DOI: 10.31401/WS.2021.proc.11

Solar wind stream structure by IPS observations at decameter wavelengths

Kuhai[1,2]N.V., Kalinichenko[1]M.M., Konovalenko[1]O.O., Olyak[1]M.R., Brazhenko[3]A.I.

[1] Institute of Radio Astronomy of NASU, Kharkiv, Ukraine;
2 Oleksandr Dovzhenko Hlukhiv National Pedagogical University, Hlukhiv, Ukraine;
[3] Gravimetrical observatory of Geophysical institute of NASU, Poltava, Ukraine;
E-mail: nkuhai@gmail.com

Abstract.

This work is to demonstrate the potential of the solar wind streams investigations by using interplanetary scintillation observations with the decameter radio telescopes UTR-2 and URAN-2 (Ukraine). The paper includes the description of the techniques used for observations, registration, data processing and analysis. The examples of registrations of corotating flows and streams associated with ICME are shown. Statistics of velocity and spectral index of the interplanetary turbulence for slow and fast solar wind streams is also given.

Introduction

The solar wind observed anywhere in the heliosphere is a collection of streams with different parameters. In this collection of streams, two types of solar wind streams can be distinguished according to their velocity: slow streams with the velocity of around 350 km/s and fast streams with the velocity of around 750 km/s [*Lang*, 1996]. The slow streams are associated with bright coronal streamers, whereas coronal holes and coronal mass ejections (CMEs) are associated with the fast streams. The fast streams have a significant impact on space weather in the heliosphere in general and near the Earth in particular. Therefore, the development of effective methods for detecting solar wind streams, studying their parameters, dynamics and laws to which they obey is of particular interest. Spacecraft measurements allow us to find solar wind streams and obtain their parameters with high accuracy *in situ* [see e.g. *Paularena et al.*, 1997]. There is another possibility to find and investigate solar wind streams. Radiation from compact cosmic radio sources is scattered by density irregularities in the interplanetary plasma. Observations of the intensity fluctuations (interplanetary scintillations or IPS [*Hewish, et al.*, 1964]) caused by this scattering also enable us to detect solar wind streams and study their characteristics [*Coles*,1996; *Gosling and Pizzo*,1999]. The accuracy of the second method is lower than the first one, but it gives us possibility to study solar wind streams anywhere in the heliosphere including the high heliolatitudes where such studies are very rare. Investigations of the solar wind and its stream structure by using IPS techniques are actively made at frequencies of few hundred megahertz [see e.g. *Dennison and Hewish*, 1967; *Kojima et al.*, 1982; *Bourgois et al.*, 1985; *Fallows et al.*, 2008]. In recent years, such work has been actively carried out at decameter radio waves [*Falkovich*, 2010; *Kalinichenko et al.*, 2019]. Decameter radio waves allow conclusions to be made on the solar wind stream parameters both at small and large elongations. The last ones correspond to the solar wind beyond Earth's orbit where high frequencies are only weakly scattered by the rarefied interplanetary plasma.
The aim of this work is to demonstrate the potential of the investigations of the solar wind streams by using interplanetary scintillation observations at decameter radio waves.

Radiotelescopes.

Ukraine has a radio astronomical system URAN which includes the largest in the world decameter radio telescope UTR-2 (that is situated near East Ukrainian city Kharkiv) and four smaller radio telescopes belonging to the different institutions of National Academy of Sciences of Ukraine: URAN-1 (near Zmiiv), URAN-2 (near Poltava), URAN-3 (near Lviv) and URAN-4 (near Odesa), [*Konovalenko et al.*, 2016], Fig.1. The distances between some radio telescopes of URAN system are the next: UTR-2 - URAN-2 is 153 km, UTR-2 - URAN-3 is 946 km and URAN-2 - URAN-3 is 810 km. The operational frequency range of the Ukrainian low frequency radio telescopes is 8 to 32 MHz, decameter radio waves. These are large antenna arrays consisting of hundreds of antenna elements.

