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Multi-wavelength analysis of young pulsars: an overview

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Abstract. Young pulsars emit a broad spectrum of radiation that range from radio to gamma ray energies. These pulsars are considered as rotation powered pulsars that spin rapidly and are strongly magnetized. Following the discovery of pulsars nearly four decades ago, the population of known pulsars already reached a number of roughly two thousand. This known population of pulsars includes both millisecond and normal pulsars that were discovered by several telescopes. We analyze both HartRAO radio data and Fermi gamma ray data of the Vela pulsar. We also explore a proposed method of probing the electron column density of the instellar gas through analyzing the gamma ray diffuse data associated with the Fermi two-year observation. This paper serves as an overview of gamma ray and radio timing analysis of bright young pulsars with respect to the use of open source timing analysis tools (Tempo2, Psrchive, Enrico and the Fermi tools). We reason that the multi-wavelength picture of pulsars can help clarify questions regarding the origin of pulsed radiation emission mechanisms in several energy bands, but that radio observations will prove adequate for timing noise analysis, given the accurate and long radio data sets. The process of identifying gravitational waves in timing data, rests on gaining a deeper insight into the timing noise phenomena.

Key words. Multi-wavelength timing–Fermi–Gamma ray pulsars–Vela pulsar–Fermi tools–Enrico–Radio Timing

1. Introduction

Pulsars are rapidly spinning and highly magnetized objects that are born during supernovae explosions. These objects contribute significantly to the fields of astrophysics and nuclear physics due to its peculiar high core density and fast spin-periods that range from milliseconds to several seconds (Lorimer, 2005). These objects produce pulse trains that can be observed in several bands that includes radio and gamma rays (Schlickeiser , 2002) and can be observed and modeled remarkably accurate. This modeling also aids in the search for small gravitational wave signatures in the times of arrival (TOA) of these pulse trains.

The Vela gamma ray data that are available in the LAT Data set, which was released one year after the Fermi launch, can be analyzed using the Fermi Science Tools. These tools will be used for the analysis of pulsed gamma ray data of the Vela pulsar which can be found in the Fermi two-year catalog

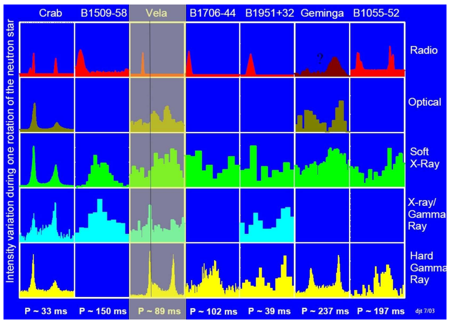

Fig. 1. Multi-wavelength pulses of seven well-known pulsars adapted from Thompson (2004). The pulse-comparison line for the Vela pulsar clearly illustrates the radio lag and the possibility of different emission regions for the observed radiation. This figure represents the true fingerprint of pulsars.

(see `http://fermi.gsfc.nasa.gov/ssc/data/access/lat/2yr_catalog/`). We also attempt to analyze radio data of the Vela pulsar obtained with the 18cm receiver of the HartRAO 26m radio telescope. The Vela pulsar is radio bright (at Jansky level, Abdo et al. , 2009; Lorimer, 2005) and this characteristic simplifies the signal folding procedure (since the signal-to-noise ratio is roughly 1500). These two analyses will produce pulse shapes that are similar to radio and gamma ray pulses highlighted in Fig. 1 (Becker , 2009). However, to understand pulsar emission and characteristics, we need to construct a timing model that is accurate enough to include various contributions to the modeled TOA. These contributions include glitches, giant pulses and timing noise exhibited by both normal and millisecond pulsars (Lorimer, 2005). Timing accuracy of pulsars changes from one energy band to another. Thus, before one can start constraining timing models, one must first be able to perform timing analysis in various energy bands.

2. Modeling the pulse train

Modeling the pulse train (or TOA) of the pulsar as accurately as possible will help (the theorist) to constrain certain fundamental assumptions regarding the pulsar model and the timing model. The barycentric TOA of the pulse could be modelled by including all the effects that cause a delay on the arrival time of the pulse (Lorimer, 2005). This is:

$$TOA = t_{topo} + t_{corr} - \Delta_{DM} + \Delta_{solar\ barycenter} + \Delta_{GW}, \quad (1)$$

where t_{topo}, t_{corr}, Δ_{DM}, $\Delta_{solar\ barycenter}$ and Δ_{GW} represent the time measured on earth, the clock corrections, dispersion measure, barycentric corrections of the solar system and delays in the TOA caused by gravitational wave (GW) stochastic backgrounds produced by merging super massive black holes (Backer and Hellings , 1986). The strain on spacetime induced by GW backgrounds scales as a power law of the frequency of the chosen gravitating source, $h = A_g(\frac{f_g}{yr^{-1}})^{\alpha}$. These backgrounds are very low frequency disturbances in spacetime and are in the nanohertz frequency range (Backer and Hellings , 1986).

