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UDC number:

OBSERVATIONS OF WEAK GALACTIC OH MASERS IN 1.6 GHZ FREQUENCY BAND USING IRBENE RT32 RADIO TELESCOPE

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Abstract:

Ventspils International Radio Astronomy Centre (Ventspils University of Applied Sciences) is implementing the scientific project "Complex investigations of the small bodies in the Solar system" (lzp-2018/1-0401) related to the research of the small bodies in the Solar system (mainly, focusing on asteroids and comets) using methods of radio astronomy and signal processing. One of the research activities is weak hydroxyl (OH) radical observation in the radio range - single antenna observations using Irbene RT-32 radio telescope. To detect weak (0.1 Jy) OH masers of astronomical objects using radio methods, a research group in Ventspils adapted the Irbene RT-32 radio telescope working at 1665.402 and 1667.359 MHz frequencies. Novel data processing methods were used to acquire weak signals. Spectral analysis using Fourier transform and continuous wavelet transform were applied to radio astronomical data from multiple observations related to weak OH maser detection. Multiple observation sessions of OH maser objects (R LMi, RU Ari, V524 Cas, OH 138.0+7.2, etc) were carried out in 2020-2021.

Introduction:

The main goal of the research is to determine the lowest possible level of the detection using Ventspils International Radio Astronomy Centre radio telescope 1.6 GHz system and using implemented data processing methods, with the aim to successfully detect OH masers on comets which are weak in radio frequency range in near future. Previous research [1, 2, 3, 4] show that the typical peak source flux densities of the comet in 1.6 GHz frequency band are in the range of 0.004 Jy to 0.04 Jy, although the flux density of the bright comets OH masers could reach 0.4 Jy [5]. Using radio methods opposed to optical methods, gives a possibility to clarify comet behaviour near the Sun.

There are four known (1612.231, 1665.402, 1667.359 and 1720.530 MHz) hyperfine transitions of OH at 18 cm wavelength which have been used for 40 years, historically to observe comets, but only two of them - 1665.402 MHz and 1667.359 MHz - are with potential for the weak object detection because of the RFI in other frequency bands. The 18 cm line is the result of an excitation from resonance fluorescence, whereby molecules absorb solar radiation and then re-radiate the energy. The OH molecule absorbs the UV solar photons and cascades back to the ground state Lambda doublet, where the relative populations of the upper and lower levels strongly depend upon the heliocentric radial velocity (the 'Swings effect') [6].

Theoretical estimations of the overall radio telescope 1.6 GHz system were done before the observation phase and it shows the possibility to detect weak objects if the integration time is large enough, but it was necessary to prove the estimations using observations. It should be noted that the radiation of comets has a tendency to decrease, for example, the comet OH brightness usually fades very fast, and the comets are not the best choice for the proof of estimated calculations. That's why the multiple interstellar OH maser observations were carried out and the choice of targets was done evaluating the target brightness level. For example, the targets with flux densities around 0.3 Jy and 2 Jy were chosen to simulate bright OH maser on a comet with flux density ~0.5 Jy.

Used instruments and methodologies:

Preparation of the Irbene RT-32 radio telescope includes design and installation of the dedicated low-cost L-band (18 cm wavelength) receiver, capable of receiving hyperfine transitions of the interstellar OH masers and the OH masers of comets. A suitable receiver was developed by VIRAC team, and it consists of a compact feed horn with dual circular polarized channels and parabolic reflector, which together with existing Cassegrain antenna forms a triple mirror system. Uncooled low noise amplifiers are used for both channels (right and left circular polarization), which allows us to achieve system noise temperatures of less than 60 K. Estimated aperture efficiency at 1.65 GHz is between 30 and 50 % which translates to RT-32 radio telescope gains of at least 0.1 K/Jy [7]. The overall estimated sensitivity SEFD is between 650 and 900 Jy depending on the elevation of the antenna and the weak object detection could be a challenging task. The main activities to increase the overall sensitivity were related to implementation of effective methods during the data recording and processing steps.

The theoretical estimations of the sensitivity level of Irbene RT-32 1.6 GHz system were carried out before the observations. The main research goal is to adapt RT-32 radio telescope for comet OH maser detection, but at the beginning it was necessary to check RT-32 readiness level for weak object observations using more stable objects, for example interstellar OH masers. Weakness of the radio signal of a comet OH maser is the main challenging factor. The calculated results of the noise floor dS vs integration time show - the detection of the source with the flux density below 0.4 Jy is possible by RT-32 antenna if integration time is larger than 8 hours and total power bandwidth (BW) - 10 KHz [8].

