Studies of the interstellar medium using pulsar observations

Wojciech Lewandowski[1], Jarosław Kijak[1], Leszek Błaszkiewicz[2,3], Karolina Rożko[1] and Andrzej Krankowski[2]

1. Janusz Gil Institute of Astronomy, University of Zielona Góra, Szafrana 2, 65–516 Zielona Góra , Poland
2. Space Radio-Diagnostics Research Centre, University of Warmia and Mazury, Prawocheńskiego 9, 10–720 Olsztyn, Poland
3. Faculty of Mathematics and Computer Sciences, University of Warmia and Mazury, Słoneczna 54, 10–710 Olsztyn, Poland

One of the most important effects occurring during the propagation of the pulsar-emitted radio waves through the interstellar medium (ISM) is the temporal pulse broadening caused by the scattering of the signal on interstellar matter. Our latest studies of this phenomenon performed for the largest sample of pulsars ever used for this purpose, have shown that the amount of the observed pulse broadening strongly depends on the observing frequency. However, the slope of the dependence is different from the theoretical predictions based on simple scattering models of the turbulent ISM. Low frequency observations are crucial for the study of the scattering phenomenon, since it is at frequencies below a few hundred megahertz where the effects of scattering are the strongest. Therefore the newly constructed telescopes (such as LOFAR, MWA or LWA) and the future ones (such as SKA) that are working in this frequency range will be perfect instruments to study the ISM effects on pulsar radiation. In this field the progress can be made using smaller telescopes such as single stations of LOFAR. Here we present the first results of interstellar scattering observations using the PL-612 LOFAR station, located in Bałdy near Olsztyn, Poland.

1 Interstellar scattering

The temporal and angular broadening of the pulsar profiles is caused by the scattering of the radio waves emitted by a pulsar in the ionised interstellar medium (ISM). Such scattering may happen along with other effects such as an interstellar dispersion of the signal, as well as the interstellar scintillations. The current models of the interstellar scattering predict that the frequency dependence of the observed parameters is closely bound to the density fluctuations caused by turbulent ISM. Most of the models assume, that the turbulence spectrum in the ISM is the same as the Kolmogorov's spectrum, however there is increasing observational evidence that suggests otherwise (see Lewandowski et al., 2013, 2015a,b). The geometry of this phenomenon is the other factor which influence the observed parameters of the scattering and scintillation phenomena. In the simplest models it is usually assumed, that most of the scattering of the pulsar signal happens in a single *thin screen* - a small region along the pulsar's line-of-sight with increased ISM density and/or the strongest density fluctuation. The observed parameters of both phenomena depend on the location of such *thin screen* along the line of sight. There is also some observational evidence indicating that the scattering may occur in a more complicated geometry (like in multiple screens instead of one), however the analytical theory of such occurrences is not fully developed yet. Only the multi-frequency study of the

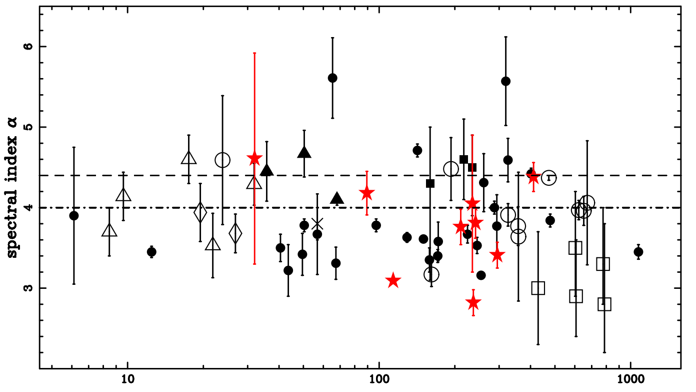

Fig. 1: A plot of the spectral index of pulse broadening α versus the dispersion measure (DM) taken from Lewandowski et al. (2015b). Diffetent plot marks represent data taken from different literature sources - see Lewandowski et al. (2015b) for a full reference list.

scattering and scintillation properties will allow us to separate the geometry effects from the influence of the ISM's turbulence spectrum on the observed parameters. The observations and data analysis shown here may be used in the future as the basis, as well as the testing ground for theoretical models of scattering with more complicated geometries.