Most timing analysis codes include all these effects. Several platforms exist for modeling the GW background influence on the TOA (Hobbs et al. , 2006). Interstellar scattering of the pulse due to cold ionized gas effectively broadens the pulse and increases the error in the TOA prediction. In radio astronomy the measure of dispersion is calculated through the multi-frequency observations of pulsars (knowing the TOA in several bands). The delay caused by pulse dispersion is dependent on the radio band of observation and the dispersion measure.

The density of free electrons between the pulsar and the receiver could also be probed by using the diffuse emission Fermi data. Cosmic rays (or protons) bombard the interstellar gas to produce pions (π^0, π^+ and π^-) that decay into electrons and gamma rays (Schlickeiser , 2002). The amount of integrated free electrons between the pulsar and observer could directly relate to the dispersion measure, this could be cross-correlated with dispersion measure derived from radio timing of the pulsar. The proposed method is as follows: protons (p) bombard the interstellar gas (X) to produce a cascade of particles, this is: $p + X \rightarrow He^3, H^2, p, \pi^0, \pi^+, \pi^-$. Knowing the gamma ray flux that arises from galactic diffuse emission in the ROI of the source, one could estimate the number of free electrons between the pulsar and the observer. For example, to view the diffuse emission in the data set of the Vela pulsar (whatever the region of interest) the user can create a counts maps of the ROI, see Fig.2 (Abdo et al. , 2009). The total free electron density consists of the electrons contributed by cosmic ray interaction and ionization. This method of probing the dispersion measure through gamma ray diffuse emission maps could be useful for the process of blind pulsar searches in radio/gamma rays. These searches could be simplified if the dispersion measure is known, since the process of coherent dispersion is computationally intensive (Lorimer, 2005).

Fig. 2. Counts map of the ROI associated with the Vela pulsar.

3. Gamma ray timing of the Vela Pulsar

Detailed installation instructions for both the Science Tools and Enrico can be found at `http://enrico.readthedocs.org` and `http://fermi.gsfc.nasa.gov/ssc/data/analysis/software/`. There are several methods to install these software packages, but the recommended method involves the installation of the Fermi tools through downloading the source code. Installing Enrico is the simplest part since the user only needs to retrieve the binary distribution from the website (a binary distribution of a software package is a folder that contains the pre-compiled software). To manipulate any `.FITS` file one also needs to install HEASOFT from the Fermi site (see `http://heasarc.nasa.gov/lheasoft/`). This software package allows the user to access FITS files, view or plot certain columns and concatenate several photon data files, which is possible since the FITS files retrieved from the Fermi data server are decomposed into smaller FITS files. There are also a number of tutorials on the Fermi site, which include several pulsar gating and likelihood analysis tutorials, see `http://fermi.gsfc.nasa.gov/ssc/data/analysis/scitools/pulsar_gating_tutorial.html` and `http:///data/analysis/scitools/likelihood_tutorial.html` for detailed tutorials and tool commands. Both these tutorials include the process of data retrieval and extraction from the Fermi data server.

For the Fermi analysis of the Vela Pulsar (Abdo et al. , 2009) we used a photon data set from dates MET=239557417 to MET=240105600 between the energy range 300 MeV to 300000 MeV. After the data set had been retrieved from the server, the user will have to perform a selection of photon energies to use in the data set. These steps form part of the pre-processing of data and allow the users to select a subgroup of photon energies that correspond to their source of interest. Assuming that the photon data set is called `Vela_PH00.FITS` and that the space craft file is called `Vela_SC00.FITS`, one could use the commands:

```
> gtselect evclass=2 (this makes a
sub selection)

Input FT1 file[] Vela_PH00.FITS
Output FT1 file[] Vela.FITS
RA  (degrees) (0:360) [] INDEF
Dec  (degrees) (-90:90) [] INDEF
radius (degrees) (0:180) [] INDEF
start time (MET in s) (0:) [] INDEF
end time (MET in s) (0:) [] INDEF
lower energy (MeV) (0:) [] 100
upper energy (MeV) (0:) [] 300000
maximum zenith angle value
(degrees) (0:180) [] 100
Done.
```