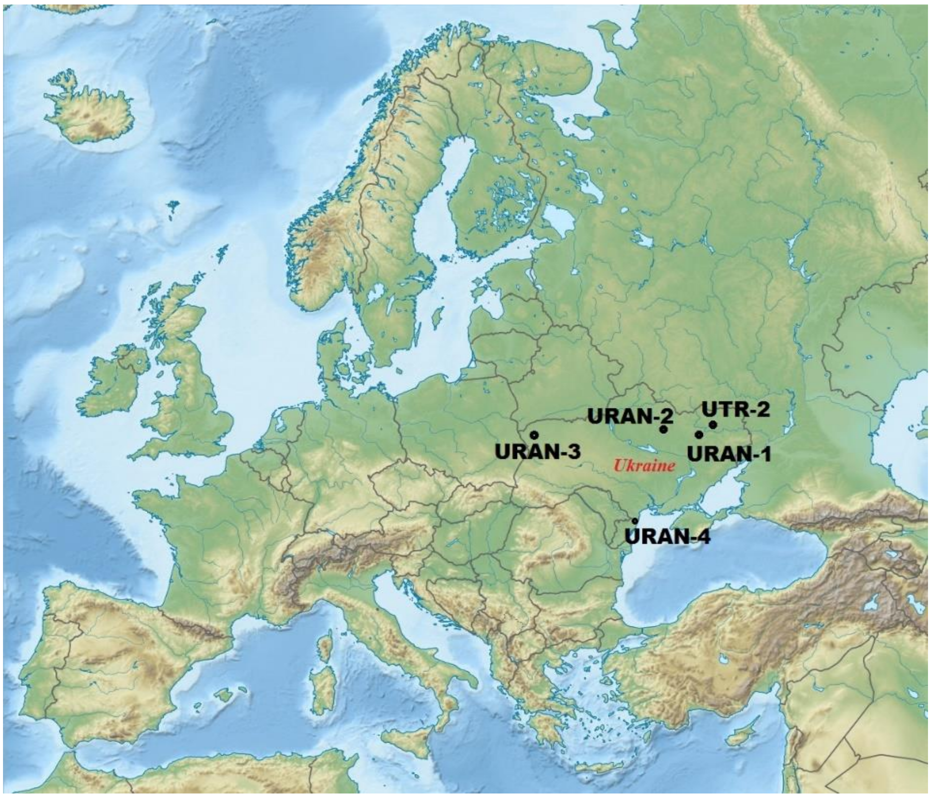

Fig.1. A map of the locations of UTR-2 and URAN radio telescopes throughout Ukraine

Observations

Since 2011, IPS observations have been regularly carried out synchronously with the radio telescopes UTR-2 and URAN-2. If the task requires it, other radio telescopes of URAN system are periodically connected to work. IPS observations are carried out monthly. An ordinary observational session usually lasts for 7 days (1 weak). The list of the observed sources includes several dozen of compact radio sources with small angular size at decameter radio waves (equal or less than 5 arc seconds). These are powerful pulsars and quasars. The radio sources with larger angular size are used for ionosphere monitoring. These are a super nova remnant Cassiopeia A, a radio galaxy Virgo A and others.

Data processing

Records are obtained by using digital spectrum analyzers with parameters: instant band of analysis is 33 MHz (sampling frequency is 66 MHz); the number of channels is 8192; the time and frequency resolutions are 0.5 ms and 4 kHz, respectively; the ADC resolution is 16 bit. The use of the high linearity wideband receivers and records from several radio telescopes allow us to apply a special technique for selecting data, which are not corrupted by Earth's ionosphere and interferences, and to achieve sensitivity that is close to maximal [*Kalinichenko*, 2013]. Fig.2a shows an example of IPS records obtained synchronously with the radio telescopes UTR-2 and URAN-2.

The solar wind stream structure is obtained by fitting the model theoretical characteristics to the experimental ones. Power spectrum (Fig.2b) and dispersion dependence which is obtained from spatial cross-correlation function (Fig. 2c) are usually used as such characteristics. We consider spectrum and cross-correlation function as a sum of contribution from each stream. The model equations are obtained by using Feinman path integral technique [*Frehlich*, 1987]. Among other things, the applied technique uses the fact that power spectra and dispersion dependences depend on stream parameters in different ways [*Olyak*, 2013]. For corotating streams these technique gives good results and allows us to estimate the width of the solar wind stream.