2 Frequency dependence of scattering

The estimates of the scatter time frequency scaling index α may be used to ascertain the spectrum of the turbulence in the ionised interstellar medium. Simplest models predict, that for the thin-screen scattering the frequency scaling index α should be between 4.0 and 4.4 (the later is the value obtained with the assumption of Kolmogorov's turbulence).

Löhmer et al. (2001, 2004) noticed that for pulsars with large dispersion measure (DM) values the scatter time spectral scaling index α tends to be much lower than the theoretically predicted values. This can possibly be explained only by the existence of multiple scattering screens or anisotropy effects. However, we have shown (Lewandowski et al., 2013, 2015a,b) that such deviations from the model predictions are common for pulsars regardless of their DM value, including the closest ones (see Fig. 1). In such cases the possibility of the occurrence of multiple scatterings is rather doubtful. The number of pulsars that seem to behave this way is steadily growing, and the deviations from the simple model predictions are much more common that it was previously assumed (see also Geyer et al., 2017; Krishnakumar et al., 2017). Hence we believe that the term *anomalous scattering* used by the original researchers does no longer apply, as this kind of behaviour appears to be pretty common occurrence in the pulsar population.

3 Scattering versus the dispersion measure

The amount of observed scattering is proportional to the strength of the electron density fluctuations along the line of sight, rather than to the column density of the

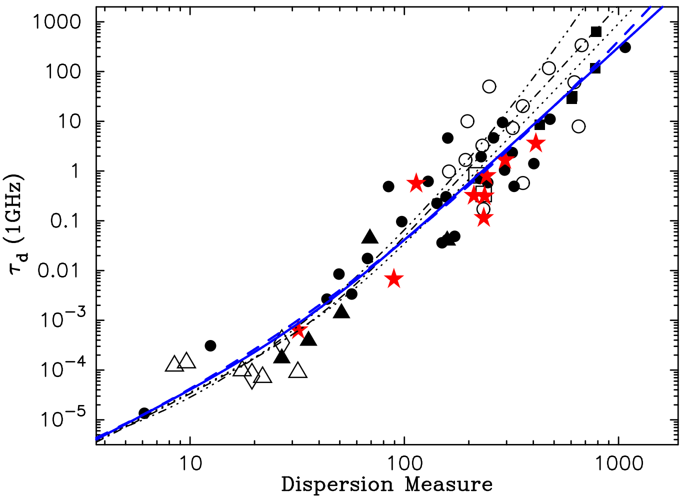

Fig. 2: The amount scatter time (normalized to the frequency of 1 GHz) versus the dispersion measure. Plot taken from Lewandowski et al. (2015b). Diffetent plot marks represent data taken from different literature sources - see Lewandowski et al. (2015b) for a full reference list.

electrons (which is measured by the DM). However, the more distant pulsars with higher DM values tend to show more scattering (Bhat et al., 2004; Lewandowski et al., 2015a,b). Fig. 2 shows the observed (and normalized) scatter time in ms, versus the dispersion measure for pulsars with multi-frequency scatter time measurements. Notice the large spread of data on the plot: for a given DM value the scatter time for two different pulsars may differ by up to three orders of magnitude.

4 Pulsar observations using the PL-612 LOFAR station

PL-612 is one of the three polish LOFAR stations (see Błaszkiewicz et al., 2016). A group of scientific institutions in Poland formed the Polish LOFAR Consortium named POLFAR in 2007 (Krankowski et al., 2014). The agreement was signed by the representatives of the Jagiellonian University (JU), the Space Research Center of Polish Academy of Sciences (SRC PAS), the University of Warmia and Mazury (UWM), the Nicolaus Copernicus University, the University of Zielona Góra, the Nicolaus Copernicus Astronomy Centre of Polish Academy of Sciences, the University of Szczecin, the University of Environmental and Life Sciences and the Pionier company - Polish Optical Internet.

