

Caltech-NRAO Stripe 82 Survey (CNSS) Paper V: AGNs that transitioned to radio-loud state

Aleksandra Wołowska¹, Magdalena Kunert-Bajraszewska¹, Kunal P. Mooley^{2,3}, Aneta Siemiginowska⁴, Preeti Kharb⁵, C. H. Ishwara-Chandra⁵, Gregg Hallinan³, Mariusz Gromadzki⁶, and Dorota Koziel-Wierzbowska⁷

¹*Institute of Astronomy, Faculty of Physics, Astronomy and Informatics, NCU, Grudziądzka 5/7, 87-100, Toruń, Poland*

²*National Radio Astronomy Observatory, P.O. Box O, Socorro, NM 87801, USA*

³*Cahill Center for Astronomy, MC 249-17, California Institute of Technology, Pasadena, CA 91125, USA*

⁴*Center for Astrophysics | Harvard & Smithsonian, Cambridge, MA, United States*

⁵*National Centre for Radio Astrophysics (NCRA) – Tata Institute of Fundamental Research (TIFR), S.P. Pune University Campus, Post Bag 3, Ganeshkhind, Pune 411007, India*

⁶*Astronomical Observatory, University of Warsaw, Al. Ujazdowskie 4, 00-478 Warsaw, Poland*

⁷*Astronomical Observatory of Jagiellonian University, ul. Orła 171, 30-244 Kraków, Poland*

Abstract

A recent multi-year Caltech-NRAO Stripe 82 Survey (CNSS) revealed a group of objects that appeared as new radio sources after >5–20 years of absence. They are transient phenomena with respect to the Faint Images of the Radio Sky at Twenty Centimeters (FIRST) survey and constitute the first unbiased sample of renewed radio activity. Here we present the follow-up, radio, optical and X-ray study of them. The group consist of 12 sources, both quasars and galaxies with wide redshift ($0.04 < z < 1.7$) and luminosity ($22 < \log_{10}[L_{1.4\text{GHz}}/\text{W Hz}^{-1}] > 24.5$) distribution. Their radio properties in the first phase of activity, namely the convex spectra and compact morphology, allow them all to be classified as gigahertz-peaked spectrum (GPS) sources. We conclude that the spectral changes are a consequence of the evolution of newly-born radio jets. Our observations show that over the next few years of activity the GPS galaxies keep the convex shape of the spectrum, while GPS quasars rapidly transform into flat-spectrum sources, which may result in them not being recognized as young sources. The wide range of bolometric luminosities, black hole masses and jet powers among the transient sources indicates even greater population diversity in the group of young radio objects. We also suggest that small changes of the accretion disc luminosity (accretion rate) may be sufficient to ignite low-power radio activity that evolves on the scale of decades.

Key words: galaxies: active-galaxies, evolution-galaxies, quasars, recurrent-activity

1. Introduction

Radio-loud active galactic nuclei (AGNs) constitute a small fraction of the active galaxy population in which accretion onto the central supermassive black hole of a galaxy generates a relativistic jet that transport relativistic plasma and magnetic field out to large distances creating a characteristic radio morphology (Longair et al. 1973; Kellermann et al. 2016). As the radio source evolves it goes through different phases of development. During the first stages of nuclear activity called the Gigahertz-Peaked Spectrum (GPS) and compact Steep Spectrum (CSS) sources, the radio jets have sizes smaller than a few kpc and reside within the interstellar medium of the host galaxy. Their radio spectra have convex shapes with peak emission frequency inversely proportional to the source size (Fanti et al. 1990; Orienti & Dallacasa 2014; O’Dea & Saikia 2020). If the jets are free

to expand further, to the intergalactic medium, the source evolves into Fanaroff-Riley type I (FRI) or type II (FRII) morphology (Fanaroff & Riley 1974) reaching sizes of a few hundred kpc. The large size is thus simply an effect of old age and this is the essence of the theory of evolution of radio AGNs (Fanti et al. 1990; Readhead et al. 1996; O’Dea 1998; Snellen et al. 2000; Kunert-Bajraszewska et al. 2010; An and Baan 2012). Moreover the activity is expected to be cyclical e.g. (Best et al. 2005; Saikia & Jamrozy 2009).

However, statistical studies have revealed that there is an excess of compact sources with peaked spectra, in comparison to fully developed, large radio-galaxies (O’Dea et al. 1991; Snellen et al. 2000; An and Baan 2012). This indicates that not all GPS and CSS sources evolve into extended structures and different reasons for this premature cessation of radio activity is debated in the literature. One of the most popular is the presence of very dense environment in the host galaxy that can significantly hinder or even prevent the de-

velopment of the source above a certain size called the frustration scenario (O’Dea & Baum 1997; Wagner & Bicknell 2011; Mukherjee *et al.* 2016). This is especially true for weak jets that will not be able to break through the dense clouds of gas. In a different scenario the interaction between the jets and the post-merger environment may cause the enhancement of radio emission resulting in their over-abundance in radio selected samples (Morganti *et al.* 2011; Tadhunter *et al.* 2011; Dicken *et al.* 2012). However, the correlation of radio power with X-ray luminosity (which is considered as a measure of AGN bolometric luminosity) does not confirm this hypothesis (Kunert-Bajraszewska *et al.* 2014). And finally the excess of compact sources can be explained by a short time scale episodic activity of radio objects. According to this scenario, the radiation pressure instabilities in an accretion disk make the radio sources to be transient on timescales $< 10^4 - 10^5$ years (Reynolds & Begelman 1997; Czerny *et al.* 2009; Kunert-Bajraszewska *et al.* 2010; Wołowska *et al.* 2017; Silpa *et al.* 2020). In addition the duration of the radio activity phase may scale with the jet power such as the low power objects are more short-lived and may stay compact for most of its lifetime (Hardcastle *et al.* 2019; Capetti *et al.* 2019; Kunert-Bajraszewska *et al.* 2020). Perhaps, as it has been recently suggested by Wójtowicz *et al.* (2020), the supermassive black holes behave similarly to galactic X-ray binaries in which the radio jets are produced most efficiently during the high/hard states, and suppressed during the soft states. The dramatic changes in radio luminosity that occurs during the state changes should be visible in radio surveys dedicated to slow transient phenomena.

To date, there have been rather few radio surveys dedicated to slowly variable and transient sources and they all have a number of limitations. The majority of these surveys were single, multi-epoch interferometric pointings with a limited field of view and as a result the number of variables and transients is low (e.g., Carilli *et al.* 2003; Mooley *et al.* 2013). The Caltech-NRAO Stripe 82 Survey (CNSS; Mooley *et al.* 2016, 2019) and the Very Large Array (VLA) Sky Survey (VLASS; Lacy *et al.* 2020) brings a new quality. The CNSS was a dedicated radio transient survey carried out with the Jansky VLA between December 2012 and May 2015. Observations of the 270 deg² of the SDSS Stripe 82 region were carried out over 5 epochs at S band (2–4 GHz; center frequency of 3 GHz) and with a uniform thermal rms noise of $\sim 80 \mu\text{Jy}$ per epoch. In this survey, many variable/transient sources were discovered, a large fraction of them being of AGN origin. Among them, comparison with the existing survey data namely the Faint Images of the Radio Sky at Twenty-Centimeters (FIRST; White *et al.* 1997) and the VLA survey of the SDSS Southern Equatorial Stripe (VLA-Stripe 82; Hodge *et al.* 2011), has revealed transient sources on timescales < 20 years that are likely associated with renewed AGN activity.

The first discovered switched-on radio activity was in CNSS quasar VTC233002–002736 which increased its flux density about ten times or more at 1.4 GHz over a 15 year period (Mooley *et al.* 2016). Another example of such

behaviour in the CNSS, found in quasar 013815+00, has been reported recently by Kunert-Bajraszewska *et al.* (2020). The transition from radio-quiet to radio-loud phase in this source is coincided with changes in its accretion disk luminosity which we interpret as a result of an enhancement in the SMBH accretion rate. Very recently the detection of changing-state AGNs has been also reported by Nyland *et al.* (2020) as a result of VLASS survey. Their quasars show a large flux density increase in the S-band and convex radio spectra, as in our CNSS objects. Similar radio behaviour has been also reported in a group of narrow-line Seyfert 1 (NLS1) galaxies considered so far to be radio-quiet (Lähteenmäki *et al.* 2018).

In this paper we report a total sample of 12 slow transient sources on timescales < 20 years that were detected in the whole CNSS survey covering the 270 deg² of the SDSS Stripe 82 region. The sample includes both the first discovered CNSS quasar VTC233002–002736 (hereafter 233001–00) and quasar 013815+00 already widely discussed by Kunert-Bajraszewska *et al.* (2020) (Table 1). We present follow-up comprehensive, multi-epoch and multi-wavelength study of these sources as well as the discussion about their nature and implication of this discovery on the jet formation and triggering mechanism theories.

Throughout this paper we assume a cosmology in which $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_m = 0.3$ and $\Omega_\lambda = 0.7$. The radio spectral index α is defined in the sense $S \propto \nu^\alpha$.

2. Sample Selection

Using the first three epochs of observations of the CNSS survey (Mooley *et al.* 2016, Mooley *et al.* in preparation), carried out between 2013 December 19 and 2014 February 17, we prepared a deep 3 GHz image mosaic of the full Stripe 82 region using AIPS IMAGR and FLATN tasks and a corresponding 5σ source catalog using AIPS SAD. For the $\sim 27,000$ sources in the catalog, the median local RMS noise is $\sigma = 69 \mu\text{Jy}$.

We then compared this CNSS catalog with the catalogs from the FIRST (White *et al.* 1997) and NVSS (Condon *et al.* 1998) surveys, carried out at 1.4 GHz, in order to find possible new radio sources (i.e. transient candidates) in the CNSS. We retained only those CNSS sources that: 1) are point-like, i.e. having the ratio of the integrated-to-peak flux densities less than 1.5 (as done by Mooley *et al.* 2016), 2) have signal-to-noise ratio larger than 10, 3) have coverage within the FIRST footprint and are absent in FIRST and NVSS catalogs, 4) have flux density larger than 2.8 mJy (i.e. implied spectral index $\alpha > 1.4$, between CNSS and FIRST source detection threshold of around 1 mJy), and 5) away from bright sources ($6'$ region around $> 100 \text{ mJy}$) to mitigate false positives due to imaging artifacts.

For the resulting 20 sources we inspected the FIRST image cutouts and noted that 5 of them were detected at $\sim 4\sigma$ significance. We rejected these sources and prioritized 9 out of the remaining 15 (that are relatively bright radio sources and/or have a host galaxy that is detected in the SDSS) for multi-wavelength follow up. We also included three serendipitous

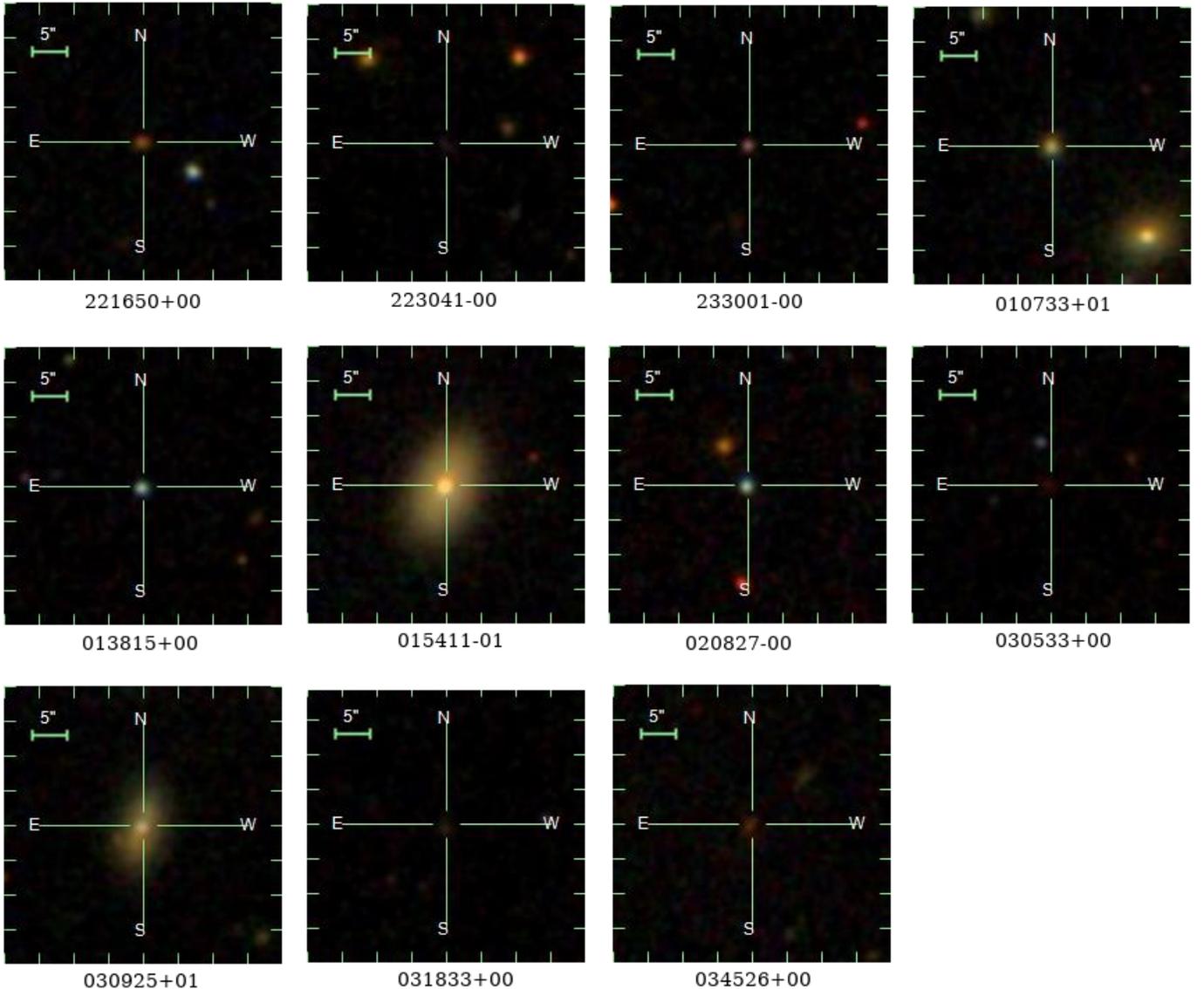


Figure 1. Cut-out images from SDSS available for 11 out of 12 sources from our sample.

sources (221650–00, 010733+01 and 013815+00; seen to have host galaxies distinctly detected in the SDSS while investigating CNSS sources that were absent in FIRST). The three sources follow the selection criteria mentioned above except 221650–00, which has 3 GHz flux density around 2 mJy. The sample of 12 sources¹ thus selected for multiwavelength follow up is given in Table 1.

