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Data Reduction of Multi-wavelength Observations

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Abstract. We are developing a software to combine gamma-ray data from multiple telescopes with the aim to cross calibrate different instruments, test their data quality and to allow the confirmation of transient events using different instruments. In particular, we present the first applications using pulsar data from the AGILE and Fermi satellites and show how we solved the issues relative to combining different datasets and rescaling the parameters of different telescopes. In this way we extend the energy range observed by a single telescope and we can detect fainter objects. As a second step, we apply the technique of pulsar gating to the imaging data of the satellites combined, to look for pulsar wind nebulae. The same procedure is adopted in the radio domain, using data from the Sardinia Radio Telescope (SRT). We aim to be able to use similar techniques for multifrequency datasets spanning a large range of the electromagnetic spectrum. We also present the work in progress to include the automatic search for gamma-ray counterparts within the pipeline for pulsar search in radio.

1. Introduction

Multi-messenger astronomy is becoming the key to understand the Universe from a more comprehensive perspective. We believe that in most cases the data, and the technology, are already in place and it is important to provide a package that is easily accessible and usable to combine datasets from multiple telescopes, at different wavelengths. In order to achieve this, we want to produce a data analysis pipeline that allows to reduce the data from different instruments without the need of a detailed previous knowledge of the subtlety of the observations in each field. Ideally the specifics of different observations are automatically dealt with, while the necessary information about how to handle the data in each case is provided by a tutorial included in the program.

We first focus our project on the study of pulsars and their wind nebulae (PWNe) at radio and gamma-ray frequencies. In this way we aim to combine time-domain and imaging data-sets and two extremes of the electromagnetic spectrum. Also, with regards to the science, the emission has the same non-thermal origin for pulsars at radio and gamma-rays and the population of electrons is believed to be the same at these energies in PWNe. Final goal of the project will be to unveil the properties of these objects by being able to track their behaviour using at best all the available multi-wavelength data.

2. Data Reduction

The first tests were performed choosing the Crab pulsar as our target. The Crab is the third brightest pulsar in gamma-rays and is very well studied at all frequencies of the radio domain and outside. The Crab is the youngest known pulsar in our Galaxy and it is embedded by a PWN with a filled structure called a 'plerion'.

For the gamma-rays we took advantage of the publicly available archives from the two new generation gamma-ray satellites AGILE (Tavani et al. 2009) and Fermi-LAT (Atwood et al. 2009). For the radio we reduced data taken in the context of the scientific commissioning of SRT using the new SARDARA backends (SArdinian Roach-2 Digital Architecture for Radio Astronomy, Melis et al. in prep.).

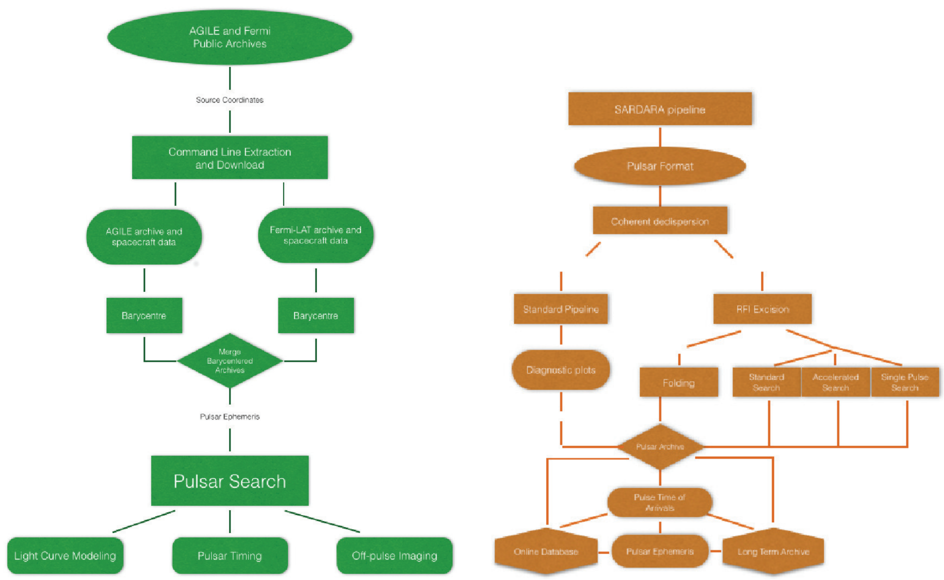

Figure 1. Schematic views of the pipelines for pulsar analysis. *Left:* Gamma-rays. *Right:* Radio.

2.1. The pipeline

We have automated the search of the publicly available gamma-ray data with the creation of a single command line script which, in its simplest approach, takes the coordinates of the source as its input and it extracts all the available observations for an extraction radius of 10 degrees around the source, plus the corresponding spacecraft data. Given a pulsar ephemeris we can barycentre the data relative to each satellite and then combine them to do a search in pulse period and period derivative according to a similar scheme as the one described in Pellizzoni et al. (2009). In the case of a pulsar surrounded by a PWN, we can subtract the pulsed flux from the data and reanalyse the tagged off-pulse data to search for diffuse emission around the source, since the pulsar is usually dominant at medium-energy gamma-rays (see Pellizzoni et al. 2010).