The PL-612 station, operated by the UWM's Space Radio-Diagnostics Research Centre was the first to be equipped with the pulsar observing system, similar to the one used by the member of German LOng Wavelength consortium (GLOW). The system was developed and constructed with the help of GLOW, especially the group at the University of Bielefeld.

For the purpose of pulsar observations we currently use the lower frequency range of the HBA antennas, with 36 MHz or 72 MHz bandwidth centered around 150 MHz . The data acquisition system is based on the one employed by GLOW for the use with the German LOFAR stations. Two workstations with two Xeon-3 processors each (40 cores) and 128 GB of RAM are processing the raw voltage data using the LOFAR und MPIfR pulsare (LuMp) software system originally developed by James Anderson[1]. After storing voltages after analog station beam-former the data is coherently dedispersed offline and split into 183 frequency channels by forming a polyphase filterbank during dedispersion as implemented in DSPSR (van Straten & Bailes, 2011). For regular pulsar observations the data is folded to form 10-second sub-integrations, however the single-pulse observations are also possible. Further analysis and interference cleaning is made with the help of the PSRCHIVE package (Hotan, van Straten & Manchester, 2004). The narrow-band interference is removed using a median filter as implemented by the zap routine in PSRCHIVE (Hotan et al., 2004). Finally the cleaned data is prepared for further analysis. More information about pulsar observations with the PL-612 station can be found in the article by Leszek Błaszkiewicz et al. in these proceedings.

5 Observations of pulse broadening using PL-612 LOFAR station

The low frequency observations with LOFAR are excellent extension of the research done on this topic so far (see Lewandowski et al., 2013, 2015a,b; Geyer et al., 2017; Krishnakumar et al., 2017), as the current knowledge about the frequency dependence of pulse broadening is somewhat limited to mid- and high-dispersion measure pulsars. For sources with DM below $100\,\mathrm{pc\,cm^{-3}}$ interstellar scattering manifests itself (usually) only at frequencies below 200 MHz, which is perfect for LOFAR observations. The high fractional bandwidth of LOFAR receivers and a steep slope of the scattering frequency dependence makes it possible to measure the evolution of pulse broadening within the observed bandwidth. For example, in observations centered at 150 MHz, with 75 MHz bandwidth we expect that the profile broadening at the lower end of the bandwidth will be about 8 times larger than at the upper edge of the band (assuming standard scattering models).

The low-DM part of the α versus DM plot shown in Fig. 1 definitely seems under-populated, which is due to the fact that such objects exhibit pulse broadening only at low radio frequencies. This will change in the near future with the new generation of low-frequency radio telescopes already working or should be operating soon. For a sample of strong pulsars even the small telescopes such as a single LOFAR station may be successfully used for interstellar scattering observations. Therefore, we started an observing project using the PL-612 station.

First pulsar data were gathered in the summer of 2016, and the regular pulsar observations started in autumn. The observations are conducted at the frequency of about 150 MHz, with 72 MHz bandwidth. These parameters give us a large fractional bandwidth, which means that the frequency evolution of scattering is observable within the band (see the examples in Fig. 3). The process of splitting of the bandwidth into several sub-bands, and estimation of the amount of pulse broadening separately in each band, allows us to estimate the frequency scaling slope α from a single observation.

Relatively easy access to the telescope allows us not only to study different objects, but also check for the variability of scattering properties, which may arise due to the ISM inhomogeneity and anisotropy effects which are predicted in the theory

