A REVIEW OF VERY HIGH-ENERGY GAMMA-RAY PULSAR OBSERVATIONS

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In this proceeding, I first introduce the problem of very high-energy gamma-ray emission from pulsar magnetospheres, and subsequently I present a short review of all the major observational results that have been published to date. Lastly, I briefly discuss the status of models that attempt to explain the features of gamma-ray radiation from pulsars.

1 Introduction

It was quite recently that pulsars joined the very high-energy (VHE; E > $\sim$100 GeV) gamma-ray source class list with the surprising detection of the Crab pulsar above 100 GeV by VERITAS and MAGIC [1,2]. The VERITAS detection extended the VHE spectrum up to 400 GeV, and the most recent observations by MAGIC have extended it even further, up to 1.5 TeV [3]. The gamma-ray spectra up to 10 GeV or so that have been seen for pulsars are well described by a broad curvature radiation component that originates due to the electrons and positrons in the magnetosphere that follow curved trajectories as they are confined to the magnetic field lines. This curvature radiation component ends at GeV energies where the emission becomes radiation-reaction limited [4]. The spectra in the 100 MeV – $\sim$10 GeV energy band of pulsars detected by the *Fermi*-LAT (the large area telescope aboard the *Fermi* satellite) have all been well-described by an exponential cutoff as expected for curvature radiation [5], though statistics are sparse above $\sim$ 10 GeV due to the reduced sensitivity of the *Fermi*-LAT at these high energies. Based on the recent VHE detections of the Crab pulsar, it seems to be the case that curvature radiation is not adequate for a full explanation; the combined *Fermi*-LAT and VERITAS SED favors a power-law fit above $\sim$ 10 GeV [1,2,3].

More work must be done in the VHE band in order to fully understand the physics of the gamma-ray radiation from pulsar magnetospheres. A detection of another pulsar at VHEs could provide valuable insight into the locations and mechanisms of the particle acceleration, in addition to helping understand the geometry of the pulsar magnetosphere. To that end, all three major imaging atmospheric Cherenkov telescope (IACT) collaborations have been active in the area of pulsar research, with results on other pulsars published since the Crab detection in 2011. Those pulsars are the Vela pulsar (H.E.S.S. II) [6], the Geminga pulsar (MAGIC and VERITAS) [7,8], and PSR J1023+0038 (VERITAS) [9]. These results, along with all of the work that has been done on the Crab pulsar with IACTs, are summarized in the following sections.

Three of the aforementioned pulsars (the Crab, Geminga, and Vela) happen to be the three brightest steady[a] sources of gamma rays as seen by the *Fermi*-LAT, which is not a coincidence. Indeed, the *Fermi*-LAT is an important tool for VHE pulsar observations for several reasons:

[a] Though pulsars are periodic in emission, since they are not seen to flare, they are typically considered "steady."

- Pulsars can be prioritized for VHE observations based on their brightness (or other criteria) as seen in the LAT data
- Spectra derived from LAT data can be fitted with some function above a certain energy (e.g., 10 GeV) to predict a potential VHE flux level or put VHE upper limits into context
- Phase regions selected for ON or OFF counting for VHE pulsar searches can be defined by the characteristics of pulse profiles obtained from LAT data.

2 The Crab Pulsar

The Crab pulsar (PSR B0531+21) is the left over neutron-star remnant of an historic supernova that was observed in the year 1054 AD, and it is one of the most powerful known gamma-ray pulsars [10]. Located at a relatively nearby distance of 2.0 kpc with a spin period of ∼33 ms, it is also one of the most energetic pulsars, with a spin-down luminosity of $4.6 \times 10^{38}\,\mathrm{erg\,s^{-1}}$. Furthermore, the Crab Nebula surrounding the pulsar is one of the best-studied sources of VHE gamma rays, which has helped the accumulation of data than can be used to probe the much fainter pulsed VHE emission.

