Radio properties of the OH megamaser galaxy IRAS 02524+2046

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ABSTRACT

We present results from VLBI observations of continuum and OH line emission in IRAS 02524+2046 as well as arcsecond-scale radio properties of this galaxy using VLA archive data. We found that there is no significant detection of radio continuum emission from VLBI observations. The arcsecond-scale radio images of this source show no clear extended emission. The total radio flux density at L and C bands are approximately 2.9 mJy and 1.0 mJy, respectively, which indicates a steep radio spectral index between the two bands. A steep spectral index, low brightness temperature, and high q-ratio (i.e., the far-infrared to the radio flux density), which are three critical indicators in the classification of radio activity in the nuclei of galaxies, are all consistent with the classification of this source as a starburst galaxy from its optical spectrum. The high-resolution line profile reveals that we detected both the 1665 MHz and 1667 MHz OH maser lines, which show two and three clear components, respectively. The channel maps show that the maser emission are distributed in a region of ~210 pc × 90 pc. The detected maser components in different regions indicate similar double spectral features, which might be evidence that this galaxy is at a stage of major merger as seen from the optical morphology.

Key words: galaxies: active – radio lines: galaxies – galaxies: starburst – radio continuum: galaxies

1. Introduction

OH megamasers (OHMs) are rare, luminous masers found in (ultra)luminous infrared galaxies (ULIRGs), which represent different phases in the evolution of gas-rich mergers (Sales et al. 2019; Roberts et al. 2020). IRAS 02524+2046 (hereafter IRAS 02524) is a luminous infrared galaxy (LIRG) and one of the most luminous known OHM galaxies (McBride et al. 2013; Darling & Giovanelli 2002a, 2006) with a redshift $z = 0.1814$. This object has the most unusual spectrum of the Arecibo OHM survey, showing multiple strong narrow components in both the OH 1665 MHz (OH1665) and OH 1667 MHz (OH1667) lines. The optical morphology of this source is elliptical-like with a single tidal tail (Vignali et al. 2005), which indicates that this galaxy might also be at stage one of the merging process, and the optical spectrum is typical of a starburst galaxy (Vignali et al. 2005).

The results from the Arecibo Observatory observations of IRAS 02524 show strong variability in many spectral components in the OH lines, suggesting that variable features are smaller than 1 pc (0.3 mas) with a brightness temperature $T_b > 8 \times 10^{11}$ K (Darling et al. 2007). Generally, there are two types of OHM emission: the first type is the diffuse low-gain maser emission with the emitting population of OH inverted by photons from the infrared continuum. The other is the compact high-gain emission observed by Very Long Baseline Interferometry (VLBI), arising from the inverted population, which could be collisionally pumped (Pihlström et al. 2005). High-resolution radio continuum studies play a key role in directly imaging and determining the nature of the nuclear power sources, such as active galactic nuclei (AGNs) and/or starbursts, and OHM studies can enhance our understanding of the kinematics on parsec scales in the nuclear region (Momjian et al. 2006). So far, we found that the radio properties of this source are barely available in the literature.

We observed this source with Very Long Baseline Array (VLBA) for both the OH line and continuum emission on 2017 February 17. Our main aim is to study the radio properties of this source and its high-resolution OH line emission distribution. The details about our observations and archive radio data collection are presented in Sect. 2. The results and discussions are presented in Sects. 3 and 4, respectively. In Sect. 5 we present the conclusions. Throughout the paper, cosmological parameter values of $H_0 = 73$ km s$^{-1}$ Mpc$^{-1}$, and $\Omega_{\text{matter}} = 0.27$, and $\Omega_{\text{vacuum}} = 0.73$ are adopted.

2. Observations and data reduction

2.1. VLBI observations

We performed continuum and OH line observations with the VLBA on 2017 February 17 for 8 hours, including all ten VLBA antennas. We used J2059+1925 (located $\sim 1\"$ from IRAS 02524) as the phase-referencing calibrator. We also analyzed archival data with VLBA (BD0075, P.I.: Darling J.) and the European VLBI Network (EVN; GD018, P.I.: Diamond P.) experiments; the two projects included both the continuum and OH line observations. The VLBA project BD0075 was performed on 2001 October 14; the observation spanned 12 hours with 8 hours integration time on IRAS 02524, including all ten VLBA antennas.
antennas. The EVN project GD018 was performed on 2005 March 4, including the following 11 antennas: Jodrell Bank (JB), Westerbork (WB), Effelsberg (EF), Onsala (ON), Medicina (MC), Noto (NT), Torun (TR), Urumqi (UR), Very Large Array (VLA), Green Bank (GB), and Arecibo (AR). The basic information about the three VLBI observations are listed in Table 1.