A spectrometer backend based on software defined radio USRP X300/310+TwinRX is used to record data using 16 bit + 16 bit (real + imaginary part) per sample [9]. For spectral data calibration, the frequency switching method [10] is currently used and the object is observed in 4 phases - local oscillator with noise diode on/off and reference local oscillator with noise diode on/off. This allows the calculation of system temperature, which together with position and degrees per flux unit gives us a spectrum of spectral flux density. To improve time resolution, data is overlapped (in this case with a 66.1% overlapping coefficient which was chosen for its effectiveness [11]), creating bins of data which must be processed using Fourier transform with the addition of Blackman-Harris windowing function. Each bin results in an individual spectrum and to get the result, all spectrums are averaged. To prevent numerous technical errors, it's important to monitor the system temperature to check for anomalies in data. Since data is still valid for the part where the read system temperature is invalid, it's possible to predict potential system temperature values for a specific time moment. In this system it is realized using wavelet transformation, using a low precision wavelet to get the shape of the spectrum, and replacing incorrect value by this predicted value. Data processing is implemented to collect data using long integration time and to calculate as the result the spectrum of the object. To decrease the noise level of the spectrum the multiple observation sessions were combined.

Results:

To verify calculations of the estimation model and to evaluate the RT-32 radio complex sensitivity level, multiple observations of interstellar OH masers in 1.6 GHz were performed. To check RT-32 readiness level for weak object observations the observations of variable star R LMi (spectrum shown in Figure No. 1), OH/IR star Ru Ari (spectrum shown in Figure No. 2), variable star U Aur (spectrum shown in Figure No. 3), OH/IR star OH 138.0 +7.2 (spectrum shown in Figure No. 4), variable star V524 Cas were carried out. All obtained results are summarized at Table No.2.

Table No.1 lists the observed objects and their parameters. The first four columns include the source name, source type and J2000 equatorial coordinates. In Column No. 5 the observation lines are shown. Column No. 6 contains the flux density at the total intensity peak or peaks (if spectrum consists of multiple parts), together with the noise level (1σ). In Column No. 7 hours needed for detection ~3σ or ~2σ for weaker objects. Column No. 8 gives the velocity of peak flux density.

The results from the first observations of variable Star of Mira Cet type R LMi showed successful detection in both frequencies and R LMi was chosen as a calibrator target for other observations as well. Overall, the data set of R LMi consists of 50 hours of observation data. The spectrums of both data sets are shown in Figure 5, where the noise level of the 2 hours data set is ~ 0.52 Jy, but the noise level of the 50 hours data set is 0.10 Jy which is promising to detect OH masers on bright comets. Figure 6 and Figure 7 show results of the applied methodology if the radiation of the observed target is weak. Results of the 2-hour data set processing are not clear because of the high SNR, but usage of multiple data processing methods reduces SNR, thus the object can be detected.

Three of five objects were detected successfully in both frequencies, although the SNR in the weaker signals was ~2σ. The characteristics of the spectrums and the obtained velocities were compared with results from scientific publications [12, 13, 14] and *maser.db* [15] page. The obtained results have been verified and are considered correct. Target OH 138.0 +7.2 was detected only at 1.667 GHz, but previous research showed that in other observatory observations the detection at 1.665 GHz was not clear. Although variable star V524 Cas was not detected of any frequency band, this could be explained by the fact that the magnitude of the variable star has decreased compared to previous observations in 1999, when the flux densities were 0.2 Jy (at 1665 MHz frequency) and 0.1 Jy (at 1667 MHz frequency) [16].

Based on processed observation data and the corresponding results, it is concluded that practically the sensitivity level is 6.7 times larger than estimation in the theoretical model. This can be explained by unstable receiver activity during the large observations, where system temperature is changing stochastically. For example, to detect targets with the flux density ~ 0.4 Jy, more than 22 hours are needed, for ~0.04 Jy detection - more than 300 hours are needed, which is cost ineffective to use radio telescopes for the observations of comet OH maser.