3. Observations and data reduction

We have undertaken a multi-frequency follow up campaign for the 12 transient objects including X-ray (XMM-Newton and Chandra X-ray Observatory), radio (VLBA, VLA and GMRT) and optical studies (Keck, SALT) at different resolution. We have also multi-epoch VLA spectra of all our

¹ The full sample of “switched-on” radio AGN will be reported in Mooley et al. in preparation.

sources. Additionally a set of SDSS photometric and spectroscopic data exists for some of them. The basic parameters of the whole sample of transient sources have been gathered in Table 1. More details on one of these sources, 013815+00, can be found in a separate publication CNSS Paper IV (Kunert-Bajraszewska et al. 2020).

3.1. Radio data

3.1.1. VLA observations

All sources from our sample detected by the CNSS project are transient with respect to the FIRST survey. Their 3 GHz VLA flux density measurements in five survey epochs are presented in Figure 2 and show that after the burst of radio activity the flux density stabilizes at an average level from a few to a dozen mJy. In addition multi-frequency observations of some of the transient sources were carried out with the

Table 1. Basic properties of the total sample of 12 transient radio sources.

Name	RA	DEC	ID	z	$3\sigma_{FIRST}$	S _{1.4}	logL _{1.4}	S ₅	logL ₅	LAS	LLS	r'
(1)	h m s	° ' "	(4)	(5)	[mJy]	[mJy]	[W Hz ⁻¹]	[mJy]	[W Hz ⁻¹]	[mas]	[h ⁻¹ pc]	[mag]
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
221650+00	22:16:50.44	+00:54:29.14	G	0.55*	0.39	0.52	23.1	3.20	24.5	1.1	7.1	20.98
221812-01	22:18:12.95	-01:03:44.23	-	-	0.51	1.60	-	14.67	-	5.4	-	-
223041-00	22:30:41.44	-00:16:44.29	G	0.84*	0.37	0.98	23.8	5.94	25.2	5.9	45.0	22.54
233001-00	23:30:01.81	-00:27:36.53	Q	1.65	0.32	3.45	24.6	6.89	25.7	5.7	48.3	21.32
010733+01	01:07:33.51	+01:12:22.78	G	0.12	0.47	3.03	22.9	2.20	22.9	0.8	1.6	19.13
013815+00	01:38:15.06	+00:29:14.07	Q	0.94	0.32	1.48	24.5	3.68	25.0	8.5	67.0	19.77
015411-01	01:54:11.67	-01:11:49.74	G	0.05	0.45	3.79	22.3	6.38	22.6	3.0	2.9	15.41
020827-00	02:08:27.06	-00:52:08.04	Q	1.34	0.49	1.90	24.2	8.02	25.7	0.9	7.7	19.55
030533+00	03:05:33.12	+00:46:09.93	G	0.42*	0.41	0.88	23.4	5.05	24.5	1.0	5.3	24.30
030925+01	03:09:25.99	+01:14:57.89	G	0.04	0.35	3.69	22.1	9.60	22.6	0.5	0.4	16.90
031833+00	03:18:33.64	+00:26:35.97	G	0.40*	0.34	0.79	23.2	4.81	24.5	1.8	9.7	21.76
034526+00	03:45:26.00	+00:41:56.12	G	0.45*	0.40	1.22	23.5	9.76	24.9	1.2	6.9	20.27

NOTE—Columns are listed as follows: (1) source name; (2,3) VLA coordinates in J2000.0; (4) optical ID from SDSS, G - galaxy, Q - quasar, (5) spectroscopic redshift, * means photometric redshift; (6) this is the 3σ noise level at the location of the source measured in the 1.4 GHz FIRST images (White et al. 1997); (7) the latest value of 1.4 GHz flux density measured based on our VLA observations; (8) log of the K-corrected radio luminosity at 1.4 GHz calculated based on the flux density from column 8 and α_{thick} index obtained from spectral modeling; (9) the latest value of 5 GHz flux density measured based on our VLA observations; (10) log of the K-corrected radio luminosity at 5 GHz calculated based on the flux density from column 11 and α_{thin} index obtained from spectral modeling; (11) Largest Angular Size as the deconvolved major axis of the source measured in 4.5 GHz VLBA image; in the case of resolved object 013815+00 the angular size is measured in the 4.5 GHz contour map; (12) Largest Linear Size; (13) magnitude in SDSS r' filter. 013815+00 quasar discussed in (Kunert-Bajraszewska et al. 2020) is included.

VLA in B configuration as part of the CNSS survey (2012-2015), using 5 receivers covering the spectrum from 1000 to 16884 MHz (L, S, C, X, Ku). Observing setup was the correlator with 16 spectral windows and 64 2-MHz-wide channels. Observations were continued in November 2016 under the project name VLA/16B-047 (6 hours), in A configuration, using the same receivers and observing setup. The last epoch of observations was obtained in November 2019 (project VLA/19B-209, 6 hours) in D configuration using 4 receivers (S, C, X, Ku).

The target sources divided into groups, based on their coordinates, were observed with integration time from 2 to 10 minutes depending on the configuration and band. 3C48 was the primary flux density calibrator and several phase calibrators chosen from the VLA calibrator manual were also observed during the run. Then the detailed calibration and imaging of VLA data was carried out using CASA² software. The data from single spectral windows (128 MHz each) for each source were extracted to be imaged and measured separately. In order to obtain good spectral coverage while maintaining high signal-to-noise ratio, four adjacent spectral win-

dows were averaged in each band to measure average flux, resulting with 4 measurements of a flux per four bands, and 2 measurements for L-band which consists of only 8 spectral windows. The final measurements with error estimations are presented for 11 sources in Figure 3 and are gathered in Table 7.

3.1.2. VLBA observations

VLBA C-band observations were conducted from 26 February to 2 May 2016 under the project name VLBA/16A-007. Each of 12 sources was observed on separate days along with the phase calibrator and fringe-finder with the integration time varied from 2 to 4 hours. Total time assigned for a project was 45 hours. Additionally we divided the available bandwidth at C-band receiver into two sub-bands centered at 4.5 and 7.5 GHz. This strategy allowed us to obtain images of our sources at two frequencies in one scan. Data reduction (including editing, amplitude calibration, instrumental phase corrections and fringe-fitting) was performed with the standard procedure using the NRAO AIPS³ software. After this stage the AIPS task IMAGR was used to produce the

² <http://casa.nrao.edu>

³ <http://www.aips.nrao.edu>

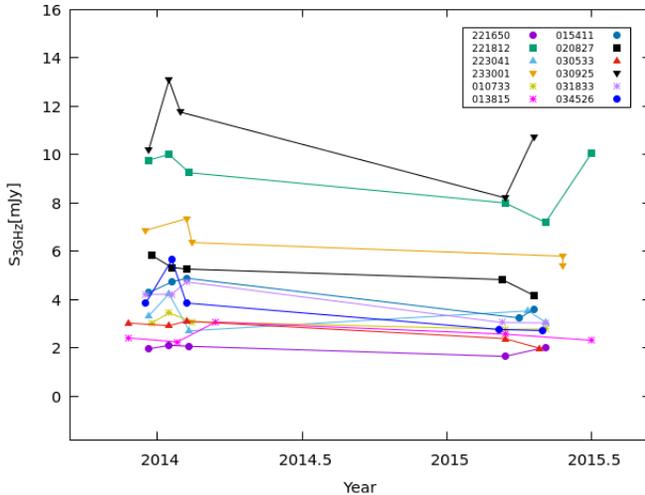


Figure 2. 3GHz CNSS light curves measured in the five survey epochs.

final total intensity images. Most of the sources appeared to be very compact, unresolved or slightly resolved with VLBA even at the higher frequency. The slightly extended sources were fitted by two Gaussian models using task JMFIT and the solution accepted only if the separation between the two components was larger than about one beam size, otherwise the object was classified as one single extended source. We considered only source components with peak brightness $\geq 3\sigma$. Finally, in the case of four our sources the components fulfilling the above criteria were found. These are: 010733+01, 034526+00, 030925+01 (see section 5 and Figure 10) and 013815+00 (Kunert-Bajraszewska et al. 2020). The estimated angular and linear sizes of the sources measured in the 4.5 GHz image are listed in Table 1.

3.1.3. GMRT observations

To complement the spectra at low frequencies, sub-GHz observations with upgraded GMRT in Band-3 (250-500 MHz) and Band-4 (550-850 MHz) were carried out on 16th and 19th March 2018, as a project 33_016. Total allocated time was 26 hours. Unfortunately, the Band-3 data were corrupted and we could not obtain meaningful results. A good quality data were obtained only for Band-4. Eight out of twelve observed sources were detected and analyzed using a CASA based pipeline (<http://www.ncra.tifr.res.in/~ishwar/pipeline.html>). The details of the pipeline are available in Ishwara-Chandra et al. (2020). In order to obtain as many measurement points as possible, with maintaining sufficient S/N ratio, data were divided into a few spectral windows, each one processed separately, and added to the radio spectrum plot (Figure 3). The exception is the source 030533+00 for which we were unable to perform the correct flux calibration. The GMRT flux density measurements are presented in Table 7.

3.2. Spectral modeling

In order to characterize the significant changes of the radio spectra of our sources we have fitted each spectrum with the

analytical function. Since the standard non-thermal power-law model is not enough to represent peaked sources showing significant curvature in their spectra, we followed the approach by (Snellen et al. 1998) and used the modified power-law model:

$$S(\nu) = \frac{S_p}{(1 - e^{-1})} \times \left(\frac{\nu}{\nu_p}\right)^{\alpha_{thick}} \times (1 - e^{-(\frac{\nu}{\nu_p})^{\alpha_{thin} - \alpha_{thick}}}) \quad (1)$$

where α_{thick} is the optically thick spectral index, α_{thin} the optically thin spectral index, and S_p and ν_p are the peak flux density and peak frequency, respectively. In some cases model does not fit the lowest and highest frequency sides of the spectrum perfectly. In case of those sources, model was fitted using the approximate values for some of the free parameters. All fitted models are accurate to within the limits of the error. The obtained values for each epoch of observation are given in Table 3 and the fitted spectra are presented in Figure 3.

Since the GMRT observations were carried out at a different time compared to the VLA observations, only VLA data were fitted in each epoch. However, the low frequency GMRT data are also indicated on the plot. The fits made characterize the significant changes that occur mainly in the optically thin part of the spectra of our objects. At lower frequencies, as might be expected, the spectrum is more stable. It is also very likely that there are no changes at the GMRT frequencies. Therefore, the location of these points in relation to the modeled VLA radio spectrum curve influenced the choice of the best model.

3.3. X-ray observations

We obtained X-ray observations of a sub-sample of the transient radio sources with XMM-Newton and Chandra (see Table 2). Two objects were observed in 2016 using XMM-Newton/EPIC (Program 078345) with exposure time of ~ 24 ksec on each source. The third one was available in the archive (ObsID 0673002341) and was observed as part of the Stripe 82 X-ray (82X) survey (LaMassa et al. 2013).

Five objects were observed by Chandra with ACIS-S3 using the standard aim point location and the 1/8 subarray read-out mode, with the ~ 15 ksec exposure time on each source. The observations were carried out in a few months at the turn of 2017 and 2018. The Chandra data were reduced using CIAO 4.11 (Fruscione et al. 2006) with the calibration files from CALDB 4.8.5. We assumed a circular extraction region for each source, with the radius $1.5''$, which also contains the entire radio emission. The background regions consisted of an annulus with the radius between $4 - 8''$ centered on the source. Two sources have been detected in these observations. In the case of no detection upper limits on the flux densities have been estimated using `aprates` tool in CIAO (see Table 2).

We calculated the hardness ratios for the detected sources following the method of (Park et al. 2006) and assuming $HR = \frac{H-S}{H+S}$, where S and H are the source counts for soft (0.5-2keV) and hard (2-7keV) band (Table 2).

Table 2. Results of X-ray observations.

Name	Instrument	Epoch	Counts 0.5 – 7 keV	$S_{0.5-2\text{keV}}$ [10^{-15} erg s $^{-1}$ cm $^{-2}$]	$S_{2-10\text{keV}}$	$\log L_{2-10\text{keV}}$ [erg s $^{-1}$]	HR	ObsID
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
221650+00	XMM-Newton	Nov 2016	< 49.8	< 4.5	< 9.4	< 43.1	–	0783450101
221812–01	Chandra	Apr 2018	< 4.8	< 1.9	< 3.5	–	–	20421
223041–00	XMM-Newton	May 2016	< 58.2	< 17.4	< 36.5	< 44.1	–	0783450201
233001–00	XMM-Newton	May 2012	$45.1^{+8.0}_{-7.7}$	12.9 ± 2.2	23.5 ± 4.1	44.6	$-0.53^{+0.15}_{-0.14}$	0673002341
010733+01	Chandra	Aug 2018	< 3.6	< 1.4	< 2.5	< 41.0	–	20422
015411–01	Chandra	Oct 2018	10 ± 3	2.3	5.6	40.5	$0.02^{+0.28}_{-0.29}$	20423
030925+01	Chandra	Nov 2017	9 ± 3	1.7	7.5	40.4	$0.49^{+0.16}_{-0.45}$	20424
034526+00	Chandra	Dec 2017	< 3.6	< 1.5	< 2.8	< 42.3	–	20425

NOTE—Columns are listed as follows:(1) source name, (2) instrument used for observations, (3) epoch of observations; (4) number of photon counts; (5)&(6) X-ray flux; (7) luminosity; (8) hardness ratio $HR = \frac{H-S}{H+S}$, where $S = 0.5 - 2$ keV and $H = 2 - 7$ keV; (9) observation ID. Errors in *Chandra* counts calculated as $\sqrt{\text{counts}}$. ‘<’ marks 90% upper limit. $\Gamma=1.7$ was assumed for the flux estimation.

3.4. SALT spectroscopy

Three transient objects (010733+01, 015411–01, 030925+01) have been observed with the Southern African Large Telescope (SALT, Buckley et al. 2006) under the project 2019-1-SCI-023, using Robert Stobie Spectrograph (RSS, Burgh et al. 2003). The observations were carried out on 10th July (010733+01, 015411–01) and 9th August 2019. The on source exposure time was 1800/600/300 seconds respectively and was done in the long slit mode with the slit width of 1.5". Additional 4 seconds was used on an exposure of the Xenon calibration lamp. We used the 4x2 binning read-out option which allowed us to reach the signal to noise ratio $S/N=100$. In order to cover main lines of interest we used PG0900 VPH grating with 15.8725 degree tilt angle giving us the wavelength coverage from 4463Å to 7523Å. For central wavelength of 5900Å the spectral resolution was $R=1065$. Order blocking was done with the UV PC03850 blocking filter. The sources were observed on a clear night with $\sim 2''$ seeing.