2.1 Past Results

The first results searching for pulsed gamma rays from the Crab pulsar in the current generation of IACTs came in November of 2008 with the MAGIC collaboration reporting a detection above an energy of 25 GeV [11]. MAGIC observed the Crab between 2007 October and 2008 February, accumulating a total of 22.3 h of data. The analysis of the data revealed a detection of pulsed gamma rays above 25 GeV at the 6.4σ level and a hint of emission above 60 GeV at the 3.4σ level. This detection implied an unusually high cut-off energy for the gamma-ray spectrum, indicating that the emission likely originates far from the pulsar in the magnetosphere and therefore excluding theoretical scenarios in which the emission is produced closer to the pulsar (e.g., polar-cap models). Furthermore, these observations revealed that the ratio P2/P1 increases with increasing energy and becomes >1 at around 60 GeV [11], thus indicating that the dominant peak becomes P2 at VHEs.

A few years passed before the next major result concerning the gamma-ray emission from the Crab pulsar, and that was the detection of pulsed gamma rays above 100 GeV by VERITAS [1], first announced in August of 2011[b]. VERITAS observed the Crab between 2007 September and 2011 March, obtaining a total of 107 h of data, which resulted in a detection at a level of 6σ [c]. The VERITAS data showed a narrowing of the pulse widths compared to what is seen at lower gamma-ray energies by the *Fermi*-LAT, and a proposed explanation was given of an acceleration region that becomes smaller following along the magnetic field confining the particles. The VHE spectrum measured extended to 400 GeV, and was well-characterized by a power law with a spectral index of $3.8 \pm 0.5_{\mathrm{stat}} \pm 0.2_{\mathrm{sys}}$. Combining the VERITAS spectrum with that obtained from *Fermi*-LAT data >100 GeV, a power law with an exponential cutoff characterization of the spectrum was significantly excluded for the first time [1]. Though the gamma-ray spectra seen for pulsars up to a few tens of GeV can be explained by a curvature radiation mechanism, the VERITAS detection posed the challenge that a new component is required for a complete explanation (at least for the Crab).

Updated results on the Crab pulsar from MAGIC came around the same time as the VERITAS announcement, with an addition of 34 h more (59 h total) of quality-selected data obtained in the winter of 2008/2009 [2]. In addition presenting phase-resolved spectral measurements in the energy range 25–100 GeV (which have since been superseded by the latest MAGIC results [3]),

[b]Though published in October, the arXiv submission date is 2011 August 18.
[c]This significance was calculated using the *H*-Test [12].

a variability study was performed by comparing the Crab pulsar fluxes seen in the 2007/2008 season and the 2008/2009 season. No significant variability was found on the timescale of a year [2], though this does not preclude the possibility of variability on other timescales. Lastly, P1 and P2 were shown to be narrower in the MAGIC data compared to their appearance in the *Fermi*-LAT data, and the measured Crab pulsar flux significantly deviated from an exponential cutoff extrapolation of the *Fermi*-LAT data [2]. The MAGIC and VERITAS results in 2011 thus independently confirmed one another in these regards.

2.2 Recent Results

MAGIC has detected bridge emission above 50 GeV from the Crab pulsar after analyzing a data set comprising 135 h of observations. The bridge region is defined as the phase range between P1 and P2, and an excess corresponding to 6.2σ is found after subtracting the background [13]. The detection of a bridge region above 50 GeV in the Crab pulsar light curve further complicates the task of modelling the gamma-ray emission—models need to be able to predict the spectral shape, the location and shape of the sharp peaks seen in the light curve, and now the bridge emission as well.