Conclusions and future work:

Developed flux detection threshold estimation model which is related to noise floor dS vs integration time shows that the detection of the source with the flux density below 0.4 Jy is possible using radio telescope RT-32 complex if the spectral channel bandwidth is small and integration time is large [7-11], however the 1.6 GHz receiver is not stable, and the data noisiness is substantial.

It should be noted that radiation of the target source tends to decrease, for example, the comet OH brightness usually fades fast, and it is challenging to detect the maser during the entire integration time.

To continue weak maser research the sensitivity of the RT-32 radio complex needs to increase using - 1) installation of a new cryogenic 1.6 GHz frequency band receiver (development process will start at 2022); 2) more effective data processing tools, for example, weak OH signal filtration from background noise using the Karhunen–Loève Transform for detection and RFI identification, isolation, and removal.

Using existing RT-32 1.6 GHz receiver and data processing methods only a small fraction of weak OH masers (flux density below 0.5 Jy) can be identified, but after the increased sensitivity of RT-32 radio complex, it will be possible to measure delay and frequency of interference using hyper-fine transitions of OH molecules. Previous experience with acquiring and processing data from the DA14 asteroid [17 - 10] on February 15, 2013, offers a good experience to develop methods for the comets OH maser location detection and its behaviour approaching the Sun.

Comparison of radio and optical observations for the same events on the same comets in order to get further insights in the physics of OH masers on comets.

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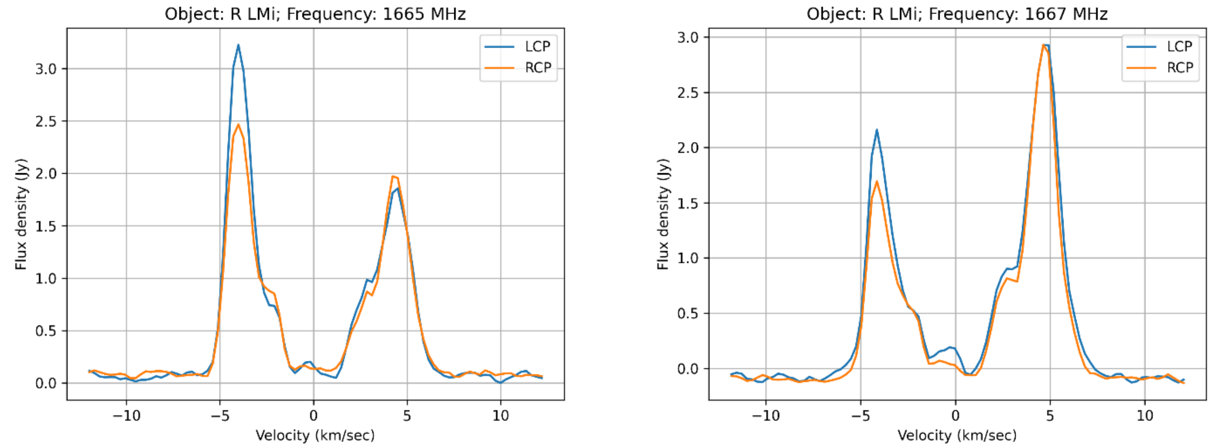

Figure 1. Object - variable star R LMi. Frequency - 1665 MHz (Left side) and 1667 MHz (Right side). Polarisation - Left circular polarisation (in blue) and right circular polarisation (in orange).