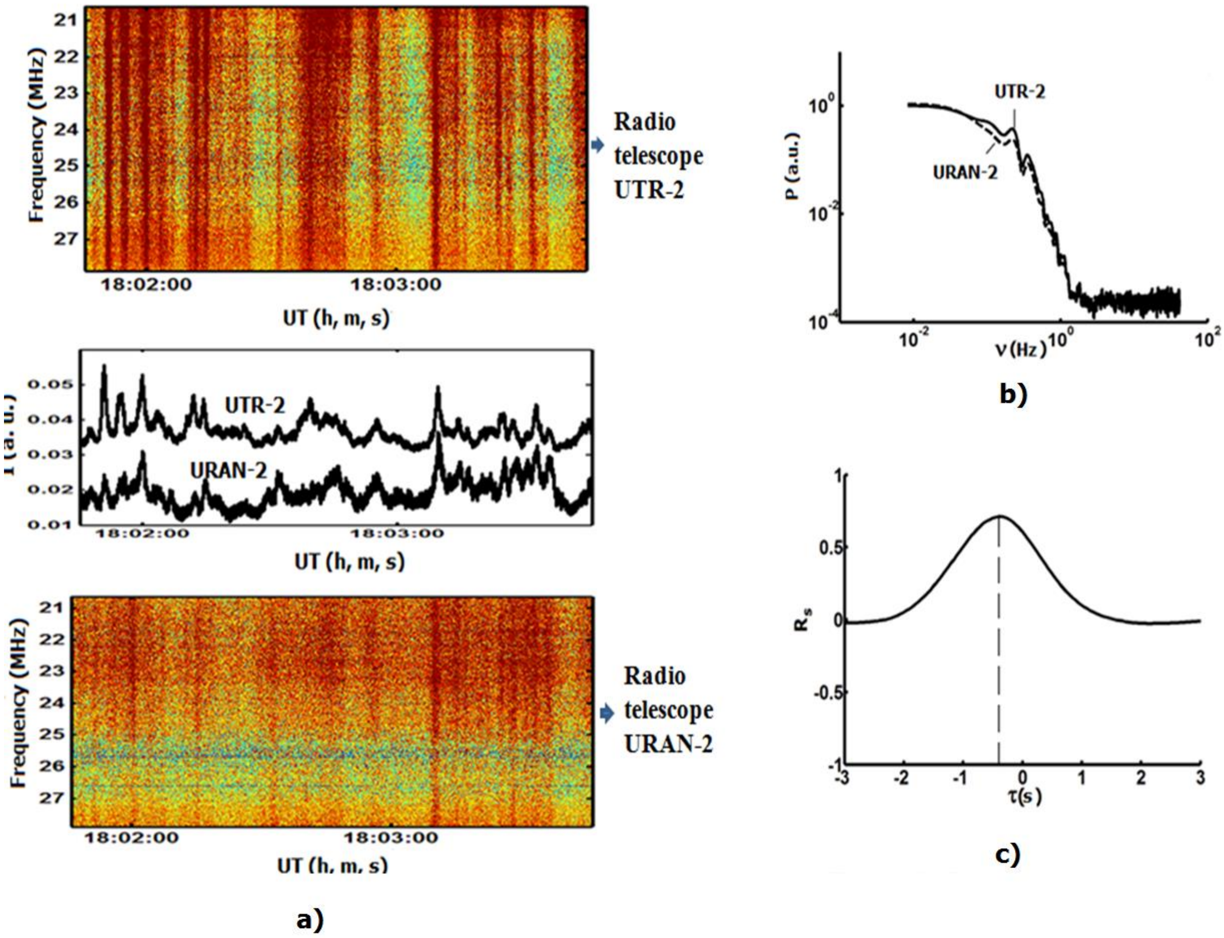

Fig.2. . a) an example of IPS records obtained synchronously with the radio telescopes UTR-2 and URAN-2;b) synchronous power spectra, c) spatial cross-correlation function