[1] https://github.com/AHorneffer/lump-lofar-und-mpifr-pulsare/

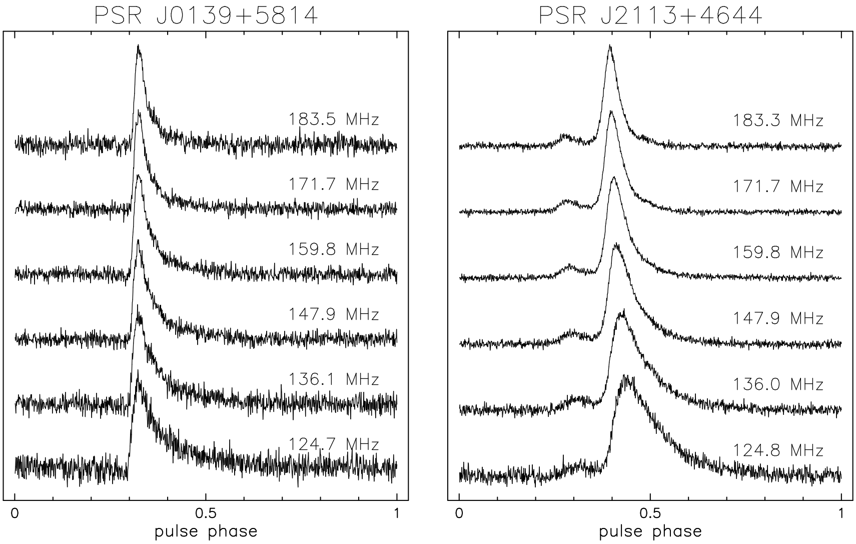

Fig. 3: Two examples of pulse profile sets (relative flux vs. pulse phase) based on observations from the PL-612 LOFAR station. The observing bandwidth of 72 MHz was split into six sub-bands, and the increase of the pulse broadening towards lower frequencies is clearly visible. The dispersion measure for the pulsars shown is $73.8\,\mathrm{pc\,cm^{-3}}$ for J0139+5814 and $141.3\,\mathrm{pc\,cm^{-3}}$ for J2113+4644.

of interstellar scattering. These effects were only sparsely studied until now, as this kind of research requires long-term observations which are usually hard to conduct using larger telescopes due to observing time constrains. On the other hand, small telescopes, such as LOFAR stations in Poland are perfect tools for conducting such long-term monitoring projects.

Acknowledgements. We thank to the Ministry of Science and Higher Education of Poland for granting funds for construction of three polish LOFAR stations (decision No. 6339/IA/158/-2013.1 of July, 11 2013), Polish contribution to the International LOFAR Telescope (decision No. DIR/WK//2016/05) and for maintenance of the LOFAR PL-612 (decision No. 220815/E-383/SPUB/2016/2). Poznan Supercomputing and Networing Center (PSNC) and Olsztyn Metropolitan Area Network (OLMAN) are responsible for the IT and Network service of polish part of LOFAR system and local PL-612 Bałdy IT infrastructure maintenance respectively. We would like to thank GLOW Consortium (particularly to radio astronomy group of Facultat für Physik of Universität Bielefeld) for permission to use software for pulsar observations and help. Computer Center at University of Zielona Góra has aided this research, in part, with its computing resources. The paper was partially supported by the grant DEC-2013/09/B/ST9/02177 of the Polish National Science Centre.

References

Bhat, N. D. R., et al., *ApJ* **605**, 759 (2004)

Błaszkiewicz, L., et al., *Acta Geophysica* **64**, 293 (2016)

Geyer, M., et al., *MNRAS* **470**, 2659 (2017)

Hotan, A. W., van Straten, W., Manchester, R. N., *PASA* **21**, 302 (2004)

Krankowski, A., et al., in Microwaves, Radar, and Wireless Communication (MIKON), 2014 20th International Conference, volume 1, 6899926 (2014)

Krishnakumar, M. A., Joshi, B. C., Manoharan, P. K., *ApJ* **846**, 104 (2017)

Lewandowski, W., Dembska, M., Kijak, J., Kowalińska, M., *MNRAS* **434**, 69 (2013)

Lewandowski, W., Kowalińska, M., Kijak, J., *MNRAS* **449**, 1570 (2015a)

Lewandowski, W., et al., *MNRAS* **454**, 2517 (2015b)

Löhmer, O., et al., *ApJL* **562**, L157 (2001)

Löhmer, O., et al., *A&A* **425**, 569 (2004)

van Straten, W., Bailes, M., *PASA* **28**, 1 (2011)