A study of the Milky Way scattering properties based on multi-frequency VLBA observations of the AGN core sizes

PoS(EVN2021)017

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We present the results on the analysis of scattering properties of the Galaxy, based on multi-frequency (1.4 – 86 GHz) Very Long Baseline Interferometry (VLBI) data of active galactic nuclei (AGN) over the entire sky, with the exception of the region of far southern latitudes of the celestial sphere. The data of simultaneous observations at two frequencies, 2 and 8 GHz, and non-simultaneous multi-frequency observations of the apparent AGN VLBI jet origin (the core), allowed us to derive the characteristic value of the power-law index for the unscattered and scattered sources. We constructed the first detailed sky distribution map of the radio emission scattering power in the Galaxy and analyzed its properties. The scattered sizes of the cores are found to be significantly larger within the Galactic plane $|b| < 10°$.

**** European VLBI Network Mini-Symposium and Users' Meeting (EVN2021) ****
**** 12-14 July, 2021 ****
**** Online ****

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1. Introduction

Due to the presence of interstellar ionized turbulent gas in our Galaxy, radio waves coming from distant sources are subject to propagation effects. In this study, we consider diffraction dominated scattering of radio emission coming from active galactic nuclei (AGN). The AGN are numerous, uniformly distributed over the sky and compact enough. Thus, these sources are appropriate to probe the scattering screens and their distribution in the interstellar medium of our Galaxy and to study the effects of diffraction scattering on the observational characteristics of AGN [e.g., 1, 2].

The AGN VLBI core is a compact feature observed in the region where the jet stops being opaque to synchrotron radiation, and its optical depth at a given frequency becomes $\tau_\nu \approx 1$. An observed AGN core size scales with wavelength of observation as $\theta \propto \lambda^k$, where $k = 1$ if the radiation is not scattered [3, 4]. In the case of scattering, we consider two competing models of scattering screens: (1) the Gaussian screen model [5, 6] predicts the measured angular size of a distant source to be proportional to the wavelength with the power-law index $k = 2.0$ [7, 8]; (2) the model with a Kolmogorov power-law spectrum of electron density fluctuations [8–11]. In this case, the power-law index is $k = 2.2$.

Using the highest to date number of experimental VLBI data from multi-frequency observations of thousands of AGN, we investigate a large-scale distribution of scattering properties of the Galaxy.

2. AGN VLBI core measurements

Our analysis is based on the VLBI observations of AGN jets at eight frequencies ranging from 1.4 to 86 GHz compiled in the Astrogeo database[1]. For the purposes of our study, we use fully calibrated sets of data in the spatial frequency domain. In total, we analyzed over 80 000 individual observations of 14 483 sources observed from 1994 to 2020 with different VLBI arrays, including the VLBA, EVN, LBA, and GMVA.

We apply the approach based on model-fitting of interferometric visibilities and describe the source brightness distribution with two Gaussian components, representing the core and the extended jet emission. The brightest component of the two is considered to be the radio core; if the jet direction at a lower frequency is opposite to that at a higher frequency, we switch the two components (see Plavin et al. 2022, ApJS, submitted, for the details). We exclude the measurements if the core size uncertainty exceeds 50%. This criterion effectively filters out unresolved sources as well.

3. Distribution map of scattering properties in the Galaxy

Using the data of geodetic VLBI observations performed simultaneously at 2 and 8 GHz we derived angular sizes of the AGN cores at 2 and 8 GHz and estimated the power-law index k from the frequency dependence $\theta_{\rm obs} \propto \nu^{-k}$ for 3405 sources over the sky. These data allowed us to construct the first detailed distribution map of radio emission scattering power in the Galaxy (Fig. 1). It shows that the scattering screens are concentrated in the Galactic plane ($|b| < 10^\circ$) and their distribution is highly inhomogeneous. The characteristic value of the power-law index k for

