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Compact Sources of OH Maser Emission in the Star-Forming Region Cep A

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Abstract—In the paper, archival data of the RadioAstron ground–space interferometer project concerning observations of radiation in the OH hydroxyl lines (1665 and 1667 MHz transitions) in the Cep A source have been analyzed. The observations have been carried out on January 7, 2013. The duration of the observation session was about one hour. Ground-based radio telescopes at the Zelenchuk Observatory (Special Astrophysical Observatory of the Russian Academy of Sciences, North Caucasus, Russian Federation), in Yevpatoria (Crimea, Russian Federation), and at the Torun Astronomy Center (Republic of Poland) have participated in the observations. No interferometric response has been detected at the ground–space bases. Several compact sources with angular sizes from 10 to 20 milliarcseconds have been detected at the base between the radio telescopes in Torun and at the Zelenchuk Observatory. These angular sizes correspond to linear sizes of 7.5–15 astronomical units (AU). It has been shown that the detected compact sources are distributed over a region of 750–1500 AU.

Keywords: radio interferometry, compact radio sources, RadioAstron, source Cep A

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1. INTRODUCTION

In the direction of the constellation Cepheus, the local spiral arm contains young stars, stellar associations, and star formation regions. These regions are active in their development: a bipolar flow, a compact H II zone, OH, H_2O and methanol masers are found in them, the corresponding collection is brought together in [1]. Typically, OH emission from a single UCH II region appears to arise in multiple bright spots that are distributed over a region of the sky with a characteristic size of 10^3–10^4 AU.

OH and H_2O masers in the source Cep A are variable, for example, strong outbursts in the OH line at a frequency of 1665 MHz with a flux increase of 250 times over 16 months were observed in 1985 [2], while in 1986, in H_2O masers, short bursts: two times in 2.4 days [3]. OH masers are markers of newly formed O- and early B-type stars that are still deeply embedded in their dense parent material.

Mapping with the VLA radio interferometer revealed that the maser emission originates in the molecular shell surrounding the ultra-compact H II region (UCH II) [4].

It should be noted that the study of the structure of H_2O masers in the direction of the Cep A source within the RadioAstron project was presented earlier in the study of Sobolev et al. [5]. These authors discovered a compact source of maser emission in the water vapor line at a frequency of 22 235 MHz with linear dimensions comparable to the size of the Sun.

In our study, the results of the analysis of archival data from the RadioAstron ground–space interferometer project concerning observations of radiation in the OH hydroxyl lines (1665 and 1667 MHz transitions) from the Cep A source are presented.

2. OBSERVATIONS

In 2011, the Russian Academy of Sciences and the Federal Space Agency created an orbital space observatory with a 10th radio telescope, which when operating together with a ground-based network of radio telescopes, formed the RadioAstron ground–space interferometer. The space radio telescope revolved around the Earth in an elongated elliptical orbit with an apogee distance of 350 000 km, which made it possible to increase the resolution of the ground–space interferometer by 25 times compared to a single, separately operating ground-based VLBI network. This interferometer was used in four frequency ranges: 316–332, 1636–1692, 4804–4860, and 18 372–25 132 MHz. Over seven years of work, many new and unique scientific results were obtained [6].

The scientific program of the RadioAstron project was divided into several stages. The first phase consisted of testing the performance of the ground–space interferometer, including obtaining interferometric responses at ground–space bases for different types of astronomical objects; this phase of the program was carried out in 2011–2012. The next phase was called the Early Science Program (ESP). ESP included research on the most promising objects with the aim of obtaining the most significant scientific results. At this stage, the tests of the interferometer operating modes were also completed, including the correlation mode of the hydroxyl OH radio lines (1665 and 1667 MHz) and the water vapor H_2O (22 235 MHz) radio lines.

During the ESP phase, observations of the Cep A source were carried out to analyze the properties of the emission in the OH hydroxyl lines (1665 and 1667 MHz transitions). The archived data of observations conducted on January 7, 2013 were analyzed. The duration of the observation session was about one hour. Ground-based radio telescopes at the Zelenchuk Observatory (32), Evpatoria (70) and Torun (32) took part in the observations (the diameters of the radio telescope mirrors are given in brackets).

Data were recorded in scans lasting 570 s with 30-s breaks between scans. Ground-based radio telescopes used four-level signal quantization, while the space radio telescope used two-level quantization. The recording was carried out in a 16-MHz band in two polarization channels with left (LCP) and right (RCP) circular polarization. The projection of the interferometer base between the Zelenchuk Observatory radio telescope and the radio telescope in Torun was 10 million wavelengths, while the ground–space bases were approximately 20 times larger.