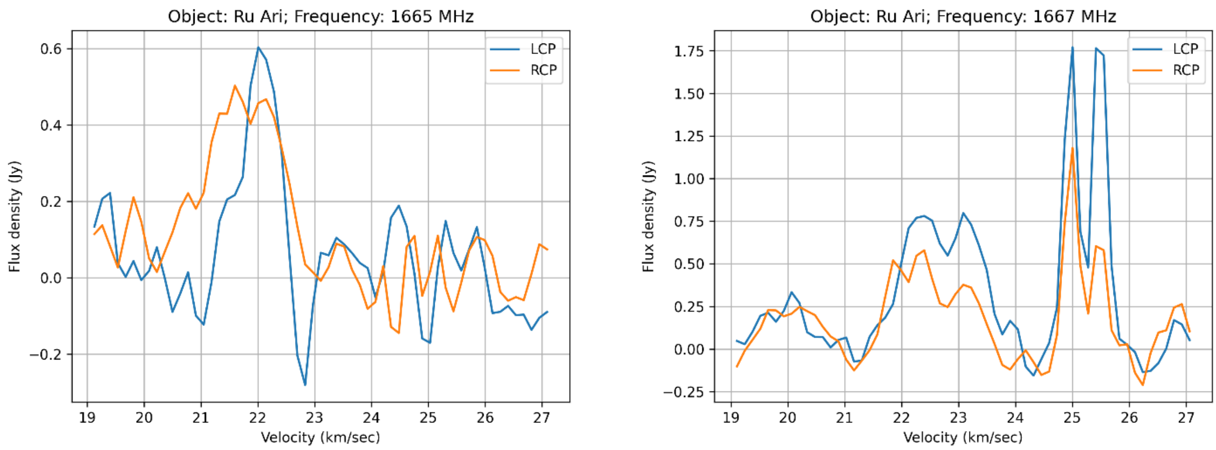

Figure 2. Object - OH/IR star Ru Ari. Frequency - 1665 MHz (Left side) and 1667 MHz (Right side). Polarisation - Left circular polarisation (in blue) and right circular polarisation (in orange).

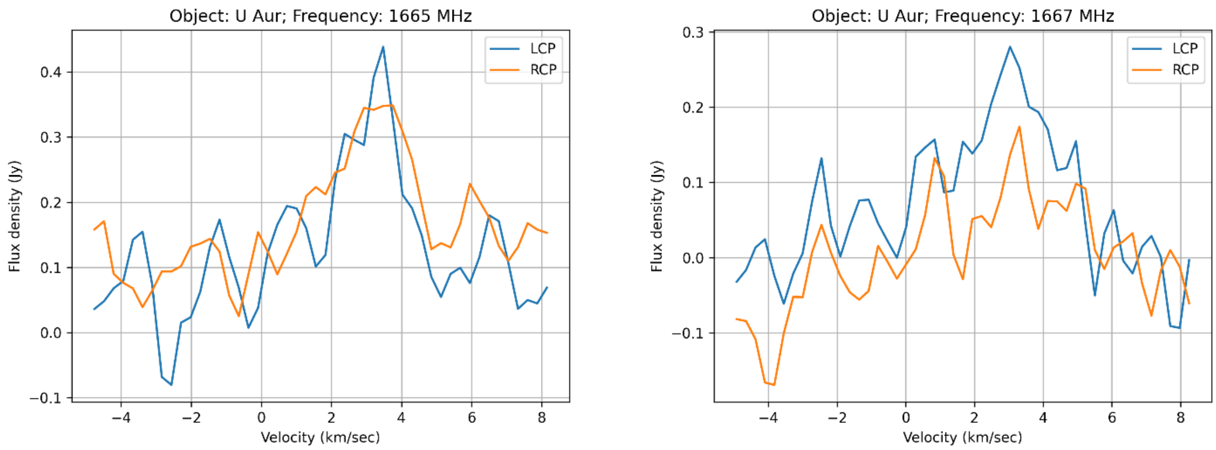

Figure 3.Object - variable star U Aur. Frequency - 1665 MHz (Left side) and 1667 MHz (Right side). Polarisation - Left circular polarisation (in blue) and right circular polarisation (in orange).

