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## Recurrence plots of pulsar profiles

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**Abstract:** Pulsars are rotating neutron stars that have an emission of electromagnetic radiations which is continuous but beamed. Therefore, an observer sees a pulse of radiation when the beam sweeps across his line-of-sight. Averaging over many pulses, a pulse profile specific of the observed pulsar is obtained. Here we propose the use of a recurrence plot for showing it. This plot can highlight specific behaviours in pulse profiles.

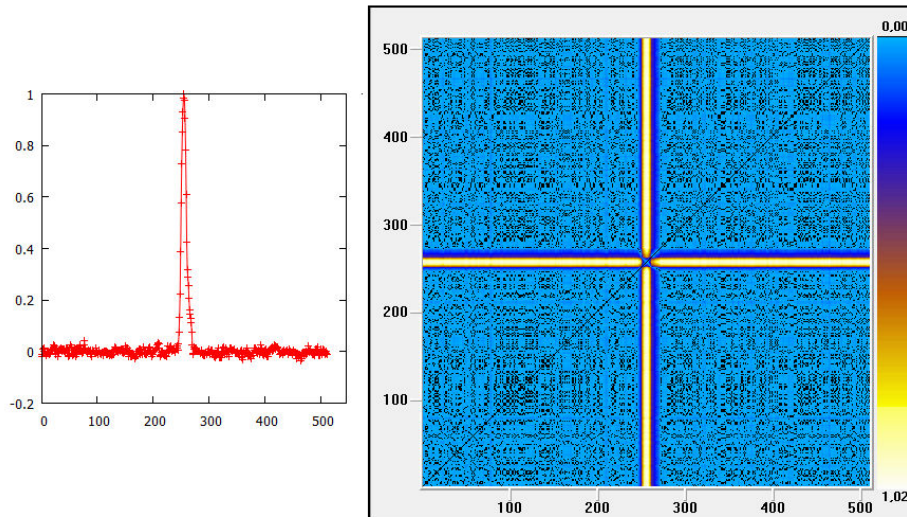
**Keywords:** Recurrence Plots, Pulsars, Pulse Profiles.

Pulsars are rotating neutron stars that have an emission of electromagnetic radiations which is continuous but beamed, so an observer sees a pulse of radiation each time the beam sweeps across his line-of-sight [1]. The existence of neutron stars was proposed in 1934 by W. Baade and F. Zwicky [2], only a year after the discovery of the neutron. In 1939, also Oppenheimer and Volkoff discussed the massive neutron stars [3]. Since these stars were thought to be too faint to be detectable, they received little attention until 1967, when Franco Pacini pointed out that rotating neutron stars can have large magnetic fields and then electromagnetic waves would be emitted [4]. The first pulsar was discovered in November 1967 during a low-frequency-81-MHz survey of extragalactic radio sources, by Jocelyn Bell. She and her advisor, A. Hewish, were using a radio telescope to detect radio scintillations, which are fluctuations in the signals from distant radio sources produced by interstellar plasma. From this discovery, pulsars became an important task of radio astronomy [5].

