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Analysis of the Dispersion Measure Variations in a Sample of 68 Pulsars from Observations by low Frequency Array (LOFAR).

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Abstract
We present dispersion measure (DM) variations analysis for 68 pulsars with data collected from LOFAR. The observations were taken using six International LOFAR Stations in Europe: FR606 in France, SE607 Sweden and DE601, DE602, DE603 stations in Germany over the period of 3.5 years (between June 2014 and November 2017) at the frequency of 150MHz with 80MHz of bandwidth during this time the total number of pulsars observed with FR606 and used is 21, SE607-13 pulsars while a set of 34 sources was obtained from four stations in Germany which makes the total of 68 pulsars. We show that, the variations of the DM measurements show various trends along the span of the observation: increasing or decreasing, and in some cases more changes from one trend to another, (e.g PSRs J1543-0620 and PSR J2048-1616). We find that for a number of pulsars results show consistency with the Kolmogorov distribution (e.g PSRs J1913-0440 and PSR J2157+4017) while other sources show significant difference (PSRs J108+6608 and JO614+2229.We also obtain the DM derivatives (i.e. dDM/dt) for some pulsar in order to examine the correlation between the DM and its derivative. The result of this correlation shows a best-fit with a square-root dependence of 0.6±0.2, which is comparable with the result that was previously obtained by Hobbs et al. (2004), who shows a dependence of square-root between the DM and its derivative; with a gradient of 0.57±0.09.

Key words: *Pulsar, general - ISM Structure, Dispersion measure, LOFAR*

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I. Introduction

The interstellar medium (ISM) is the matter radiation and magnetic fields that occupy the space between the stellar systems in a galaxy. When the radio emission from a pulsar reaches an observer on Earth, it has propagated through different components of the ISM. Throughout this propagation, the emission from pulsar interacts with the free electrons in the ionized gas of the ISM. As a result, three main effects of the ISM on the emission from pulsars can be observed. These effects are scattering, scintillation and dispersion (Lorimer and Kramer 2005).

Example of dispersion can be seen clearly in the frequency-resolved pulse profile from radio pulsars. This effect is best noticed in delay between emitted pulses at lower frequencies, which arrive later, and the pulses emitted at the higher frequencies (e.g Figure 1.1).The so called dispersion

Measure (DM) denotes the amount of ionized ISM between a pulsar and an observer. It also determines the delay time between pulses received at higher frequency compared with its lower frequency counterpart.

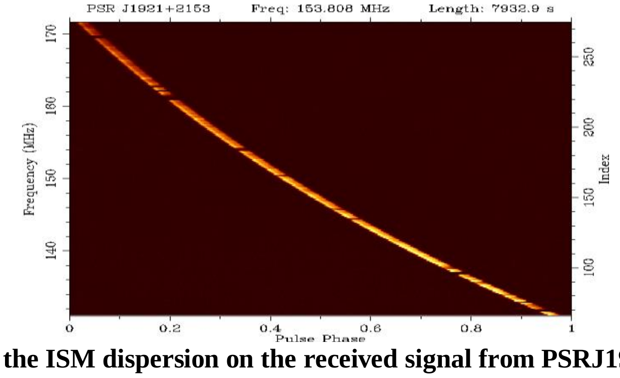

Figure1.1: The effect of the ISM dispersion on the received signal from PSRJ1921+2153.

The plot shows the dispersion in the frequency profile, where the received pulse at lower frequencies arrive later than the emitted pulses at the higher frequencies. The gaps along the pulses of this plot are removed frequency channels due to RFI. This pulsar is included in this study.