### 2.2. VLA archival data

In order to study the radio properties of this source, we also used the VLA archive data. There are four VLA observations available for IRAS02524 and the list of VLA observations is summarized in Table 2. The project name “NVSS” in this table stands for NRAO VLA Sky Survey.

### 2.3. Data reduction

The VLBA, EVN, and VLA data in this paper were all calibrated using the NRAO Astronomical Image Processing System (AIPS) package. The initial calibration of VLBA and EVN data followed an online tutorial\(^2\) and the main procedures included ionospheric correction, amplitude calibration, editing, instrumental phase corrections, and antenna-based fringe-fitting of the phase calibration. We then applied the solutions to the target source, and for the velocities of the OH lines we also corrected the effects of the Earth’s rotation and its motion within the solar system. The calibration of VLA data follows standard procedures in AIPS.

We flagged the channels that may contain OH emission lines for making the images of the continuum emission. After the calibration in AIPS, we imported the calibrated data into the DIFMAP package (Shepherd et al. 1995) to obtain the continuum and OH line images. Because the weakness of continuum and line emission gives rise to a low signal-to-noise ratio (S/N), no self-calibration was performed.

### 3. Results

#### 3.1. Radio continuum emission in IRAS 02524

We reduced our VLBA project and other two VLBI observations listed in Table 1, and no significant continuum emission was detected at a 3\(\sigma\) level. In order to study the continuum emission, we only included the OH emission line-free channels. The sensitivities of the three observations for continuum emission range from about 10\(\mu\)Jy beam\(^{-1}\) to 50\(\mu\)Jy beam\(^{-1}\).

The VLA observations of this source are listed in Table 2; there are three epoch observations at \(L\) band and one epoch at \(C\) band. The image from VLA-A array at \(C\) band overlaid on the SDSS \(R\)-band gray image of this source is presented in Fig. 1, which shows that the radio continuum emission has similar emitting regions as in the optical. Other images are presented in Fig. A.1 and these images all show no significant extend structure. The peak and integrated flux density are presented in Table 2, the \(L\)-band flux density of this source is approximately 2.9 mJy, and the \(C\)-band value is about 1.1 mJy. The spectral indexes \(\alpha_{\text{total}}\) and \(\alpha_{\text{peak}}\) oderived using the total flux and peak flux are approximately \(-0.8\) and \(-1.2\), respectively.

We also observed this source with the Russian RATAN-600 radio telescope in December 2019; our preliminary results show that the radio flux was not detected at all observed frequencies. The most sensitive RATAN radiometer is at 4.7 GHz, we estimated the flux density upper limit at this frequency is equal to 1 mJy, which is consistent with our VLA \(C\)-band result in Table 2. The RATAN-600 observations are presented in more detail in Appendix A.

#### 3.2. High angular resolution OH line emission

Our VLBA project (BC229B) shows no clear spectrum from the calibrated visibility data, hence we investigated the velocity profile of the spectrum from the calibrated EVN project GD018, which is presented in Fig. 2. We can see that we detected both the OH main lines (OH1665 line and OH1667 line). The profiles are consistent with the single-dish line profiles observed by the Arecibo telescope (McBride & Heiles 2013), which were 20% flux density of the single-dish observations is restored.

