Flux density measurements of GPS candidate pulsars at 610 MHz using interferometric imaging technique

M. Dembska\textsuperscript{1}, R. Basu\textsuperscript{2,3}, J. Kijak\textsuperscript{2} and W. Lewandowski\textsuperscript{2}

\textsuperscript{1} German Aerospace Center, Institute for Space Systems, Robert Hooke Str. 7, D-28359 Bremen, Germany
\textsuperscript{2} Institute of Astronomy, University of Zielona Góra, Lubuska 2, 65-265 Zielona Góra, Poland
\textsuperscript{3} National Centre for Radio Astrophysics, Pune University Campus, Postbag 3, India 411007

ABSTRACT
We conducted radio interferometric observations of six pulsars at 610 MHz using the Giant Metrewave Radio Telescope (GMRT). All these objects were claimed or suspected to be the gigahertz-peaked spectra (GPS) pulsars. For a half of the sources in our sample the interferometric imaging provides the only means to estimate their flux at 610 MHz due to a strong pulse scatter-broadening. In our case, these pulsars have very high dispersion measure values and we present their spectra containing for the first time low-frequency measurements. The remaining three pulsars were observed at low frequencies using the conventional pulsar flux measurement method. The interferometric imaging technique allowed us to re-examine their fluxes at 610 MHz. We were able to confirm the GPS feature in the PSR B1823−13 spectrum and select a GPS candidate pulsar. These results clearly demonstrate that the interferometric imaging technique can be successfully applied to estimate flux density of pulsars even in the presence of strong scattering.

Key words: pulsars: general - pulsars: individual: B1750−24, B1800−21, B1815−14, B1822−14, B1823−13, B1849+00

1 INTRODUCTION
In the case of most pulsars, their observed radio spectra can be described using a power law with a negative spectral index of $-1.8$ or (for a small fraction of sources) two power laws with spectral indices of $-0.9$ and $-2.2$ with a break frequency $\nu_b$ on average of 1.5 GHz (Maron et al. 2000). Some pulsars also exhibit a low-frequency turnover in their spectra (Sieber 1973; Lorimer et al. 1995). A spectrum of that kind is characterized by a positive spectral index below a peak frequency $\nu_p$ of about 100 MHz (with a few exceptions when the spectrum peaks at frequencies up to several hundred MHz). However, Kijak et al. (2011b) pointed out a small sample of pulsars that peak around 1 GHz and above. Such an object, called the gigahertz-peaked spectrum (GPS) pulsar, is described as a relatively young source that has a high dispersion measure (DM) and usually adjoins a dense, sometimes extreme vicinity. This suggests that the GPS in pulsars might be caused by either the conditions around neutron stars or the physical properties of the interstellar medium.

The strongest argument for environmental origin of the high-frequency turnover in radio pulsars spectra is the evolution of PSR B1259−63 spectrum. Kijak et al. (2011a) showed that the spectrum of the pulsar at the various orbital phases exhibits both a shape and a peak frequency evolution due to the orbital motion of the pulsar around its companion Be star LS 2883 on a very elliptical orbit. The PSR B1259−63 spectrum demonstrates a strong similarity with the gigahertz-peaked spectra, especially when the pulsar in its motion gets closer to its companion star. Kijak et al. (2011a) proposed two effects which can be responsible for the observed variations, the free-free absorption in the stellar wind and the cyclotron resonance in the magnetic field associated with the disk of Be star. Both these processes assume the absorption to be caused by external factors, like in the cases of the isolated GPS pulsars (Kijak et al. 2011a).

Kijak et al. (2013) studied the radio spectra of two magnetars PSRs J1550−5418 and J1622−4950 and in both cases their radio spectra clearly peak at the frequencies of a few GHz. Both these magnetars are associated with supernova remnants and hence surrounded by ionized gas which can be responsible for the free-free absorption of the radio waves. The authors concluded that the GPS feature in radio magnetars spectra can be of environmental origin, in the same way as it occurs in the vicinity of GPS pulsars.

