Using upper limits on the hadronic emission of pulsar to investigate the cosmic ray dipole: building the bridge between gamma-ray astronomy and cosmic rays.

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The origin of cosmic rays remains one of the most intriguing questions in astrophysics even after several decades. Due to their charged nature, these particles are deflected during their propagation, losing information about the position of the sources. For that reason, cosmic ray astronomy becomes impossible. Nevertheless, multi-messenger analysis arises as a promising tool to unveil this long-standing puzzle. Neutral particles, such as gamma rays and neutrinos are not deflected during their propagation and, thus, point back to their origin. In many astrophysical environments, the creation of such particles is directly related to the acceleration of cosmic rays.

In the last years, current state-of-the-art experiments have measured small, yet statistically significant, deviations for isotropy in the distributions of arrival direction of cosmic rays. The most notable of those is a dipole in the distribution, whose amplitude and direction have been measured over several decades in energy by different experiments. Even though cosmic rays diffuse in their propagation through magnetic fields, some imprints about the position of the initial sources may be left in the data, especially for closer and more intense sources. At the same time, the field of gamma-ray astronomy and modeling of gamma-ray sources has matured to the level at which several populations of sources, such as pulsars, are detected and their fluxes measured with statistical confidence in the high and very-high energy

range. The emission of gamma rays in these extreme objects may be related to the acceleration of leptons or hadrons. In recent years a combination of both particle populations has been preferred to describe the production of gamma rays. In the case of a hadronic contribution, the emission of cosmic rays from such sources is expected.

Measurements of spectra of TeV sources with IACTs or Water Cherenkov wide-field Observatories could either verify the presence of a hadronic contribution to the emission or impose upper limits for such emission.

In this project, we propose using pulsars as a possible source of cosmic rays and understanding the expected cosmic ray anisotropy signal coming from these sources. In a first study, we propose to go over pulsar spectra measured by IACTs and WCDs and use the upper limits for the hadronic emission calculated using the spectrum derived from these detectors to model upper limits on their possible cosmic ray emission. This step is feasible given the expertise in pulsar modeling and gamma-ray source analyses of some of the authors of this project. With such predictions on the cosmic ray emission, we would simulate their galactic propagation on Monte Carlo propagation codes, e.g., GALPROP[1], resulting in their contribution to the total anisotropic signal. The obtained contribution can then be compared to current cosmic ray dipole data. Once again, such a step is feasible, given the expertise of some of the authors in cosmic ray propagation and anisotropy studies.

If this proves to be a fruitful study, we propose a more long-term study by using the next generation of IACTs and WCDs, i.e., CTA and SWGO, in which a much larger number of pulsars are expected to be measured as well as higher energies and better resolution. In an optimistic scenario, this could lead to a better understanding of the dipole in the region in which the shifting to a predominance of galactic to extragalatic sources is expected, i.e., around the ankle. Such understanding, if possible, would be crucial for unveiling the sources of very and ultra high energy cosmic rays.

[1] This step also provides the opportunity of testing systematics of galactic propagation with different codes, such as GALPROP and CRPropa. This is an important study, given that most phenomenological cosmic ray works rely on these and no proper comparison study has been done yet. Again, this step is feasible given the expertise of the authors.