results of the analysis of the gamma-ray emission from this pulsar, including spatial analysis, as well as of the temporal and spectral analysis of this source.

PACS 95.85.Pw – γ-ray.
PACS 97.60.Gb – Pulsars.

1. – Introduction

PSR J2021+4026 [1] is one of the first gamma-ray pulsars discovered by *Fermi* LAT [2] using blind search techniques [3]. This pulsar was found in the error box of the EGRET source 3EG J2020+4017 and its association with the supernova remnant SNR G78.2+2.1 [4] was proposed, implying a pulsar distance estimate of 1.5 ± 0.4 kpc. The spin period of 265 ms and the period derivative of $5.5 \times 10^{-14}\,\mathrm{s\,s^{-1}}$ characterize it as a young ($\tau_c = 77$ ky) and energetic ($10^{35}\,\mathrm{erg\,s^{-1}}$) pulsar. PSR J2021+4026 is located close to the recently detected VERITAS source VER J2019+407 [5] and to a 4.2σ MILAGRO excess J2021.5+4026 [6], both probably related to the VHE emission of the supernova remnant. Deep searches with *Chandra* and *XMM-Newton* have been conducted to identify a firm X-ray counterpart: so far the most plausible is the X-ray source labeled as S21 in [7], or 2XMMJ202131.0+402645 [8] found later in archival searches in the 2XMM catalog. No X-ray pulsations have been found so far, mainly because of the faintness of the source. Moreover, searches in radio and optical did not return any plausible point

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source counterpart [8]. Recently, the AGILE team report of variability in the source 1AGL J2022+4032, coincident with the interior of the radio shell of the SNR [9]. We report here the most recent analysis of the gamma-ray emission of PSR J2021+4026 based on the *Fermi* LAT data.

2. – Gamma-ray observations

The Large Area Telescope (LAT) aboard *Fermi* is an electron-positron pair conversion telescope sensitive to gamma rays of energies from 20 MeV to 300 GeV. The LAT is made of a high-resolution silicon microstrip tracker, a CsI hodoscopic electromagnetic calorimeter and an Anticoincidence Detector for charged-particles background identification. The full description of the instrument and its performance can be found in [2]. For the timing analysis we used LAT data covering the period from 2008 August 4 to 2010 May 27, while for spectral analysis we included gamma rays up to 2010 August 8. We adopted the Instrument Response Functions (IRFs) P6_V3 and selected photons in the diffuse event class (lowest background contamination) and we excluded observations when the pulsar is viewed at zenith angles $> 105°$, where Earth's albedo gamma rays increase the background contamination. Time intervals where the Region Of Interest (ROI) intersects the Earth's albedo were also excluded.

3. – Results

Fermi LAT provides densely-sampled, high-precision timing observations, that can be used for producing timing solutions based solely on gamma rays, as described in [10, 11]. We then used LAT data to produce Time of Arrivals (TOAs) for PSR J2021+4026 and then adopted TEMPO2 [12] to build a timing solution. Starting from geocentered photons, as described in [11], we produced a timing solution with a rms timing noise of 2500 μs and the best timing position at RA(J2000) = $20\,\mathrm{h}\ 21\,\mathrm{m}\ 29.85\,\mathrm{s} \pm 0.02_{stat}\,\mathrm{s}$, Dec (J2000) = $+40°\ 26'\ 46.2'' \pm 0.4_{stat}''$, which is about $9''$ from S21. This position does not rule out S21 as potential counterpart, in particular if consider the relatively large (though unknown for now) systematic uncertainty. A lower bound on the systematic uncertainty on the timing position was estimated by [11] to be $2.5''$, and more data will help to better reduce the timing noise and constrain the timing position. Adopting this timing solution we build the full-band light curve based on photons above 300 MeV and within $0.9°$ from the pulsar timing position (fig. 1). In order to estimate the diffuse background contribution we used the *Fermi* Science Tool *gtsrcprob*(1) to assign to each photon a probability of coming from the source. The contribution of the non-pulsar photons can be calculated from the sum of the probabilities associated to the diffuse background and to the nearby sources. The light curve shows two clear peaks P1 and P2 separated by ~ 0.48 in phase, with a hint of a third peak around 0.76 in phase. The pulse profile of PSR J2021+4026 shows a clear dependence on the energy, with the ratio P1/P2 between the peak heights that decreases with energy, as observed in other gamma-ray pulsars [10], and a high DC component, as observed for other pulsars like Geminga [10]. We performed a phase-averaged spectral analysis using the maximum-likelihood estimator *gtlike* included in the standard *Fermi* Science Tools. The fit was performed over energies from 0.1 to 100 GeV and considering a ROI of $10°$ around the pulsar. We modeled the diffuse