Figure 2 shows three evident components in the OH1667 lines: 54291.9–54323.4 \(\text{km s}^{-1}\), 54110.7–54221.0 \(\text{km s}^{-1}\), and 53961.0–54000.4 \(\text{km s}^{-1}\). We made the images of the three components by combining the channels together (see Figs. 3

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1. [https://www.cv.nrao.edu/nvss/](https://www.cv.nrao.edu/nvss/)
2. [http://www.aoc.nrao.edu/~amiodusz/sumschool14/vlbaspectut.shtml](http://www.aoc.nrao.edu/~amiodusz/sumschool14/vlbaspectut.shtml)

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### Table 1. Parameters of the high-resolution observations.

| Observing date | Frequencies (GHz) | Array configuration | Phase calibrator | Program |
|----------------|-------------------|---------------------|------------------|---------|
| 2001Oct14      | 1.4               | VLBA                | J0257+1847       | DA0075  |
| 2005Mar04      | 1.4               | EVN                 | J0257+1847       | GD018   |
| 2017Feb17      | 1.4               | VLBA                | J0259+1925       | BC229A  |

### Table 2. Parameters of the VLA observations.

| Observing date | Frequencies (GHz) | Array configuration | Program | Integrated flux (mJy) | Map peak (mJy beam\(^{-1}\)) |
|----------------|-------------------|---------------------|---------|----------------------|-----------------------------|
| 1993Nov01      | 1.4               | VLA-D               | NVSS    | 2.600 ± 0.500        | 2.21                        |
| 2002Jan25      | 4.9               | VLA-A               | AD0461  | 1.077 ± 0.136        | 0.58                        |
| 2003Aug04      | 1.4               | VLA-A               | AD0483  | 2.990 ± 0.463        | 2.74                        |
| 2005Mar04      | 1.4               | VLA-B               | GD0018  | 3.104 ± 0.332        | 3.20                        |

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and A.2). We also made channel maps for each channel from 54110.7–54221.0 km s\(^{-1}\). These maps show similar structure to the combined channel map, which are presented in Fig. A.3. The flux density of OH1665 line is much lower than the OH1667 line. We combined the channels from 54160.8–54239.5 km s\(^{-1}\) and 54286.7–54326.1 km s\(^{-1}\), and the combined channel maps are presented in Fig. 4. We can see that the maser emissions are resolved into a number of components and distributed in similar region of about 70 mas (210 pc) in the north–east direction and less than 30 mas (90 pc) in the east–west direction.

The two VLBA observations listed in Table 1 have much lower baseline sensitivities than the EVN project GD018 (joint observation of EVN and large radio telescopes; see Sect. 2.1), neither project shows evident spectrum. We averaged channels in the frequency range from 1411.5 MHz to 1412.5 MHz, which corresponds to the OH1667 line component from 54110.7 to 54221.0 km s\(^{-1}\) (see Fig. A.4), and we found that we only detected the brightest component in Fig. 3.

4. Discussions

4.1. Radio continuum

We found that there is no significant continuum emission above a 3σ level with the VLBI observations listed in Table 1. The dirty map of EVN project GD018 (see Fig. A.5) shows that there is tentatively some possible continuum emission at the center of the map with a peak of about 50–60 µJy beam\(^{-1}\). While this possible emission also looks like noise due to data reduction, we estimated that the flux density upper limit of VLBI observations of this source is approximately 50–60 µJy beam\(^{-1}\), which can yield a brightness temperature to be \(\sim 1 \times 10^8\) K using the beam size of this observation. This is consistent with a starburst origin similar to that seen in IRAS 12032+1707 (Pihlström et al. 2005). Further radio observations of sufficiently high sensitivity are needed to study the high-resolution radio continuum structure of this source. These results indicate that no compact emission of high-brightness temperature is present in this galaxy. We found that the \(\alpha_{\text{total}}\) and \(\alpha_{\text{peak}}\) are about –0.8 and –1.2, respectively, which is consistent with optically thin synchrotron radiation and is characteristic of normal spirals, extended starbursts and compact starbursts in ULIRGs (Sales et al. 2015). The brightness temperature \((T_B)\) of the continuum emission at C-band with VLA observations (project AD0461) is \(~ 5 \times 10^2\) K. These results agree with the classification of this source, from its optical spectrum, as a starburst galaxy.