If by this stage the user encounters any problems with the Fermi tools, the following command can be invoked:

```
> fhelp <fermi tool>
```

The user can also download the ephemeris of the Vela pulsar from `http://fermi.gsfc.nasa.gov/ssc/data/access/lat/ephems/`. This file can be used to assign phases to each photon in the data set. This could be done by using the Fermi-plugin in the Tempo2 code (Ray et al. , 2011).

```
tempo2 -gr fermi
-f Vela.par
-ft1 Vela_PH00.fits
-ft2 Vela_SC00.fits
- options
```

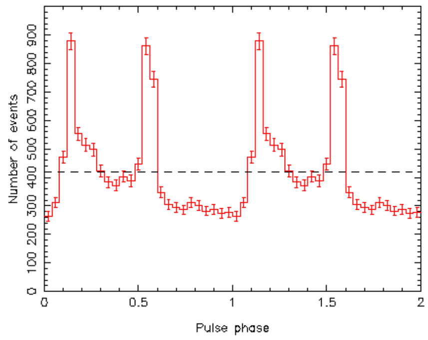

Fig. 3. Folded light curve of the Vela pulsar, clearly showing two peaks (F_1 and F_2), an off-pulse phase (between F_1 and F_2) and a bridge emission phase after F_2 (Hobbs et al. , 2006; Ray et al. , 2011).

The process of classifying the object as a pulsar is simplified if the user knows the ephemeris of the pulsar. If it is not known, then the process becomes more involved. Likelihood analysis can be done via binned or unbinned analysis (the unbinned analysis is the preferred analysis method of Fermi data if one uses large data sets). The user could use an encapsulated Python package (called Enrico) that contains all the steps mentioned above in a somewhat an automated package. This software package is optimized and produces admirable publishable figures (see Fig. 4 and Fig. 5). The user can consult the site `http://enrico.readthedocs.org` for more information and installation guides. Within the same working folder (that contains all the data files, spacecraft files and diffuse models) the user can initialize the Enrico package by following a few simple commands from Sanchez and Deil (2013); first create a `config`-file that contains all the time-cut and energy range information:

```
>enrico_config Vela.conf
```

The user must answer some simple questions regarding the data files and energy ranges for the pulsar photon data that was downloaded by hand (these data files are located in the user's working folder). The package reads the two-year Fermi catalog and automatically creates a `.xml` file for the chosen point sources in the ROI:

```
>enrico_xml Vela.conf
```

The user can then use Enrico to produce a SED for Vela by using the command:

```
>enrico_sed Vela.conf
```

4. Radio timing of the Vela pulsar

Radio data of the Vela pulsar was analyzed using Psrchive (Hotan et al. , 2004). This software allows the user to produce a standard pulse that can be used to calculate times of arrival (TOA). The software also performs de-dispersion of the pulses by using the fact that each pulse is observed in several frequency bands in the line of sight of the pulsar (Lorimer, 2005). Psrchive links with a pulsar catalog and uses the known parameters to perform the analysis. The time delay between two frequencies due to dispersion (f_1 and f_2) is $\Delta t = 4.15 \times 10^6 \mathrm{ms} \times (f_1^{-1} - f_2^{-1}) \times DM$, here DM represents the dispersion measure which is equal to $DM = \int_o^d n_e dl$, with d the distance

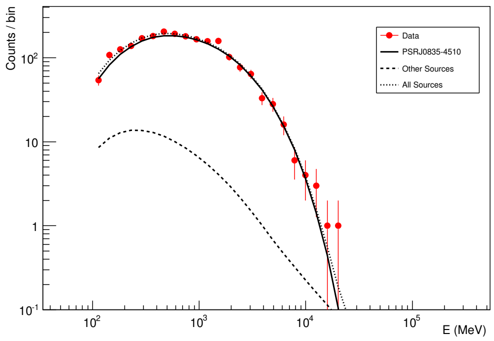

Fig. 4. Fitted SED of the Vela Pulsar fitted with a clear power law with exponential cut-off, $\frac{dN}{dE} = KE^{\alpha} \exp\left(-(\frac{E}{E_c})^{\beta}\right)$ (Becker , 2009).