The dispersion of a pulsar signal is one of the important characteristics of the ISM. The refractive index (n) of the ionized gas can be obtained from the plasma frequency f_p as follows,

$$n = \sqrt{1 - \frac{f^2p}{f2}} \qquad (1)$$

Note that, the electron density, n_e in ISM environment is given in cm^{-3}.As the approximate value of n_e= 0.03 cm^{-3} gives a plasma frequency, f_p, of 1.5 kHz, then we can approximate the refractivity ($n - 1$) to be -2.4×10^{-10} for a frequency, f, of 100kHz.See Lyne and Graham-Smith (2012) for full explanation. The plasma frequency can be obtained as,

$$f_p = \frac{n_e e^2}{\pi m_e} \approx 8.5kHz\,(\frac{n_e}{cm^{-3}})^{1/2} \qquad (2)$$

Where n is the refractive index of the ionized gas and f is the frequency of the wave, e and m are the electronic charge and mass respectively. Since the group velocity of the traveling pulses is
$v_g = cn$, where c is the speed of light in vacuum, thus for the given electron densities, the group velocity is

$$v^2{}_g = c\,(1 - \frac{n_{e\,e^2}}{\pi m_{ef^2}}) \qquad (3)$$

The travel time T through the distance L, therefore, will be in the form

$$T = \int_O^L \frac{dl}{v_g} = \frac{L}{C} + \frac{e^2 \int_O^L n_{e\,dl}}{2\pi m c v^2} = \frac{L}{C} + 1.345\,X\,10^{-3} v^{-2} \int_O^L n_e\ dl \quad (4)$$

This equation shows the travel time in vacuum (the first term) with an additional term which represents the dispersive delay t. The extra term contains the dispersion measure (DM) given as follows,

$$DM = \int_O^L n_{e\,dl} \qquad (5)$$

The DM measures the electron density between the pulsar and the observer, with units $cm^{-3}pc$, the delay due to dispersion can be written in the form

$$t = D \text{ x } \frac{DM}{f^2} \qquad (6)$$

where D is the dispersion constant which can be given as,

$$D = \frac{e^2}{4\pi mc} = 4.1488 \text{ x } 10^3 MHz^2 pc^{-1} cm^3 \qquad (7)$$

If we have two different frequencies (f_{low} and f_{high}), then equation (6) can be written in another useful form as,

$$\Delta t = D \text{ x } DM \text{ x } (\frac{1}{flow^2} - \frac{1}{fhigh^2}) \qquad (7)$$

II. Observations

The data upon which the study was based were collected from international Low -Frequency AR ray (LOFAR) telescope (ILT) high-band antennas (HBAs), described in detail by Van Haarlem et al. (2013). Specifically, the observations were taken using six international LOFAR stations Europe: Nancay station (FR606) in France, the Onsala station (SE607) in Sweden and four stations in Germany (DE601 - Effelsberg, DE602 - Unterweilenbach, DE603 – Tautenburg, DE605 - Julich) over the period of 3.5 years (between June 2014 and November 2017) at the frequency of 150MHz with 80MHz of bandwidth. During this time the total number of pulsars observed with FR606 and used is 21, SE607-13 pulsars while a set of 34 sources was obtained from four stations in Germany which makes the total of 68 pulsars. The raw data for this observation can be obtained from the LOFAR long time archive (https://lta.lofar.eu). Proposal (LC0-014, LC1-048, LC2-011, LC3-029, LC4-025, LT5-001, LC9-039 and LT10–014. Table 1 shows detailed information on the observation characteristics for each source.

III.Data analysis and Results

The basic processing in this work has been carried out with the psrchive (Hotan et al. 2004; van Straten et al. 2012) software package. As a first step, the data were cleaned from radio frequency interference (RFI), by using a modified version of the 'surgical' algorithm of the clean.py script from the coastguard (Lazarus et al. 2016) python package to remove affected frequency channels and sub-integrations. In the rare case of outliers due to remaining RFI, the observations were also manually inspected and additional cleaning was applied using the psrchive program pazi. On average, 9.0% of data were removed in this process. Pulse profiles can be polarization dependent, so the total intensity profile can be significantly distorted if the different polarization channels are not calibrated correctly, which affects the ToAs. As LOFAR antennas are static, there are several time-dependent projection effects to take into account. We improve the initial timing model (i.e. ephemeris file) for each pulsar in the data set. An updated timing model is very important to obtain a precise DM measurement and improve other pulsar parameters e.g. period derivative, position and proper motion. To achieve this goal, we prepared a bash script that makes use of two python scripts make templates.py and make toas. py which were written by Lucas Guillemot (LPC2E/Orleans; private communication, 2018). To get a precise time series of the DM, we used tempo2 to fit for DM for each observation individually. This approach avoids any correlation of the measured DMs with other (time-dependent) timing parameters. To mitigate the impact of outlier ToAs on our measured DM, we apply an automatic To A rejection scheme as was done similarly in Tiburzi et al. (2019).