The preliminary data reduction (gain and amplifier cross-talk corrections, bias subtraction, amplifier mosaicing, and cosmetic corrections) was done with a semi-automated pipeline from the SALT PyRAFpackage⁴ by SALT observatory staff (Crawford et al. 2010). We performed further reduction including wavelength calibration, background subtraction, extraction of 1D spectra and flux calibration using the IRAF package. We could only obtain relative flux calibrations, from observing spectrophotometric standards in twilight during other night, due to the SALT design, which has a time-varying, asymmetric and underfilled entrance

pupil. As a result there is a difference in the level of continuum between the SALT and SDSS observations. To remove this effect we took only a part of the SALT spectra corresponding to the SDSS aperture into consideration. Further, we rescaled the SALT spectrum using a scaling function found by comparing the SALT and SDSS spectra. However, the spectrum of the source 015411–01 turned out to be of poor quality for reliable measurements due to low signal to noise ratio ($S/N < 3$) and strong sky lines distorting $H\alpha$ and [N II] emissions. Finally, we prepared the SALT spectra of two objects, 010733+01 and 030925+01, for the dispersion and line measurements described in the next section. The SALT spectra are presented in Figure 9.

3.5. Emission line measurements

To track the brightness changes in the optical and UV range of presented sources, we have collected all available photometric data points since 1992 till 2008 from the Sloan Digital Sky Survey (SDSS) and data gathered since 2005 to 2014 from the Catalina Sky Survey (CRTS; (Drake et al. 2009)). Both CRTS and SDSS data for all investigated sources showed no significant changes over the whole period of observations. Slight fluctuations visible in SDSS photometric measurements are within the limit of error for all sources.

The good quality SDSS spectroscopic observations are available for 5 out of twelve of our objects. These are 010733+01, 015411–01, 020827–00 and 030925+01 which we analyze in this paper and the quasar 013815+00 presented in Kunert-Bajraszewska et al. (2020). Additionally the Keck (DEIMOS) spectroscopic observation of source 233001–00 (Mooley et al. 2016) and SALT (RSS) observation of sources 010733+01 and 030925+00 have been also

⁴ <http://pysalt.salt.ac.za>

processed and analyzed in this work. All spectra were corrected for Galactic extinction with the reddening map of (Schlafly & Finkbeiner 2011), and shifted to the rest-frame wavelength by using the SDSS redshift (Figure 9).

In the case where the continuum of the source was dominated by AGN emission the decomposition of the spectra has been done using the IRAF package and assuming the following components: power law (representing the emission from an accretion disk), FeII pseudo-continuum, and suite of Lorentzian and Gaussian components to model the broad and narrow emission lines. In order to remove the contribution from FeII emission, iron template from (Bruhweiler & Verner 2008) was fitted to both spectra. The template was convolved with Gaussian profile with different dispersion values for kinematic broadening of FeII lines, in order to find the most accurate one.

Spectra strongly contaminated by the host galaxy starlight were processed with the code STARLIGHT (Cid Fernandes et al. 2011) in order to fit their continua and measure stellar velocity dispersion. The code allows the user to adjust the model to observed spectrum using the Markov chain Monte Carlo method, and a database containing 150 spectra of star populations of different ages and metallicity. Obtained results provide abundant information about the source, such as percentage share of individual star populations in the observed spectrum, their masses, and the line broadening parameter, which allows to calculate star dispersion coefficient using a relation:

$$\sigma_*^2 = vd^2 - \sigma_{inst}^2 + \sigma_{base}^2 \quad (2)$$

where vd is the line broadening parameter, and σ_{base} and σ_{inst} are stellar model and instrumental velocity dispersion, respectively.

The emission lines were fitted with Lorentzian/Gaussian function (with single or multiple components, depending on a line) to determine fluxes and FWHMs. All the widths of the narrow lines were corrected by the instrumental resolution. The properties of the emission lines resulting from the fit to each spectrum are listed in Table 5.

The error estimation of the continuum flux density was made using the root mean square method (rms). The uncertainty of the line flux measurements has been estimated using the standard formula for noise averaging $\sigma_f = \sigma_c L / \sqrt{N}$, where σ_c is the rms of continuum flux density, L is the integration interval and N is a number of spectrum samples. The error of the line width has been calculated by finding minimum and maximum width of the Lorentz/Gaussian line fit at which the integral of the fit changes by σ_c keeping the amplitude of the fit fixed.

4. Calculations of physical parameters

The k-corrected luminosities of our sources are calculated with:

$$L = 4\pi D_L^2 S_\nu (1+z)^{-(1+\alpha)} \text{ W Hz}^{-1} \quad (3)$$

where D_L is luminosity distance, S_ν is flux density at given frequency, z is redshift and α is thin or thick spectral index depends on the spectrum shape at given frequency.

In order to calculate the jet kinetic power we used the relation established for evolved radio sources in the form discussed by (Rusinek et al. 2017) namely:

$$P_j = 5 \times 10^{22} \left(\frac{L_{1.4\text{GHz}}}{\text{W Hz}^{-1}} \right)^{6/7} \text{ erg s}^{-1} \quad (4)$$

and the corresponding 1.4 GHz luminosity is calculated based on our VLA measurements.

The black hole mass of quasars was estimated from MgII λ 2799 line and luminosity at 3000Å, using the following relation (Trakhtenbrot & Netzer 2012):

$$\frac{M_{\text{BH}}}{M_\odot} = 5.6 \times 10^6 \left(\frac{\lambda L_{3000}}{10^{44} \text{ erg s}^{-1}} \right)^{0.62} \left[\frac{\text{FWHM}(\text{MgII})}{10^3 \text{ km s}^{-1}} \right]^2 \quad (5)$$

Then the bolometric AGN luminosity was calculated (Table 6) using λL_{3000} and a conversion factor of 5.3 to convert from monochromatic to bolometric luminosity (Runnoe et al. 2012).

In the case of sources with a significant host contribution in the spectra we used the established scaling relation $M_{\text{BH}} - \sigma_*$ (Kormendy & Ho 2013) to get their black hole masses:

$$\log \left(\frac{M_{\text{BH}}}{M_\odot} \right) = 8.49 + 4.38 \times \log \left(\frac{\sigma_*}{200 \text{ km s}^{-1}} \right) \quad (6)$$

However, for two sources, the measurement of stellar velocity dispersion turned out to be problematic. In this case, to estimate the mass of the black hole, we used the velocity dispersion of [O III] line core ($\sigma_{[\text{OIII}]} = \text{FWHM}_{[\text{OIII}]} / 2.35$) which can serve as a surrogate for the σ_* (Liao & Gu 2020).

Then, in order to calculate their bolometric luminosities we used either $H\alpha$ or $H\beta$ line measurements corrected for the reddening in host galaxies by requiring $H\alpha/H\beta = 3$ and bolometric correction factor defined by (Netzer 2019) for narrow $H\beta$ line:

$$k_{\text{bol}} = 4580 \times \left(\frac{L_{H\beta}}{10^{42} \text{ erg s}^{-1}} \right)^{0.18} \quad (7)$$

The method used to estimate the black hole mass and bolometric luminosity for each source is listed in Table 6.

For comparative purposes, in Figure 8 additional samples were placed and that require explanation. Sources classified as Narrow Line Radio Galaxies (NLRG), Broad Line Radio Galaxies (BLRG) and Radio-Loud Quasars (RLQ) are from Rusinek et al. (2017). All these objects, with a few exceptions that we have removed from the samples, have FR II radio morphologies. A sample of FR I type radio sources is from Capetti et al. (2017). Their bolometric luminosity was calculated based on the [OIII] luminosity with the correction factor $L_{\text{bol}} = 3500 L_{[\text{OIII}]}$ (Best and Heckman 2012). The group of objects marked in Figure 8 as Young Radio Sources

(YRS) is a collection of CSS and GPS sources from Liao & Gu (2020) and Wójtowicz *et al.* (2020). We cross matched the objects from the sample of Liao & Gu (2020) with available radio databases to get their 1.4 flux density. This resulted in a 21% reduction in the sample size. The spectroscopic data have been taken from the articles directly.

The jet kinetic power of all sources presented in Figure 8 was computed using the formula 4. It is a calibrated Willott *et al.* (1999) formula based on calorimetry of radio lobes. But some studies suggests, that in the young radio sources may occur the enhancement of radiative efficiency of compact radio-emitting jets and lobes due to their direct interaction with the interstellar medium of host galaxies (Tadhunter *et al.* 2011; Dicken *et al.* 2012). This in turn can cause the over-estimate of their jet power when using the calorimetric formula (Wójtowicz *et al.* 2020). However, this hypothesis is not confirmed by the correlation of radio power with, considered as a measure of AGN bolometric luminosity, the X-ray luminosity (Kunert-Bajraszewska *et al.* 2014). Hence we calculated the jet power of all our sources in the same way.

5. Notes on individual sources

All sources are transients with respect to the FIRST survey. They were undetected in the FIRST (1995-2011) at the sensitivity level of < 0.5 mJy at 1.4 GHz but discovered in the CNSS observations (2012-2015) to have brightened significantly (an average of a factor of 6.5 for quasars and a factor of 4.5 for galaxies) and become radio-loud sources. Three out of twelve sources, namely 221812–01, 223041–00 and 010733+01, have been already detected in earlier deep VLA-Stripe 82 survey performed in 2007-2009 (Hodge *et al.* 2011). The others were found based on the CNSS survey between 2012 and 2013 (Mooley *et al.* 2019). They were detected at the mJy level ranging from 1 to 13 mJy.

221650+00. This is a very compact source, unresolved in high-resolution VLBA observations (Figure 10). The two VLA spectra taken over a period of 3 years show a further increase in source brightness with a slight change in spectral slope (Figure 3). Careful inspection of the VLA-Stripe 82 image from 2009 may indicate a marginal detection of this source at the level of 0.43 ± 0.12 mJy. It is below the catalog detection limit at this position which is 0.54 mJy/beam (Hodge *et al.* 2011). Only SDSS photometry is available for this object.

221812–01. This source has been detected in 2009 in VLA-Stripe 82 survey (Hodge *et al.* 2011) with integrated flux density of 1.39 ± 0.11 mJy at 1.4 GHz which is in agreement with our observations. There is also radio emission at these coordinates in FIRST observations from 1995 at the 3σ noise level (much below the catalog detection limit at this position), which excludes reliable measurement. This however, indicates about threefold increase in the source flux density noticed several years later.

The source is unresolved in the high-resolution VLBA observations (Figure 10) and has a typical GPS spectrum which does not show large changes over time (Figure 3).

Table 3. Results of spectral modeling of VLA radio data.

Name	Epoch	S_p [mJy]	ν_p [GHz]	$\nu_p(1+z)$ [GHz]	α_{thin}	α_{thick}
(1)	(2)	(3)	(4)	(5)	(6)	(7)
221650+00	Nov 2016	2.20 ± 0.04	3.00 ± 0.10	4.65	-0.74 ± 0.03	2.50 ± 0.15
	Nov 2019	3.20 ± 0.06	3.00 ± 0.09	4.65	-0.63 ± 0.03	2.50*
221812–01	May 2014	12.93 ± 0.22	3.88 ± 0.13	-	-1.03 ± 0.05	2.61 ± 0.08
	Jun 2015	14.43 ± 0.45	4.10 ± 0.44	-	-1.06 ± 0.14	2.20*
	Nov 2016	13.37 ± 0.25	4.10 ± 0.21	-	-1.03 ± 0.06	2.38 ± 0.09
	Nov 2019	14.53 ± 0.53	4.50 ± 0.17	-	-1.09 ± 0.09	2.15*
223041–00	Nov 2016	6.70 ± 0.18	5.13 ± 0.18	9.44	-0.85 ± 0.07	1.83 ± 0.15
	Nov 2019	5.76 ± 0.17	3.69 ± 0.15	6.79	-0.63 ± 0.05	1.80*
233001–00	Sep 2012	10.39 ± 0.07	4.39 ± 0.05	11.63	-0.74 ± 0.07	1.45 ± 0.25
	May 2014	7.55 ± 0.21	3.82 ± 0.15	10.12	-0.98 ± 0.06	1.45*
	Nov 2016	6.60 ± 0.15	2.40 ± 0.19	6.36	-0.35 ± 0.05	1.85 ± 0.22
	Nov 2019	5.60 ± 0.22	2.20 ± 0.16	5.83	-0.17 ± 0.03	1.85*
010733+01	Oct 2015	3.73 ± 0.21	2.60 ± 0.37	2.91	-0.71 ± 0.05	0.85*
	Nov 2016	3.65 ± 0.17	2.30 ± 0.21	2.58	-0.69 ± 0.05	1.20 ± 0.15
	Nov 2019	-	-	-	-0.68 ± 0.04	-
015411–01	Apr 2015	4.16 ± 0.05	4.60 ± 0.12	4.83	-1.09 ± 0.04	0.47 ± 0.03
	Jun 2015	3.79 ± 0.13	4.60 ± 0.37	4.83	-1.35 ± 0.15	0.47 ± 0.05
	Nov 2016	5.48 ± 0.07	4.50 ± 0.26	4.73	-0.57 ± 0.04	0.73 ± 0.03
	Nov 2019	6.43 ± 0.06	4.15 ± 0.26	4.36	-0.55 ± 0.03	0.75*
020827–00	Nov 2016	4.48 ± 0.22	2.58 ± 0.26	6.03	-0.37 ± 0.05	2.15 ± 0.33
	Nov 2019	-	-	-	-0.31 ± 0.01	-
030533+00	Jun 2015	4.46 ± 0.13	3.54 ± 0.16	5.03	-0.47 ± 0.04	2.23 ± 0.16
	Nov 2016	5.33 ± 0.08	4.85 ± 0.20	6.89	-0.70 ± 0.04	1.82 ± 0.11
	Nov 2019	4.93 ± 0.09	4.40 ± 0.12	6.25	-0.72 ± 0.08	1.80*
030925+01	Apr 2014	12.45 ± 0.33	4.46 ± 0.10	4.64	-1.15 ± 0.06	2.15 ± 0.20
	Jun 2014	15.71 ± 0.34	3.16 ± 0.09	3.29	-0.64 ± 0.03	2.27 ± 0.25
	Feb 2015	17.70 ± 0.41	3.13 ± 0.10	3.25	-0.75 ± 0.04	2.10*
	Jun 2015	17.77 ± 0.47	3.12 ± 0.10	3.24	-1.09 ± 0.05	2.75 ± 0.22
	Nov 2016	11.72 ± 0.11	2.72 ± 0.06	2.83	-0.98 ± 0.02	2.43 ± 0.10
031833+00	Jun 2015	5.77 ± 0.23	4.25 ± 0.10	5.95	-1.75 ± 0.12	2.30 ± 0.09
	Nov 2016	5.65 ± 0.09	3.70 ± 0.05	5.18	-1.60 ± 0.04	2.50 ± 0.07
	Nov 2019	5.80 ± 0.13	3.55 ± 0.08	4.97	-1.65 ± 0.07	2.40*
034526+00	Jun 2015	10.23 ± 0.10	7.33 ± 0.13	10.27	-0.99 ± 0.08	1.78 ± 0.03
	Nov 2016	13.06 ± 0.15	6.80 ± 0.09	9.72	-0.93 ± 0.03	1.70*
	Nov 2019	11.70 ± 0.12	6.77 ± 0.09	9.72	-0.95 ± 0.03	1.75 ± 0.04

NOTE—Columns are listed as follows: (1) source name; (2) epoch of observation; (3) the peak flux density; (4) observed frequency of the peak (spectral turnover); (5) rest-frame peak frequency; (6) spectral index of the optically thin part of the radio spectrum; (7) spectral index of the optically thick part of the radio spectrum, * indicates index values that have been fixed to obtain a proper fit; The values quoted in column 3-7 were obtained via modeling described in paragraph 3.2.