(1) `http://fermi.gsfc.nasa.gov/ssc/data/analysis/scitools/overview.html`

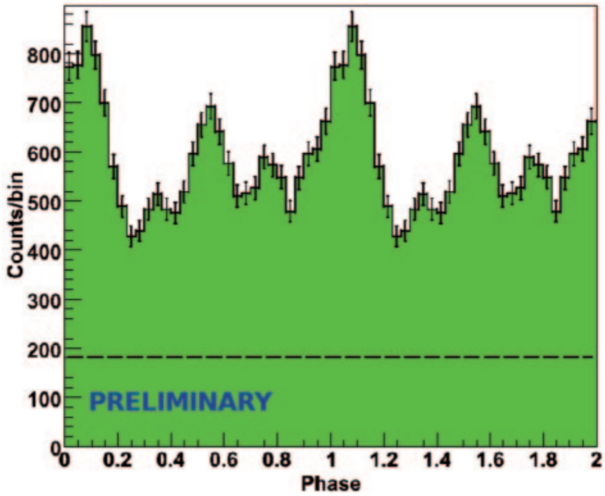

Fig. 1. – Light curve of PSR J2021+4026 above 300 MeV. The dashed line represents the contribution of the diffuse emission and of the nearby sources, evaluated using the Fermi Science Tool *gtsrcprob* (see text for details).

background, including Galactic interstellar emission, extragalactic gamma-ray emission and residual cosmic-ray background, using the models(2) gll_iem_v02 for the Galactic part and isotropic_iem_v02 for the isotropic one. In the fit we kept free all the sources within 5° of the pulsar, while for sources between 5° and 9° we kept free only the normalization of the flux. All the sources have been modeled using the *Fermi* 1FGL catalog [13], while all pulsars have been described by a power law with exponential cutoff according to the data reported in the *Fermi* LAT pulsar catalogue [14]. We fit the spectrum of PSR J2021+4026 with a power law with exponential cutoff, obtaining a spectral index $\Gamma = (1.817 \pm 0.016)$ and a cutoff energy $E_0 = (2.67 \pm 0.06)$ GeV, resulting in a photon flux of $(1.69 \pm 0.06) \times 10^{-6}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ (see fig. 2).

4. – Discussion

Fermi detection of PSR J2021+4026 provided for the first time a pulsar identification of the bright EGRET source located at the Gamma Cygni supernova remnant. However there are still some open questions regarding this source. First of all, the only plausible X-ray counterpart is several arcseconds from the best position obtained by gamma-ray timing. More data and a better characterization of the systematic uncertainties will help to assess the plausibility of the X-ray counterpart. Another open question concerns the third peak in the light curve: more data and a better timing solution will help to confirm it. A third peak can be explained by the Two Pole Caustic (TPC) model [15], a scenario that can also provide a natural explanation for the high DC component of the pulse profile. Finally, another unsolved question regarding this pulsar is its distance and the relation with the supernova remnant. A distance of 1.5 kpc implies a surprisingly large

(2) `http://fermi.gsfc.nasa.gov/ssc/data/access/lat/BackgroundModels.html`

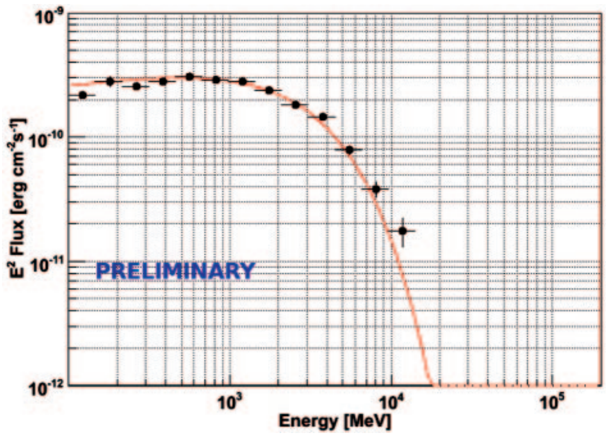

Fig. 2. – Phase-averaged spectrum of PSR J2021+4026 (see text for details).

gamma-ray efficiency, and the age of 6.6 ky, which is smaller by an order of magnitude than the characteristic age of the pulsar derived by timing. A foreground object could lead to a more realistic gamma-ray efficiency, thus finding a plausible counterpart at other wavelengths will provide a very powerful tool to also solve this key question.

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