Data correlation was performed using the ACC correlator [7] in spectral mode. The fundamental quantity in interferometric measurements is the visibility function of $\tilde{V}_{AB}(\nu,t) = \tilde{E}_A(\nu,t)\tilde{E}_B^*(\nu,t)$, which is the product of electric fields (voltage) recorded by radio telescopes A and B. The correlator produces this value and averages the complex values of $\tilde{V}_{AB}(\nu,t)$ for some specified time that is sufficiently small to provide the necessary resolution in isolating the residual interference frequency f_r. In our case, the time step of the correlator's data output Δt was equal to one second. Frequency step $\Delta\nu$ is determined by the specified number of channels $N_{\rm ch}$. Data recording was carried out in a 16-MHz band. To ensure the required frequency resolution, the number of channels was set to 32768. Thus, the frequency step between spectral channels was 0.488 kHz, which corresponds to a velocity resolution of 0.088 km/s.

Function $\tilde{V}_{AB}(\nu,t)$ in most cases is called a cross-spectrum. To determine correctly the amplitude of the visibility function, the Fourier transform over time of a set of functions $\tilde{V}_{AB}(\nu,t)$ is used on the time interval $T_{\rm int}$, which gives the visibility function $\tilde{V}_{AB}(\nu,f)$ in coordinates: signal frequency ν and interference frequency f. In our case, $T_{\rm int} = 400$ s, i.e., the total duration of the observation session was used to isolate interference responses. In order to maintain continuity over time, the 30-s breaks between scans were filled with a noise signal. The interference frequency resolution was $\delta f = 1/3400 = 0.3$ MHz. The shift in interference frequency in different spectral details is caused by the shift of the emitting objects relative to the phase correlation center.

3. RESULTS

The results of the spectral analysis are shown in Figs. 1 and 2 and in Table 1. The emission spectrum of hydroxyl OH in the 1665.401-MHz transition recorded on January 7, 2013 at the Zelenchuk observatory radio telescope is shown in Fig. 1. The System Equivalent Flux Density (SEF) level was 250 Jy. The upper part of the figure shows the spectrum obtained in the receiver channel with left circular polarization, while the lower part of the figure shows the spectrum related to right circular polarization. At the 1667.358-MHz crossover frequency, no signal that was significantly above the noise level ($F_\nu < 2$ Jy) was detected.

The parameters of the detected lines and interference responses are shown in Table 1. The first column of the table gives the radial velocity determined from the position of the maximum of the inscribed Gaussian function, the second column gives the line half-width, the third column gives the maximal flux density, the fourth column gives the amplitude of the visibility function of the selected response at the base between the Zelenchuk Observatory and the radio telescope in Torun in relative units, the fifth column gives the signal-to-noise ratio for the selected response, the sixth column gives the value of the interference frequency, and the seventh column gives the angular size of the compact source at the level of the half-width of the diameter in milliarcseconds (mas).

The presence of interference responses, the parameters of which are given in Table 1, is demonstrated in Fig. 2. In the left-hand circularly polarized channel, interference responses are visible at four radial velocity values: −3.5, −7.0, −8.6, and −10.1 km/s, while at velocities of −7.0 and −8.6 km/s, there are two compact sources. In the right-hand polarized channel, the interference response is detected at a frequency corresponding to −14.2 km/s, while the noticeable width of the interference frequency indicates the possible presence of several compact components.

Based on the relative amplitude of the visibility function, it is possible to estimate the angular dimensions of radiation sources under the assumption of a spherically symmetric Gaussian brightness distribu-

