Search for the next very-high-energy gamma-ray pulsar

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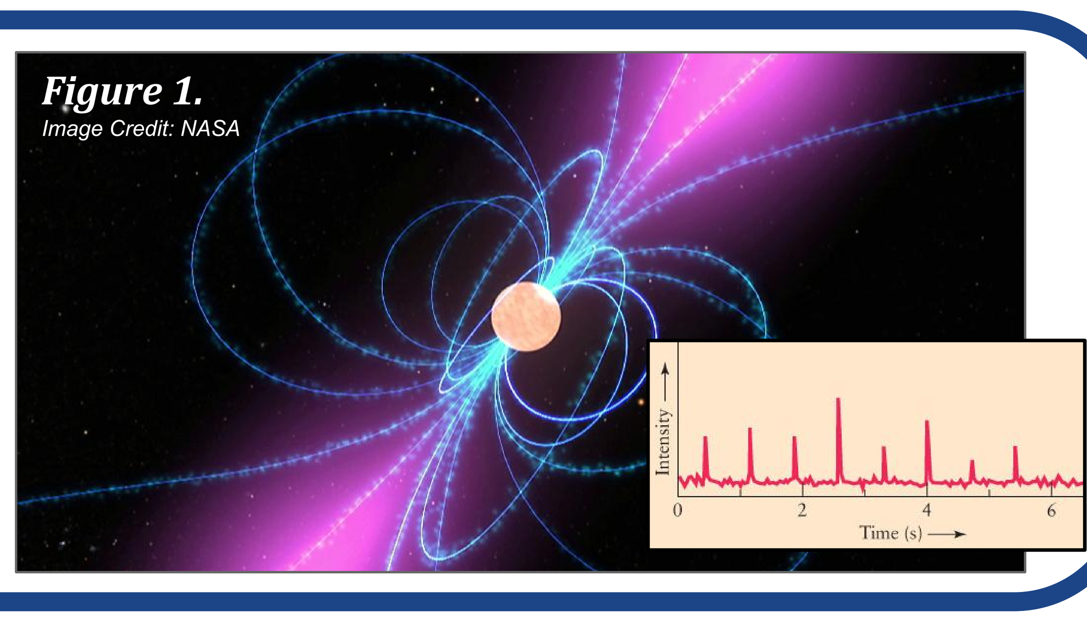
Introduction

When heavy stars have burned all their nuclear fuel, neutron degeneracy pressure is the only force able to halt their collapse into a black hole. The resulting objects are called Neutron Stars and have a diameter of only about 20 km but weigh more than our sun. They spin at very high frequencies (up to 700 times per second) and have strong magnetic fields due to the conservation of both the angular momentum and magnetic energy from the former star. The most energetic neutron stars are capable of transforming their rotational energy (gradually slowing down) to emit pulsed radiation from radio up to gamma rays, operating as so-called *pulsars*.
Figure 1 shows an artist's impression of a pulsar. The red hot sphere is the neutron star, while the blue lines depict the intense dipole-like magnetic field. Radiation beams that sweep the universe like a lighthouse are shown in magenta. When such a beam hits the earth, a periodic signal can be detected as shown in the inset. The precision of the time intervals between those *pulses* can compete with the accuracy of atomic clocks.



What is a VHE gamma-ray pulsar?

Pulsars are mostly observed in the radio band where over 2500 have been found so far. A very-high-energy (VHE) gamma-ray pulsar, however, is capable of emitting photons with an energy up to 10^{11} times the energy of visible light. While over 200 pulsars are known to emit gamma rays in the MeV to GeV regime, only two pulsars have been detected at very-high energies above 50 GeV, the Vela and Crab pulsar. The reason behind this difference is that the vast majority of gamma-ray pulsars seem to exhibit a spectral cut-off at around a few GeV (see figure 2).
However, in the case of the Crab pulsar the spectrum continues and emission up to ~1 TeV was recently detected. So far the Crab pulsar is the only pulsar that exhibits such a high energy tail. The Vela pulsar is the brightest steady source of gamma rays in the sky and maybe therefore still detectable at VHE despite its cutoff.