Most recently, the MAGIC collaboration reported the detection of pulsed emission from the Crab pulsar reaching up to 1.5 TeV in energy [3]. The Crab data set used is 318 h of good quality data recorded between 2007 February and 2014 April, and P2 (the dominant peak at these energies) shows significances of 6.0σ and 3.5σ for lower energy thresholds of >400 and >950 GeV, respectively. Phase-resolved spectra are derived for P1 and P2, and both are well described by simple power laws across the approximately one decade in energy probed in the data analysis. The spectral indices derived from power-law fits >150 GeV are $3.2 \pm 0.4_{\text{stat}} \pm 0.3_{\text{sys}}$ and $2.9 \pm 0.2_{\text{stat}} \pm 0.3_{\text{sys}}$ for P1 and P2, respectively [3]. The MAGIC and *Fermi*-LAT spectra for P1 and P2 are reproduced here in Figure 1.

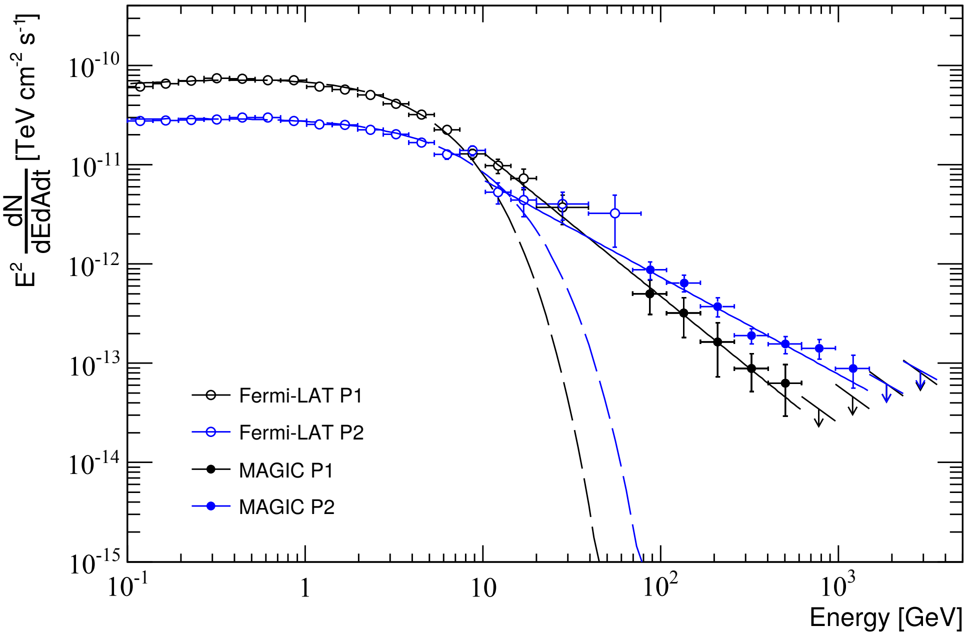

Figure 1 – MAGIC and *Fermi*-LAT phase-resolved Crab pulsar spectra. The black and blue straight lines are power-law fits to the data above 10 GeV. The arrows represent 95% confidence level upper limits, with the slope of the line indicating the assumed spectral index for the upper limit calculation. The dashed lines are fits to the *Fermi*-LAT data of a power law with an exponential cutoff for P1 and P2. Figure from [3].

3 Other Pulsars Observed by IACTs

In this section, I briefly summarize the results obtained by H.E.S.S., MAGIC, and VERITAS for three pulsars other than the Crab in chronological order from the first publication appearing in the literature for the pulsar in question.

3.1 The Geminga Pulsar

The Geminga pulsar (PSR J0633+1746) is located at the relatively close distance of ∼250 pc [14,15] and is the second-brightest steady gamma-ray emitter as seen by the *Fermi*-LAT, making it an obvious target for VHE observations. The Geminga pulsar has a period of ∼240 ms and a spin-down power of $3.2 \times 10^{34}\,\mathrm{erg\,s^{-1}}$ [14]. It is the first radio-quiet gamma-ray pulsar ever detected [16]. The gamma-ray pulse profile of Geminga shows two peaks separated by a bridge of emission, similar to what is seen for the Crab and Vela pulsars. Like for other gamma-ray pulsars, the Geminga pulsar spectrum >100 MeV can be described by a power law with an exponential cut-off [5]; however, [17] has claimed that the spectral tail may be better characterized by a simple power law.