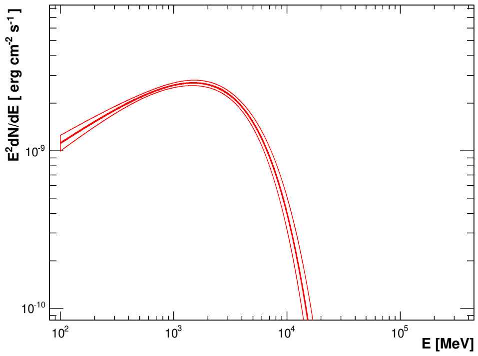

Fig. 5. Just the fitted SED of the Vela Pulsar fitted with a clear power law with exponential cut-off. Also included in the figure is the error band illustrating the goodness of fit. The cut-off for the fit is in the range of 1-10GeV (Backer and Hellings , 1986).

to the pulsar. The data that was analyzed contained 1024 channels and was centered around the 1700 MHz band. To sample the data we used the `psrplot` command, which produces a figure that shows the pulses in each observational band. The effect of dispersion can also be seen (see Fig. 6). From here all the data files can be filtered (remove all the bad channels), summed (to produce a single pulse per observational file) and de-dispersed using the `pazi`, `pam` and `pas` commands, respectively. At this stage the observational data files are considered cleaned, de-dispersed and considerably smaller in size.

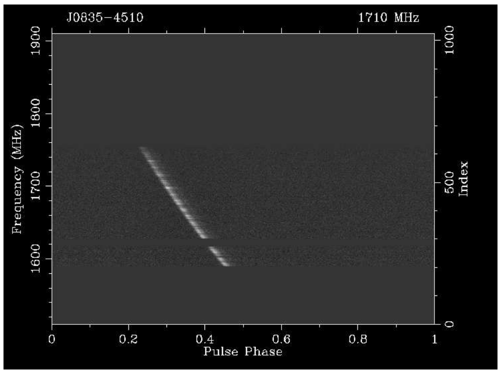

Fig. 6. Frequency cleaned observation data run.

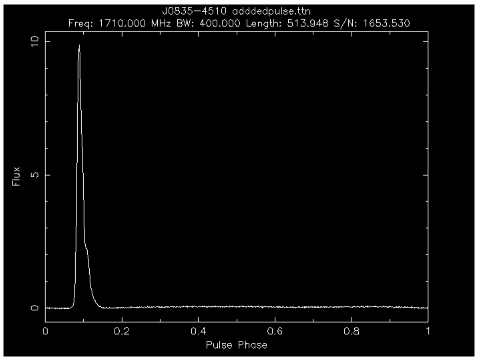

Fig. 7. Standard Vela pulse. This particular pulse was produced by using the observation with the highest SNR and summing the frequency bands to produce one standard pulse that will be used in the calculation of the arrival times of pulses.

The last stage of the analysis involves the production of a standard pulse that can be used to create a timing file. But first, some statistics (specifically signal-to-noise levels) need to be retrieved for each observation. This is done with the command `psrstats` and the user can now select a pulse that has the highest SNR. This pulse could be used as a standard pulse, but still needs some smoothing and base lining (see Fig. 7). At this stage a file containing the TOA for all the pulses for the observation can be created using `pat`. Lastly the TOA can be modeled using standard `tempo2` software to calculate the residuals of the observed TOA against the modeled TOA (see Fig. 8). Tempo2 models the TOA according to an accurate timing model contained in the software.

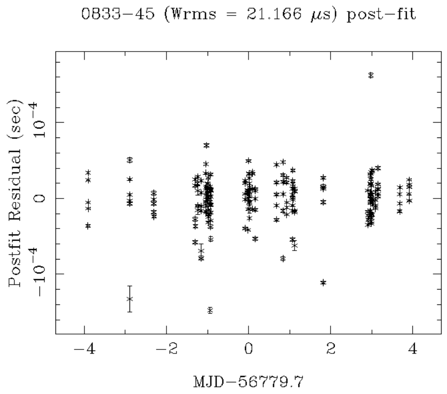

Fig. 8. TOAs residuals as calculated by the Tempo2 code (Hobbs et al. , 2006).

5. Conclusions

Multi-wavelength analysis of pulsars can help to probe the origin of radio, gamma ray and X-ray pulsed emission that are associated with young and old recycled pulsars. However, accurate and lengthy radio observations of pulsars remains the preferred method if one wishes to constrain the search of gravitational wave stochastic signatures in pulsar timings. This is due to error in the TOA (Lorimer, 2005) that scales linearly with the width of the pulse ($\sigma_{TOA} \propto W$).

Timing noise is a leading effect in pulsar timing analysis that threatens the detection of stochastic gravitational wave signatures. This effect can be seen as irregularities in the residuals of the pulsar over a time period of several years and could be linked to effects in the magnetosphere (Lyne et al. , 2010). This work forms part of a campaign for the analysis of timing noise in pulsars frequently observed with the Hartebeesthoek radio telescope over long (decades) time spans.

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