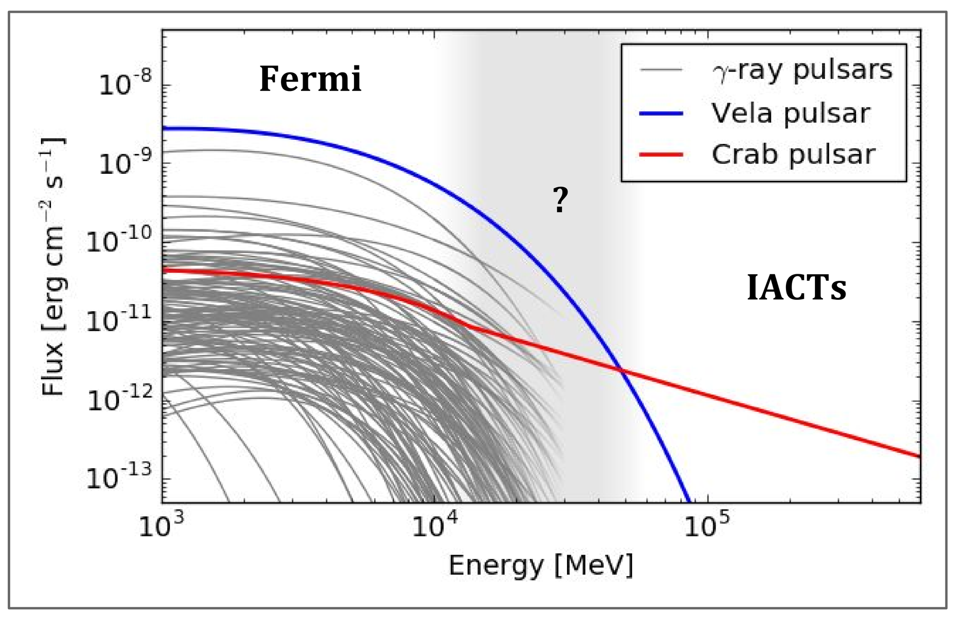


Figure 2.: *The spectral energy distributions for over 100 gamma-ray pulsars. The two pulsars detected at VHE are marked with a blue and a red line, respectively. The grey shaded region illustrates the critical energy range we are investigating in this project, using both space based and ground-based instruments (see box on the right).*

How do we search for it?

From the new wealth of gamma-ray pulsars, discovered by Fermi since its launch in 2008, we try to look for the best candidates to propose follow-up observations with IACTs.
We set up an analysis pipeline to extract photons from Fermi-LAT data based on their probability to originate from one of the candidates (figure 5). This probability mainly depends on the reconstructed direction of the photon and on the amount of background from nearby sources. Using a Markov chain Monte Carlo method we then try to find a valid timing model for the pulsar that allows us to assign a rotational phase to each of the extracted photons and to build a pulse profile of our candidate (figure 6). If the photons detected at the highest energies (>50 GeV) stem from the pulsar they should fall in the same rotational phase as the peaks in the pulse profile at lower energies.

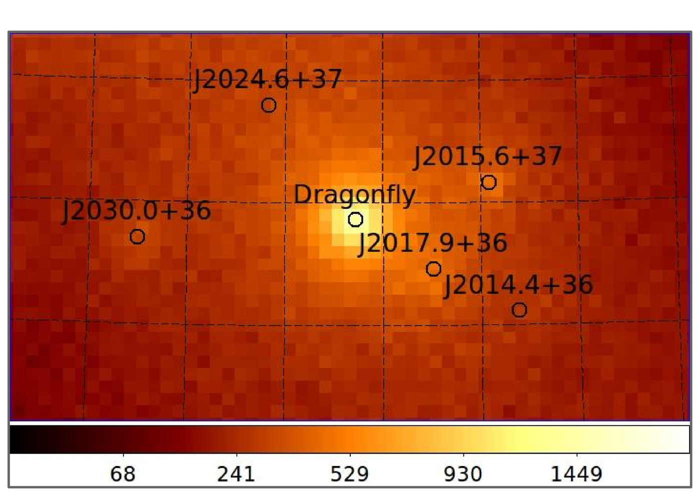


Figure 5.: *An example of a Fermi-LAT photon counts map above 100 MeV around the Dragonfly pulsar. The locations of some background sources are marked by circles. The grid has a spacing of 1 degree.*

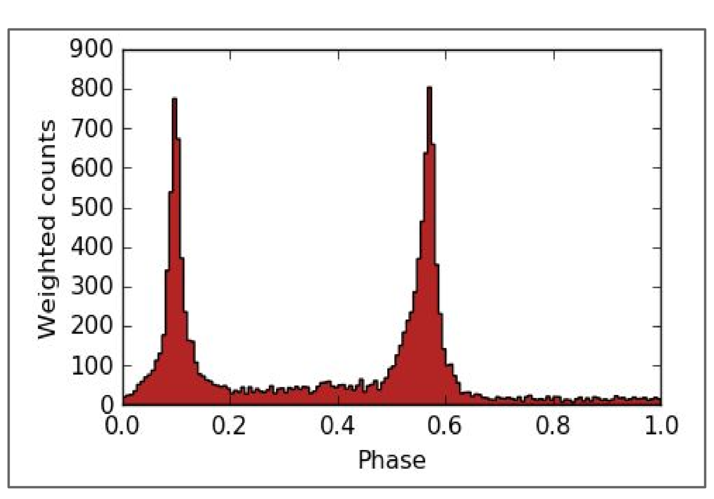


Figure 6.: *The pulse profile of the Dragonfly pulsar above 100 MeV. Rotational phases from 0 to 1 correspond to one full rotation of the pulsar. It is typical for gamma-ray pulsars to exhibit two sharp peaks.*

What instruments do we use?