Corotating streams

Fig.3 shows an example of the reconstructed stream structure of the solar wind for 3 successive days (January 12, 13 and 14, 2016) obtained by processing UTR-2 - URAN-2 IPS data. The different streams are marked by the different colors, the higher velocity, the deeper red color is used). The data was obtained during observations of Crab Nebula which contains the compact source with angular size about 2 arc seconds. The compact radio source in Crab Nebula is associated with a pulsar J0534+2200. It is seen that on the first day, January 12, only one powerful flow (marked A) is detected on the line of sight to the radio source. The next day, January 13, the stream A becomes weaker and it becomes possible to see the stream B, which is situated ahead of the stream A. The next day, January 14, the streams A and B are pushed by the next stream C. The solar wind speed, which was estimated by using the method of interplanetary scintillations, agreed with the speed measured onboard the Solar and Heliospheric Observatory (SOHO), Wind, and other spacecrafts near the Earth. What is the nature of the solar wind streams detected with the interplanetary scintillation method? These can be both streams in the ordinary sense and the large-scale structures within one stream.

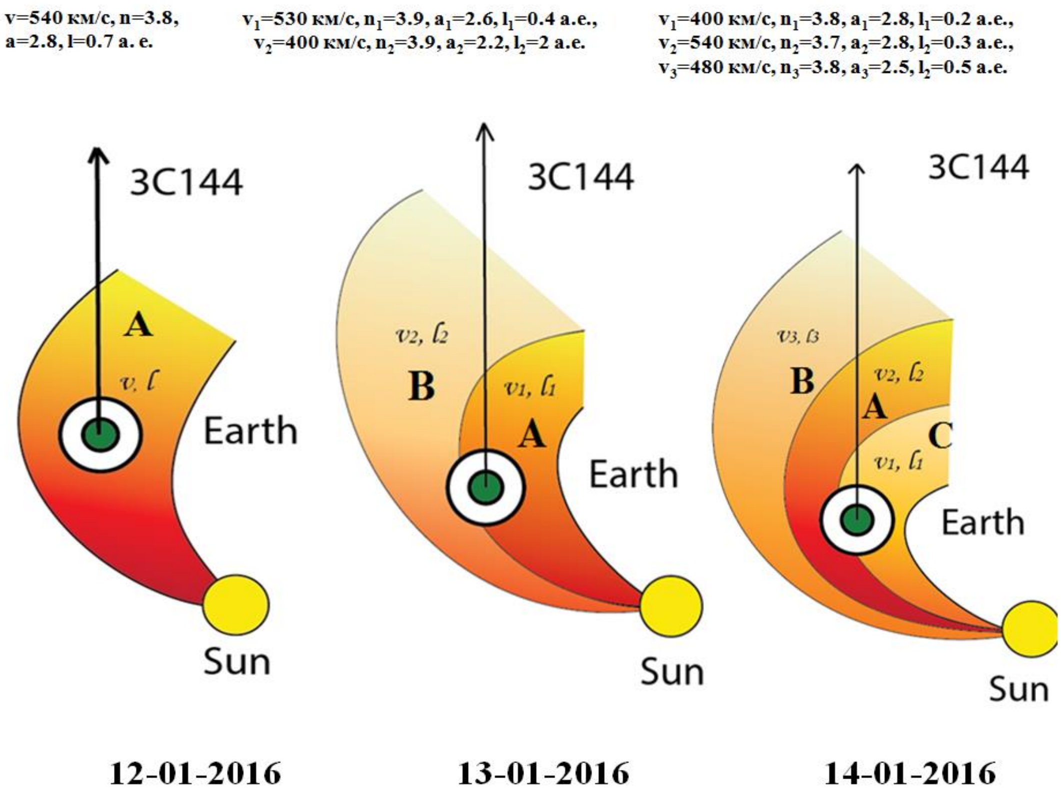

Fig.3. The reconstructed stream structure of the solar wind for 3 successive days (January 12, 13 and 14, 2016). The estimated parameters of the streams A, B and C are marked at the top of Figure too.