VERITAS Observations & Analysis

The VERITAS campaign on Geminga resulted a total of 71.6 h of quality-selected data recorded taken between 2007 November and 2013 February. Events were phase-folded using an *XMM-Newton* timing solution for data obtained before the launch of the *Fermi*-LAT and using a publicly available *Fermi*-LAT solution[d] for all other data. The two emission peaks in the gamma-ray light curve were used to define regions of expected signal for the VHE data by fitting asymmetric gaussians >5 GeV for P1 and >10 GeV for P2 to measure their width. Unfortunately, no evidence of pulsed emission from the Geminga pulsar was found in the VERITAS data, thus only flux upper limits were reported. For the complete explanation of this analysis and the results, please refer to the VERITAS publication on the Geminga pulsar [18].

MAGIC Observations & Analysis

The MAGIC campaign on the Geminga pulsar resulted in 63 h of good quality data recorded between 2012 December and 2013 March. Events were phase-folded with a *Fermi*-LAT timing solution (see footnote *d*). The P1 region was selected by fitting an asymmetric Gaussian to the *Fermi*-LAT light curve >5 GeV and >10 GeV for P2. No significant evidence for pulsed emission was found in any of the three energy ranges (>50 GeV, 50–100 GeV, 100 − −200 GeV) tested in the MAGIC gamma-ray data [8], so only upper limits on a possible flux were reported. For full details of the MAGIC Geminga campaign (including the steady-source search), please see the MAGIC collaboration publication [8].

Neither the MAGIC nor VERITAS upper limits constrain a simple power-law extrapolation of the *Fermi*-LAT data above 10 GeV. Observations with a future-generation instrument operating in the VHE band could help determine whether or not the Geminga pulsar spectrum extends to VHEs as a simple power law, as seen for the Crab pulsar.

3.2 PSR J1023+0038

PSR J1023+0038 is an eclipsing binary located at a distance of 1370 pc [19] comprising a millisecond pulsar (MSP) rotating rapidly (P =1.69 ms) and orbiting a G star every 4.8 h [20]. This system was first identified as a low-mass X-ray binary with an accretion disk in 2001 [21]. Later observations showed that the accretion disk had disappeared [22], and an MSP was detected in the

[d] www.slac.stanford.edu/˜kerrm/fermi˙pulsar˙timing/

radio band in 2008 [20]. In 2013, it was reported in two seperate ATels that the radio pulsations had disappeared [23] and the accretion disk had reformed [24]. It had been thought that MSPs are spun-up to their rapid rotation periods via accretion of material off of a companion star, and this was the first time that such a system had been caught in the act of "recycling." Only a hint (3.7σ) of pulsed gamma-ray emission was seen in the *Fermi*-LAT data before the disappearance of the pulsar, so no gamma-ray spectral information is available [25].

VERITAS Observations & Analysis

Before the disappearance of the radio MSP, VERITAS obtained 18 h of observations on the location of the PSR J1023+0038 system. The data were phase-folded using a radio timing solution, and a test for a signal using the *H*-Test was conducted. No significant hint of pulsed gamma-ray emission from the MSP PSR J1023+0038 was found in the data, resulting in upper limits on a possible flux. For the full details of the analysis, including a search for a steady emission component, please see [9].

3.3 The Vela Pulsar

As the brightest steady source seen by the *Fermi*-LAT [28], the Vela pulsar (PSR J0835–4510) makes a prime candidate for a VHE pulsar search. Though not a young pulsar, Vela is located nearby at a distance of ~287 pc [29] and has a spin-down power of 6.3×10^{36} erg s^{-1} with a period of 89 ms. In the gamma-ray light curve, Vela shows two sharp peaks separated by a complex bridge region, with P2 seen as the dominant peak at gamma-ray energies above ~300 MeV [30].