IV.Results

Table1: The summary of observation, dispersion measure derivative for pulsars in this study. Where PSR is the name of pulsar, DM Fitting Range is the date range between the first and the last observation of the pulsar in MJD, dDM/dt is the dispersion measure derivative and dDM/dterr is the uncertainty of the DM derivative.

PSR	DM Fitting Range (MJD)	dDM/dt (cm^{-3}pc/yr)	dDM/dt err	PSR	DM Fitting Range (MJD)	dDM/dt (cm^{-3}pc/yr	dDM/dt err
J0141+6009	56852-58048	0.000 04	0.000 08	J0055+5117	57137-58075	0.000 12	0.001 87
J0323+3944	56887-58048	0.000 67	0.0001	J0108+6608	56539-58048	-0.0010	0.000 33
J0332+5434	56887-58049	0.000 24	0.000 03	J0139+5814	56582-58074	0.000 71	0.000 13
J0454+5543	56887-58056	0.000 02	0.000 03	J0304+1932	56532-58027	0.000 03	0.000 12
J0543+2329[#]	56887-58056	0.004 92	0.009	J0343+5312	56525-58069	0.001 27	0.001 23
J0613+3731[*#]	56851-58056	-0.032 50	0.0004	J0358+5413	56542-58076	-0.001 55	0.000 08
J0814+7429	56886-58056	-0.000 19	0.0001	J0406+6138	56699-58074	-0.000 05	0.000 23
J0837+0610	56886-58056	-0.001 15	0.000 06	J0452-1759	56525-58077	0.001 53	0.000 44
J0953+0755	56865-58056	-0.000 06	0.000 04	J0528+2200	56525-57965	0.001 08	0.000 18
J1136+1551	56768-58055	0.000 57	0.000 03	J0614+2229	56570-58047	0.000 15	0.000 12
J1239+2453	56886-58055	-0.000 94	0.000 03	J0629+2415	56524-58075	-0.001 97	0.000 14
J1509+5531	56769-58055	-0.001 18	0.0001	J0820-1350	56532-58075	0.000 82	0.000 13
J1543-0620	56941-57159	-0.003 83	0.0006	J0823+0159	56532-58077	-0.000 44	0.000 24
J1645-0317[#]	56803-58055	-0.001 04	0.043 17	J0826+2637	56531-57873	-0.000 15	0.000 04
J1740+1311	56863-57964	-0.001 92	0.0002	J0922+0638	57453-58075	0.003 53	0.000 31
J1825-0935	56886-58055	-0.0001	0.0001	J0946+0951	57451-58076	-0.000 31	0.001 48
J1933+2421[#]	56865-58055	0.023 18	0.086	J1543-0620	56934-58074	-0.001 43	0.000 06
J2018+2839	56886-58055	-0.000 15	0.000 02	J1740+27[**]	57228-58075	0.001 19	0.000 72
J2113+4644[#]	56886-57965	-0.034 42	0.153	J1752-2806	56552-58034	0.001 10	0.000 22
J2225+6535	56859-58055	-0.006 56	0.0004	J1820-0427	56531-58074	0.006 42	0.000 52
J2313+4253	56859-58055	0.000 48	0.000 05	J1834-0426	56531-58083	-0.000 01	0.000 26
J0051+0423	57376-58118	-0.000 74	0.0002	J1900-2600	56530-57271	0.001 50	0.001 82
J0102+6537[#]	57369-58118	-0.008 06	0.003	J1913-0440	56552-58076	-0.007 80	0.000 37

[#] Pulsars excluded from analysis
[**] LOTAAS discovered
[*] LOTAS discovered

Table2: The dispersion measure derivative for pulsars in this study. Where PSR is the name of pulsar, DM Fitting Range is the date range between the first and the last observation of the pulsar in MJD, dDM/dt is the dispersion measure derivative and dDM/dterr is the uncertainty of the DM derivative.