Pulsars with a high-frequency turnover in their spectra have represented the smallest group of the radio pulsar spectra types. However, Bates, Lorimer & Verbiest (2013) estimated that the number of such sources may constitute up to 10% of the whole pulsar population. The sample of GPS pulsars was extended to include PSR J2007+2722, whose flux density mea-
measurements were presented by Allen, Knispel & Cordes (2013). Recently, Dembska et al. (2014) reported two newly-identified GPS pulsars. One of them, PSR B1740+1000, is the first low-DM pulsar that exhibits the gigahertz-peaked spectrum. This case, along with the GPS phenomenon in radio magnetars, led the authors to conclude that the GPS candidate selection criteria need to be revisited. In future searches for new GPS pulsars, the presence of interesting (or extreme) environments, instead of the high DM, could play a crucial role in the source selection process.

Dembska et al. (2014) also pointed out that the small number of the currently known GPS pulsars may be the result of our limited knowledge of pulsar spectra in general, especially below 1 GHz. The authors outlined the need for a more extensive sample of GPS sources to establish a plausible statistics about those objects. However, in the cases of some GPS candidate pulsars the standard pulsar flux measurement methods are affected by strong scattering at low frequencies. The phenomenon causes the pulse profiles to become broader, i.e. pulses attain roughly exponentially decaying scattering tail. It has been shown that the characteristic broadening of the pulse, \( \tau_{sc} \), depends on both the observing frequency, as well as DM (the empirical relation was given by Bhat, Cordes & Camillo 2004). Recent results on scattering were discussed by Lewandowski et al. (2013) in their analysis of 45 pulsars, based on the Giant Metrewave Radio Telescope (GMRT) and the Effelsberg Radio Telescope observations. Since the scattering becomes stronger at lower frequencies, for a given pulsar the flux becomes increasingly underestimated then. For high-DM pulsars at low frequencies, when the scattering time is greater than the pulsar period by a significant factor, one will see no pulsed emission. Thus, the flux density measurements required to construct radio pulsar spectra using “traditional” methods can be difficult or sometimes impossible to conduct. For these cases the only way to determine the pulsar flux is using the interferometric imaging techniques (see for example Kouwenhoven 2000).

The interferometric measurements of pulsar fluxes at both 325 MHz and 610 MHz using the GMRT have been demonstrated by Basu, Athreya & Mitra (2011) and Basu, Mitra & Athreya (2012). The imaging techniques provide a superior alternative to the standard flux measurements, especially in our studies since the sources we selected for observations are high-DM pulsars. For some of them the imaging techniques are the only secure means to estimate their flux. There is at least two reasons for employing imaging techniques. Firstly, flux calibration in an interferometer is more robust due to the baseline lying at zero level thereby reducing errors made during the baseline subtraction of a normal pulsar observation. Secondly, the instrumental and atmospheric gain fluctuations on very short time scales can be corrected using self-calibration of the interferometric data. The corrections are determined by flux densities of constant and bright background sources in the field and hence would not be affected by the pulse variation of the relatively weak pulsar at a field center.

In this paper we present flux measurements of six pulsars observed at the 610 MHz frequency band of the GMRT using interferometric imaging technique. The sources selected for our studies are GPS pulsars or GPS candidates. We chose the 610 MHz band for these studies, firstly, because the frequency is low enough to estimate whether a given object is indeed a GPS pulsar, secondly, due to the higher probability of detecting GPS pulsars at 610 MHz than at lower frequencies as a result of their inverted spectra at sub-GHz frequencies and finally, to avoid the RFI and other systematic effects that are prominent at lower frequencies. This analysis allowed us to inspect flux densities of some objects and select a strong GPS candidate pulsar. We were able to confirm that the the interferometric imaging technique can be successfully applied to estimate flux density of pulsars.