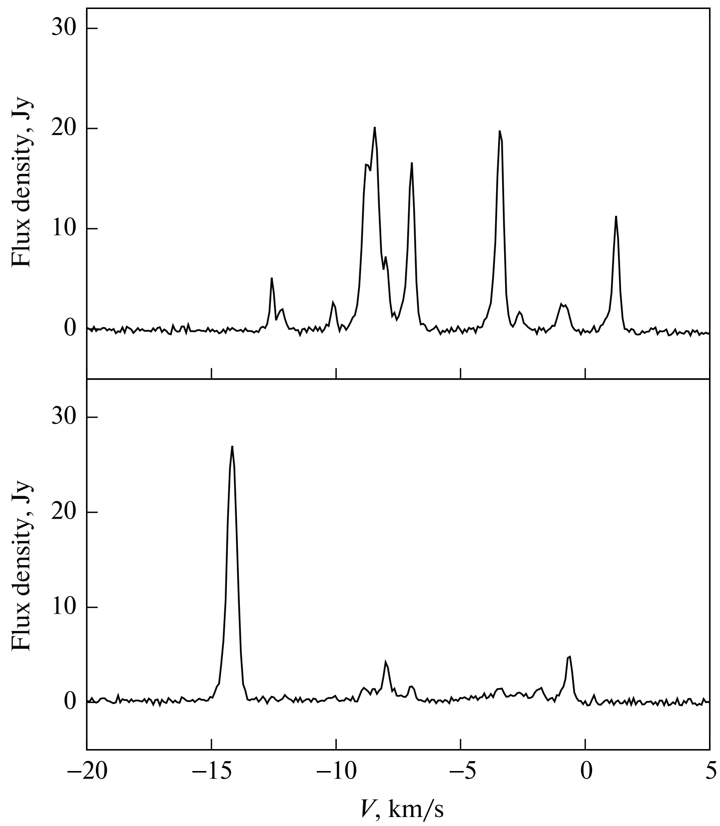

Fig. 1. Emission spectrum of the Cep A source at a frequency of 1665 MHz in channels with left circular polarization (top) and right circular polarization (bottom) on the Zelenchuk observatory radio telescope.

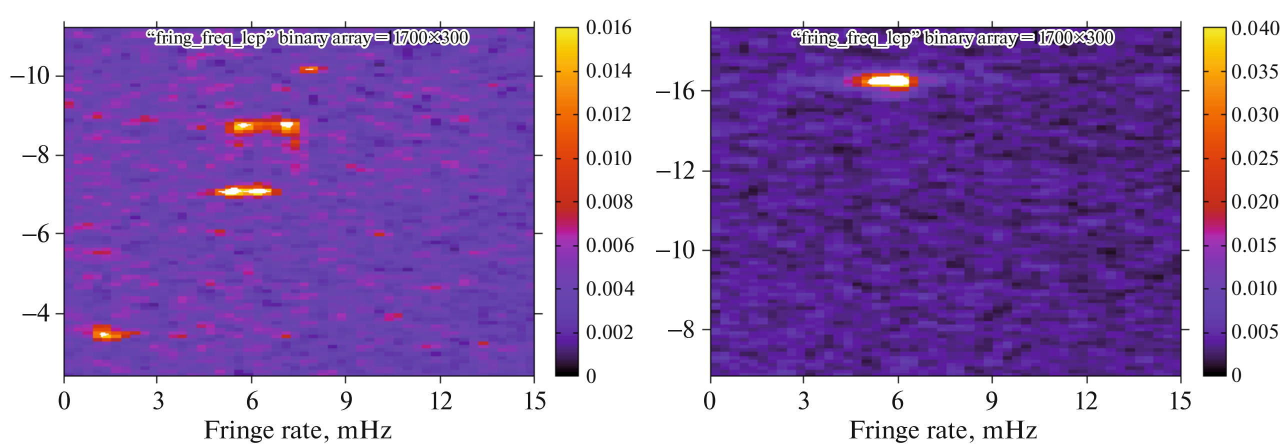

Fig. 2. Interferometric response of Cep A in the left-hand circularly polarized channel (left) and in the right-hand circularly polarized channel (right). The abscissa axis shows the residual interference frequency in MHz, and the ordinate axis shows the radial velocity values in km/s.

tion. The evaluation formula for this case can be found in Lobanov's publication [8]:

$$\theta_{\mathrm{H}} = \frac{0.530}{B}\sqrt{\log(1/V)},$$

where θ_{H} is the diameter of the source at half intensity in radians, B is the projection of the base that is expressed in wavelengths, and V is the amplitude of the visibility function in relative units.

4. DISCUSSION

Strong changes are observed in the emission spectrum of the hydroxyl OH lines in the 1665.4-MHz transition. Lecht et al. [9] tracked the variability of the amplitude of selected lines over the interval from 2007 to 2024. For a line at a velocity of ~−14 km/s, they found a change in amplitude from 10 to 150 Jy. Cohen and Brebner [2] noted an increase in line amplitude at velocity of −8.9 km/s more than 250 times in time interval of 16 months, and. in the first observations in September 1983, this line was completely absent from the spectrum (<0.1 Jy). The emergence of new lines was also noted in the study of Bartkiewicz et al. [10]: the appearance of about ten new lines was noted when analyzing spectra with high sensitivity of ~0.1 Jy. The measured parameters of the detected lines presented in Table 1 will be useful for understanding the nature of the OH-maser emission variability in the star-forming region Cep A.