There is no optical identification for this object and it has not been detected in X-rays (Table 2).

223041–00. A detection of this source is already present in VLA-Stripe 82 survey. The observations was made in 2008 and the integrated flux of the source amounts to 0.86 ± 0.06 mJy which is in agreement with our observations. The VLA measurements show the time-varying GPS spectrum (Figure 3). The source is unresolved in VLBA observations (Figure 10). Only SDSS photometry is available in case of this object.

233001–00. This is a compact quasar unresolved in high-resolution VLBA observations (Figure 10). Its radio spectrum is characterized by large changes that are traced from

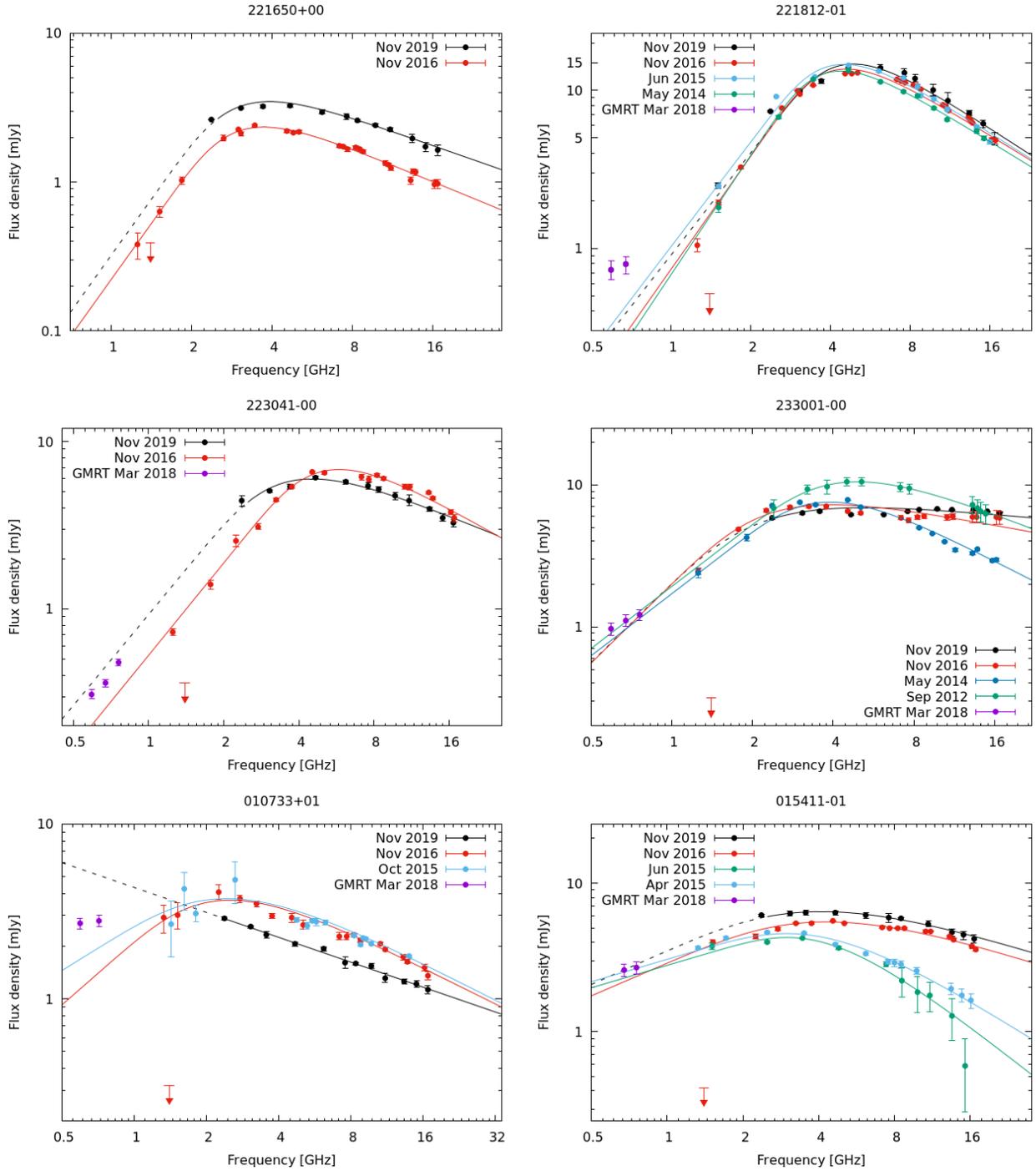


Figure 3. Multi-epoch radio spectra with fitted models, including VLA measurements in the range 1-20 GHz and GMRT points in the range 550-850 MHz. The red arrow indicates the 3σ upper limit at 1.4 GHz from the FIRST survey.

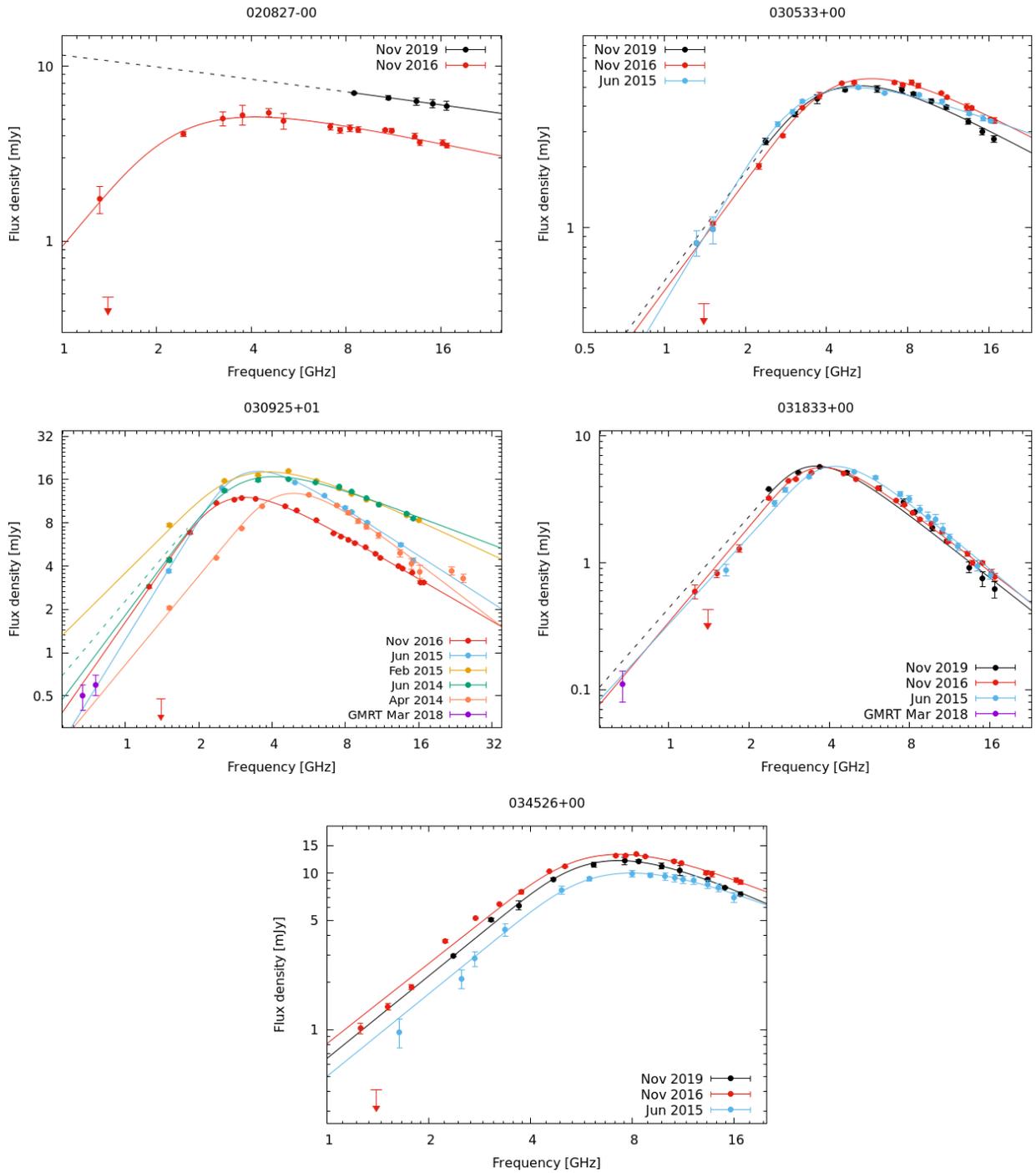


Figure 3. Continued

2012 when this source was discovered (Mooley et al. 2016). During the first few years of observations the peak of the spectrum moved toward lower frequencies and the radio spectrum evolved from steep to flat spectrum (Figure 3). The good quality optical-UV spectroscopic observation of this quasar has been made with DEIMOS at Keck II in 2012 (Mooley et al. 2016), i.e. in its radio-loud phase (Figure 9). The spectrum shows a strong broad MgII line typical of unobscured AGN (Tables 5 and 6). There is also a detection of 233001-00 in X-rays (Table 2). The value of the hardness ratio indicates the soft X-ray spectrum but detailed spectral studies require deeper X-ray observations.

010733+01. Radio emission of 010733+01 is not present in the FIRST image but the source has been detected in 2007 in VLA-Stripe 82 survey with integrated flux density of 2.80 ± 0.06 mJy which is in agreement with our observations. The multi-epoch VLA measurements show the time-varying GPS spectrum (Figure 3). The 7.5 GHz VLBA observations revealed the presence of two components in the source: the central one, which is probably a radio core with flux density 1.63 ± 0.01 mJy and the NE jet-like feature with flux density 0.42 ± 0.02 mJy (Figure 10). This source has not been detected in X-rays (Table 2).

The optical spectroscopic observations of this galaxy has been made in 2015 (SDSS) and 2019 (SALT), both in its radio-loud phase (Tables 5 and 6). The comparison of the two spectra show, that there are no significant differences between the measurements. The emission line ratios we have measured indicate that in this galaxy the ionizing radiation comes from an AGN and star-forming regions (Figure 4).

015411-01. The SE extension is detected at both 4.5 and 7.5 GHz VLBA images of this object and may suggest the presence of a small jet (Figure 10). The VLA measurements show a significant flattening of the spectrum with time in its optically thin part (Figure 3). There is also weak X-ray detection of this source with intermediate value of the hardness ratio (Table 2). The spectroscopic observations of this object has been made by SDSS in 2000, i.e. in its radio-quiet phase and after the burst of its radio activity in 2019 with SALT (Tables 5 and 6). However, the poor quality of the SALT spectrum made reliable measurements impossible.

020827-00. This is a compact quasar unresolved on VLBA resolution (Figure 10). Its radio spectrum is flat with a peak at about 5 GHz (Figure 3). The SDSS spectroscopic observation of it has been made in its radio-quiet phase (Tables 5 and 6). It exhibits strong broad MgII emission line typical for unobscured AGN (Figure 9).

030533+00. Compact source with a small SW extension visible at 7.5 GHz in the VLBA observations (Figure 10). The VLA observations show typical GPS spectrum (Figure 3). Only SDSS photometry is available in case of this object.

030925+01. There are two epochs of VLBA observations made for this source (Fig. 10). The 4.5 and 7.5 GHz VLBA images from June 2015, when the source is in its high state, show the presence of two compact features: the central one with flux densities 11.52 ± 0.04 and 8.68 ± 0.03 mJy, and the NW component with flux densities 3.84 ± 0.04 and

2.00 ± 0.04 mJy at 4.5 and 7.5 GHz, respectively. The radio spectral index amounts to 0.56 and 1.24 for the central and NW features, respectively. Thus the initial radio structure of 030925+01 is core-jet type with the central component being a radio core. However, the same observations performed almost one year later (March 2016) show only single compact object (Fig. 10). The multi-epoch VLA observations performed in 2014-2016 revealed significant changes in flux density and peak frequency of the spectrum (Figure 3).

The spectroscopic observations of this object has been made by SDSS several times between 2000 and 2001., i.e. in its radio-quiet phase, and after the burst of its radio activity in 2019 with SALT (Tables 5 and 6). Out of all SDSS spectra, we chose the spectrum from MJD 52258 (plate 412, fiber 402), indicated by SDSS as the best quality. The spectra from both (2001 and 2019) epochs are very similar and display many narrow lines typical for obscured AGN. According to the available line ratios in both phases, 030925+01 is probably a 'composite' emission source, which includes radiation from an accreting SMBH in addition to young stars (Figure 4).

The SDSS optical image shows that 030925+01 has a disturbed structure which may indicate a recent merger event and thus greater presence of dust and gas in this galaxy.

There is also weak X-ray detection of this source made in November 2017 (Table 2). The X-ray spectrum appears to be relatively hard, although more counts are needed to confirm this result.

031833+00. This is a slightly extended source without any clear features in VLBA observations (Fig. 10). Its radio spectrum has a typical GPS shape (Figure 3). Only SDSS photometry of this source is available.

034526+00. This object has been resolved into two components in 7.5 GHz VLBA observations (Fig. 10). The central component which is probably the radio core has a flux density of 6.81 ± 0.03 mJy. The SW component is a jet-like feature with flux density 2.36 ± 0.03 mJy.