### 2 OBSERVATIONS AND DATA ANALYSIS

We recorded the interferometric data on six pulsars using the GMRT that is located near Pune, India and consists of an array of 30 distinct dishes, each with a diameter of 45 meters, and a total of 435 baselines. The dishes are spread out over a region of \( \sim 27 \text{ km} \) and roughly resemble a Y-shaped array. The data were recorded at the 610 MHz frequency band with a bandwidth of 33 MHz spread over 256 frequency channels. All the six sources were observed on three separate dates: 30 December 2012, 6 January 2013 and 13 January 2013, each observation separated by a week, to account for variations in the pulsar flux over long time scales.

The observations were carried out using standard schemes where strategically placed calibrators were interspersed with the

![Flux Variation of Sources in Field of View](image-url)

**Figure 1.** The figure shows the variation of the flux value of the surrounding sources in the field of view across the three observing runs. The strong sources in the fields with the pulsars PSRs B1750–24 and B1849+00 at the field centers were identified and their average flux across the three sessions were calculated. The ratio of the flux of each source with respect to the average flux and as a function of the average flux is plotted in the figure, with each session marked with different symbols. The ratios are scattered around unity with the noise in the scatter decreasing with the increasing flux levels. This demonstrates the analysis process to be correct and consistent for all the three observing sessions.

| Pulsar   | \( DM \) \( \text{(pc cm}^{-3}\text{)} \) | Age \( \text{(kyr)} \) | \( P \) \( \text{(sec)} \) | \( \tau_{sc} \) \( \text{(sec)} \) | Associations |
|----------|---------------------------------|----------------|----------------|----------------|----------------|
| B1750–24 | 762                            | 593            | 0.528          | 2.38           |                |
| B1815–14 | 622                            | 2270           | 0.291          | 0.457          |                |
| B1849+00 | 787                            | 356            | 2.18           | 6.19           |                |
| B1800–21 | 234                            | 15.8           | 0.133          | 0.030          | 1, 2, 3        |
| B1822–14 | 357                            | 195            | 0.143          | 0.279          | 1              |
| B1823–13 | 231                            | 21.4           | 0.101          | 0.0337         | 1, 2           |

1 – HESS (High Energy Stereoscopic System)  
2 – X-PWN (X-ray pulsar wind nebula), 3 – SNR (supernova remnant)
Flux density measurements of GPS candidate pulsars at 610 MHz

Table 2. Flux density measurements resulted from the interferometric imaging observations in three observing sessions (S₁, S₂ and S₃ respectively) along with the uncertainties which include calibration errors, the rms noise in the maps and fitting errors. (S) denotes the weighted mean of all results (presented along with its uncertainty) for a given pulsar.

| Pulsar   | S₁ (mJy) | S₂ (mJy) | S₃ (mJy) | (S) (mJy) |
|----------|----------|----------|----------|-----------|
| B1750−24 | 3.65±0.28 | 3.90±0.25 | 3.98±0.25 | 3.9±0.3   |
| B1815−14 | 24.5±1.8  | 24.6±1.5  | 26.1±1.5  | 25.1±1.6  |
| B1849+00 | 15.2±1.1  | 15.5±1.0  | 16.1±1.0  | 15.39±0.95|
| B1800−21 | 8.22±0.60 | 6.75±0.42 | 7.82±0.48 | 7.4±0.9   |
| B1822−14 | 3.31±0.36 | 3.43±0.35 | 4.18±0.38 | 3.5±0.6   |
| B1823−13 | 3.51±0.26 | 3.42±0.22 | 3.53±0.23 | 3.5±0.2   |

