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David Carreto Fidalgo

Revealing the Most Energetic Light from Pulsars and Their Nebulae

Doctoral Thesis accepted by
the Complutense University of Madrid, Madrid,
Spain

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Para António.

Supervisor's Foreword

Very-high-energy (VHE) gamma-ray astronomy provides a unique view to the most extreme phenomena in the Universe. The observation of such energetic gamma-ray radiation implies the presence in the source of some kind of mechanism which is able to accelerate charged particles to ultra-relativistic energies. Pulsars, and their surrounding nebulae, are one of the main classes of galactic sources where these processes take place.

Pulsars are fast-rotating and highly magnetized neutron stars. Although they are mostly visible in radio, more than two hundred have been detected by the *Fermi*-LAT space telescope. Above a few GeV, the emission from *Fermi*-LAT pulsars typically drops exponentially, as predicted by classical pulsar models. Therefore, not long before Dr. David Carreto Fidalgo started his thesis, it was thought that pulsars could not emit in the VHE energy domain. The situation changed when the MAGIC telescopes, located in the Canary Island of La Palma, detected emission from the Crab Pulsar.

David's main goal was to study the high-energy radiation detected in the Crab Pulsar and to answer the long-standing question up to what energies pulsars are able to radiate. To this end, he analyzed more than 400 h of the Crab Pulsar data taken by MAGIC. The analysis of such unprecedented large data set, collected over nearly a decade of observations, was a real challenge. The arduous work that the author presents in a great detail resulted in a great discovery: Pulsars can emit radiation beyond TeV energies. The implications of pulsed TeV gamma rays for pulsar models are clearly discussed in the thesis. The results suggest that the emission at these energies is produced in the outer regions of pulsar magnetospheres, via inverse Compton scattering.

The detection of ultra-energetic pulses from the Crab provided a unique data set to address questions of fundamental physics. Quantum gravity models predict the violation of the Lorentz invariance, that is, the change of the speed of light with energy. If so, photons emitted in the Crab Pulsar at the same time but with different energies would be detected with a relative delay. Exploring a new methodology, based on Bayesian inference, the author is able to obtain competitive limits on the invariant energy scales of the speed of light.

To shed more light on the pulsar emission mechanism at the highest energies detected in the Crab, we would need to find other pulsars exhibiting a similar behavior. The thesis addresses also this topic, by searching among the *Fermi*-LAT pulsars for candidates to emit in the VHE range. The author found a millisecond pulsar that would be a prime target for gamma-ray observatories in the Southern Hemisphere, such as the upcoming CTA-South.

The final part of the thesis deals with the search for pulsar wind nebulae. Although they are a common class of VHE gamma-ray emitters in the inner Milky Way, they are hardly found in the outer part of our galaxy. This motivated the author of this thesis to conduct observations around a young and energetic pulsar, PSR J0631+1036, situated near the galactic anticenter. The results corroborate the relationship between the luminosity of pulsar wind nebulae and the interstellar radiation field.

Apart from the remarkable detection of the most energetic light ever been seen from a neutron star, the reader will find in the thesis a comprehensive introduction to the research field of gamma-ray astronomy, covering both its experimental and theoretical aspects. And all this is written in a pleasant and didactic style that the reader will surely enjoy.

Madrid, Spain
May 2019

Prof. Marcos López Moya

Preface

The observation of very-high-energy (VHE, >100 GeV) gamma rays is key in studying the nonthermal sources of radiation in our Universe. Pulsars and pulsar wind nebulae (PWNe) are two source classes that are known to emit VHE gamma rays. While pulsar wind nebulae are the dominant VHE gamma-ray source class in our galaxy, only two pulsars have been detected above 100 GeV so far. Most pulsar models explain gamma-ray emission via synchro-curvature radiation in the radiation-reaction-limited regime, which leads to a sharp cutoff in the pulsar spectrum at energies of a few GeV. However, the detection of pulsed emission from the Crab Pulsar up to hundreds of GeV by MAGIC and VERITAS suggests that classical pulsar models do not provide a full picture of the emission mechanisms at work. TeV pulsar wind nebulae, on the other hand, are observed via their inverse Compton radiation and are primarily found around young and energetic pulsars located toward the inner Milky Way. Detections of TeV PWNe in the outer part of our galaxy are scarce but could provide valuable input for the connection between the interstellar radiation field and the PWN luminosity.