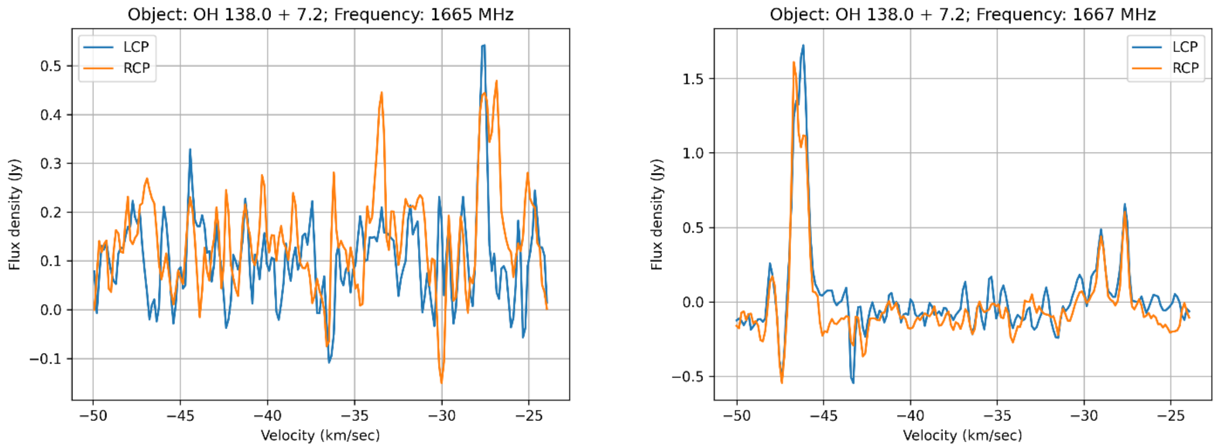

Figure 4. Object - OH star OH 138.0 + 7.2. Frequency - 1665 MHz (Left side) and 1667 MHz (Right side). Polarisation - Left circular polarisation (in blue) and right circular polarisation (in orange).

Table No.1 Obtained results of weak OH masers observations using RT-32 and 1.6 GHz receiver

Name	*Type*	*RA*	*Dec*	*Line (MHz)*	*Flux density (noise level) in Jy*	*Hours needed for detection with ~3σ*	*V(LSR), km/s*
1	2	3	4	5	6	7	8
R LMi	Variable Star of Mira Cet type	09 45 34.28	34 30 42.83	1665	3.22 and 1.95 (0.12)	2	-4.01 and 4.22
				1667	2.92 and 2.16 (0.12)	2	-4.14 and 4.63
Ru Ari	OH/IR star	02 44 45.50	12 19 02.89	1665	0.60 (0.3)	12 (2σ)	22
				1667	1.76 and 0.78 (0.5)	6 and 10	25.00 and 22.25
U Aur	Variable Star of Mira Cet type	05 42 09.06	32 02 23.58	1665	0.43 (0.2)	22 (2σ)	3.47
				1667	0.28 (0.2)	22 (2σ)	3.03
OH 138.0 +7.2	OH/IR star	03 25 08.40	65 32 07.06	1665	no clear detection (0.3)	16 hours observed	-
				1667	1.72 and 0.6 (0.3)	6 and 16	-46.15 and -27.63
V524 Cas	Variable Star of Mira Cet type	00 46 00.13	69 10 53.63	1665	no detection	26 hours observed	-
				1667	no detection	26 hours observed	-

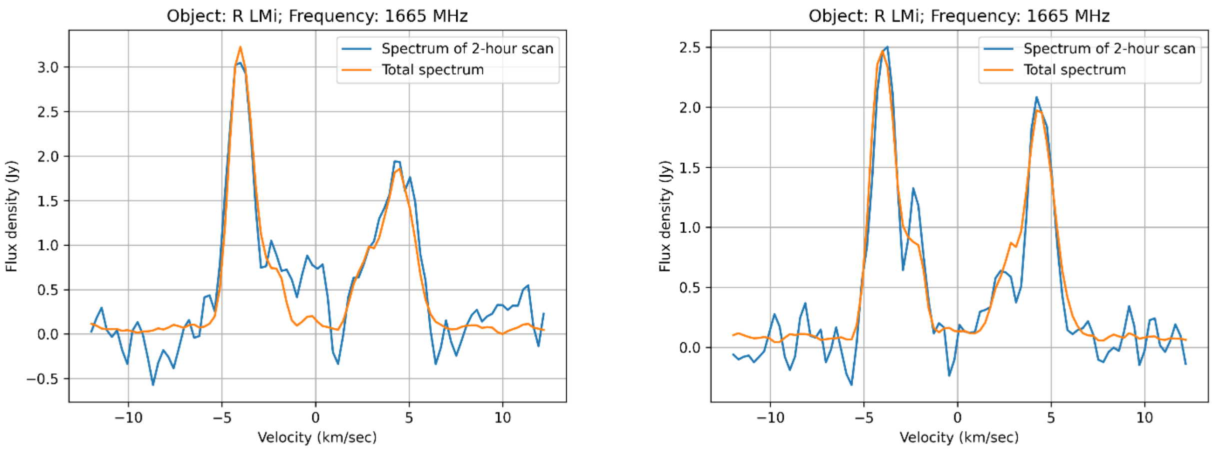

Figure 5. Object -variable star R LMi, frequency - 1665 MHz, polarisation - left circular polarisation (left side) and right circular polarisation (right side). Spectrum of 2-hour data set shown in blue, spectrum of 50-hour data set shown in orange