3 RESULTS

Table 1 gives the list of sources with some of their basic parameters (DM, age and period). All these objects are either confirmed or candidate GPS sources. As it is clear from the table, the sample was subdivided into two categories. We have made rough estimates of the scattering timescales using either observational data (Lewandowski et al. 2013) or the predictions derived from a single thin screen model (using the scatter time frequency scaling index $\alpha = 4$). For the first group of pulsars, PSRs B1750−24, B1815−14 and B1849+00, the pulse broadening at 610 MHz is large, hence the interferometric imaging provides the only mean to estimate flux for these sources. The flux density of the remaining pulsars, PSRs B1800−21, B1822−14 and B1823−13, was measured at low frequencies by conventional pulsar observations. [Lorimer et al. 1993; Kijak, Gupta & Krzeszowski 2007; Kijak et al. 2011b], however since the predicted (or measured) scatter time estimates are a significant fraction of the pulsar periods, there is a possibility for the flux densities measured that way to be underestimated. Additionally, these three sources have counterparts in the High Energy Stereoscopic System (HESS) observations with indications of pulsar wind nebula (PWN) around them [Kijak et al. 2011b] and [Kijak et al. 2011b] reported PSRs B1822−14 and B1823−13 as GPS pulsars, and PSR B1800−21 is considered as a GPS candidate. We included these pulsars in our studies to re-examine their flux values at 610 MHz where some profile broadening due to scattering is also present.

For the six pulsars we constructed radio spectra, combining flux density measurements from the literature [Lorimer et al. 1995; Maron et al. 2000; Kijak, Gupta & Krzeszowski 2007; Kijak et al. 2011b and references therein] and the ATNF (Australian Telescope National Facility) pulsar catalogue together with the new results shown in Table 2 (see online material for the maps of the pulsars that were used to estimate their flux density at 610 MHz). The spectra are presented in groups, depending on their morphological properties. Our studies show that for the high-DM pulsars, namely PSRs B1750−24, B1815−14 and B1849+00, their spectra resemble a simple power law. We were able to confirm the GPS feature in the spectrum of PSR B1823−13 and pointed out two sources, PSRs B1822−14 and B1800−21, suspected to be gigahertz-peaked spectra pulsars which require further investigation. The fits presented in the paper were obtained by the implementation of the nonlinear least-squares Levenberg-Marquardt algorithm. The results of the fitting procedure are given in Tab. 3.

PSRs B1750−24, B1815−14 and B1849+00 have very high DMs in excess of 600 pc cm$^{-3}$. Their spectra are shown in Figure 2. These objects are characterized by a significant pulse broadening due to interstellar scattering (of the order of several periods). As

1 http://www.atnf.csiro.au/research/pulsar/psrcat/Manchester et al. 2005
mentioned above, the sources were suspected to be GPS pulsars but our analysis suggest that their spectra can be fit by a power law.

In the case of PSR B1815−14 the interferometric imaging technique was used to inspect its flux density measurements at 610 MHz due to a strong pulse scatter-broadening (over a full pulse period, see [Lewandowski et al. 2013]). Previous observations suggested that the pulsar spectrum shows a turnover feature. Our new result, accompanied by a large scatter time estimate, suggests a significant underestimation in the previous flux measurements for this pulsar at 610 MHz.

Table 3. Fitted parameters to data of four pulsars, PSRs B1750−24, B1815−14 and B1849+00 (using a power-law, where \( \xi \) is a power index) and B1823−13 (using the same function (1) as in [Kijak et al. 2011b]). The implementation of the nonlinear least-squares Levenberg-Marquardt algorithm was used to perform the fitting procedure. The parameters are given with a reduced \( \chi^2 \). For more details on data excluded from the fitting procedure see Figs 2a−4a.

| Pulsar     | Fitted parameters | \( \chi^2 \) |
|------------|-------------------|--------------|
| B1750−24   | \( \xi = -1.0 \pm 0.14 \) | 7.5          |
| B1815−14   | \( \xi = -1.75 \pm 0.07 \) | 0.95         |
| B1822−14   | \( \xi = -0.48 \pm 0.08 \) | 2.5          |
| B1849+00   | \( \xi = -1.9 \pm 0.2 \)    | 9.6          |
| B1823−13   | a = 0.95 \pm 0.18, b = 0.28 \pm 0.11 | 3.4          |
|            | c = 0.61 \pm 0.03     |              |

The classification of the PSRs B1750−24 and B1849+00 spectra was not possible before due to very limited flux density measurements at frequencies below 1 GHz. It seems clear that the spectrum of PSR B1849+00 one is a typical steep pulsar spectrum. The PSR B1750−24 spectrum can also be described by a single power law but at the same time it is relatively flatter than a usual pulsar spectrum (a spectral index of \(-1.0\); the fits and the resulting spectral indices are presented in Fig. 2).

