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Study of scattering material with RadioAstron-VLBI observations

Andrey Andrianov∗ **, T.V. Smirnova, V.I. Shishov, M.V. Popov, N.S. Kardashev, V.I. Soglasnov**
Lebedev Physical Institute
E-mail: andrian@asc.rssi.ru, tania@prao.ru, shishov@prao.ru, mwpopov@gmail.com, nkardash@asc.rssi.ru, vsoglasn@asc.rssi.ru

C. Gwinn
University of California at Santa Barbara
E-mail: cgwinn@physics.ucsb.edu

M. Johnson
Harvard-Smithsonian Center for Astrophysics
E-mail: mjohnson@cfa.harvard.edu

H. Bignall
Curtin University of Technology
E-mail: hbignall@gmail.com

A. Deller
Netherlands Foundation for Research in Astronomy
E-mail: deller@astron.nl

M. Kramer
Max-Planck-Institut fur Radioastronomie
E-mail: mkramer@mpifr.de

The RadioAstron spacecraft presents an unique opportunity to measure properties of interstellar scattering. Pulsars offer a variety of observables for study of interstellar scattering. Observations of scattering of nearby pulsars and intra-day variable quasars point to the existence of a component of the interstellar medium (ISM) which has properties quite different from the more distant, diffuse ISM. We observed several nearby pulsars as part of RadioAstron's Early Science Program (ESP). These included pulsars B0950+08, B1919+21 and B0329+54. We present here some results concerning the distribution and properties of scattering material in the direction to these pulsars obtained with cosmic interferometer.

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∗Speaker.

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1. Introduction. Scattering of pulsars.

The RadioAstron spacecraft presents an unique opportunity to measure properties of interstellar scattering. The fluctuations responsible for scattering radio waves from astronomical sources are small-scale ($\sim$0.1 AU) fluctuations in the electron density of the interstellar medium. Pulsars offer a variety of observables to study interstellar scattering. The time series of electric field emitted by the pulsar is convolved with an impulse-response function due to scattering, when sampled at the observer plane [1]. This impulse-response function reflects the reinforcement or cancellation of radiation that has traveled along different lines of sight, as deflected by the propagation medium. The impulse-response function has a typical timescale τ_d, reflecting the range of travel times from source to observer. The bandwidth of scintillations $f_d \approx 1/(2\pi\tau_d)$ is the range of frequencies for which the cancellation or reinforcement persists. The impulse-response function has a characteristic scale in the observer plane L_{ISS} that reflects the relative variations in the path lengths as the position of the observer changes. The angular scale of the scattering disk – the region on the sky from which the observer receives radiation – is $\theta_{sc} \approx \lambda/L_{ISS}$, where λ is the observing wavelength. For transverse velocity of the pattern $V_\perp$, the timescale of scintillation is $t_d = L_{ISS}/V_\perp$.

Observations suggest the presence of three components of scattering media in the Milky Way. The first is unevenly distributed media in the space between the spiral arms of the Milky Way (component A) [2-4]. The second is a more-uniformly distributed component, in a cavity of depleted electron density extending as far as 300 pc from the Sun (component B). This cavity is observed in X-ray observations [5], and is associated with scintillations of pulsars with dispersion measures of 3 to 30 cm^{-3} pc [6]. For Components A and B, the spatial spectrum of density fluctuations appears to follow a Kolmogorov law, with a power-law index $\gamma = 11/3$ through 6 orders of magnitude of length scale [7,8]. The third (Component C) is located only $\approx$ 10 pc from the Sun. The scintillation of nearby pulsars B0950+08 and J0437-47 is caused by this component [9, 10]. This component is also responsible for the variability of intra-hour-variable quasars at centimeter wavelengths [11-15].

2. Nearby interstellar scattering.

Some radio-loud active galactic nuclei show variations in intensity on timescales of a few hours, and are known as IDV sources. Studies of the most remarkable such sources have revealed a time lag in temporal variability between antennas at separations of an Earth radius, confirming the identification of the variability as scattering, and providing an estimate of the spatial scale of scattering L_{ISS} [11-15]. Timescales of the scintillations vary annually, as the Earth's orbit carries it with and against the motion of the scatterers. The derived velocity $V_\perp$ and scale of variation L_{ISS} implies a distance of only $\approx$ 10 pc for the scattering media. The medium that scatters IDV sources appears to be highly elongated (10:1) [12], presumably due to a strong and ordered magnetic field.