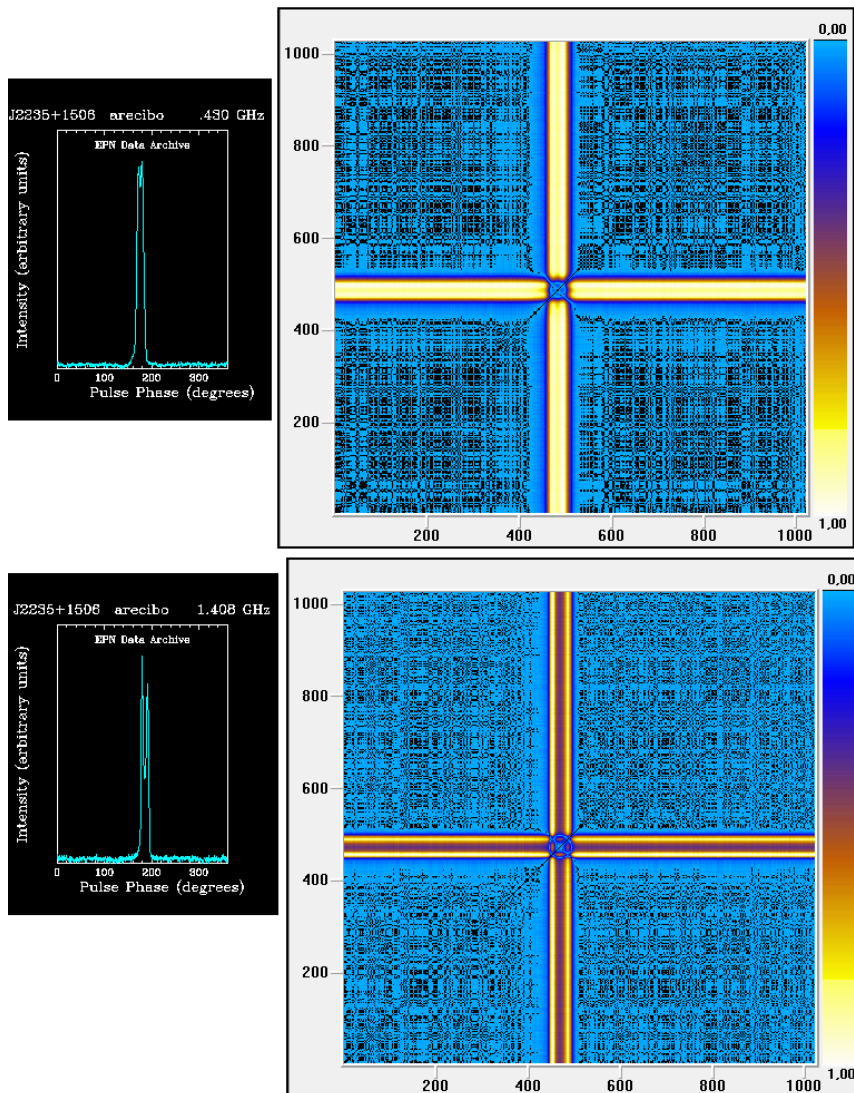
The large part of researches on pulsars are based on their pulsar timing, which is the regular monitoring of the rotation of the neutron star by tracking the times of arrival of the radio pulses. This timing has a noise given by the rotational irregularities observed in all pulsars, noise which is observable as random wandering in the pulse frequency or phase [1]. As stressed in [1], pulsar timing unambiguously accounts for every single rotation of the neutron star over long periods of time. This precise tracking of rotational phase allows pulsar astronomers to probe the physics of neutron stars and test gravitational theories in the strong-field regime [1]. For pulsar timing, astronomers are recording radio data so that, averaging over many pulses, yields a high signal-to-noise average pulse profile. Although individual pulse shapes vary considerably, the shape of the average profile is quite stable.

We can find data and pulse profiles at the EPN Database of Pulsar Profiles, <http://www.epta.eu.org/epndb/>. The pulse profiles are usually plotted in Cartesian graphs. Here, we propose the use of recurrence plots for showing them. Since a recurrence plot reveals all the times when a certain datum attains again the same value, it can be a good choice for highlighting specific features of the pulse profiles. A recurrence plot is therefore a visualisation of a square matrix, where the elements of the matrix are corresponding to those times at which a state of a dynamical system is recurring [6,7].

Let us propose some examples of recurrence plots of pulse profiles. In the Figure 1, we can see a single peak profile: on the left, the plot of 512 ASCII data from PSR J2307+2225 is given [8], and on the right, the corresponding recurrence plot. The recurrence plot is obtained by means of the Visual Recurrence Analysis (VRA) software in the Cold Fire layout [9]. The black dots in the background are showing the presence of noise and chaotic data besides the peak of emission.