Interplanetary coronal mass ejection

Interplanetary coronal mass ejection (ICME) reveals itself in IPS data at decameter wavelengths as a sharp increase of scintillation level (Fig.4a,b). Since the plasma density in ICME is many times higher than in the undisturbed solar wind (Fig. 4c), ICME makes the main contribution to the observed interplanetary scintillations. And since the ICME dimension in the radial direction is a fraction of an astronomical unit, it is logical to model ICME by a phase screen model. Fig.4d shows an example of ICME movement in the interplanetary plasma reconstructed by using IPS observations made with the radio telescopes UTR-2 and URAN-2. It should be emphasized that it is important to trace the ICME throughout the heliosphere including region beyond the Earth's orbit. Why are ICME observations beyond Earth's orbit important? As ICMEs continue slowing at the distances of several astronomical units from the Sun, the investigations of ICME dynamic beyond Earth's orbit will allow us to construct a reliable model of ICME propagation in the heliosphere. Such model for instance makes possible a precise prediction of the arrival time of ICME at the Earth that is the key problem in the space weather science. Decameter radio waves are very useful for such investigations.

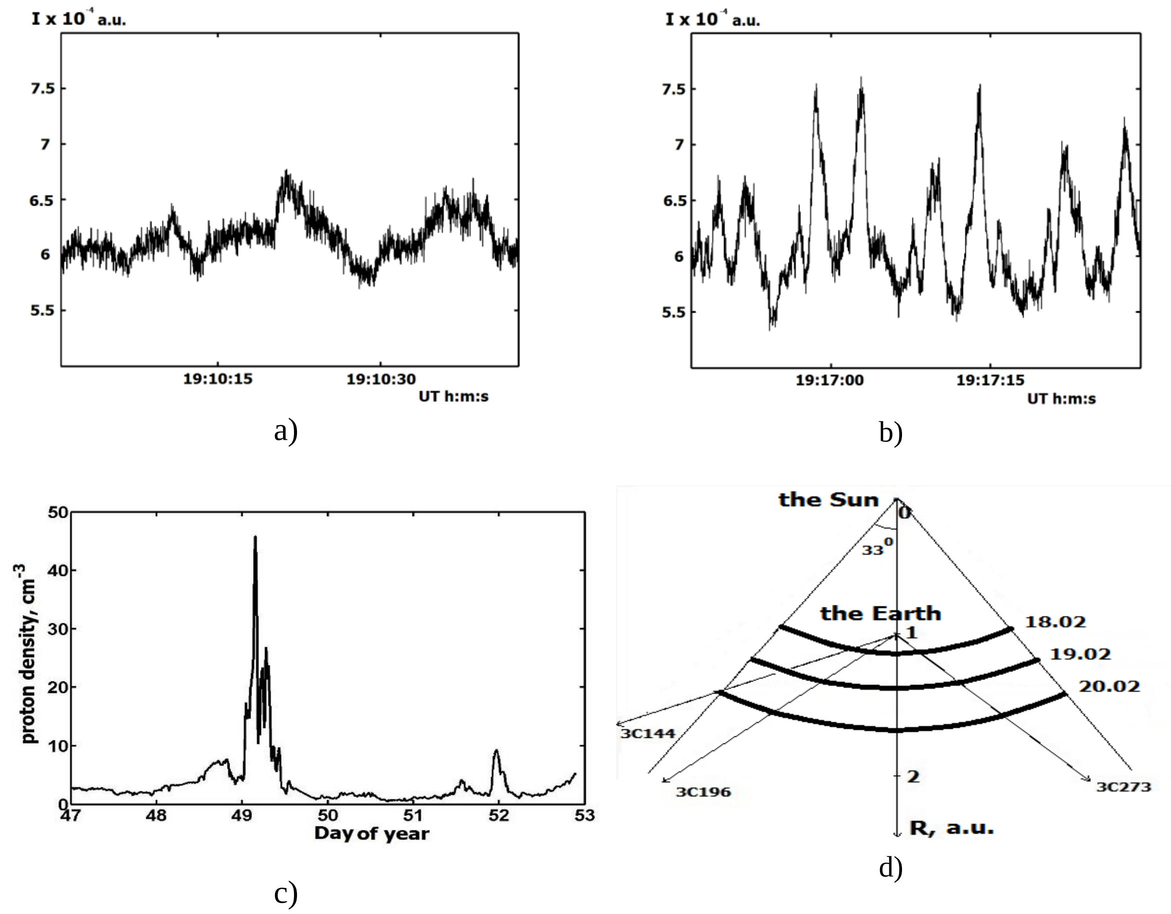

Fig.4. Interplanetary scintillations: a) before and b) during ICME passing across the line of sight to the radio source. Proton density including ICME measured by "Wind" spacecraft - c). The position of ICME in the interplanetary medium obtained by IPS data - d)

Statistics of stream parameters