PSR	DM Fitting Range (MJD)	dDM/dt (cm^{-3}pc/yr)	dDM/dt err	PSR	DM Fitting Range (MJD)	dDM/dt (cm^{-3}pc/y)	dDM/dt Err
J0335+4555	57355-58118	-0.000 06	0.000 13	J1921+2153	56543-58075	-0.000 03	0.000 02
J0540+3207	57376-58118	-0.000 12	0.000 27	J1932+1059	56700-58048	0.000 25	0.000 01
J0546+2441#	57377-58119	-0.191 11	0.486 58	J1935+1616	56532-58076	0.002 61	0.000 33
J0700+6418#	57370-58119	-0.028 21	0.053 79	J1943-1237#	57452-58075	-0.004 11	0.142 43
J0815+4611**	57363-58119	0.000 72	0.000 43	J1948+3540#	57132-58076	-0.009 87	0.006 87
J0921+6254	57363-58119	0.000 22	0.0002	J2022+2854	56573-58076	0.000 19	0.000 02
J1115+5030	57362-58119	0.000 49	0.0003	J2022+5154	56524-58074	-0.000 07	0.0001
J1321+8323	57363-58118	0.000 02	0.000 82	J2048-1616	56524-58082	0.000 12	0.000 14
J1840+5640	57705-58118	-0.000 30	0.000 18	J2219+4754	56531-58075	0.001 34	0.000 04
J2321+6024#	57376-58118	-0.000 36	0.004 04	J2257+5909	56538-58076	0.014 42	0.0008