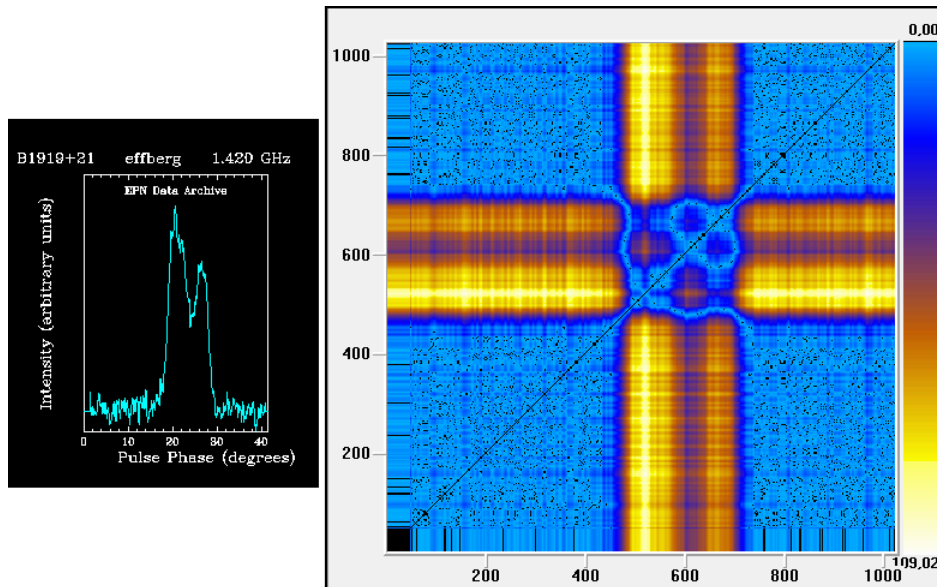


**Figure 1:** On the left, the plot of 512 ASCII data of the pulse profile from PSR J2307+2225 [8]. On the right, the corresponding recurrence plot.



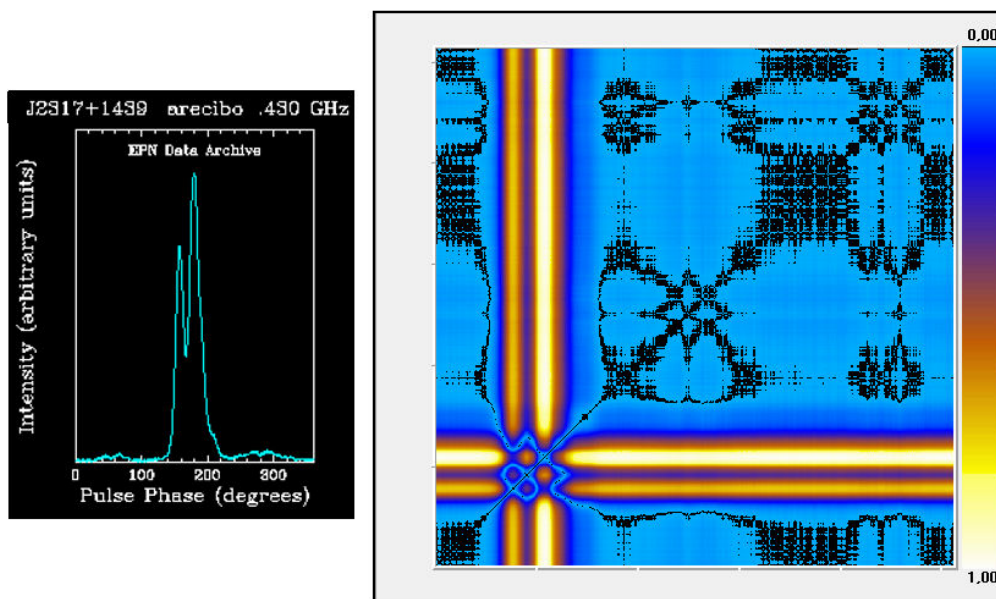
**Figure 2:** On the left, the plot of 1024 ASCII data of the pulse profile of PSR J2235+1506 [10]. On the right, the corresponding recurrence plot.

In the Figure 2 we can see an example of a pulse profile with two narrow peaks [10]. The two panels are showing data at two different frequencies. In this plot too, the black dots in the background are showing the presence of noise. In the Figure 3 we can see the first discovered pulsar: J1919+21. At the time of its discovery, the power and regularity of the signal was thought to resemble a beacon; for a certain time, this source was nicknamed "LGM-1" (for "Little Green Men"). This pulsar is located in the constellation of Vulpecula. This pulsar has profile which is giving a beautiful recurrence plot.