There are also other parameters used in the literature to classify AGN and starburst galaxies; one parameter is the logarithm of the ratio of the far-infrared (FIR) to the radio flux density \((q\text{-ratio})\) (Yun et al. 2001), which suggests that the contribution from the AGN to the total radio emission becomes more significant with a decrease of \(q\). Specifically, the \(q\)-ratio is defined as \(q = \log[3.36 \times 10^5 (2.585 S_{60\mu m} + S_{100\mu m})/S_{\text{radio}}]\) (Helou et al. 1985; Condon et al. 1991), where \(S_{60\mu m}\), \(S_{100\mu m}\), and \(S_{\text{radio}}\) are IRAS 60 µm, 100 µm flux, and radio flux density, respectively. IRAS 02524 has been detected by IRAS at 60 µm with a flux density of 0.958 Jy and at 100 µm with a flux density of \(~ 4.79\) Jy (Darling & Giovanelli 2002a). In addition, the VLA fluxes in Table 2, the \(q\) value for IRAS 02524 is estimated to be 2.92 at 1.415 GHz, and \(q \approx 3.26\) at 4.86 GHz, which is much larger than the threshold of \(q < 2.50\) (Baan & Klöckner 2006) to be an AGN.

The \(T_B\), \(\alpha\) and \(q\)-ratio parameters are critical in the classification of radio activity in the nuclei of galaxies. Baan & Klöckner (2006) defined an activity factor as \(\beta_r = 0.308(q - 0.75 * T_B + 3 * \alpha - 1)\), which represents a weighted qualification of the three diagnostic parameters with different weights. Starburst-like sources have a positive value of \(\beta_r\) and AGN-like sources have negative values. We calculated the value of \(\beta_r\) for IRAS 02524, which is about 1.32, indicating that this object is much more like a starburst-like source.

Using a starburst-dominated sample, Herrero-Illana et al. (2017) show that the infrared luminosity \(L_{IR}\) (between 8 µm and 1000 µm) and the radio luminosity at 1.4 GHz are the star formation rate (SFR) indicators, and the relations are as follows: SFR = 4.5 \(\times 10^{-44}\) \(L_{IR}\) and SFR = 1.02 \(\times 10^{-28}\) \(L_{1.4\text{GHz}}\). IRAS 02524 has been detected by IRAS at 60 µm with a flux density of 0.958 Jy (Darling & Giovanelli 2002a); we thereby calculated the SFR from \(L_{IR}\) to be 199.7 \(M_\odot\) yr\(^{-1}\). Such a SFR would produce a nonthermal radio flux 2.15 mJy at 1.4 GHz. The \(L\)-band radio flux of this source from VLA observations is roughly 2.9 mJy (see Table 2), which favors that the radio continuum emission in this galaxy is probably dominated by starbursts.

4.2. Emission from OHM

In this paper, we detected both the OH1667 and OH1665 line emissions with VLBI. It seems that all the line components found in single-dish observations are available in our VLBI OH line spectrum (see Fig. 2), but only with roughly 20% of the single-dish flux density restored. This means that all the components probably have some contributions from compact maser clouds. Based on Arecibo telescope observations, Darling & Giovanelli (2002) found that the hyperfine ratios (1667–1665 MHz flux density ratio) for individual narrow features in the spectrum are \(R_H = 1.4, 5.63, 1.88\) from high to low velocity, while McBride et al. (2013) found that there are only two peaks in the OH1665 line emission that align with peaks in the OH1667 line emission. We found also that VLBI OH line spectrum only show two peaks in the OH1665 line emission, which is consistent with the results in McBride et al. (2013). We calculated the \(R_H\) for the two components are roughly 1.81 and 8.99 from high to low velocity (see Fig. 2).

The VLBI images of maser line emission (see Figs. 3–4 and Figs. A.2–A.3) show that the components are all distributed in
Fig. 3. Combined channel map of the OH1667 line emission in IRAS 02524 observed with the EVN project GD018.

Fig. 4. Combined channel map of the OH1665 line emission in IRAS 02524 observed with the EVN project GD018.

an area less than 70 mas (210 pc) in the north–east direction and less than 30 mas (90 pc) in the east–west direction. Darling et al. (2007) found that IRAS 02524 shows strong variability in many spectral components in the OH lines, suggesting that variable features are smaller than 1 pc (0.3 mas) with a brightness temperature $T_b > 8 \times 10^{11}$ K. We tried to fit the brightest components in the channel maps and found that the size of the brightest component is about 3 mas in size, and $T_b$ is $\sim 4 \times 10^9$ K, which indicates that the maser components might still be compact and needs higher angular resolution observations.