In order to be able to follow pulsars regularly, at all frequencies, it is fundamental to keep up-to-date pulsar ephemerides. Nowadays this is also possible using gamma-ray data (see Kerr et al. 2015), but also traditionally, and where it is possible, an accurate ephemeris is obtained by regular timing of pulsars using a radiotelescope. Both with SRT and gamma-ray data combined we aim to create a pulsar ephemeris database that can be used for the pulsar analysis.

The radio observations performed locally are digitised through a ROACH-2 backend[1] and then converted into the format `psrfits` (Hotan et al. 2004) which is easily readable from all the standard pulsar analysis packages. The data are mitigated from radio frequency interference, dedispersed and folded. In the case of a known pulsar we will produce integrated pulse profiles and accumulate time of arrivals of these standard templates in order to obtain a timing model to produce the ephemeris. Purpose of our project is also to find new pulsars from the error boxes of the gamma-ray-only pulsars or unidentified gamma-ray sources and for this we need a search pipeline, which is being developed by integrating the already available programs from the `presto` (Ransom 2001) and `psrchive` (van Straten et al. 2012) suites for pulsar analysis. We are first completing a performance study of SRT to estimate its flux limits. This is also a first fundamental step for future searches of fast transients with SRT.

2.2. First Results

We present here the first results obtained from our collection and analysis of data.

The left-hand side of Figure 2 shows the Crab pulsar light-curve at $E > 100\,\mathrm{MeV}$ obtained from the combination of 1 yr of AGILE and Fermi-LAT data using a public ephemeris from the Fermi database. While this is only a test, much better results can be obtained by combining a longer data span, for which a precise ephemeris covering the whole time interval is needed.

On the right-hand side of Figure 2 we present the first image of a PWN observed with SRT, obtained at 6.5 GHz, with 1 GHz bandwidth, in a 20 min observation using the SARDARA backend. The image can be refined by using pulsar gating techniques and, especially at lower radio frequencies, the use of this technique will also be applied to look for pulsars in imaging data.

3. Conclusions and Future Work

Given a pulsar ephemeris, we are already able to dig into the public archives of AGILE and Fermi and to obtain pulsar light curves from each instrument. We have managed to combine in phase both datasets so as to cross check the long term performance stability of both instruments, to obtain a larger dataset and, finally, to improve our sensitivity to structures at sub-millisecond level in the pulsar profiles. Gamma-ray observations with declinations above ~ -30 degrees can be followed up with radio observations, and viceversa: future radio searches for pulsars and fast transients with SRT will be automatically cross-searched in gamma-rays for counterparts thanks to an embedded database in the analysis pipeline. From all the available data we collect time-stamps in order to create timing models for the pulsars and make them available for subsequent analyses. Once we have obtained a good solution for the pulsar, we are able to apply the technique of the subtraction of the pulsed flux to look for diffuse emission around a pulsar: typically a PWN, but cases have been observed of pulsar ‘tails’ in X-rays.

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[1]https://casper.berkeley.edu/wiki/ROACH-2_Revision_2

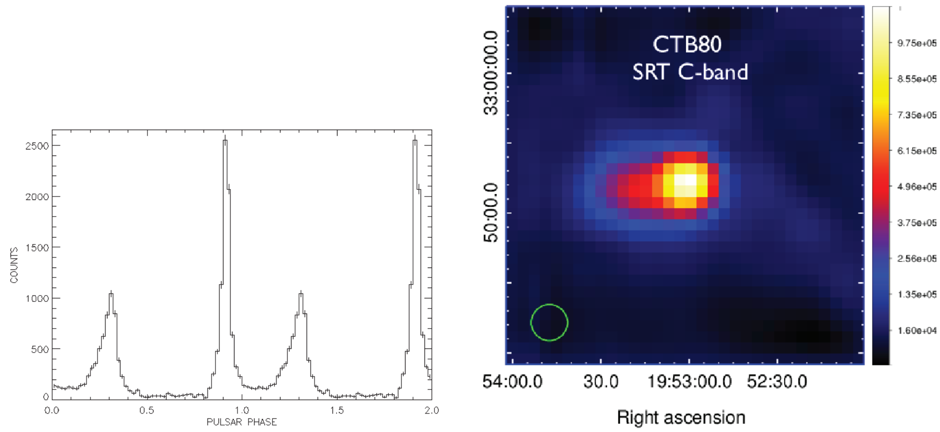

Figure 2. First results of our pipelines. *Left:* Crab pulsar light-curve at $E > 100$ MeV from combined AGILE anf Fermi data. *Right:* 6.5 GHz imaging of PWN CTB 80 with SRT.

With these procedures we aim to considerably reduce the time and man-power needed to perform pulsar surveys and follow-up studies of observations at different wavebands. As a future development, we envisage the extension of the number of wave-bands involved in our combined databases, starting from the X-rays, which already provide the broadest set of publically available data products, and subsequently millimeter and microwaves. The novelty of the approach relies in the planned availability of both data products like pulsar ephemerides and light curves or images from standard automatic pipelines run on the data, but also in the possibility to retrieve raw data at different wavelengths and analyse them, all through a procedure that will be mostly wavelength independent.

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