The detected spread of residual interference frequency values from 1.2 to 8.0 MHz indicates the spatial separation of the detected compact sources of maser emission. As early as 1968, Moran et al. [11] has proposed a method for estimating the angular distance between components based on the difference in interference frequencies. This approach was further developed by the mapping method through an interference frequency analysis [12]. To implement mapping by the interference frequency analysis method, an interferometer including more than two radio telescopes is required, and the observation time must be sufficiently long for the bases between the radio telescopes to rotate through a significant position angle. Only two telescopes (Torun and Zelenchuk) participated in our observations; the data recorded by the radio telescope in Yevpatoria turned out to be unsuitable for processing. The projection vector of the base between Torun and Zelenchuk turned only 10 degrees in one hour of observation. From the obtained values of the interference frequency from 1.2 to 8.0 MHz, it is only possible to estimate the separation of compact sources at an angular distance from 1″ to 3″ along the projection vector of the interferometer base.

Several publications (see, for example, [10, 13, 14]) present maps of the locations of maser sources in the star-formation region of Cep A. The sources are located in groups in a region with angular dimensions of approximately 4″ × 4″. This picture is consistent with the scatter of residual interference frequency values from 1.2 to 8.0 MHz found in our study.

Sources of OH maser emission in star formation regions have been previously studied by ground-based VLBI systems. Reid et al. [15] discovered several dozen compact components in the W3OH region. Most components were found to be unresolved with angular dimensions less than 4 mas. Some had angular dimensions of ~10 mas and were elongated in shape. Kent et al. [16] studied the W49N and NGC 6334 region using the ground-based VLBI method. They found compact sources with milliarcsecond sizes in the W49N area of 3″ × 6″ with corresponding linear dimensions pf 0.2 × 0.4 pc. In source W51, Benson et al. [17] identified two regions of the compact source concentration with the angular resolution of the VLBI system of 7 × 13 mas, and each area had spatial dimensions 3×10^{16} cm. Fix et al. [18] observed the region G351.78–0.54 located at a distance of 6.5 kpc using the VLBI method and discovered maser emission sources in the OH hydroxyl line with angular dimensions of 50 mas. The authors attributed such large angular dimensions to the influence of radio wave scattering on inhomogeneities in the interstellar plasma.

Table 1. Results of the analysis of spectra and visibility functions

V_{LSR}, km/s	ΔV, km/s	F_{peak}, Jy	VIS	RMS	FR-rate, MHz	θ, mas
1	2	3	4	5	6	7
Left polarization						
0.2	0.17	11.2				
−1.0	0.29	3.1				
−3.5	0.21	19.4	0.05	11.4	1.2	18
−7.0	0.18	16.0	0.09	16.7	5–7	16
−8.6	0.46	18.2	0.07	14.7	5.5–8.5	17
−10.1	0.13	2.6	0.36	12.0	8.0	10
−12.2	0.19	2.1				
−12.6	0.10	5.0				
Right polarization						
−0.68	0.21	6.1				
−8.0	0.15	3.5				
−14.2	0.28	28.2	0.14	40	5.5–6.5	15

The first column gives the radial velocity determined from the position of the maximum of the inscribed Gaussian function, the second column gives the line half-width, the third column gives the maximal flux density, the fourth column gives the amplitude of the visibility function (VIS) of the selected response at the base between the Zelenchuk Observatory and the radio telescope in Torun in relative units, the fifth column gives the signal-to-noise ratio for the selected response (RMS), the sixth column gives the value of the interference frequency, and the seventh column gives the angular size of the compact source at the level of the half-width of the diameter in units of mas.

5. CONCLUSIONS

In observations of the Cep A source, the ground–space interferometer baselines in projection onto the celestial sphere were ~36000 km or 200 million wavelengths. No interferometric responses were detected in any component of the OH hydroxyl spectrum at the 1665.5-MHz transition. Consequently, the angular dimensions of the studied maser emission sources significantly exceed the λ/B value or 1 mas.

Several compact sources with angular dimensions of 10–20 mas were discovered at the ground bases of the interferometer (Zelenchuk–Torun). These angular dimensions correspond to linear dimensions of 7.5–15 AU at the adopted distance to the Cep A complex of 725 pc.

Based on the measured values of the residual interference frequency, it was concluded that the discovered compact sources of maser radiation in the hydroxyl lines are distributed in space with characteristic dimensions of 750–1500 AU.

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CONFLICT OF INTEREST

The author of this work declares that he has no conflicts of interest.

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