[1] http://astrogeo.org/vlbi_images/

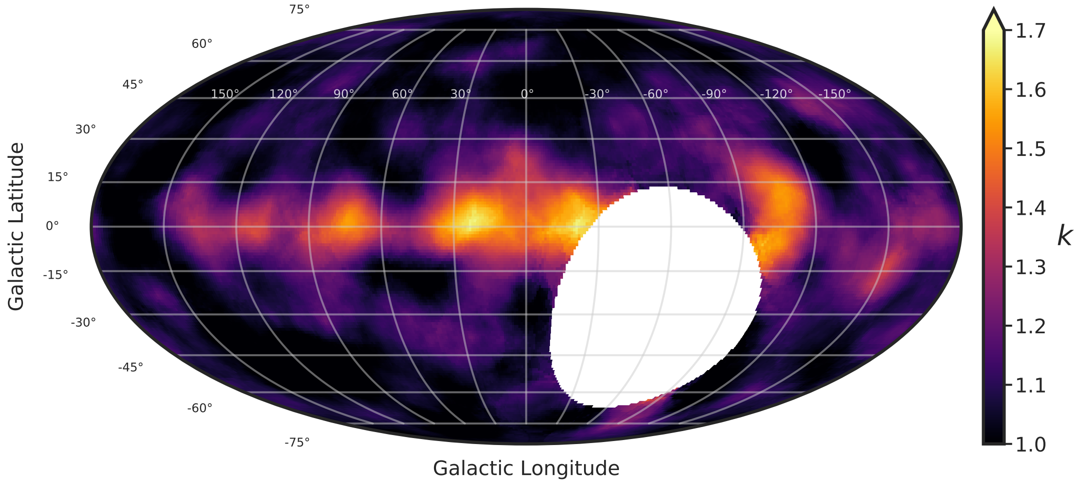

Figure 1: Distribution map of the k index derived from the AGN core sizes simultaneously measured at 2 GHz and 8 GHz over the sky. The color of each pixel of the map reflects the average over 10° area value of the k index at this location. The yellow color indicates the strong scattering regions, the black color points to the regions where scattering is absence.

the sources seen outside the Galactic plane ($|b| > 10°$) is $k = 1.01 \pm 0.01$. This is consistent with the theoretical prediction for the unscattered AGN cores with synchrotron self-absorption [3, 4]. For the sources observed through the Galactic plane, the obtained characteristic value of this index is $k = 1.65 \pm 0.02$.

The regions of the Galaxy characterized by strong scattering demonstrate a significant spatial correlation with the locations of high Hα intensity radiation [12]. The strongest galactic scattering regions include the Galactic Centre, the Cygnus region, Vela and Cassiopeia–A supernova remnants. We also found an increase of the scattering strength outside the Galactic plane in the location of Orion Nebula (M42).

4. Scattering index calculations using multi-frequency AGN data

We also considered the observed core size of AGN as a function of the intrinsic and scattered sizes $\theta^2_{\rm obs} = \theta^2_{\rm int} + \theta^2_{\rm scat}$, where $\theta_{\rm int} = \theta_{\rm int,\,1\,GHz} \cdot \nu^{-k_{\rm int}}$ and $\theta_{\rm scat} = \theta_{\rm scat,\,1\,GHz} \cdot \nu^{-k_{\rm scat}}$ [13]. Using multi-frequency observations of the AGN seen through the Galactic plane, we derived the characteristic value of the scattering index $k_{\rm scat}$, which corresponds to the best fit of the intrinsic $\theta_{\rm int,\,1\,GHz}$ and scattered $\theta_{\rm scat_{1\,GHz}}$ core sizes at 1 GHz according to the equation for $\theta_{\rm obs}$ mentioned above. Table 1 contains information about the datasets were used for fitting, the number of sources, and the results. Fitting was performed with the power-law index $k_{\rm int} = 1$, as it was determined earlier in Sec. 3 for sources located outside the Galactic plane. The resulting value of the scattering index, derived from different sets of multi-frequency data, ranges from $1.94^{+0.08}_{-0.07}$ through $2.03^{+0.16}_{-0.05}$. These results are consistent with both the Gaussian screen and Kolmogorov turbulence models. Detailed observations of an individual scattering screens are required to determine which of the two scenarios prevails for most directions in the Galaxy.