The general motivation for studying *pulsars* and *pulsar wind nebulae* at very high energy (VHE, >100 GeV) is manifold. Pulsars are exotic objects with core densities several times higher than atomic nuclei and surface gravities 10^{11} times stronger than the Earth's. At the same time, they spin up to a factor 10^7 faster than the Earth and their magnetic fields can surpass the Earth's by 15 orders of magnitude. Because of these extreme conditions, pulsars can give insights into physics of ultra-dense matter, tests for general relativity, and the promise of a direct detection of low-frequency gravitational waves. Most of them use their enormous rotational energy to emit electromagnetic radiation via detailed processes we do not fully understand yet. The modeling of their emission drives ever-more sophisticated electrodynamic calculations, for which VHE observations provide valuable input.

Most of the rotational energy of a pulsar is dissipated via relativistic winds that interact with the surrounding medium to generate luminous pulsar wind nebulae. These sources allow us to probe relativistic shocks, particle acceleration as well as particle diffusion and propagation in our galaxy. Pulsar wind nebulae are prime candidates to explain the puzzling positron excess above 10 GeV in the cosmic ray flux. To solve this puzzle, VHE energy observations of these objects are key.

The principal goal of this thesis is to study the very-high-energy emission of the Crab Pulsar. We aim to answer the long-standing question up to what energies pulsars are able to radiate and what is the emission mechanism behind it. We further exploit the pulsed VHE emission from the Crab to investigate fundamental physics testing for Lorentz invariance violation (LIV), in terms of a wavelength-dependent speed of light. To deepen our understanding of the pulsar emission mechanism at the highest energies, further pulsars have to be discovered above 100 GeV. To this end, we search among pulsars already detected at around 1 GeV for the best candidates to emit gamma rays in the VHE range. Another aim of this thesis is to discover a new pulsar wind nebula toward the outer part of our galaxy with the MAGIC telescopes.

The thesis is structured into three parts:

Part I

This introductory part gives a brief overview of the instruments and astrophysical sources in VHE astrophysics. It also introduces the reader to pulsar and pulsar wind nebulae physics and describes in detail the MAGIC experiment together with the Imaging Atmospheric Cherenkov Telescope (IACT) technique.

Part II

The main part of this thesis starts with the discovery of VHE emission from the Crab Pulsar above 400 GeV. We characterize its pulse profile as well as the phase-resolved VHE spectra up to ~ 1.2 TeV and discuss our results with respect to different emission scenarios. In Chap. 6, we exploit the VHE emission of the Crab Pulsar to test for Lorentz invariance violation, in terms of a wavelength-dependent speed of light. The last chapter of this part is devoted to the search for VHE pulsar candidates with *Fermi*-LAT.

Part III

We describe the search of a TeV pulsar wind nebula around the young and energetic gamma-ray pulsar PSR J0631+1036 with the magic telescopes. PSR J0631 lies near the galactic anticenter, and a tempting hot spot at its position was reported by the Milagro collaboration based on their full eight-year data set.

Summary and Conclusions

In the last chapter of this thesis, we give an extended summary and concluding remarks about the results in view of the future Cherenkov Telescope Array (CTA) Observatory.

Appendix

The appendix provides more background information about pulsar timing and a quick overview of physical interaction processes in VHE astrophysics. We also describe the On-Site Analysis (OSA) chain of MAGIC, which is the system in charge of the low-level analysis of MAGIC data. During his Ph.D. studies, the author worked continuously on OSA to improve and maintain its workflow. In the end, we provide some more technical details about the main analysis of this thesis.

Madrid, Spain Dr. David Carreto Fidalgo

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