PSR B1823−13, whose spectrum is presented in Figure 3 was classified as a GPS pulsar by [Kijak et al. 2011b]. The object was included in our sample to re-examine its flux density measurement at 610 MHz. It is noteworthy that new measurements indicate a larger flux density than previous GMRT observations which were carried out using the instrument in phased array mode, thus standard pulsar flux measurement methods were applied (Kijak et al. 2011b). Even if one disregards the earlier measurements and uses only the interferometrically derived flux, the spectrum continues to exhibit a GPS feature. However, it seems clear that this object requires further observations at frequencies below 600 MHz which we plan to perform in future projects.

PSR B1800−21, whose spectrum is presented in Fig. 4 can be treated as a new, very promising GPS candidate pulsar. It is a young, Vela-like pulsar, associated with a supernova remnant (Kijak et al. 2011b). Previously the spectrum seemed to be flat at low frequencies but our estimate, which indicates a much smaller flux density than in the previous measurements at 610 MHz, suggests a positive spectral index in the low-frequency range. New results clearly imply that the earlier flux measurements should be verified.

PSR B1822−14 is the last pulsar in our sample. Its spectrum is presented in Figure 5. Similar to the case of PSR B1823−13, the flux density measured using the interferometric imaging techniques is greater than the values from standard method. PSR B1822−14 was identified as a GPS pulsar (Kijak et al. 2011b), however the interferometric measurements suggest otherwise – the spectrum of the pulsar seems to be a power law (with spectral index of \(-0.48\)) when including new measurements which may indicate that the earlier measurements were affected by interstellar scattering. This pulsar definitely needs further investigation and possibly additional measurements at lower frequencies.

Figure 2. The spectra of PSRs B1750−24, B1815−14 and B1849+00, pulsars with high DMs (see Tab. 1). Open circles denote the GMRT interferometric observations. Measurements marked with black dots are taken from literature (Maron et al. 2004, Kijak, Gupta & Krzeszowski 2007, Kijak et al. 2011b and references therein) and the ATNF pulsar catalogue. The straight lines represent our fits to the data using power-law function (in the case of PSR B1815−14 the flux measurements at 610 MHz marked with black dots were excluded from the fitting procedure). The power indices resulted from the fitting procedure are given on each panel, for more details see Tab. 3.
with very high-DMs (mates in Tab. 1). We inspected the spectra of these three pulsars to estimate their flux at this frequency (see the scatter time estimation both diffractive and refractive scintillations. As the diffractive scintillations may vary from days to months. However, the refractive modulation index $\Delta m_{\text{RISS}} \propto f^{0.57}d^{-0.37}$ for high-DM pulsars should be relatively small at the frequency of 610 MHz. To account for refractive scintillations influence, we performed our flux measurements on three epochs (separated by no less than a week). For the purpose of constructing pulsar spectra we are using an average of values obtained from these measurements. We have to note however, that in this regard the interferometrically measured flux density values are not affected any more than the ones resulting from the standard observing procedure. Pulsar flux measurements regardless of the method used will be affected by the scintillation-driven flux variation in exactly the same way.

As mentioned in the Introduction, for high-DM pulsars, and especially when the observations are conducted at low observing frequencies, the pulsar profiles can be affected by interstellar scattering to such an extent that it is difficult, or even impossible to perform flux measurement using the standard profile-based method. Strong scattering causes the profiles to attain scattering tails, what may significantly affect the observed profile background level so that the proper baseline required for the standard flux measurement can not be found. Especially prone to such errors will be the cases where the scatter time is comparable to the pulse period, as one will still be able to see a prominent pulse, while the scattering tail will hide the proper baseline level. One has to remember that even a “moderate” length of the scattering tail may still affect the profile baseline and cause erroneous results, especially when the observations are affected by a high noise level (Lewandowski et al. 2013). In some circumstances the influence of scattering may even change the appearance of the spectrum by mimicking a turnover feature, which may lead to an erroneous identification of a pulsar as a GPS source, like in the case of PSR B1815−14.