Pulsars excluded from analysis
** LOTAAS discovered
* LOTAS discovered

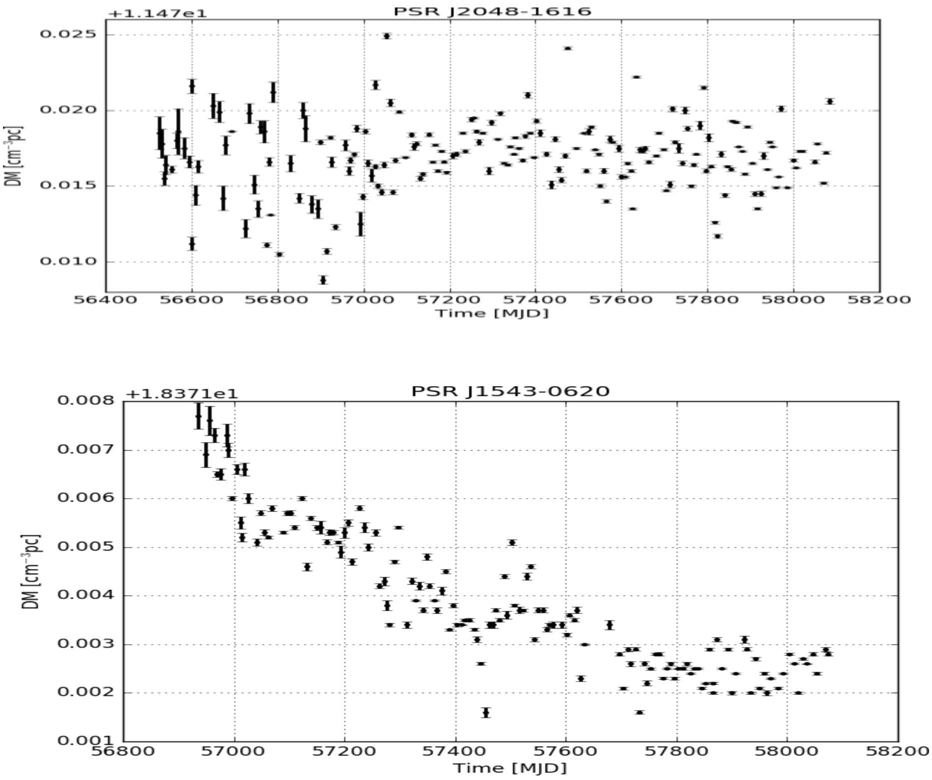

Figure: 1 shows The DM variation for PSRJ1543−0620 and PSR J2048-1616

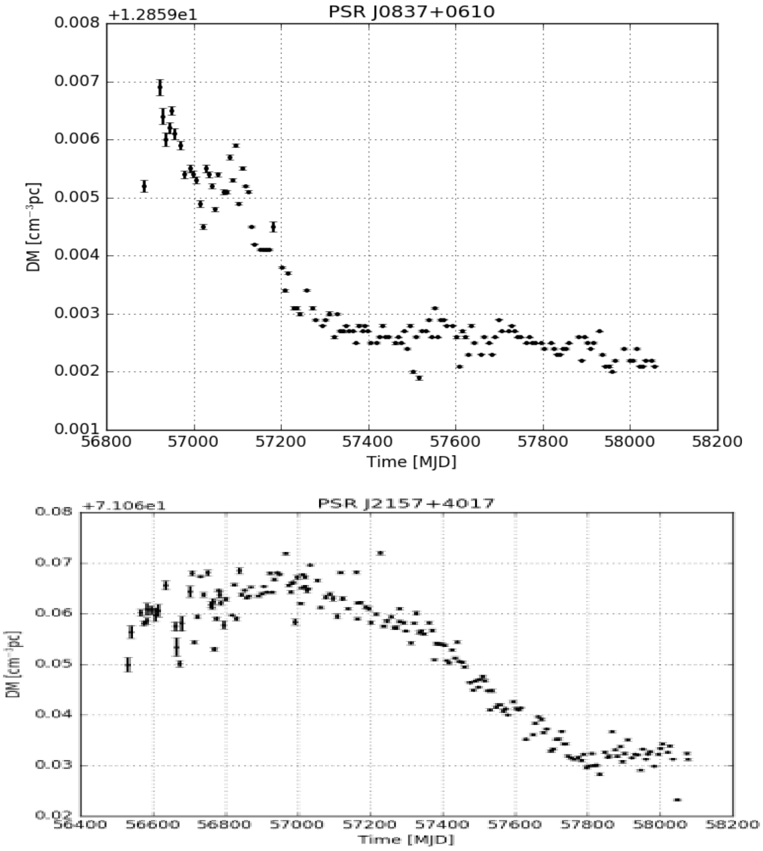

Figure 3 shows the DM variation for PSRs J0837+610 and J2157+4017

Following a similar procedure mentioned above, we used the DM and its derivative measured from data to plot the DM values against the absolute values of the DM derivative. We then performed a linear fit to the result. At this stage, we only included the DM derivative values with an uncertainty less than 0.003. The result of this analysis showed a best fit with a square-root dependence of 0.6±0.2, which is compatible with the value found by Hobbs et al. (2004)

DM and DM Derivatives (dDM/dt)

For each pulsar included in this paper, we have obtained DM measurements. Figure 1and 2 shows the DM variations for PSR J1543-0620 and PSR J2048-1616. The two pulsars showed a clear decreasing trend and a flat trend in their DM measurements, respectively. The scale variations for all pulsars showed different types of variations which is ranging from large-scale variations e.g., PSRs J1136+1551, J1933+2421, J1645-0317 and J1943-1237 to small-scale variations e.g., PSRs J2022+2854, J0826+2637, J1840+5640 and J0332+5434. Some pulsars have also shown more changes from one trend to an other along the span of the observation e.g., PSRsJ1921+2153, J2157+4017,J1955 +5059 andJ0837+0610. An example of these pulsars was presented in Figures 2. In this figure, PSR J0837+0610 (top panel) shows a clear decreasing trend in early observations with short-term variation in the spread points around MJD57100 which could be attributed to the underestimation of the DM uncertainties. In the bottom panel, we also see a clear decreasing trend between the points MJD57000 and 57800. The DM derivative is the linear change of the DM over the span of the data. Practically, it was determined for each pulsar by applying near fit to the DM measurements. The unit of DM derivative is cm^{-3} pc yr^{-1}. Table 1 and 2 shows the measured values of the DM derivative and the uncertainties for all pulsars included in our study. Another useful result is to obtain measurements of the correlation between the DM and its derivative. This correlation can be estimated by plotting the DM values against the absolute values of the DM derivative. Then, a linear fit was applied to the plot. This analysis method was first applied by Backer et al. (1993), which they concluded that the absolute value of DM derivative is proportional to the square root of DM. Another study was done by Hobbs et al. (2004) who showed a best fit of, and a gradient of 0.57±0.09.

