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First pulsar observations with the MAGIC telescope

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A few regions of the sky containing pulsars have been observed by the MAGIC Telescope [2] during its commissioning phase, namely PSR B1957+20, and PSR J0218+4232. In this work we report on the analysis of these data, looking for γ-ray emissions both in continuous and pulsed mode. Constrains to different theoretical models about γ-ray emission from pulsars and plerions will be discussed.

1. Introduction

During the first year of operation of the MAGIC telescope quite some time has been devoted to the Crab pulsar and a dedicated contribution is presented in this conference [16]. Beside Crab, for the current study, a small subset of pulsar systems was observed and analyzed as part of an ongoing program to search for galactic sources of GeV emission. These sources were chosen based on their similarity to some other detected sources and on the prediction of emission given the various models of γ-ray production in pulsars. A deeper analysis have been done with two of these sources, PSR B1957+20 and PSR J0218+4232.

No evidence has been found of pulsed or unpulsed emission from the pulsars at high energies. These non-detections place limits on photon densities, magnetic field strengths, and emission regions in plerionic systems, since both pulsars are in binary systems. Both, PSR B1957+20 and PSR J0218+4232 are millisecond pulsars in energetic binary systems, detected in X-rays. The X-ray emission may be due to the interaction of the pulsar wind with the companion. Those energetic systems are believed to be as well γ-ray emitters, not only by interaction between the two stars [15][7] but also, several models of millisecond pulsars [4] propose pulsed γ-ray emission from the pulsar inner magnetosphere up to $\sim$100 GeV. Different modelization of millisecond pulsars ([13] (and reference therein) and [6]) predict a high cutoff energy E_o in their spectra, at a $\sim$ 100 GeV, while for canonical pulsars this cutoff is expected to happen at a few GeV. These models are based in magnetic field strength and pair production considerations: although these pulsars have low surface magnetic fields ($B_s \sim 10^9\ G$), their short periods allow them to have large magnetospheric potential drops, but the majority do not produce sufficient pairs to completely screen the accelerating electric field. Thus the spectra are very hard power-laws with exponential cutoffs up to 100 GeV. On the other hand, ablation and heating of the companion star are believed to be caused by X- or γ-rays generated in a intrabinary shock between the pulsar wind and the star. This process has been observed by HESS in the similar system PSR B1259-63. The observed flux of γ-rays, modulated within the orbit, were detected at 5% of the Crab emission.

The observations of each of these pulsars were carried out in very different conditions and therefore it is necessary to analyze them in different ways to extract a steady signal. The different procedures and observation conditions will be explained for each pulsar. In addition statistical tests were applied to the γ-like events arrival times to search for pulsed emission. The standard corrections were performed in arrival times and the ephemeris used were obtained from the ATNF database, summarized in Table1.

Table 1. PSR J0218+4232 & PSR B1957+20 ephemeris (ATNF pulsar database).

	PSR J0218+4232	PSR B1957+20
Epoch (MMJD)	50864.00	48196.00
Puls. Frequency (Hz)	430.4610663457	622.122030511
Freq. Deriv. s/s	-1.4340E-14	-6.5221E-15
Puls. Period (s)	0.0023230904678309	0.00160740168480632
Rot Period (days)	2.028846084	0.3819666069

2. Observations and Data Analysis

2.1 PSR B1957+20

PSR B1957+20 is one of the fastest pulsars known, with period P∼1.6 ms and spin down luminosity $\dot{E} = 1 \times 10^{35}$ erg$\cdot s^{-1}$. The pulsar is in a 9.16-hour binary orbit with a low-mass companion star. Observations of the pulsar PSR B1957+20 were carried out with MAGIC in October 2004 (6^{th}-16^{th}) for 6 hours effective ON time, at low zenith angle (<30°). The observations were done in a standard ON-OFF mode, pointing the telescope to the pulsar position.

The total data set has been analyzed to look for emission in both steady and pulsed modes. Only high quality data were considered for the analysis. After calibration and image cleaning, Cherenkov showers were reconstructed using the standard Hillas parameter technique [8]. To reduce the hadronic background, optimum cuts on the Hillas parameters were applied to select γ-like events. This optimization was done with the Random Forest algorithm [3], which was trained to recognize γ-ray events with Crab Nebula ON data from the same epoch and same zenith angle.

For the pulsed emission analysis, the arrival times of the Cherenkov events were registered by a GPS clock. All arrival times were then transformed to the solar system barycenter using the JPL DE200 planetary ephemerides and folded modulo the period relevant to the epoch and the source. Some very loose cuts were applied since the signal is expected to be dominant at low energies where the Hillas technique fails to discriminate γ-rays from the hadronic background.

Once the necessary corrections are applied, which also take into account the pulsar motion with respect to the companion, several periodicity tests were performed: not only χ^2 to test against a uniform distribution, but also tests based on Fourier transformations which are able to resolve more sophisticated pulse shapes (Z^4_m and H test) [5].

2.2 PSR J0218+4232

PSR J0218+4232 was discovered in 1995 [11] as a luminous radio pulsar with pulse period of 2.3 ms. It orbits a degenerate companion with orbital period of about 2 days. The radio profile of the pulsed emission is complex, showing three peaks and a continuous (DC) component.