H.E.S.S. II Observations

The H.E.S.S. array of IACTs underwent an upgrade in 2012 with the addition of a new 28 m diameter telescope called CT5 [e]. Given the large light collection area of the telescope, it has enabled the detection of fainter gamma-ray showers initiated by gamma rays with energies below 100 GeV. This has helped bridge the H.E.S.S. sensitivity into an overlapping energy regime with satellite-based gamma-ray telescopes, e.g., the currently operational *Fermi*-LAT.

The H.E.S.S. collaboration obtained 40.3 h of good quality data at zenith angles less than 40° during the CT5 commissioning period. After performing a likelihood ratio test for the presence of P2 (phase range: [0.5-0.6]) in the monoscopic data set, the Vela pulsar (P2 only) was detected at the 15.6σ level and at the 17.9σ level with the *H*-Test. As of this writing, this detection makes the Vela pulsar the second pulsar detected from the ground with the IACT technique. For a more complete account of the H.E.S.S. II detection of the Vela pulsar, please see [6].

The H.E.S.S. II spectrum of the Vela pulsar was generated using a forward-folding maximum-likelihood method above a lower-energy threshold of 20 GeV. A simple power-law fit in the energy range 20–110 GeV revealed a spectral index of $4.1 \pm 0.2_{\rm stat} \pm 0.2_{\rm sys}$, consistent with a power-law fit index derived from a *Fermi*-LAT data sample. Fitting with a log-parabola in the same energy range to test for curvature did not show a significant improvement of the fit [6]. The *Fermi*-LAT data on its own indicates a very marginal preference for curvature, when fit >10 GeV [6]. For now, the Vela P2 spectrum seen at the highest energies is consistent with both curvature and a power-law fits. Given that the Crab pulsar spectrum is seen to extend into VHEs as a simple power law, whether or not curvature is present at the highest energies in the Vela P2 spectrum is an important question that remains unanswered for the time being.

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[e] https://www.mpi-hd.mpg.de/hfm/HESS/pages/home/hess2inaug/

4 Status of Theory

It has long been postulated that particle acceleration occurs in pulsar magnetospheres in so-called "gap" regions—regions where the e^+e^- plasma is unable to freely move along magnetic field lines and short out electric fields that could build up and accelerate particles. The three canonical gap regions are the polar cap [31], the slot gap [32], and the outer gap [4]. Gamma-ray production is thought to be a result of curvature radiation in one of the gap regions, where charged particles follow curved magnetic fields lines and thus radiate electromagnetically. Curvature radiation predicts an exponentially decaying flux above energies of a few GeV, which is what is seen for (most) pulsars. Observations in the era of the *Fermi*-LAT have given favor to outer-gap-type models due to the ability of these models to reproduce the gamma-ray light curves [33] and the shape of the exponential cutoff in the spectra.

Since the detection of the Crab pulsar in the VHE gamma-ray band in 2011, much work has been done attempting to explain the VHE emission. However, the recent extension of the Crab pulsar spectrum up to 1.5 TeV [3] has posed the new challenge that the models must be able to predict the power-law shape seen in the data up to 1.5 TeV, in addition to the VHE light curve. The emitting region must be far from the neutron star surface given the energies of the detected gamma rays, since VHE gamma rays generated at smaller radial distances should be absorbed in the strong magnetic field via pair production. The VHE emission cannot be explained by curvature radiation, since the radius of curvature would need to be extremely large, on the order of the light-cylinder radius [1]. Inverse-Compton scattering of lower energy photons is most likely the fundamental mechanism, though the specifics regarding where and how it occurs are currently a subject of debate in the literature. For now, no model is capable of simultaneously predicting the Crab VHE light curve and the spectral shape [34]. For a more in-depth review of the current state of the theory in light of the recent work on the Crab pulsar, please see [34].