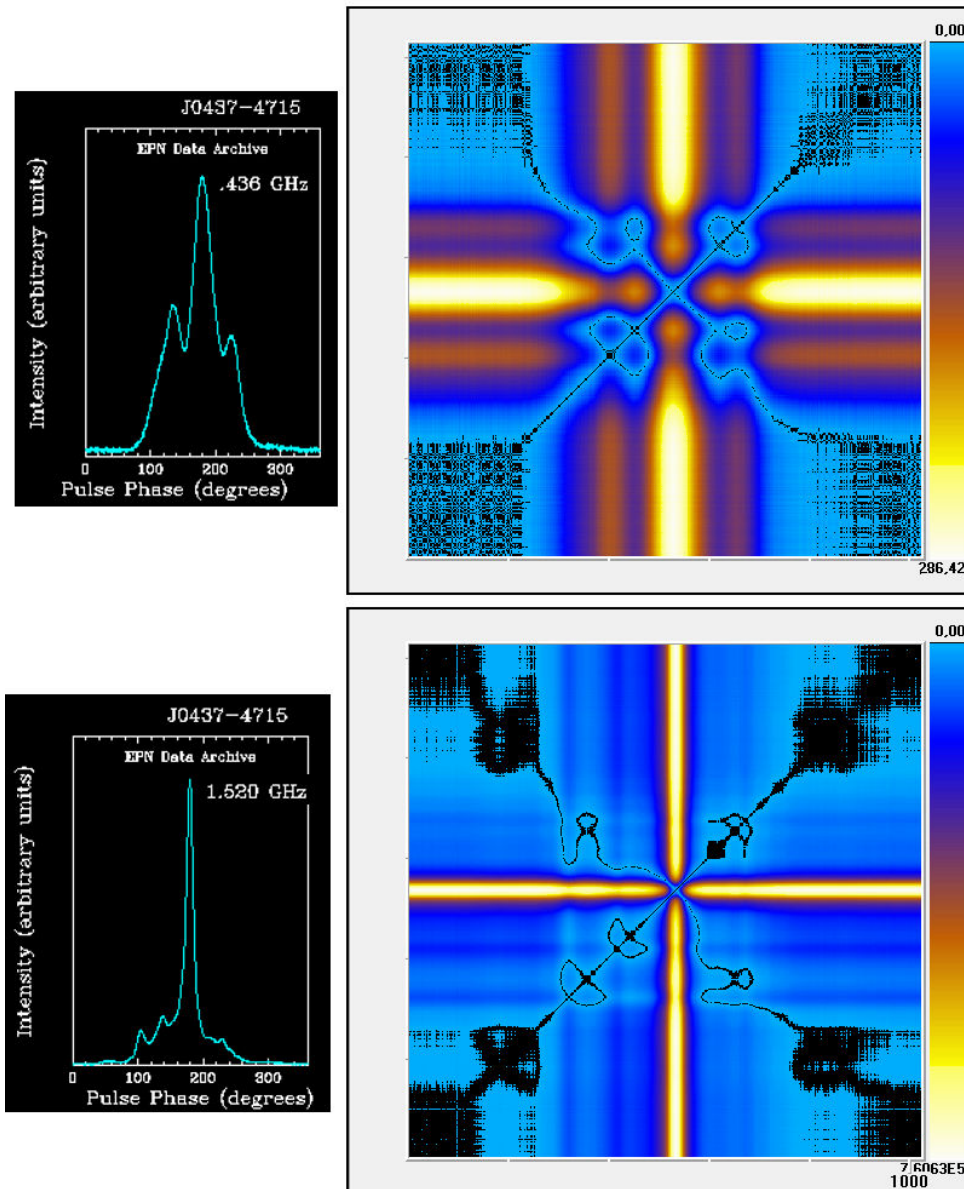
**Figure 3:** On the left, the plot of 1024 ASCII data of the pulse profile at high frequency of PSR J1919 [11]. On the right, the corresponding recurrence plot.

In the following Figure 4, we have the plot of Pulsar J2317+1439 profile [10]. Here we can see an interesting pattern in the background; this pattern is typical of a autoregressive process [7]. It could be interesting to investigate whether this is connected to the pulsar or a background effect.



**Figure 4:** Recurrence plot of Pulsar J2317+1439 [10]. The background is displaying an interesting pattern, typical of a autoregressive process [7].

In the following Figure 5, we can see the pulse profile of PSR J0437-4715. This pulsar was discovered in the Parkes 70 cm survey [12]. It is the closest and brightest millisecond pulsar (MSP) known. The pulsar rotates about its axis 173.7 times per second and therefore completes a rotation every 5.75 milliseconds [13]. It is distinguished as being the most stable natural clock known Its stability is about one part in 1015. Optical observations indicate that the binary companion of PSR J0437-4715 is most likely a low-mass helium white dwarf [13].