The VLA measurements show changes in source flux density that have occurred over several years. However, the spectrum retains the typical GPS shape with peak at very high rest-frame frequency ~ 10 GHz (Figure 3). This source has not been detected in X-rays (Table 2).

6. Discussion

The radio sources we studied in this project were discovered by CNSS (Mooley et al. 2016) and are transient with respect to the FIRST survey (White et al. 1997). Together with the quasar 013815+00 recently published by Kunert-Bajraszewska et al. (2020) they form a group of 12 objects. As the CNSS survey covers the area of ~ 270 deg² of Stripe 82, this means a detection rate on the level of one such source at about 20 deg². The current radio luminosity of these objects of $\log_{10}[L_{1.4\text{GHz}}/W \text{ Hz}^{-1}] > 22.5$ indicates that they are now in a radio-loud state (Kellermann et al. 2016). The exceptions are the two sources (015411-01 and 030925+01) that are on the luminosity boundary between the objects being powered by the SMBH and those whose radio emission

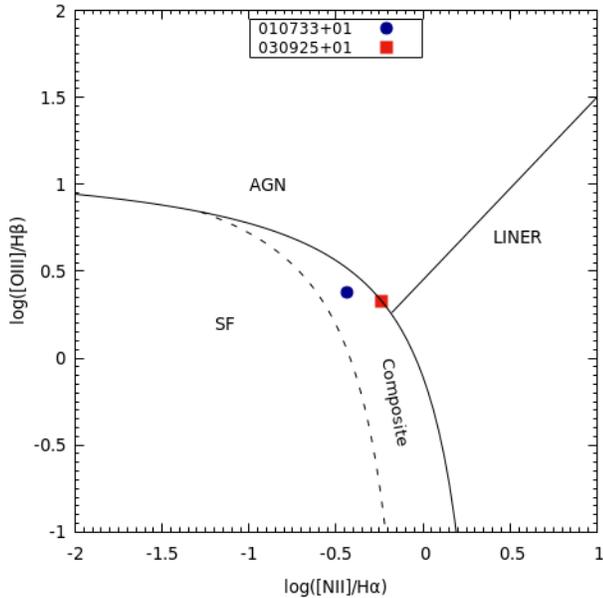


Figure 4. Emission line ratio diagram (Baldwin et al. 1981). The different lines, taken from Kewley et al. (2001); Kauffmann et al. (2003); Schawinski et al. (2007), illustrate boundaries between sources classified as star forming regions/galaxies (SF), AGNs, low ionization nuclear emission line regions (LINERs), and ‘composite’ sources.

is powered by star formation in their host galaxies (Table 1). However, this limit is not sharp (Mauch & Sadler 2007; Malefahlo et al. 2020). Presented in this article the radio characteristic of these objects and the X-ray detection favours the AGN origin of their emission.

The whole sample of 12 transient radio sources consists of three quasars with a redshift of $z > 0.9$ and eight galaxies. One object has no optical identification. The redshift distribution of our sample is shown in Figure 5 and compared to other samples of compact objects. It is visible that the composition of samples is similar although all of our objects are less radio luminous. Regardless of the luminosity, however, locally the population of compact sources is dominated by low power galaxies. Quasars are brighter than galaxies and thus it is easier to detect them at higher redshift. This is in agreement with the previous studies of the redshift distribution of radio sources and unification by orientation scheme (Jackson & Wall 1999; Berton et al. 2017).

Both groups of objects, galaxies and quasars, differ in radio, optical and X-ray properties, as well as the character and rate of changes observed since the beginning of the radio activity.

6.1. Analysis of radio properties

The follow-up multi-frequency VLA observations of our sources revealed a convex spectra peaking in the range 2–12 GHz at rest-frame (Figure 3 and Table 3). During the few years of monitoring which are the first years of radio-loud phase of the sources, most of them show variability of the radio flux density, mainly in the optically thin part of the spectrum. The most significant changes occurred in the case

of two nearby galaxies 015411–01 and 030925+01 and two quasars 233001–00 and 020827–00. In the case of the latter, a progressive flattening of the spectrum is visible. In addition, sources 233001–00, 223041–00 and 030925+01 also have a very strong peak shift towards lower frequencies. Ultimately, after the first few years of life, the new radio quasars can be classified as flat-spectrum objects while galaxies keep the convex shape of the spectrum. We interpret the GPS spectra of our sources, for both quasars and galaxies, as a burst of new radio jet activity. The observed changes and flattening of the spectra probably reflect the changes taking place in the jet itself, and thus its expansion and dissipation of energy. Moreover, the formation of a new component has a large impact on the radio spectrum mostly in the case of sources oriented at a small angle to the line of sight. This causes the source to be observed as variable at high frequencies and may explain the changes observed in some of our sources.

The changes in the optically thick part of the synchrotron spectrum of our transient sources are definitely less significant. In most cases the estimated value of their optically thick spectral index differ from the theoretical limit of $\alpha_{thick} = 2.5$ for a uniform source of synchrotron radiation (Table 3). However, about half of our sources have very inverted spectra with $\alpha_{thick} \geq 2$ and for the three sources α_{thick} even reaches the canonical value of 2.5 in one of the epoch of observations which is in agreement with their compact, unresolved morphology.

The high-resolution VLBA observations of our objects do not show any well resolved components in most cases. The presence of a small jet is visible in four sources (Figure 10) including quasar 013815+00 (Kunert-Bajraszewska et al. 2020). However, since the majority of these observations were made about 3 years after the burst of radio activity, it could have been enough time for complete jet energy dissipation in case of most of the objects and the jet is no longer visible in the radio image. The two epoch VLBA observations of galaxy 030925+01 seem to confirm such scenario. The small jet is visible on the 2015 images of 030925+01 while in 2016 only a very compact single component is present (Figure 10). In conclusion, our radio sources can be classified then either as a core-jet or point-like objects.

6.2. The peak frequency - linear size relationship

It has been shown based on different samples of radio sources that there is a continuous distribution of young AGNs along the frequency of the peak (turnover frequency) $\nu_p - l$ linear size plane (O’Dea & Baum 1997; Orienti & Dallacasa 2014; Sotnikova et al. 2019). This relationship suggests that the physical properties of the CSS and GPS sources are similar, and the only variable that depends directly on their size is their turnover frequency. The radio properties of our transient sources in their very initial phase of activity, namely the convex spectra and compact morphology, place them in the upper left part of the $\nu_p - l$ plane and make most of them follow the established relationship quite properly (Figure 5). The exceptions are three sources: 010733+01,

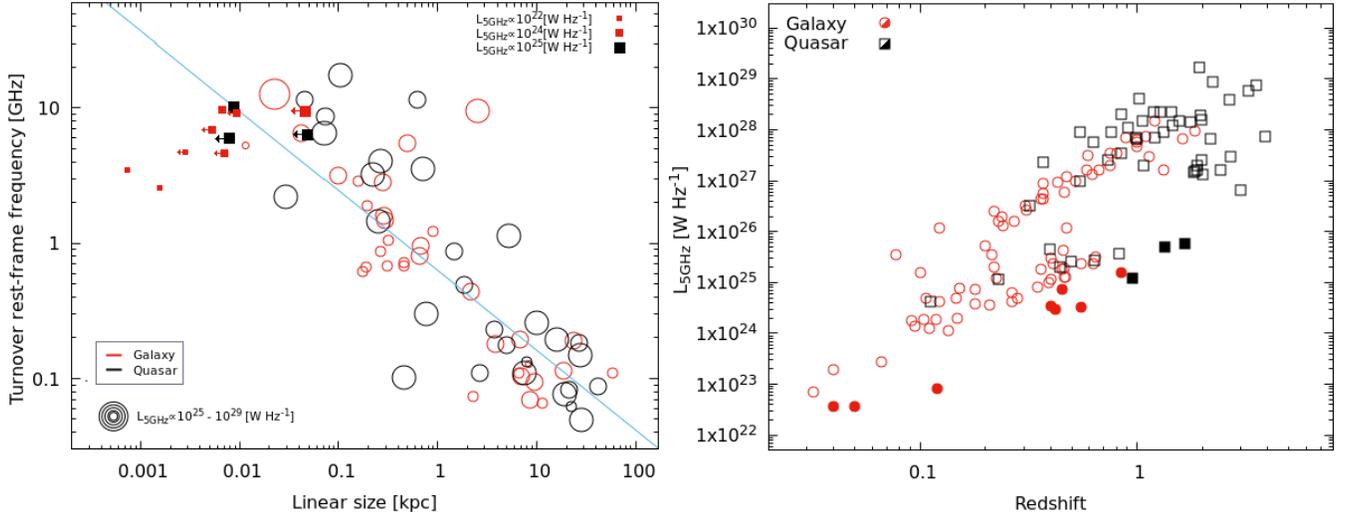


Figure 5. **Left:** The intrinsic turnover frequency vs. linear size for the CSS/GPS bulk sample from O’Dea (1998); Snellen et al. (1998); de Vries et al. (1997); Stanghellini et al. (1998); Fanti et al. (1990), (circles) with GPS sources presented in this work (squares). Sizes of circles/squares correspond with k-corrected radio luminosity at 5GHz and arrows indicate maximum linear sizes for unresolved sources. Blue solid line indicates the linear relationship $\log \nu_p = -0.21 - 0.59 \times \log \text{LLS}$, found by Orienti & Dallacasa (2014). **Right:** Redshift vs. luminosity at 5GHz for the bulk sample combined with the low luminosity CSS sources from Kunert-Bajraszewska et al. (2010) (empty points) and transient objects presented in this work (filled points) with a distinction between quasars and galaxies.

015411–00 and 030925+01, with the lowest radio luminosity $\log_{10}[L_{1.4\text{GHz}}/\text{W Hz}^{-1}] < 23$.

There are two main processes causing turnover in the spectra of CSS and GPS sources. These are synchrotron self-absorption (SSA) and free-free absorption (FFA) caused by the external or internal environment to the synchrotron emitting volume (de Kool & Begelman 1989; O’Dea 1998; Bicknell et al. 1997). There are examples of individual objects whose spectra are better described by FFA rather than by SSA (Callingham et al. 2017; Collier et al. 2018; Keim et al. 2019), or in which both mechanisms could be at work (Kameno et al. 2003). Nevertheless, the relation between the frequency of the peak ν_p (turnover frequency) and the linear size l is better reproduced by SSA over the large range of linear sizes (Jeyakumar 2016).

For our sample the values of the optically thick spectral indices do not exceed the SSA limit of 2.5, but are close to the limit in a few objects. This indicates that probably a non-homogeneous synchrotron component rather than the presence of FFA is responsible for the low-frequency absorption of their radio spectra. However, we cannot exclude the presence of thermal plasma, either external or internal to the synchrotron emitting volume which can cause the FFA effects at some stage (epoch) of the source evolution.

We conclude that many radio spectral properties of our low luminosity objects in the early stages of evolution are very similar to those of high power GPS and CSS sources. However, most of them are more compact with a relatively high frequency turnover (Figure 5). Their position on the size vs. turnover frequency plane may imply a different, more steep or parallel path of a radio galaxy development, e.g. remain compact for a longer period, or even for most of its life. In turn, in the case of quasars, a much faster and a more significant change of their radio spectral properties

means that they appear on $\nu_p - l$ plane only for a short period of time. This is in agreement with previous studies of GPS sources saying that over time, even most quasar-type GPS sources no longer meet the criteria for belonging to this class of objects (Dallacasa et al. 2000; Orienti & Dallacasa 2012; Tornainen et al. 2005; Sotnikova et al. 2019). This behavior prevents many young GPS quasars from being recognized as such and therefore they may remain hidden in the flat-spectrum quasars population.

6.3. The origin of X-ray emission

We detected three of the nine sources observed in X-rays (Table 2, counting an undetected quasar 013815+00 (Kunert-Bajraszewska et al. 2020)). These are two nearby galaxies, 015411–01 and 030925+01, with a small number of counts and a much brighter quasar 233001–00 with the X-ray luminosity of $4 \times 10^{44} \text{ erg s}^{-2}$ in the 2-10 keV energy range. These modest data prevent us from more detailed analysis of individual objects, however, allow us to trace certain emission relationships.

Kunert-Bajraszewska et al. (2014) compared the X-ray properties of GPS and CSS sources with large scale FRI and FRIIs galaxies on the radio–X-ray luminosity plane. The results suggested that there is a continuity in the properties of the small and large scale sources. Additionally, the separation into low and high excitation radio galaxies (HERG and LERG) suggests that the two different X-ray emission modes, viz. X-rays originating from the base of the relativistic jet (LERG), and X-rays being dominated by the emission from an accretion disk (HERG), are present among the younger compact AGNs. The optical spectroscopic data of our sources are not sufficient enough for the sources allocation into LERG or HERG type. However, the location of the sources on the radio-X-ray luminosity plane provides

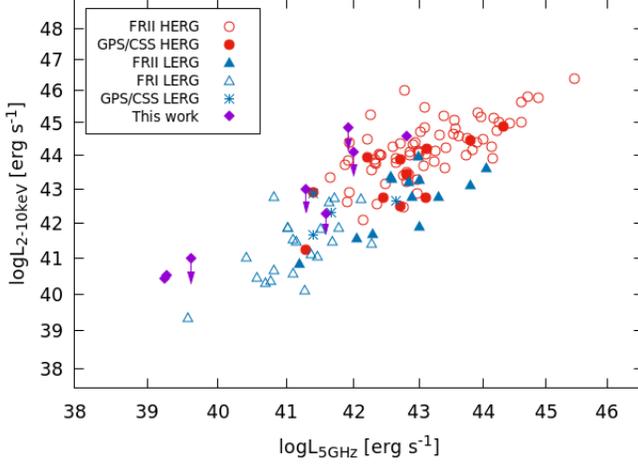


Figure 6. X-ray 2–10 keV vs. radio 5GHz luminosity diagram for AGNs sample (Kunert-Bajraszewska et al. 2014) classified as high excitation radio galaxies (HERGs, red) and low excitation radio galaxies (LERGs, blue), combined with sources presented in this work (purple diamonds). FRII HERG and FRII LERG sources are indicated with open red circles and blue triangles respectively. GPS/CSS HERG and GPS/CSS LERG sources are indicated with red circles and blue stars respectively. FRI LERG sources are indicated with empty blue triangles. Luminosities for sources presented in this work estimated from X-ray upper limit (Table 2) are indicated with arrows.

a preliminary classification, which, moreover, is arranged along the partition between strong and weak radio luminosity sources (Figure 6). Thus, the two galaxies detected in X-rays, 015411–01 and 030925+01, can probably be classified as LERG and a quasar 233001–00 as HERG types. In addition, the low [OIII] λ 5007 line luminosity of 030925+01 agrees with the interpretation of this object as a LERG.