PoS(EVN 2014)064

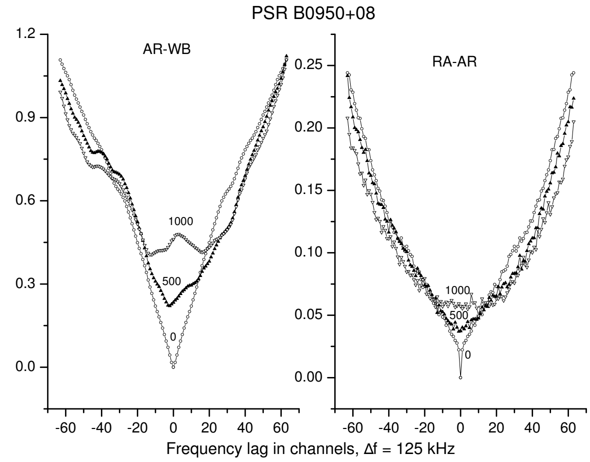

Figure 1: Mean structure functions for different time lags between pulsar spectra of PSR B0950+08 on the Arecibo-Westerbork (left) and Radioastron-Arecibo (right) baselines. The numbers for the different curves correspond to different time lags in s.

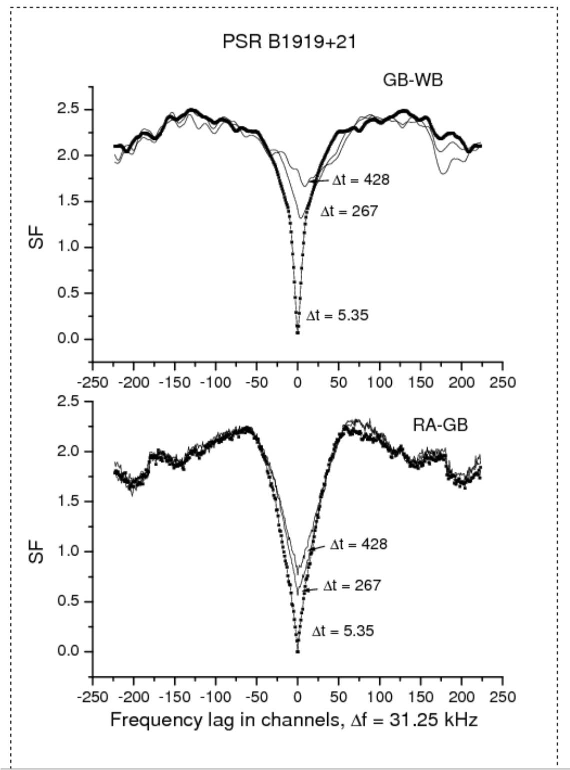

Figure 2: Mean structure functions for different time lags between pulsar spectra of PSR B1919+21 on the Green Bank-Westerbork (top) and Radioastron-Green Bank (bottom) baselines. The numbers for the different curves correspond to time lags in s.

Observations of the nearest pulsars likewise suggest an extremely close distance for the medium that scatters their radiation. These two pulsars are among the nearest pulsars, and have 2 of the

3 lowest observed dispersion measures. Pulsars B0950+08 and J0437−4715 both show scaling of scattering parameters with wavelength that depart strongly from the Kolmogorov-like scaling of more distant pulsars [9, 10]. For PSR B0950+08 the power-law index of the spectrum of plasma inhomogeneities is $\gamma = 3 \pm 0.05$ [10]. A large separation between telescopes, provided by RadioAstron-Earth baselines, is needed to separate the influence of nearby and remote scattering media.

Observations of scattering of nearby pulsars and intra-day variable quasars point to the existence of a component of the interstellar medium (ISM) which has properties quite different from the more distant, diffuse ISM. The origin of these small-scale structures and the role they play in Galactic dynamics are important problems, still under investigation. We made observations of nearby pulsars on baselines to RadioAstron, in order to investigate the distribution and properties of interstellar scattering media close to the Sun. Observing with different positions of the RadioAstron spacecraft relative to the Earth, we can study anisotropy of interstellar inhomogeneities, and thus extend the picture provided by intra-day variable sources.