$[dDM/dt]\ \approx 0.0002\sqrt{cm-^{3}}pc\ yr-^{1},$ (8)

V. Discussion

Most of the pulsars in our sample show DM variability, on diverse time scale, DM measurements for a number of pulsars were consistent with the theoretical model of the Kolmogorov power spectrum, which is used to describe the turbulence nature of the interstellar medium. To improve our sensitivity to low-amplitude variations, we computed a running average of the DM time series for each observation MJD, a weighted average over all observations was formed, weighting each DM value by the inverse of its variance. Hobbs et al. (2004) found a correlation between DM and its time derivative in their sample of 374 pulsars. When fitting a power law, they found an exponent of 0.57(9), consistent with a square-root dependence: $|dDM/dt| = 0.0002 \sqrt{DM}$ (DM in cm^{-3} pc and dDM/dt in cm^{-3} pc yr^{-1}). Applying this analysis to our data. The result of this analysis showed a best fit with a square-root dependence 0.6±0.2, which is consistent with the Hobbs et al. (2004) result, albeit not very constraining

VI. Conclusion

We present low-frequency DM time series for 68 pulsars over up to 3.5 years, obtained from observations with the LOFAR Core and the individual GLOW telescopes, all pulsars show significant variations in DM. All of the IISM-related DM variations we present are consistent with a Kolmogorov turbulence spectrum. The results of this study have shown that the DM variations are ranging from large-scale variations to small-scale variations over the span of the data. Acknowledging the caveat that LOFAR often provides a high DM precision for pulsars that are poorly timed at higher frequencies, and vice versa, we show that our LOFAR DM monitoring could be used to correct variations of the dispersive delays in higher-frequency observations from PTAs. We do not find evidence for a frequency-dependent DM, so we expect the impact of this effect to be limited.

References

[1]. Backer, D., Hama, S., Van Hook, S., and Foster, R. (1993).Temporal variations of pulsardispersion measures. The Astrophysical Journal, 404: 636 – 642.

[2]. Hobbs, G., Lyne, A., Kramer, M., Martin , C., and Jordan , C. (2004). Long-term timing observations of 374 pulsars. Monthly Notices of the Royal Astronomical Society, 353(4):1311–1344.

[3]. https://lta.lofar.eu

[4]. Lorimer, D. R. and Kramer, M. (2005).Handbook of pulsar astronomy. Cambridge University Press.

[5]. Lyne, A. and Graham-Smith, F. (2012).Pulsar astronomy. Number 48. Cambridge University Press.

[6]. Lazarus,P.,Karuppusamy,R.,Graikou,E.,Caballero,R.,Champion,D.,Lee,K.,Verbiest,J., and Kramer, M.(2016). Prospects for high-precision pulsar timing with the new effels berg psrix backend. Monthly Notices of the Royal Astronomical Society,458(1):868–880.

[7]. Hotan , A. W., Van Straten, W.,and Manchester,R. (2004). Psrchive and psrfits: an open approach to radio pulsar data storage and analysis Publications of the Astronomical Society of Australia, 21 (3):302–309. Journal of Open-Source Software, 3 (22):538.

[8]. Tiburzi, C., Verbiest, J. P. W., Shaifullah, G. M., et al. 2019, MNRAS, 487, 394

[9]. Van Haarlem, M. a., Wise, M., Gunst, A., Heald, G., McKean, J., Hessels, J., De Bruyn,A., Nijboer, R., Swinbank, J., Fallows, R., et al. (2013). Lofar: The low-frequency array. Astronomy & Astrophysics, 556: A2.

[10]. Van Straten, W., Demorest, P., & Oslowski, S. (2012). Astronomical Research and Technology, 9, 237

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