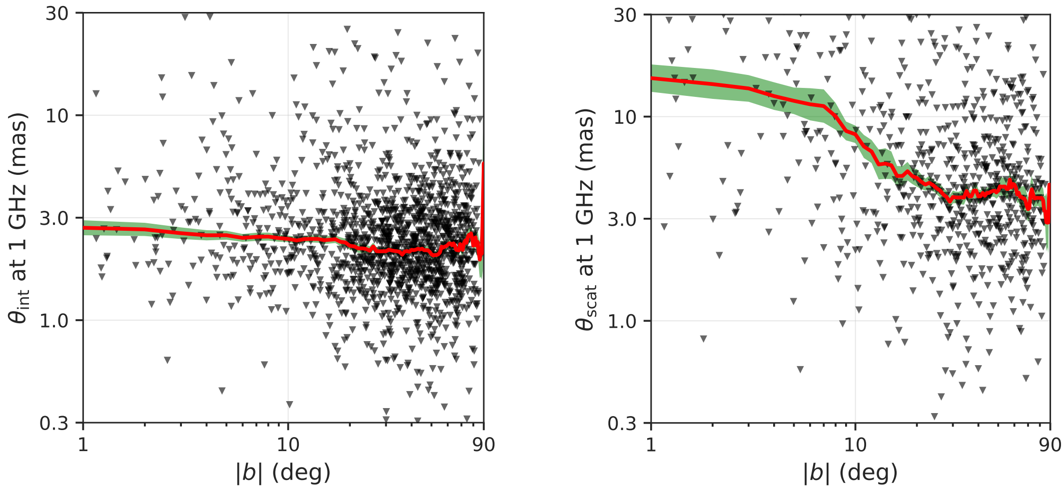

Figure 2: Intrinsic (left) and scattered (right) AGN core sizes at 1 GHz depending on the absolute value of the Galactic latitude. A triangle marker represents an individual source. The red line is the running median, followed by the green shaded area that shows the standard deviation of the median.

Table 1: Scattering indices $k_{\rm scat}$ derived from different sets of the measured AGN core sizes at the Galactic plane ($|b| < 10°$).

Dataset (1)	N (2)	$k_{\rm scat}$ (3)
All bands	215	$1.94^{+0.07}_{-0.09}$
2, 5, 8 GHz	154	$2.03^{+0.16}_{-0.05}$
2, 8, 15 GHz	60	$2.03^{+0.03}_{-0.17}$
2, 5, 8, 15 GHz	35	$1.95^{+0.11}_{-0.24}$

Columns are as follows: (1) frequency bands over which the datasets of the sources were selected for fitting; (2) the number of the sources; (3) the scattering index value.

We used $k_{\rm scat} = 1.94^{+0.08}_{-0.07}$ and set $k_{\rm int} = 1$ to fit the intrinsic and scattered core sizes at 1 GHz ($\theta_{\rm int,\,1\,GHz}$ and $\theta_{\rm scat,\,1\,GHz}$, respectively) for 1546 sources over the sky. The obtained median values of the intrinsic and scattered sizes for the sources in the Galactic plane are 2.8 and 12.0 mas, respectively, while the corresponding median values for the sources outside the Galactic plane are 2.3 and 4.4 mas, respectively. The running median (red line) in Fig. 2 (left panel) demonstrates that the median intrinsic core sizes almost do not change as it approaches the Galactic plane, while the median scattered core sizes do increase significantly (Fig. 2, right panel). This result confirms that the scattering originates in the Galactic plane. Analyzing the distributions of the obtained intrinsic and scattered core sizes at 1 GHz, we came to the conclusion that a large fraction, approximately 40%, of the AGN observed through the Galactic plane are not scattered.

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5. Conclusion

The power-law index for the unscattered AGN core is found to be $k = 1.01 \pm 0.01$. Scattering screens are concentrated mainly in the Galactic plane and are not uniformly distributed over it. Nearly 40% of the AGN observed through the Galactic plane are not scattered. The regions of the Galaxy characterized by a high Hα radiation intensity show a significant spatial correlation with strong scattering regions. The power-law scattering index $k_{\rm scat}$ ranges from $1.94^{+0.08}_{-0.07}$ through $2.03^{+0.16}_{-0.05}$. This agrees with both the Gaussian screen and Kolmogorov turbulence models.

6. Acknowledgments

This research was supported by the Russian Science Foundation project 21-12-00241.

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