Figure 3.: *A computer generated image of the Fermi satellite orbiting the earth.*

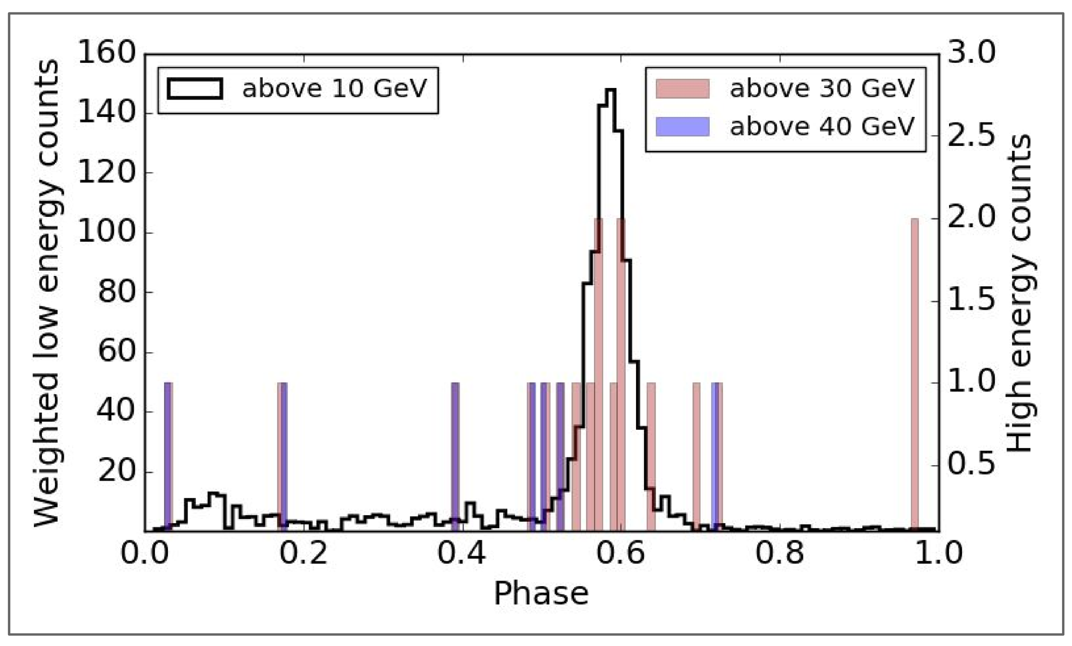
From the experimental point of view the spectral breaks of gamma-ray pulsars fall in a rather unfortunate energy range, as depicted in figure 2.
Gamma rays above ~100 MeV can be efficiently detected from space, for example by the *Large Area Telescope* (LAT) on board of the Fermi satellite. Above ~10 GeV, however, its sensitivity starts to decrease rapidly due to the limited size of the detector. From the ground, *Imaging Atmospheric Cherenkov Telescopes* (IACTs) are able to detect gamma rays in the GeV to TeV range, peaking in sensitivity at around 500 GeV. Current generation IACTs are capable of detecting gamma rays as low as ~30 GeV, but have to fight with an overwhelming background at those energies. Therefore, the exact shape of the spectral break and the maximum photon energy emitted by gamma-ray pulsars, both important ingredients for understanding the emission mechanism at work, are still poorly known.
While the LAT has a wide field of view and takes snapshots of most of the sky every 90 minutes, IACTs are pointing experiments with a field of view of about 3.5 degrees.

Figure 4.: *A picture of the MAGIC telescopes located on La Palma (Canary Islands), one of the current three major IACTs in the world.*

What have we found so far?

Our search is still work in progress. The Geminga pulsar is one of the brightest sources in the Fermi sky and therefore a tempting candidate for very-high-energy emission. Although several attempts have already been made by IACTs to detect it, we applied our pipeline on this source as a first step.
We took the weighted pulse profile above 10 GeV to evaluate the significance of pulsed emission at energies above 30 and 40 GeV. Despite significant emission above 30 GeV (at the 4 sigma level), as can be seen in figure 7, we found no photons above 40 GeV coming from the Geminga pulsar.
As a next step we plan to run the pipeline on so-called *millisecond* pulsars that by default have a more stable rotation and are therefore easier to time.

Figure 7.: *The pulse profile of the Geminga pulsar at different energies. Photons for the low energy counts (above 10 GeV) were extracted around 2 degrees of the pulsar, whereas above 30 and 40 GeV the extraction radius was 1 degree. This corresponds to a 95% containment radius of the instrument's point-spread-function at those energies.*



Conclusions

Despite the apparent spectral cut-off at a few GeV for most of the gamma-ray pulsars, the puzzling case of the Crab pulsar motivates us to search the new wealth of pulsars detected by the Fermi satellite. Our aim is to propose the best candidates for follow-up observations with IACTs that are far more sensitive in the very-high-energy regime but need guidance due to their small fields of view and limited duty cycles.

Our search is still work in progress. As a first step we applied our pipeline on the Geminga pulsar but found no significant emission above 40 GeV.

Acknowledgements
This research is conducted using the HKU Information Technology Services research computing facilities that are supported in part by the Hong Kong UGC Special Equipment Grant (SEG HKU09).