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References

1. Aliu, E. *et al*, *Science* **334**, 69 (2011).
2. Aleksić, J. *et al*, *Astrophys. J.* **742**, 43 (2011).
3. Ansoldi S. *et al*, *Astron. Astrophys.* **585**, A133 (2016).
4. Cheng, K. S., Ho, C., & Ruderman, M., *ApJ*, **300**, 522 (1986).
5. Abdo, A. A., *et al*, *Astrophys. J. S.*, **208**, 17 (2013).
6. A. Djannati-Ataï *et al* & The H.E.S.S. Collaboration, *in AIP Conf. Proc.* **1792**, 040028 (2017).
7. Aliu, E. *et al*, *Astrophys. J.* **800**, 61 (2015).
8. Ahnen, M. L. *et al*, *Astron. Astrophys.* **591**, A138 (2016).
9. Aliu, E. *et al*, *Astrophys. J.* **831**, 193 (2016).
10. Abdo, A. A., *et al*, *Astrophys. J.* **708**, 1254 (2010).
11. Aliu, E. *et al*, *Science* **322**, 1221 (2008).
12. de Jager, O. C., Raubenheimer, B. C., & Swanepoel, J. W. H., *Astron. Astrophys.* , **221**, 180 (1989).
13. Aleksić, J. *et al*, *Astron. Astrophys.* **565**, L12 (2014).
14. Bignami, G. F., & Caraveo, P. A., *ARA&A* **34**, 331 (1996).
15. Faherty, J., *et al*, *Astrophys. Space Sci.* **308**, 225 (2007).
16. Bertsch, D. L., *et al*, *Nature* **357**, 306 (1992).

17. Lyutikov, M., *Astrophys. J.* **757**, 88 (2012).
18. Aliu, E., *et al*, *Astrophys. J.* **800**, 61 (2015).
19. Deller, A. T., Archibald, A. M., & Brisken, W. F., *et al*, *Astrophys. J. L.* **756**, L25 (2012).
20. Archibald, A. M., *et al*, *Science* **324**, 1411 (2009).
21. Thorstensen, J. R., & Armstrong, E., *Astron. J.* **130**, 759 (2005).
22. Woudt, P. A., Warner, B., & Pretorius, M. L., *Mon. Not. R. Astron. Soc.* , **351**, 1015 (2004).
23. Stappers, B. W., Archibald, A., Bassa, C., et al., *The Astronomer's Telegram* **5513**, 1 (2013).
24. Halpern, J. P., Gaidos, E., Sheffield, A., Price-Whelan, A. M., & Bogdanov, S., *The Astronomer's Telegram* **5514**, 1 (2013)
25. Archibald, A. M., *et al*, (2013). arXiv:1311.5161
26. de Jager, O. C., *On periodicity tests and flux limit calculations for gamma-ray pulsars*, *ApJ*, **436**, 239 (1994)
27. Rolke, W. A., & López, A. M., *Confidence intervals and upper bounds for small signals in the presence of background noise*, *Nuclear Instruments and Methods in Physics Research A*, **458**, 745 (2005)
28. Abdo, A. A., *et al*, *Astrophys. J.* **713**, 154 (2010).
29. Dodson, R., *et al*, *Astrophys. J.* **596**, 1137 (2003).
30. Abdo, A. A., *et al*, *Astrophys. J.* **696**, 1084 (2009).
31. Sturrock, P. A. *Astrophys. J.* **164**, 529 (1971).
32. Muslimov, A. G., & Harding, A. K. *Astrophys. J.* **588**, 430 (2003).
33. Romani, R. W., & Watters, K. P. *Astrophys. J.* **714**, 810 (2010).
34. Zanin, R. *EPJ Web of Conferences*, DOI: 10.1051/epjconf/e2016- 62263-y (2017).