Since there is no simple way to account for the scattering-induced baseline level change one should refrain from using the standard method in such cases. Practically, however, it can be hard to judge if we are dealing with a profile where scattering led to an erroneous flux density estimation. We believe that at least some of the past flux measurements performed for the pulsars from our sample might have been affected by the scattering, which is discussed below. Regardless, to avoid the scattering-induced issues one needs a reliable method of pulsar flux density measurement that will not be affected by scattering.
4.2 Imaging technique and pulsar flux density

Interferometric imaging techniques at low radio frequencies have been used to determine flux density of a wide class of astronomical sources and can be easily extended to determine pulsar flux values. The estimated flux of the phase calibrator 1822−096 at 610 MHz was identical over the three widely separated observing sessions and using two different flux calibrators 3C48 and 3C286. In addition its flux estimates are in the expected range when compared with the flux densities at 325 MHz and 1.4 GHz (from the Very Large Array calibrator manual). The consistency of our calibrations over the different observing sessions was also demonstrated by the flux ratios of the surrounding background sources in the field of view, which hovered around unity (see Figure 1). Additional vindication of our results is provided by the flux density measurements of the three pulsars B1750−24, B1815−14 and B1849+00 which could not be determined at 610 MHz using conventional pulsar flux measurement techniques due to their highly scattered profiles. Our flux estimates at 610 MHz for all the three cases are consistent with the pulsar spectra determined from higher frequencies, where interstellar scattering should not affect the measurement (see Figure 2).

We now examine the cases of the three other pulsars B1800−21, B1822−14 and B1823−13 where traditional pulsar flux measurements have been carried out in the past. All of these sources adjoin interesting environments which may cause an additional absorption at frequencies below 1 GHz. Dembska et al. (2014) suggested that an influence of such environment on pulsar radio emission can manifest itself as a reverse spectrum with positive spectral index, which made these objects a plausible GPS candidates.

Two of the pulsars, PSRs B1822−14 and B1823−13, were classified by Kijak et al. (2011a) and Kijak et al. (2011b) as GPS pulsars. Obviously, one can note the discrepancies between standard and interferometric flux measurements for both sources. The interferometrically measured flux densities are larger than the ones which resulted from standard observations. We know that the pulse profile of PSR B1822−14 at 610 MHz shows a significant scattering (Lewandowski et al. 2013), thus the flux density obtained using the standard method is very likely to be underestimated. In the case of PSR B1823−13 the profile that was used by Lorimer et al. (1995) to estimate the flux density of the pulsar at 610 MHz was not published. However, the estimated scatter time at this frequency is a significant fraction of the pulse period (as in the case of PSR B1822−14). Hence one cannot rule out the possibility that conventional observations were in this case also affected by scattering.

4.3 The case of PSR B1800−21

As we pointed out above, usually the interferometric observations give better estimations of previously underestimated flux density values. Yet, one can note that in the case of PSR B1800−21 its interferometrically measured flux value is lower than the one resulted from previous measurements by Lorimer et al. (1995) and Kijak et al. (2011b). The discrepancy cannot be explained in a simple way and it is not possible to definitely point out the reason behind it. However, one still can propose possible effects causing such a variation. Assuming our latest result to be accurate and precise, there appears a chance that the difference is caused by rather external (i.e. environmental) factors. PSR B1800−21 is a young Vela-like pulsar, located at the southwestern edge of the G8.70.1 nebula, a shell-type supernova remnant (Kassim & Weiler 1990a, b). It has a plausible association with the γ-ray source HESS 1804−21 which resulted from standard observations. We know that the flux density resulted from our observations conducted on 28 December 2013 is 8.79 ± 0.67 mJy which is in a good agreement with values presented in Tab. 2. Moreover, we have time allocation for 325 MHz observations of this source – these observations are to be conducted in January 2015. Consequently, we will be able to re-examine our results and hopefully resolve the discrepancy with the standard method measurements.