The OHM emission profile is supposed to be attributed to an ensemble of many masing regions, Darling & Giovanelli (2002c) suggested that the variability of OH line emission might be caused by the compact maser emission through interstellar medium, yielding an interstellar scintillation. The three epoch VLBI images (Figs. 3 and A.4) of this source all show one dominant bright component. We can see that the peak flux density of three observations are different, which might be caused by the variability of this component. Moreover, we also can see that the EVN image (Fig. 3) also shows some weak emission regions. We think that strong variability found by Darling et al. (2007) might arise from the contributions from the brightest component shown in the VLBI images and some other analogous compact maser components that are not detectable owing to the limited sensitivity. This is because the VLBI scale flux density seems to be only one-fifth of the single-dish Arecibo observation (see Fig. 2).

Figure 3 shows that all the four regions of the OH1667 brightest line component display a similar double spectral feature, suggesting the existence of a velocity substructure in all the regions. Larson et al. (2016) present a classification scheme of merging stage of LIRGs, single nuclei, and one obvious tidal of this source (Vignali et al. 2005), which indicates that this source is possibly at a stage of major merger. Because the largest size among the regions are approximately 210 pc, the existence of a velocity substructure in all the regions support the view that this galaxy might be at a merging stage and the gas clouds might originate from two or more galaxies.
4.3. Nature of the radio emission in OHM galaxies

In general, OHM line emission has been observed in (U)LIRGs and it is likely that OHMs occur during a specific state, or stage of the merger, which are consequences of tidal density enhancements accompanying galaxy interactions (Darling et al. 2007; Pihlström 2007). The hosts of OHM galaxies usually present features of starburst and AGN, and the radio continuum emission are produced from these phenomena. There are two possible explanations for these features:

First, the OHM galaxies could represent a transition stage between a starburst and the emergence of an AGN (Darling & Giovanelli 2006). One possible scheme might be that in the initial merging stage of OHM formation, the background radio continuum mainly comes from the starburst, FIR dominates the population inversion, and the radio continuum and OHM structure are supposed to be relatively diffuse; as galaxy merging proceeds, AGN activity in producing radio continuum and inverting population ground level becomes more and more significant, the radio spectrum gets relatively flat, the structure of radio and OHMs emission becomes relatively compact, and the OHMs velocity fields become more ordered, as shown in Mrk 231 (Klöckner et al. 2003). Our results show that IRAS 02524 do not clearly show the circumnuclear structure or velocity gradients, and the radio continuum emission is consistent with starburst origin, which mean that this source might at the early stage of the merging process under this simplified view of OHMs.

Second, the OHM galaxies might originate in a central AGN, contaminated by emission of circumnuclear star-forming regions (Hekatyny et al. 2018a,b). Although the radio continuum emission of many OHMs seems to show a link with nuclear starburst, while a hidden AGN might also be possible as the LIRGs that host OHMs tend to be of infrared excess compared with those that do not (Rovilos et al. 2003; Darling & Giovanelli 2002a). Our results show that the radio emission of IRAS 02524 also seems to be produced by nuclear starburst, and it seems no evident contributions from the AGN, while also we can not exclude the existence of a hidden AGN, further high sensitivity and high spatial resolution optical spectrum observations of the nucleus in this galaxy (Hekatyny et al. 2018a).

Because the OHM galaxies are related to merging processes, it may contain two or more intervening systems or regions with much different properties. In order to understand the nature of radio emission in OHM galaxies and further test the above scenarios, high sensitivity interferometry and VLBI observations of a large number of OHM galaxies will help to determine whether these galaxies are hosting an AGN or compact starburst, their connections with the merging stages, and other environment parameters. Meanwhile, the high-resolution, optical—IR multiwavelength imaging and integral field spectroscopy analysis of a large sample of OHM galaxies are also important for understanding the nature of the nuclear region and the origin of radio emission in OHM galaxies (Sales et al. 2019; Hekatyny et al. 2018a,b).

5. Summary

We have presented the radio properties of IRAS 02524 from VLBA, EVN, and VLA observations. We found that there is no significant continuum detection above 3σ level from three epoch VLBI observations. The L- and C-band integrated radio flux from VLA observations of this source is roughly 2.9 mJy and 1.1 mJy and the spectral indexes, α_{total} and α_{peak} are about ~0.8 and ~1.2, respectively. The brightness temperature of this source is approximately 500 K from the VLA C-band observation. The L- and C-band q-ratio is ~2.92 and ~3.26, respectively, which is much larger than the threshold of q < 2.50 typical of an AGN. These parameters all show that this source is probably a starburst galaxy, which is consistent with the classification from optical spectrum of this source.