We note that the location of X-ray emitting radio sources on the radio–X-ray plane may strongly depend on the epoch of the observation. There are many examples of objects, especially flat spectrum radio quasars, in which the flaring event is detected simultaneously in radio, optical-UV, X-ray and even γ ray range (Berton et al. 2018). According to the known model of such events, the new jet component is ejected during the high state and in its initial phase carries enough energy to produce high-energy photons. It loses this ability when it becomes optically thin for synchrotron emission. In this phase we observe the peak of the radio luminosity. It is reasonable to suspect that in the case of our transient sources the burst of radio activity followed this pattern. However, since the observations of most of our objects took place several years after the ignition of the radio activity, we were unable to register the associated burst of the X-ray emission.

The exception is the quasar 233001–00, which was observed by XMM-Newton (LaMassa et al. 2013) about 2 months before the radio detection, and two nearby galaxies, 015411–01 and 030925+01. We infer that in the case of the galaxies, the X-ray emission recorded in our Chandra observations, 4–5 years after the new radio jet ejection, originates from the base of jet. However, in the case of the quasar 233001–00, it is directly related to the new ejection

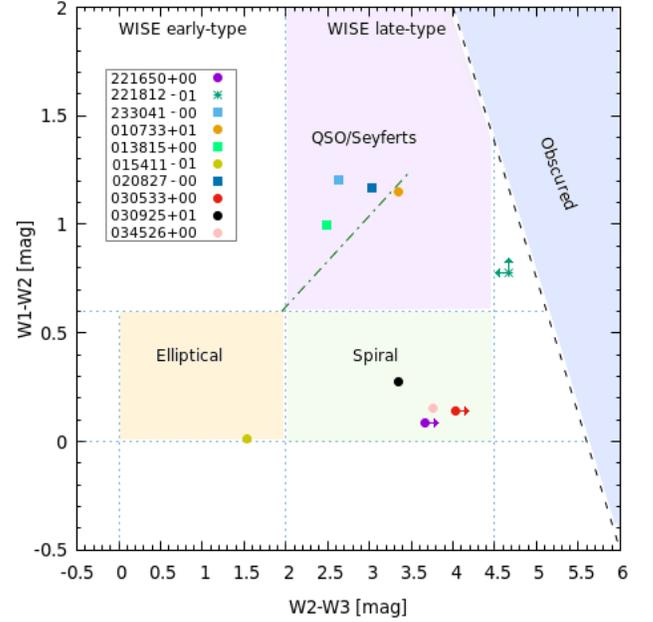


Figure 7. WISE color-color plot for sources presented in this work with early-type and late-type galaxies distinction. 013815+00 quasar from (Kunert-Bajraszewska et al. 2020) is included. Each source is marked individually, color filters are W1 - $3.35\mu\text{m}$, W2 - $4.6\mu\text{m}$ and W3 - $12\mu\text{m}$. Regions for particular galaxy populations are bounded by dashed lines and indicated with colors. Dashed dark green line indicates the WISE blazar sequence from (Massaro et al. 2012). Border limiting the region for obscured sources is determined by the linear relation $(W1 - W2) + 1.25(W2 - W3) > 7$ from (Lonsdale et al. 2015). Upper limits for particular bands are indicated with arrows pointing in adequate direction.

event. What is more, the X-ray power is higher than the radio power in our objects with a larger difference detected in the quasar 233001–00. Such trend is also visible in other high excitation objects (Figure 6). This may indicate a presence of an additional X-ray source in HERG sources, which could be related to the accreting gas.

In general, the results of our X-ray observations indicate, that the X-ray emission is rather weak in these transient radio sources. The X-ray luminosity observed in the galaxies is much lower than $10^{42} \text{ erg s}^{-1}$ which is consistent with the presence of a radiatively inefficient accretion onto a black hole with a mass within $\sim 10^6 - 10^8 M_{\odot}$ (Paggi et al. 2016). It is also possible that the total X-ray emission that we observe is a combination of the emission produced by the AGN and the stellar and hot interstellar medium (ISM) emission (see the discussion in next section).

<https://www.overleaf.com/project/5c1a0af33dacca49c468307f>

6.4. The WISE color-color diagram

Near- and mid-infrared photometry is available for most of our sources (Table 4) from the WISE mission (Cutri & et al. 2013). Figure 7 shows a WISE colour-colour plot for them and the dotted horizontal and vertical lines divide for different group of objects (Wright et al. 2010; Sadler et al. 2014). We have also adopted the host galaxy naming convention introduced by Sadler et al. (2014) for elliptical and spiral galax-

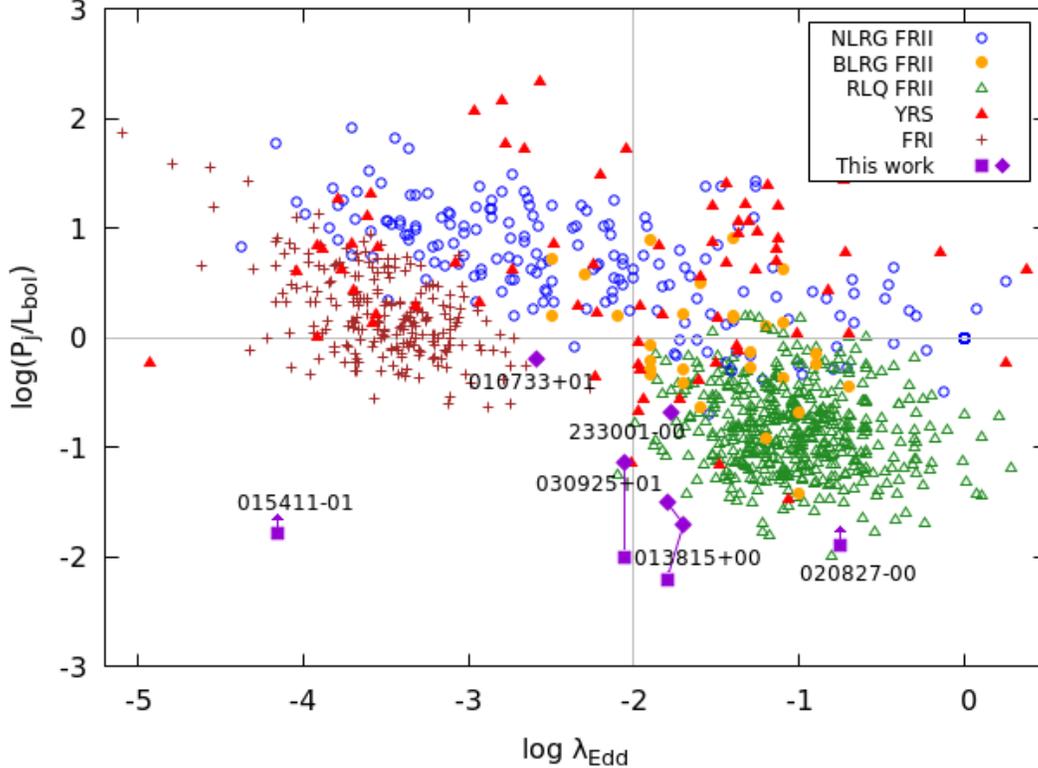


Figure 8. Distribution of AGNs on a λ_{Edd} vs P_j/L_{bol} plane. The Narrow Line Radio Galaxies (NLRG) are indicated with blue circles, Broad Line Radio Galaxies (BLRG) with yellow circles, Radio-Loud Quasars (RLQ) with green triangles (Rusinek et al. 2017). The FRI sample is shown by brown crosses (Capetti et al. 2017). The group of Young Radio Sources (YRS), consists of CSS and GPS objects from samples of (Wójtowicz et al. 2020) and Liao & Gu (2020), are indicated with red triangles. More information on samples can be found in section 4. Sources presented in this work are marked with purple points, with activity stage indicated with squares for radio-quiet and diamonds for radio-loud phase. In the radio-quiet phase the upper limits of radio emission at 1.4 GHz were used as a start point of source changes presented on the plot. The horizontal line corresponds to the level where P_j equals L_{bol} and the vertical line marks an approximate value of the Eddington ratio at which the accretion mode is changing from the radiatively inefficient (left side) to the radiatively efficient (right side) (Best and Heckman 2012; Mingo et al. 2014).

ies as the ‘WISE Early-type’ and ‘WISE Late-type’ objects, respectively.

As can be seen in the Figure 7, the vast majority of our sources are ‘WISE Late-type’ objects. However, as pointed out by Sadler et al. (2014), this class is not homogeneous but is a mixture of low and high excitation galaxies which is probably also the case with our sample of objects. Four our objects are classified as AGN based on the infrared photometry (Assef et al. 2018) in agreement with SDSS classification.

Nevertheless, regardless of the HERG/LERG division, all objects with $W2 - W3 > 2$ are thought to have gas and dust rich environments, although probably distributed in different ways, either forming a dusty torus (HERGs) or being a set of individual absorbing clouds (LERGs). This has been recently confirmed by the high, and similar, HI detection rate found in both ‘WISE Late-type’ LERGs and HERGs with a compact radio structure (Chandola et al. 2020). Since LERGs and HERGs are thought to differ in accretion mode, the presence of large amounts of gas alone does not imply high accretion rate. This difference is probably due to the feeding mechanism (Chandola et al. 2020).

6.5. Jet power and accretion process

We have analyzed the available optical spectra of our sources, and estimated the bolometric luminosities L_{bol} of their accretion disks, their black hole masses, M_{BH} and Eddington ratio $\lambda_{\text{Edd}} = L_{\text{bol}}/L_{\text{Edd}}$ (Figure 5 and Table 6). In addition, using the relation between the jet power and radio luminosity at 1.4 GHz discussed by (Rusinek et al. 2017) we estimated the power of the newborn jets in these transient objects. Whenever possible, estimates were made for both the radio-loud and radio-quiet phases of each source. In the case of the radio-quiet phase, depending on the source, we either assumed that the 1.4 GHz marginal radio emission was of AGN origin or we adopted an upper limit of radio emission as a starting point for the discussion of source changes. And so we were able to determine the physical values for both phases for two sources: 030925+01 and 013815+00. For objects 015411-01 and 020827-00, only the radio-quiet phase is calculated, and for objects 010733+01 and 233001-00, we only have data for the radio-loud phase (Table 6). The most complete set of observations gathered so far relates to the quasar 013815+00 (Kunert-Bajraszewska et al. 2020) and al-

low us to trace the changes in its radio and optical emission with greater accuracy.

In Figure 8 we plot the ratio P_j/L_{bol} against the Eddington scaled accretion luminosity, or Eddington ratio λ_{Edd} for the samples of different group of radio-loud AGNs taken from the literature, and for our sources. The value of the Eddington ratio $\log \lambda_{Edd} = -2$ is thought to be the approximate boundary between objects operating in different accretion modes, i.e. radiatively inefficient ($\log \lambda_{Edd} < -2$) and radiatively efficient ($\log \lambda_{Edd} > -2$). In the radiatively inefficient accretion regime the most of the gravitational energy is probably channeled into the jets, rather than radiative output (Mingo *et al.* 2014). In the case of our sources, we can see large differentiation in the values of the Eddington ratio. However, the quasars clearly group to the right of the dividing line. The calculated values of the jet kinetic power also show wide range in agreement with those previously obtained for other young radio sources (Wójtowicz *et al.* 2020; Liao & Gu 2020; Fan & Wu 2019).

It is also worth noting here that the location of a given source on the plot probably depends on its phase of activity. As has been recently discussed by (Kunert-Bajraszewska *et al.* 2020) on the example of a quasar 013815+00, the bolometric luminosity is a measure of accretion rate, which can change on the much shorter timescale than the lifetime of the radio source. The initial phase of high radio activity in the sources coincides with an increase of its accretion disk luminosity, which we interpret as an enhancement of the accretion process leading to the launch of a radio jet. In the following next few years, the disk brightness returns to its pre-event level while the radio luminosity still remains high. As a consequence we observe a movement of the sources along the distribution of objects on the $P_j/L_{bol} - \lambda_{Edd}$ plane as discussed by Rusinek *et al.* (2017) and shown on the example of 013815+00 (Figure 8).

7. Summary

The transient sources presented in this article constitute the first unbiased sample of newly-born radio sources discovered by the Caltech-NRAO Stripe 82 Survey. The sample consists of three quasars, eight galaxies and one object without optical identification. One of the sources, quasar 013815+00, has already been discussed in more detail in a separate paper (Kunert-Bajraszewska *et al.* 2020). We have performed the comprehensive, multi-epoch and multi-frequency study of this sample which we summarize as follows:

- The radio activity has been discovered in these objects between 2007 and 2013, and for majority of them, their radio luminosity exceeds the limit $\log_{10}[L_{1.4\text{GHz}}/W \text{ Hz}^{-1}] \sim 22.5$ above which the source is considered to be radio-loud. They might have transitioned from radio-quiet to radio-loud state either as a result of the increase in radio power or its ignition.
- All the sources, in their initial phase of activity, show convex radio spectra peaking at a few GHz, and

compact morphology typical for young AGNs, and thus can be classified as Gigahertz-Peaked Spectrum sources. The spectra change with time as a result of jet expansion which has been confirmed for some sources in the VLBA images. This transforms GPS quasars, which are likely to be seen at smaller angles, into flat-spectrum objects while galaxies keep the convex shape of the spectrum. We conclude thus that many of the young quasars can be hidden in the flat-spectrum quasars population.

- The transient sources are less radio luminous than the GPS objects studied so far. However, their placement on the $\nu_p - l$ plane, in comparison with more powerful GPS and CSS objects, shows that their behaviour is similar, with slight discrepancy from the established relation in the case of the weakest sources, suggesting their slower growth in size.
- Modeling of the radio spectra shows that these transient sources do not reach the SSA limit of the optically thick spectral index, although several objects are close to this limit. We conclude that their radio spectra consist of more than one radiative component, and the turnover of the spectrum is due to the synchrotron self-absorption process.
- The X-ray luminosities of the studied sources show a wide range of values $40 < \log_{10}[L_X/\text{erg s}^{-1}] < 45$ which indicates the diversity of young objects in our sample. The lower values are consistent with inefficient accretion mode.
- WISE infrared colours and optical observations imply that the majority of the host galaxies of our sources are spirals or other dusty, late-type galaxies with some ongoing star-formation.
- The transient sources show a wide range of bolometric luminosities, black hole masses and jet powers, suggesting that young AGNs belong to several different sub-classes of objects. The ignition of radio activity coincides with relatively small changes of bolometric luminosity and hence Eddington ratio. The changes in the accretion disk happen on the much shorter timescale than the lifetime of the newborn radio source what is visible as a movement along the $P_j/L_{bol} - \lambda_{Edd}$ plane.