Large enough volume of experimental data allows us to obtain the statistics of the solar wind stream parameters. Histograms for velocity and spectral index of the interplanetary turbulence are shown in Fig.5.

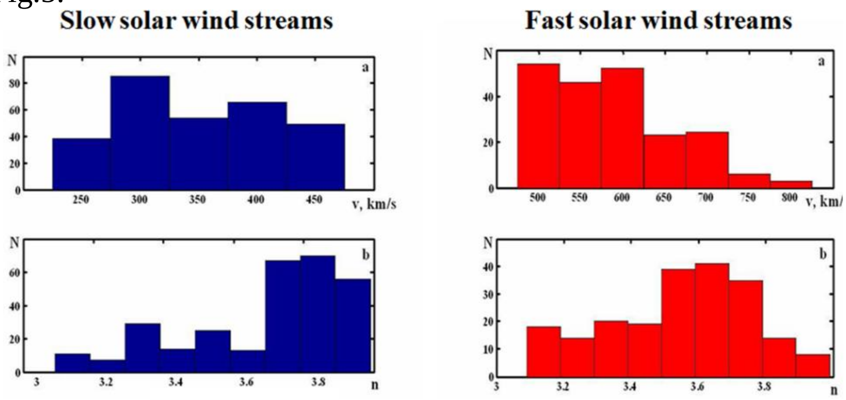

Fig.5.Statistics of parameters of slow and fast solar wind streams: v - velocity, n - spectral index of the interplanetary turbulence.

Conclusions

The results discussed in this work are important for studies of solar wind streams in the interplanetary plasma, including those related to space weather prediction problems. Studies at decameter radio waves can be an additional aid to the investigations of the solar wind streams, which are already being carried out by using IPS technique at higher frequencies and other methods, in particular, *in situ* using spacecraft measurements.

Acknowledgment

This study was supported by Target Complex Program of NAS of Ukraine for Scientific Space Studies for 2018-2022 (projects "Ground-based support by UTR-2-URAN-GURT low-frequency radio telescope system of international and Ukrainian space missions" and "Creation of low-frequency radio astronomical elements and systems for the study of objects in the Universe from the surface of the Moon") and the project "Instrumental and information connection of radio telescopes UTR-2, URAN, GURT to world networks of low-frequency radio astronomy".

References

Bourgois, G., Coles, W.A., Daigne, G., Silen, J.Turunen, T., Williams, P.J. (1985). Measurements of the solar wind velocity with EISCAT, Astron. Astrophys., 144, 452-462, 1985.

Coles, W. A. (1996), A bimodal model of the solar wind speed, Astrophysics and Space Science, 243,1, 87–96, 1996.

Dennison, P.A., Hewish, A. (1967). The solar wind outside the plane of the ecliptic, Nature, 213, 343-346, 1967.