The high-resolution radio spectrum of this source show both the OH1667 a and OH1665 lines; the profile is similar to the single-dish spectrum. The channel maps show that the emission of the OH maser lines is located in a region of about 210 pc × 90 pc region. We also showed that the detected maser clouds at different region have similar double spectral features, which suggest a velocity substructure in all the detected regions. This might be evidence that this galaxy is in the process of merging as seen from the optical morphology.

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Appendix A: Additional material

RATAN observations were carried out in December 2019 in the transit mode. Details of observations and data analysis can be found in Udovitskiy et al. (2016) and Mingaliev et al. (2017). The measurements were made at six frequencies simultaneously: 1.28, 2.25, 4.7, 8.2, 11.2, and 21.7 GHz. Parameters of the continuum radiometers are given in the Table A.1. The detection limit for RATAN single sector is approximately 5 mJy beam\(^{-1}\) under good conditions at 4.7 GHz and at an average antenna elevation. At other frequencies this value depends on the atmospheric extinction and the effective area on the certain antenna elevation.

The number of IRAS 02524+2046 observations was 14 in December 2019 and the radio flux was not detected at the most sensitive RATAN radiometer at 4.7 GHz. The flux density upper limit at this frequency is equal to 0.001 Jy. Because of a strong radio frequency interference (RFI), the bandwidths at 1.28 and 2.25 GHz are quite narrow (80 and 60 MHz, respectively) and the fluxes density at these frequencies were not detected either. Only one measurement in the radio continuum is currently known for IRAS 02524+2046 at 1.4 GHz and it is equal to 2.6 mJy (Condon et al. 1998). It might be possible to get the radio signal at 4.7 GHz with the RATAN using more long-term accumulation.

Fig. A.1. L-band radio contour images from VLA of IRAS 02524.
Fig. A.2. Combined channel maps of the OH1667 line emission in IRAS 02524 observed with the EVN project GD018.
Fig. A.3. Channel maps of IRAS 02524 observed with the EVN project GD018. The beam full width at half maximum (FWHM) is $8.6 \times 3.69$ (mas) at $-22.3^\circ$ for all the maps.
Map peak: 0.00639 Jy/beam
Contours: 0.00235 Jy/beam × (−1 1 2)

Map peak: 0.00745 Jy/beam
Contours: 0.00245 Jy/beam × (−1 1 2)

Map peak: 0.0113 Jy/beam
Contours: 0.00353 Jy/beam × (−1 1 2)

Map peak: 0.00818 Jy/beam
Contours: 0.00285 Jy/beam × (−1 1 2)

Map peak: 0.00999 Jy/beam
Contours: 0.00337 Jy/beam × (−1 1 2)

Fig. A.3. continued.
Fig. A.3. continued.
Fig. A.4. OH1667 line emission of IRAS 02524 with frequency range from 1411.5 MHz to 1412.5 MHz from two VLBA observations. The frequency range corresponds to the OH1667 line emission from 54110.7–54221.0 km s$^{-1}$; the image from EVN project GD018 at this range is shown in Fig. 3.

Fig. A.5. Dirty map of the continuum emission of IRAS 02524 from EVN project GD018.

Table A.1. RATAN-600 continuum radiometers.

| $f_0$ (GHz) | $\Delta f_0$ (GHz) | $\Delta F$ (mJy beam$^{-1}$) | BW (arcsec) |
|------------|-------------------|----------------------------|-------------|
| 21.7       | 2.5               | 50                         | 11          |
| 11.2       | 1.4               | 15                         | 15.5        |
| 8.2        | 1.0               | 10                         | 22          |
| 4.7        | 0.6               | 5                          | 35          |
| 2.25       | 0.08              | 40                         | 80          |
| 1.28       | 0.06              | 200                        | 110         |

Notes. The parameters are as follows: $f_0$ – central frequency, $\Delta f_0$ – bandwidth, $\Delta F$ – flux density detection limit per beam, and BW – beam width, i.e., the angular resolution in RA (the angular resolution in declination is three to five times worse than in RA).