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Software: CASA (McMullin et al. 2007), AIPS (van Moorsel et al. 1996), IRAF (Tody 1986, 1993), STARLIGHT (Cid Fernandes et al. 2011), CIAO (Fruscione et al. 2006), Sherpa (Freeman et al. 2001).

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APPENDIX

A1: Additional tables

Table 4. Infrared source properties

Name	W1	W2	W3	W4
	[mag] $3.4\mu m$	[mag] $4.6\mu m$	[mag] $12\mu m$	[mag] $22\mu m$
221650+00	15.82 ± 0.05	15.73 ± 0.14	< 12.07	< 8.98
221812-01	17.36 ± 0.17	< 16.59	11.91 ± 0.36	< 8.93
233001-00	16.20 ± 0.07	14.99 ± 0.08	12.37 ± 0.46	< 8.28
010733+01	15.56 ± 0.05	14.41 ± 0.06	11.06 ± 0.17	< 8.33
015411-01	12.45 ± 0.02	12.43 ± 0.03	10.91 ± 0.11	< 8.43
020827-00	15.20 ± 0.03	14.03 ± 0.04	11.00 ± 0.12	< 8.49
030533+00	15.98 ± 0.05	15.84 ± 0.14	< 11.81	< 8.69
030925+01	14.26 ± 0.03	13.99 ± 0.04	10.63 ± 0.12	8.00 ± 0.26
034526+00	15.42 ± 0.04	15.27 ± 0.10	11.50 ± 0.19	8.91 ± 0.48
013815+00	15.33 ± 0.04	14.33 ± 0.05	11.84 ± 0.27	< 8.84

NOTE—WISE colors in Vega magnitudes (Cutri & et al. 2013), as presented in Fig. 7. $<$ marks upper limit, 013815+00 quasar discussed in (Kunert-Bajraszewska et al. 2020) is included.

Table 5. Emission lines measurements of transient radio sources.

Name	Epoch	MgII		H β		[O III]		H α		[N II]	[S II]	[S II]
		$\lambda 2800$	$\lambda 2800$	$\lambda 4861$	$\lambda 4861$	$\lambda 5007$	$\lambda 5007$	$\lambda 6563$	$\lambda 6563$	$\lambda 6584$	$\lambda 6717$	$\lambda 6731$
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
233001-00	Sep 2012	54 ± 2	9294 ± 251	—	—	—	—	—	—	—	—	—
010733+01	Dec 2015	—	—	8 ± 1	182 ± 28	19 ± 1	$230\pm 11^*$	25 ± 1	$209\pm 6^*$	9 ± 1	—	—
	Jul 2019	—	—	10 ± 2	$297\pm 41^*$	17 ± 2	$322\pm 30^*$	27 ± 2	$292\pm 13^*$	10 ± 1	—	—
015411-01	Sep 2000	—	—	70 ± 9	747 ± 13	—	—	198 ± 26	719 ± 72	370 ± 13	—	—
020827-00	Sep 2001	153 ± 5	3220 ± 107	—	—	—	—	—	—	—	—	—
030925+01	Dec 2001	—	—	62 ± 4	$229\pm 15^*$	133 ± 4	189 ± 8	308 ± 3	183 ± 3	178 ± 3	51 ± 3	44 ± 4
	Aug 2019	—	—	63 ± 5	336 ± 33	169 ± 5	$370\pm 11^*$	273 ± 3	$299\pm 4^*$	128 ± 3	34 ± 3	34 ± 3

NOTE—Columns are listed as follows: (1) source name; (2) epoch of observations; (3,4) the flux and FWHM for MgII (5,6) the flux and FWHM for H β ; (7,8) the flux and FWHM for [O III]; (9,10) the flux and FWHM for H α ; (11, 12, 13) the flux for narrow lines [N II] and [S II]. The FWHM and flux are in units of km s^{-1} , and $10^{-17} \text{ erg s}^{-1} \text{ cm}^{-2}$, respectively. * marks upper limit, line is not corrected for instrumental resolution. We apply the instrumental correction for the line only if the observed FWHM exceeds the instrumental FWHM by at least 50%.

APPENDIX

A2: Optical spectra

Table 6. Radio and optical properties of transient radio sources.

Name	Epoch	Activity phase	$\log L_{\text{OIII}}$ [erg s ⁻¹]	$\log M_{\text{BH}}$ [M _⊙]	method	$\log L_{\text{bol}}$ [erg s ⁻¹]	method	$\log \lambda_{\text{Edd}}$	$\log P_{\text{j}}$ [erg s ⁻¹]	$\log P_{\text{j}}/L_{\text{bol}}$
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
233001-00	Sep 2012	RL	—	9.16	MgII	45.49	L(3000Å)	-1.78	44.81	-0.68
010733+01	Dec 2015	RL	39.84	7.13 ^a	O[III]	42.65	H α /H β	-2.59 ^b	42.46	-0.19
015411-01	Sep 2000	RQ	—	8.90	σ_*	42.85	H α /H β	-4.16	41.06	-1.78
020827-00	Sep 2001	RQ	—	8.42	MgII	45.79	L(3000Å)	-0.75	43.89	-1.90
030925+01	Dec 2001	RQ	39.69	6.75	O[III]	42.81	H α /H β	-2.06	40.80	-2.00
	Aug 2019	RL	39.80	6.75 ^c	O[III]	42.81 ^c	H α /H β	-2.06 ^c	41.68	-1.13
013815+00	Oct 2001	RQ	—	9.21	MgII	45.55	L(3000Å)	-1.84	43.33	-2.22
	Dec 2015	RL	42.27	9.36	MgII	45.70	L(3000Å)	-1.69	44.01	-1.70
	Jan 2018	RL	42.13	9.26	MgII	45.56	L(3000Å)	-1.83	44.01	-1.56

NOTE—Columns are listed as follows: (1) source name; (2) epoch of observations; (3) [OIII] λ 5700 line luminosity; (4) black hole mass; (5) method used for black hole mass estimation; (6) bolometric luminosity; (7) method used to derive the bolometric disk luminosity as described in sec. 4 (8) Eddington ratio ($L_{\text{bol}}/L_{\text{Edd}}$); (9) jet kinetic power; (10) jet production efficiency. Data for quasar 013815+00 has been taken from Kunert-Bajraszewska et al. (2020). *a* marks upper limit, *b* marks lower limit, *c* indicates adopted M_{BH} and calculations based on it.

APPENDIX

A3: VLBA images

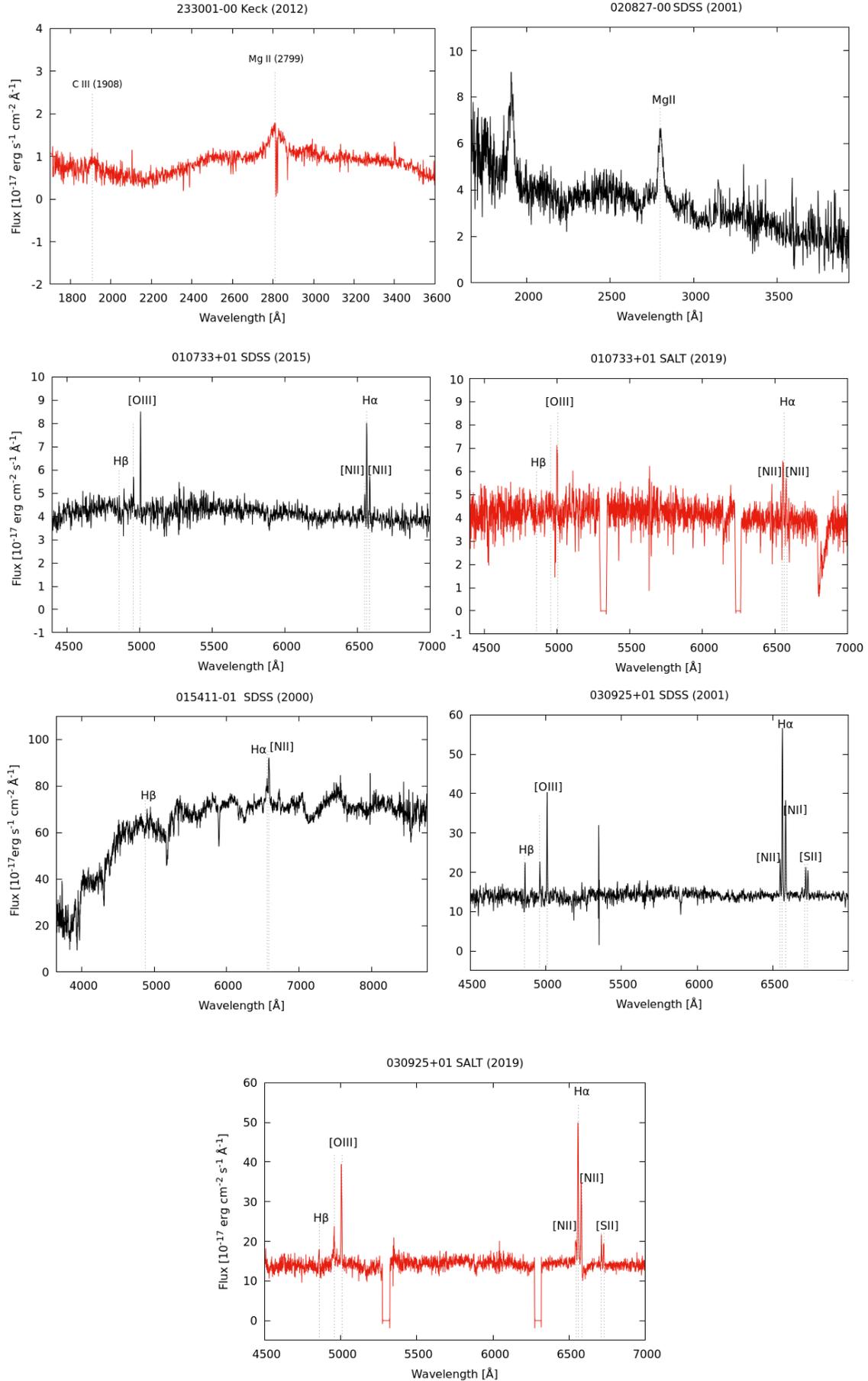


Figure 9. Available spectra of transient sources. The measurements of marked emission lines are presented in Table 5. The SDSS spectra are marked in black. Gaps visible in SALT spectra are due to a physical separation between CCDs in acquisition camera.

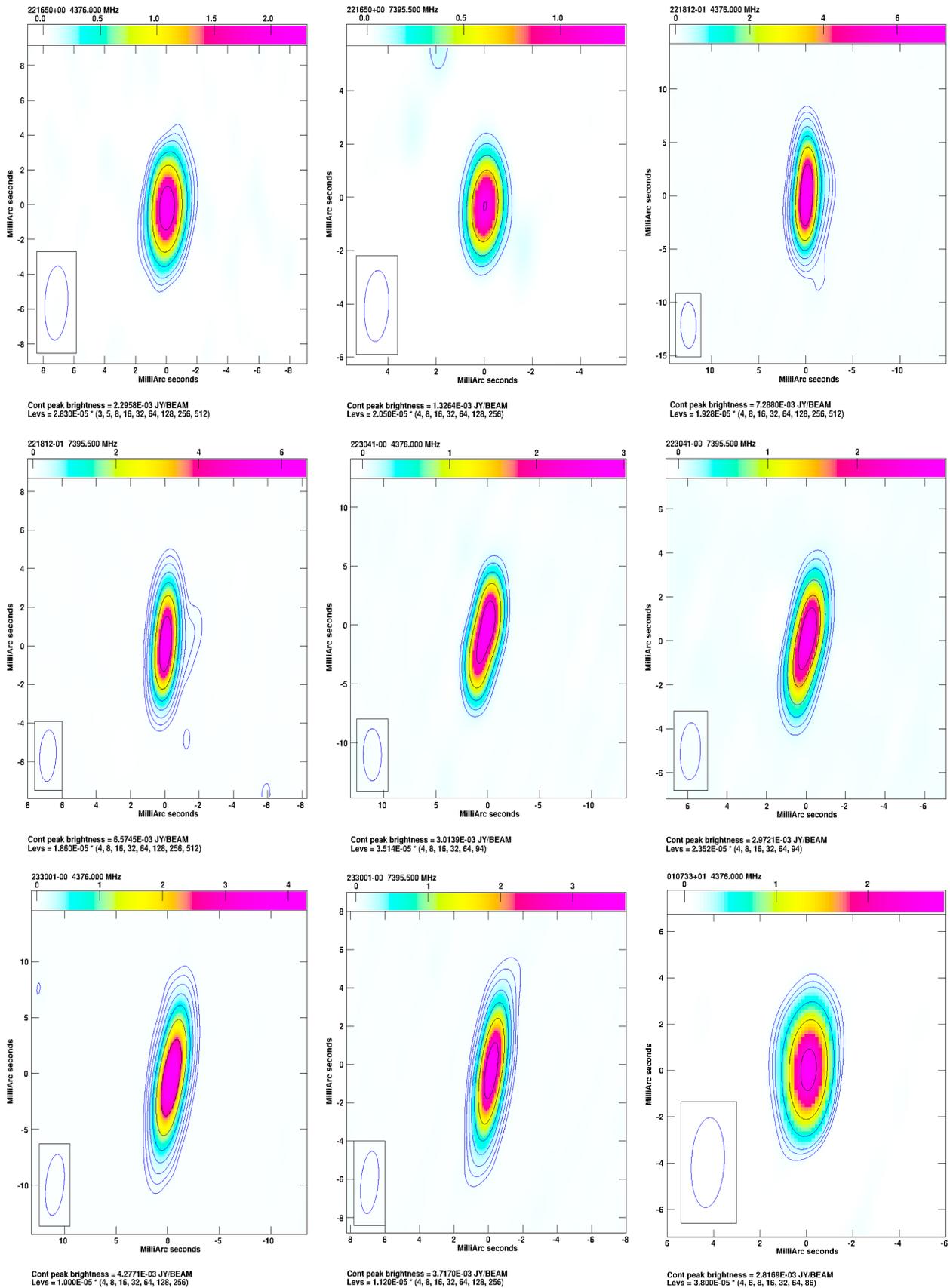


Figure 10. VLBA 4.5 and 7.5 GHz images. If more than one component has been identified in the source, they are all marked with black dots. In the case of 030925+01 the VLBA images from two observational epochs, June 2015 and March 2016, are presented at the end.