Falkovich, I.S., Konovalenko, A.A., Kalinichenko,N.N., Olyak,M.R., Gridin,A.A., Bubnov,I.N., Brazhenko,A.I., Lecacheux, A., Rucker, H. (2010), Dispersion Analysis of Interplanetary Scintillations at Decameter Wavelengths: First Results., Radio Physics and Radio Astronomy, 1, 1, 3-9,2010.

Fallows, R.A., Breen, A.R., Dorrian, G.D. (2008). Developments in the use of EISCAT for interplanetary scintillation, Ann Geophys. 26, 2229-2236, 2008.

Gosling, J.T., Pizzo, V.J.(1999). Formation and evolution of corotating interaction regions and their dimension structure. Space Science Reviews, 89, 21-52, 1999.

Frehlich, R.G., (1987). Space-time fourth moment of waves propagating in random media, Radio Science 358, 481-492, 1987.

Hewish, A., Scott, P.F., Wills, D. (1964), Interplanetary Scintillation of Small Diameter Radio Sources, Nature, 203, 4951, 1214-1217, 1964.

Kojima, K., Ishida, Y., Maruyama, K., Kakinuma, T., (1982). An observation system of interplanetary scintillation at UHF, Proc. Res. Inst. Atmos. Nagoya Univ., 29, 61,1982.

Kalinichenko, N. N., Falkovich, I. S., Konovalenko, O. O., Brazhenko, A. I. (2013). Separation of Interplanetary and Ionospheric Scintillations of Cosmic Sources at Decameter Wavelengths, Radio Physics and Radio Astronomy, 18, 3, 210-219, 2013.

Kalinichenko, N.N., Olyak, M.R., Konovalenko, A.A., Brazhenko, A.I., Kuhai, N.V., Romanchuk, A.I. (2019). Large-scale structure of solar wind beyond the Earth's orbit: reconstruction using the data of two-site measurements of interplanetary scintillations in the decameter radio range. Kinematics and Physics of Celestial Bodies, 35, 1, 17–27, 2019.

Konovalenko, A., Sodin, L., Zakharenko, V., Zarka, Ph, Ulyanov, O., Sidorchuk, M., Stepkin S., Tokarsky P., Melnik, V., Kalinichenko, N., Stanislavsky, A., Koliadin, V., Shepelev, V., Dorovskyy, V, Ryabov, V., Koval, A., Bubnov, I., Yerin, S., Gridin, A., Kulishenko, V., Reznichenko, A., Bortsov, V., Lisachenko, V., Reznik, A., Kvasov, G., Mukha, D., Litvinenko, G., Khristenko, A., Shevchenko, V., Shevchenko, V., Belov, A., Rudavin, E., Vasylieva, I., Miroshnichenko, A., Vasilenko, N., Olyak, M., Mylostna, K., Skoryk, A., Shevtsova, A., Plakhov, M., Kravtsov, I., Volvach, Ya., Lytvinenko, O., Shevchuk, N., Zhouk, I., Bovkun, V., Antonov, A., Vavriv, D., Vinogradov, V., Kozhin, R., Kravtsov, A., Bulakh, E., Kuzin, A., Vasilyev, A., Brazhenko, A., Vashchishin, R., Pylaev, O., Koshovyy, V., Lozinsky, A., Ivantyshin, O., Rucker, H., Panchenko, M., Fischer, G., Lecacheux, A., Denis, L., Coffre, A., Grieβmeier, J-M, Tagger, M., Girard, J., Charrier, D., Briand, C., Mann, G. The modern radio astronomy network in Ukraine: UTR-2, URAN and GURT. (2016). Experimental astronomy, 42, 1, 11- 48, 2016.

Lang, K.R. (1996), Unsolved Mysteries of the Sun, Sky and Telescope, 92, 2, 38, 1996.

Olyak, M.R., (2013). The dispersion analysis of drift velocity in the study of solar wind flows," J. Atmos. Sol.-Terr. Phys. 102, 185-191, 2013.

Paularena, K.I., Richardson, J.D., Lazarus, A.J., Zastenker, G.N., P.A.Dalin, P.A. (1997). IMP 8, WIND and INTERBALL observations of the solar wind. 22, 7–8, 1997, 629-637, 1997.