This millisecond pulsar has also been detected in soft and hard X-rays, and belongs to the reduced club of those showing X-ray modulation at the rotational period. As an X-ray pulsar it has a high luminosity, hard power-law shaped X-ray spectrum and a profile composed of narrow pulses. The X-ray emission is consistent with a structure of non-thermal hard pulses superimposed on a continuum of softer spectrum. The source is punctual with a size below 1 arc second.

Table 2. PSR J0218+4232 & PSR B1957+20 flux upper limits for the steady emission.

PULSAR	F ($> 115\ GeV$) ($\times 10^{-12}\ cm^{-2} s^{-1}$)
PSR B1957+20	4.5
PSR J0218+4232	1.3

In addition of the above properties this pulsar may represent the only detection of a millisecond pulsar in γ-rays. It is positionally coincident with the EGRET source 3EG J0222+4253 which has been related with both the AGN 3C66A and this source. Kuiper et al.[9] reported a 3.5 σ detection of a pulsed signal in EGRET data whose significance increased later on to 4.9 σ when it was shown that the peaks in the γ profile were aligned with the X-ray peaks.

The analysis of PSR J0218+4232 was a byproduct of dedicated observations on the AGN 3C66A, since for MAGIC the pulsar happens to be in the same field of view of the BL Lac object. Therefore the pulsar appears at a distance of 0.973^o of the center of the telescope camera, close to the limit of the trigger area ($\sim 1^o$). This fact implies a reduced effective area and MAGIC sensitivity in a factor $\sim$35% [14].

The data analyzed belong to August 2004 (20^{th}-26^{th}) and October 2004 (10^{th}-21^{th}) with a total ON observation time of $\sim$ 13 h. The mean observation zenith angle is $\sim 15^o$. Two different analysis scenarios were tried:

1. In the first scenario a lower cut on the number of photoelectrons in the image (*size* parameter) demanding at least a value of 150, was applied. Images were reconstructed from the source offset position. Those high energy/size images thus selected had enough quality to be treated through a standard set of cuts. This analysis has a nominal threshold of about 115 GeV.

2. The second approach was to select only low energy events. It allows to greatly reduce the background from cosmic rays events and exploit the soft spectrum that most models predict for the pulsed emission of pulsars. On the other hand no standard imaging is possible in this regime since images consist of very few pixels with small amplitudes.

3. Results

No excess is observed in the total data set for the millisecond pulsars neither for the binary systems. The upper limit on the integrated flux above a certain energy E_t was inferred from the MAGIC sensitivity [10] for a point-like source, as obtained from Monte Carlo calculations. Upper limits at 2σ, 95% confidence level, are listed in Table 2 for the steady emission. No evidence of pulsed emission was detected, either from the orbital modulation (in the case of PSR B1957+20) or from the pulsars at the expected frequency (see Figure. 1 and Figure. 2). Upper limits for the pulsed emission using the method explained by O.C de Jager [5] will be presented at the meeting.

4. Discussion

The data tabulated in Table 2 summarize the upper limits for unpulsed emission from the 2 systems under study. The energy threshold achieved in this analysis is still high to constrain the emission due to CR (up to 50 GeV) in the theoretical spectra [4] for isolated pulsars. However, the flux upper limit for the binary pulsar

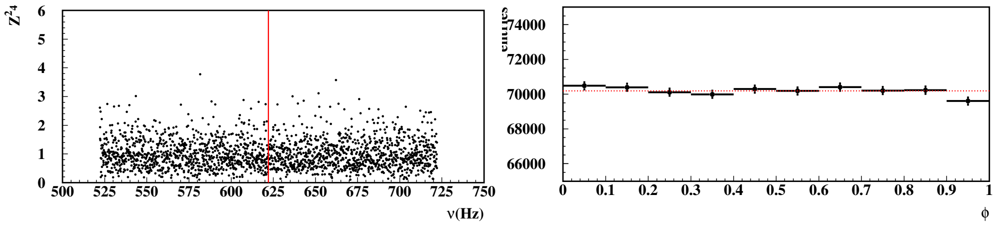

Figure 1. On the left, Z_4^2 test for a wide range of frequencies around the expected frequency of the millisecond pulsar, marked with a red line. The size of the bin is defined by 1 IFS to make sure that the folding is done for independent frequencies. On the right, the light curve at the expected frequency is represented. The result is compatible within the errors to a flat distribution (red dots line)

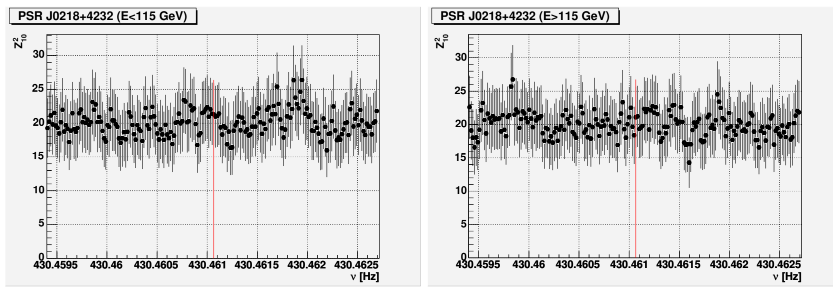

Figure 2. On the left, Z_{10}^2 test for a wide range of frequencies around the expected frequency of the millisecond pulsar, marked with a red line, for events below ∼115 GeV . On the right, the same test for events at high energies.

PSR B1957+20 is lower than the predicted value of [7]. This discrepancy can perhaps be accounted for by lower efficiency values for protons acceleration and γ-ray production.

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