We observed several nearby pulsars as part of RadioAstron's Early Science Program (ESP). These included pulsars B0329+54, B0950+08, and B1919+21. Our first scientific results obtained with ground-space interferometer were published in ApJ [16]. We studied there the distribution of scattering material in the line of sight to PSR B0950+08. Results obtained for PSR B1919+21 and B0329+54 are in preparation. Our analysis is based on fundamental behavior of structure and coherence functions. Methodic of data analysis is described in [16]. Structure function (SF) of phase fluctuations is: $D_s(\Delta\rho) = <(\psi(\rho) - \psi(\rho + \Delta\rho))^2>$, where ρ is a spatial coordinate in the observer plane and $\Delta\rho$ is a baseline of interferometer. Analysis of dynamic spectra gave us scintillation time, τ_d and decorelation bandwidth, f_d. The visibility functions were computed as the inverse Fourier transform of the complex cross-spectra. Module of cross-spectra averaged over time give us interferometric visibility or coherence function. A mean structure function (SF) is defined using intensities in square to decrease influence of noise: $SF(\Delta f, \Delta t) = <[I^2(f,t) - I^2(f + \Delta f, t + \Delta t)]^2>_{f,t}$. SF for the squared modulus of the visibility is proportional to the structure function for the modulus of visibility. Mean structure functions for different time lags Δt on the Earth and space baselines are shown in Fig. 1 and Fig.2 for PSR 0950+08 and B1919+21 correspondingly. The numbers in figures correspond to the time shift Δt in s. SFs shown in Fig.1 and Fig.2 for both pulsars have qualitatively different forms. We see that for both pulsars structure functions have two scales: a narrow component that appears only at small time lags; and a broader one that appears at both large and small time lags. These two frequency scales correspond to two effective layers of turbulent plasma, separated in space, where the scattering of pulsar emission takes place. Short baseline comprises both a narrow-bandwidth component and a broader-bandwidth component. For the long RadioAstron-Arecibo space baselines, the narrow-bandwidth component is absent; we see only the broad-bandwidth structure for PSR B0950+08. The long baseline suppresses most of the narrowband structure and some of the wideband structure for PSR B1919+21. It shows that for this pulsar cosmic interferometer resolves the small-scale structure. A large separation between telescopes, provided by RadioAstron-Earth baselines, allows us to separate the influence of nearby and remote scattering media.

At least for pulsar B0950+08 and B1919+21, scattering involves both diffractive effects from small-scale density fluctuations, and refractive effects from large-scale fluctuations. The cosmic prism disperses the scintillation pattern across the observer plane, so that particular intensity maxima and minima appear at different positions at different frequencies. The shift in frequency of the scintillation pattern with time or position leads to an asymmetry in frequency Δf of the structure function for nonzero time lag (Δt) or finite baseline length, $\Delta\rho$. We detected the presence of two scattering plasma layers along the line of sight to pulsar B0950+08. Modulation index is mainly defined by nearby layer. From analysis of the time and frequency parameters of scintillation, we found that screens are located at distances of about 10 pc,and of about 100 pc, respectively. The nearby layer dominates the temporal structure of the scintillation, while both the nearby and far layers influence the frequency structure of the scintillation. Its scattering shows similarities to that of intra-day variable extragalactic sources. We observe evidence for refraction by an interstellar plasma wedge, or cosmic prism. For PSR B0950+08, we evaluated the angle of refraction as $\Theta_{ref} = (1.1 \div 4.4)$ mas. The spectra of density fluctuations for the two layers were found to follow power laws, with indices n = 3.00± 0.08. These indices differ from the Kolmogorov value of 11/3. We found that interstellar scintillation of PSR B1919+21 is also defined by two screens of plasma inhomogeneities. Frequency structure of scintillation is defined by angular refraction of the cosmic prism located on the distance of 1.7 pc. We defined refractive angle as 100 mas. Cosmic interferometer resolves the scattering disk, the size of it is 1.5 mas. We detected the locations of two screens which are 0.7 pc and 300 pc. We see that for different lines of sight we have inhomogeneous ISM so for study of nearby medium we have to observe a number of pulsars in different directions.

3. Scattering disk resolved for pulsar B0329+54 at 92 cm with RadioAstron.

Pulsar B0329+54 was observed at 327 MHz with RadioAstron in two separate observing sessions in November 2012 and in January 2014, with baseline projections in the range from 15000 km to 235000 km. Scattering disk was resolved at space-ground baselines 15000-30000 km, its diameter was measured as 4.7 mas. At longer baselines we observed notable visibility amplitudes, randomly distributed in fringe-rate and delay with scattering time τ_s in range of 5-7 μs different for different observing sessions. With angular diameter θ and scattering time τ_s known, one can estimate the distance to the effective scattering screen; it was found to be located at about 1/3 of the distance from the observer to the pulsar. A model of uniformly distributed scattering media also would be in agreement with our results. Pulsar B0329+54 is located at a parallax distance of 1.03 ± 0.5 kpc [17] at the outer edge of the Orion spiral arm while the Sun is at the inner edge of the arm. Uniform distribution of interstellar plasma is quite probable.

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PoS(EVN 2014)064

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