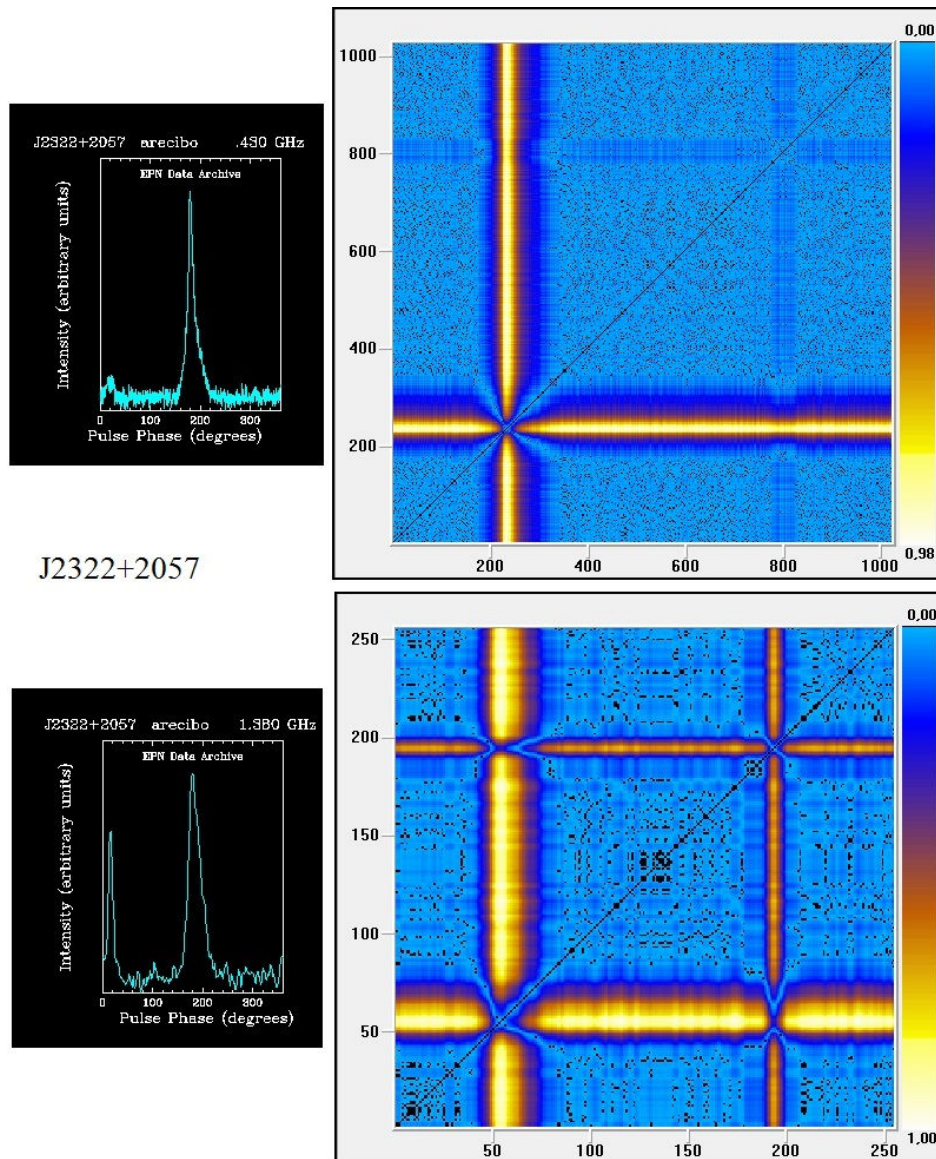


**Figure 5:** PSR J0437-4715 pulse profiles at two different frequencies [14] . Note the presence of a double notch.

Data from this pulsar are showing numerous features including an unusual double notch [15], that we can clearly see in the Figure 5. The last proposed example is given in the Figure 6. Data are from Ref.16. We have two peaks in the pulse profile. However, at the lower frequency, one of the peaks is quite faint, but, in the recurrence plot, it is visible in the background.

It is clear that we can have the same information from ASCII data and from recurrence plots. Here we proposed the use of these plots because they are highlighting the specific behaviours in pulse profiles, as

observed for Figure 4 and in the last proposed example. Further studies are planned, in particular, for investigating all the patterns which we can find in the background of these recurrence plots.



**Figure 6:** PSR J2322+2057 pulse profiles at two different frequencies [16]. Note that we can see two peaks. One is quite faint at the lower frequency, but it is visible in the recurrence plot.

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