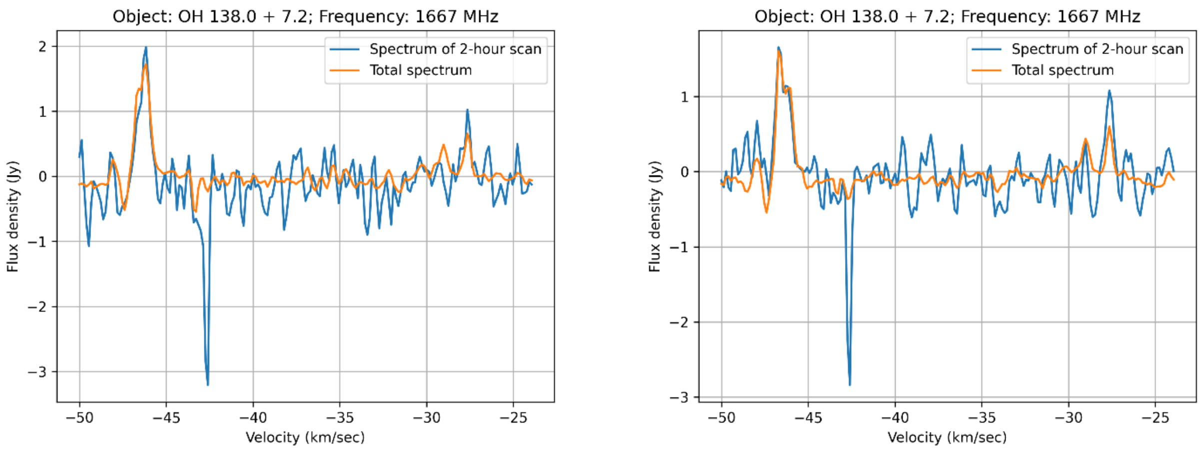

Figure 6. Object - OH star 138.0+7.2, frequency - 1667 MHz, polarisation - left circular polarisation (left side) and right circular polarisation (right side). Spectrum of 2-hour data set shown in blue, spectrum of 16-hour data set shown in orange.

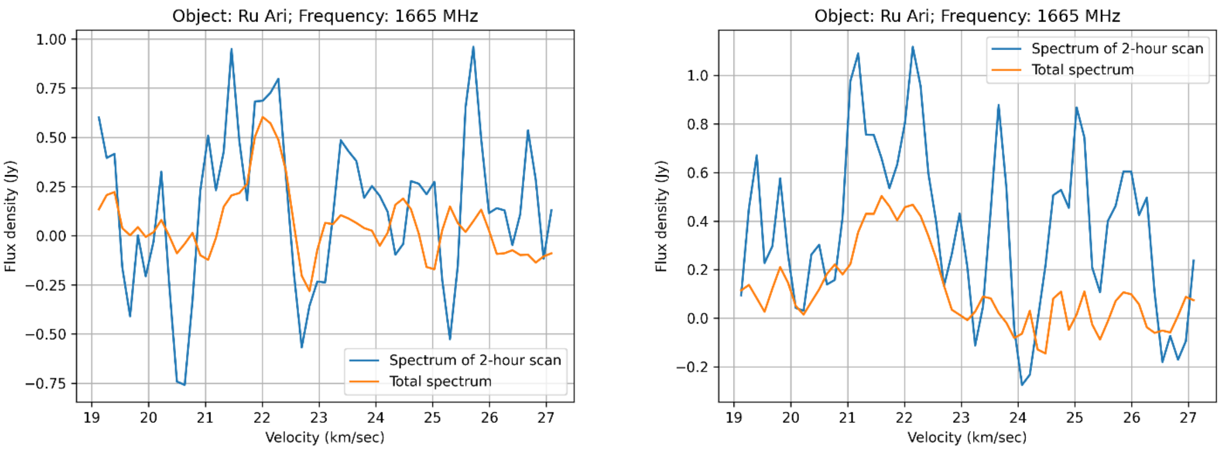

Figure 7. Object – OH/IR star Ru Ari, frequency - 1665 MHz, polarisation - left circular polarisation (left side) and right circular polarisation (right side). Spectrum of 2-hour data set shown in blue, spectrum of 12-hour data set shown in orange.