5 SUMMARY

The interferometric imaging technique allowed us to estimate pulsar flux density, making it possible to observe weak or high-DM pulsars at frequencies below 1 GHz and re-examine our previous results. In the cases of objects for which determining their flux at
Flux density measurements of GPS candidate pulsars at 610 MHz

low frequencies using standard pulsar observing methods is not possible (i.e. for a large $\tau_s$ when comparing to pulsar period), it is the only way to estimate flux for these sources. Thus, the interferometric imaging technique provides a superior alternative to the pulsar flux measurements. We believe that the technique will help us to confirm more GPS pulsars in future.

Moreover, we used this method to rule out three GPS pulsar candidates and confirm one GPS pulsar, PSR B1823−13. We also pointed out two GPS candidates, including a very promising one, PSR 1800−14, that require further investigation. Hence, our analysis clearly shows that the interferometric imaging technique can be successfully applied to estimate flux density of pulsars. The method is the only secure way to determine the flux density of high-DM pulsars which are highly scattered at low radio frequencies.

ACKNOWLEDGMENTS

We thank the staff of the GMRT who have made these observations possible. The GMRT is run by the National Centre for Radio Astrophysics of the Tata Institute of Fundamental Research. This research was partially supported by the grant DEC-2013/09/B/ST9/02177 of the Polish National Science Centre. MD was a scholar within Sub-measure 8.2.2 Regional Innovation Strategies, Measure 8.2 Transfer of knowledge, Priority VIII Regional human resources for the economy Human Capital Operational Programme co-financed by European Social Fund and state budget. We thank M. Jamrozy for this support on the preparation of the observing proposal.

REFERENCES

Aharonian, F. et al. (for H.E.S.S. collaboration) 2005, Science, 307, 1938
Aharonian, F. et al. (for H.E.S.S. collaboration) 2006, Ap. J. 636, 777
Allen, B., Knispel, B., Cordes, J. M. et al. 2013, ApJ, 773, 91
Baars, J. W. M., Genzel, R., Pauliny-Toth, I. I. K., Witzel, A. 1977, A&A, 61, 99
Basu R., Athreya R., Mitra D. 2011, ApJ, 728, 157
Basu R., Mitra D., Athreya R. 2012, ApJ, 758, 91
Bates S. D., Lorimer D. R., Verbiest J. P. W. 2013, MNRAS, 431, 1352
Bhat N. D. R., Cordes J.M., Camillo F. et al. 2004, ApJ, 605, 759
Dembska M., Kijak J., Jessner A., Lewandowski W., Bhattacharyya B., Gupta Y. 2014, MNRAS, 445, 3105
Finley J. P., Oegelman, H. 1994, ApJ, 434, L25
Higashi, Y. et al. 2008, ApJ 683, 957
Kassim, N. E., Weiler, K. W. 1990a, Nature, 343, 146
Kassim, N. E., Weiler, K. W. 1990b, ApJ, 360, 184
Kijak J., Gupta Y., Krzeszowski K. 2007, A&A, 462, 699
Kijak, J., Dembska, M., Lewandowski, W., Melikidze, G., Sendyk, M. 2011a, MNRAS, 418, L114
Kijak, J., Lewandowski, W., Maron, O., Gupta, Y., Jessner, A. 2011b, A&A, 531, A16
Kijak, J., Tarczewski, L., Lewandowski, W., Melikidze, G. 2013, ApJ, 772, 29
Kouwenhoven M. L. A. 2000, A&AS, 145, 243
Lewandowski, W., Dembska, M., Kijak, J., Kowalinska, M. 2013, MNRAS, 434, 69
Manchester R. N., Hobbs G., Teoh A., Hobbs M., 2005, AJ, 129, 1993
Maron O., Kijak J., Kramer M., Wielebinski R., 2000, A&A, 147, 195
Lorimer D. R., Yates J. A., Lyne A. G., Gould D. M. 1995, MNRAS, 273, 411
Sieber W., 1973, A&AS, 28, 237