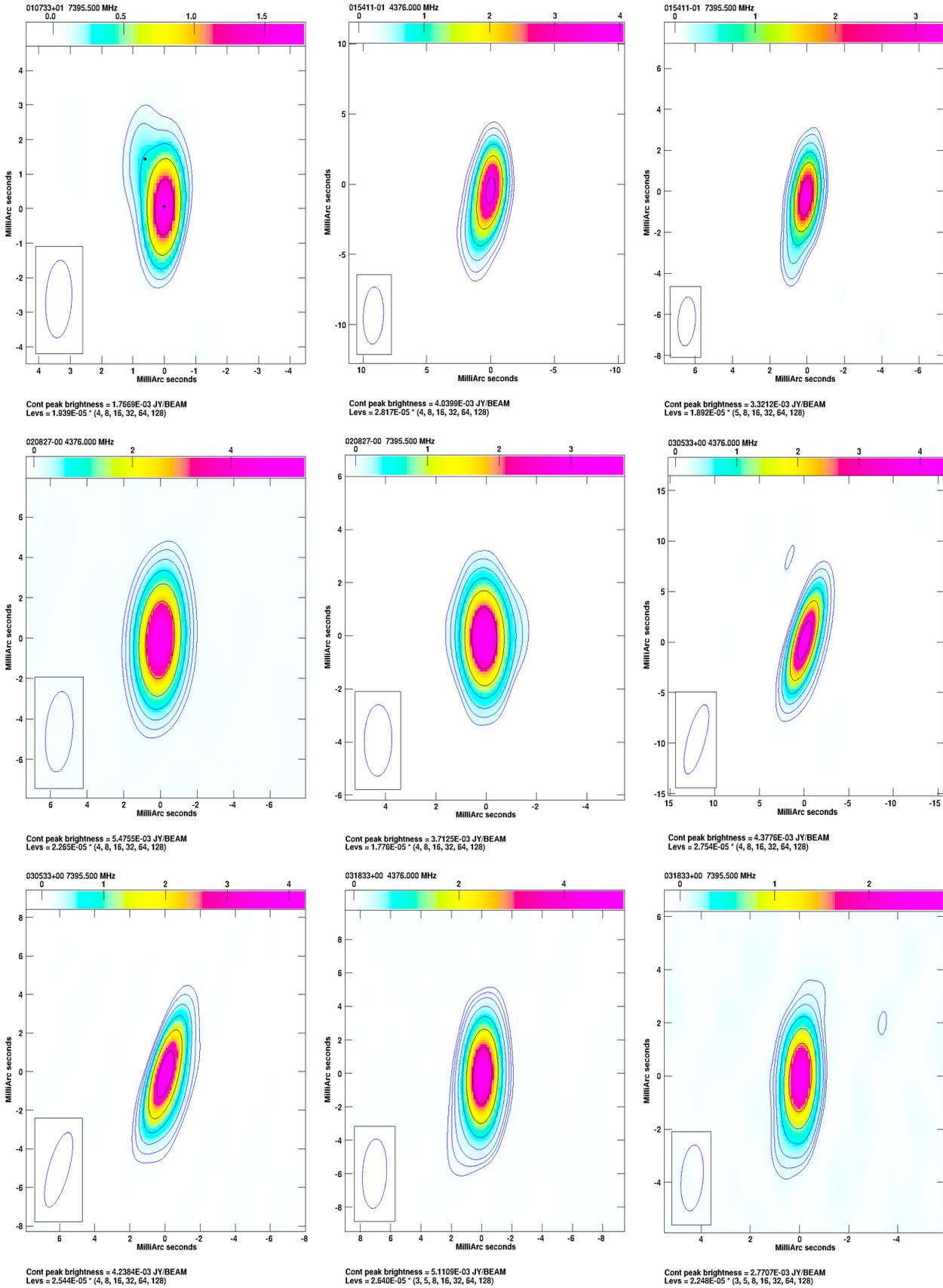


Figure 7. VLBA 4.5 and 7.5 GHz images - continued.

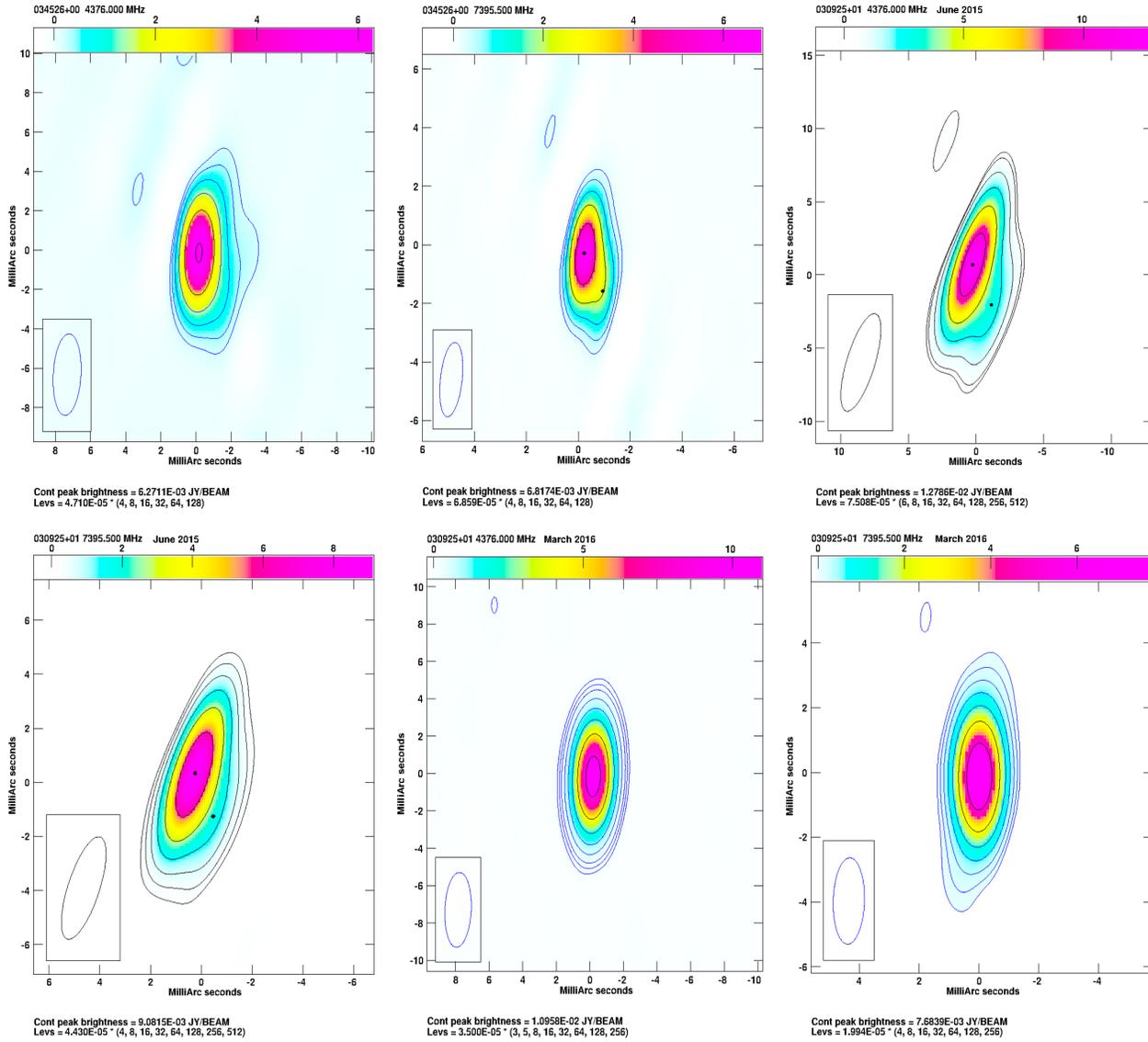


Figure 7. VLBA 4.5 and 7.5 GHz images - continued.

Table 7. VLA measurement points

2019												
Name	ν_{S1} [GHz] (1)	S_{S1} [mJy] (2)	ν_{S2} [GHz] (3)	S_{S2} [mJy] (4)	ν_{S3} [GHz] (5)	S_{S3} [mJy] (6)	ν_{C1} [GHz] (7)	S_{C1} [mJy] (8)	ν_{C2} [GHz] (9)	S_{C2} [mJy] (10)	ν_{C3} [GHz] (11)	S_{C3} [mJy] (12)
221650+00	2.37	2.63±0.02	3.06	3.14±0.04	3.69	3.22±0.07	4.67	3.25±0.07	6.16	2.96±0.10	7.59	2.76±0.12
221812-01	2.37	7.37±0.07	3.06	9.89±0.16	3.69	11.41±0.37	4.67	14.20±0.36	6.16	13.97±0.57	7.59	13.00±0.73
223041-00	2.37	4.42±0.31	3.06	5.06±0.09	3.69	5.38±0.16	4.67	6.11±0.09	6.16	5.75±0.16	7.59	5.42±0.25
233001-00	2.37	5.82±0.12	3.06	6.29±0.10	3.56	6.52±0.13	4.67	6.17±0.07	6.16	6.2±0.05	7.59	6.49±0.05
010733+01	2.37	2.89±0.05	3.06	2.58±0.05	3.56	2.32±0.10	4.67	2.06±0.06	6.16	1.93±0.05	7.59	1.62±0.12
015411-01	2.37	6.07±0.13	3.06	6.25±0.21	3.56	6.36±0.25	4.67	6.30±0.19	6.16	6.07±0.25	7.59	5.87±0.41
030533+00	2.37	2.68±0.04	3.06	3.66±0.10	3.69	4.35±0.22	4.67	4.81±0.10	6.16	4.92±0.18	7.59	4.82±0.17
031833+00	2.37	3.80±0.03	3.06	5.12±0.07	3.69	5.73±0.08	4.67	5.18±0.14	6.16	3.86±0.17	7.59	3.00±0.20
034526+00	2.37	2.97±0.05	3.06	5.05±0.13	3.69	6.22±0.39	4.67	9.14±0.18	6.16	11.35±0.45	7.59	11.99±0.70
ν_{X1}	S_{X1}	ν_{X2}	S_{X2}	ν_{X3}	S_{X3}	ν_{Ku1}	S_{Ku1}	ν_{Ku2}	S_{Ku2}	ν_{Ku3}	S_{Ku3}	
221650+00	8.37	2.59±0.04	9.76	2.42±0.04	11.09	2.26±0.07	13.37	1.96±0.12	15.06	1.72±0.12	16.69	1.64±0.14
221812-01	8.37	11.96±0.68	9.76	10.10±0.84	11.09	8.63±1.10	13.37	7.21±0.27	15.06	6.14±0.31	16.69	4.93±0.44
223041-00	8.37	5.19±0.20	9.76	4.73±0.22	11.09	4.46±0.32	13.37	3.95±0.11	15.06	3.52±0.18	16.69	3.26±0.17
233001-00	8.37	6.69±0.03	9.76	6.75±0.05	11.09	6.65±0.05	13.37	6.64±0.03	15.06	6.47±0.04	16.69	6.37±0.05
010733+01	8.37	1.59±0.02	9.76	1.55±0.05	11.09	1.32±0.08	13.37	1.26±0.04	15.06	1.22±0.05	16.69	1.13±0.06
015411-01	8.49	5.76±0.09	10.90	5.32±0.23	-	-	13.50	4.65±0.25	15.00	4.47±0.28	16.50	4.24±0.28
020827-00	8.49	7.05±0.07	10.90	6.62±0.18	-	-	13.37	6.3±0.28	15.06	6.12±0.33	16.69	5.95±0.36
030533+00	8.37	4.62±0.08	9.76	4.26±0.11	11.09	3.97±0.05	13.37	3.37±0.10	15.06	3.01±0.11	16.69	2.76±0.10
031833+00	8.37	2.53±0.07	9.76	1.91±0.11	11.09	1.48±0.05	13.37	0.92±0.09	15.06	0.75±0.10	16.69	0.62±0.09
034526+00	8.37	11.94±0.27	9.76	11.11±0.42	11.09	10.41±0.74	13.37	9.11±0.13	15.06	8.08±0.13	16.69	7.37±0.22
2016												
ν_{L1}	S_{L1}	ν_{L2}	S_{L2}	ν_{L3}	S_{L3}	ν_{S1}	S_{S1}	ν_{S2}	S_{S2}	ν_{S3}	S_{S3}	
221650+00	1.26	0.55±0.03	1.78	1.20±0.04	-	-	2.24	2.29±0.05	2.76	2.46±0.09	3.24	2.44±0.03
221812-01	1.52	1.68±0.17	1.71	3.07±0.12	-	-	2.24	7.00±0.23	2.76	8.79±0.15	3.24	10.83±0.19
223041-00	1.26	0.73±0.03	1.78	1.40±0.09	-	-	2.24	2.55±0.20	2.76	3.10±0.12	3.24	4.49±0.10
233001-00	1.26	2.46±0.13	1.78	4.87±0.10	-	-	2.24	6.62±0.18	2.76	6.93±0.21	3.24	7.00±0.14
010733+01	1.32	2.92±0.53	1.52	3.02±0.51	-	-	2.24	4.10±0.40	2.76	3.73±0.17	3.24	3.49±0.12
015411-01	1.52	4.00±0.17	-	-	-	-	2.24	4.40±0.17	2.76	4.92±0.13	3.24	5.38±0.07
020827-00	1.32	1.75±0.31	-	-	-	-	2.44	4.11±0.15	-	-	3.24	5.02±0.46
030533+00	1.52	1.05±0.02	-	-	-	-	2.24	2.02±0.07	2.76	2.87±0.06	3.24	3.95±0.05
030925+01	1.26	2.90±0.08	1.52	4.45±0.11	1.84	6.86±0.17	2.37	11.02±0.09	2.81	11.62±0.04	2.99	11.90±0.06
031833+00	1.26	0.70±0.04	1.78	1.46±0.09	-	-	2.24	3.01±0.10	2.76	4.41±0.06	3.24	5.18±0.09
034526+00	1.26	1.02±0.08	1.52	1.40±0.07	1.78	1.87±0.08	2.24	3.68±0.09	2.76	5.14±0.06	3.24	6.35±0.07
ν_{S4}	S_{S4}	ν_{C1}	S_{C1}	ν_{C2}	S_{C2}	ν_{C3}	S_{C3}	ν_{C4}	S_{C4}	ν_{X1}	S_{X1}	
221650+00	3.76	2.54±0.05	4.54	2.50±0.04	5.06	2.34±0.03	7.14	1.98±0.04	7.66	1.90±0.05	8.24	1.89±0.05
221812-01	3.76	12.16±0.21	4.54	13.82±0.11	5.06	13.96±0.10	7.14	12.64±0.23	7.66	12.26±0.26	8.24	12.07±0.19
223041-00	3.76	5.35±0.08	4.54	6.58±0.11	5.06	6.53±0.15	7.14	6.14±0.23	7.66	5.98±0.22	8.24	6.27±0.15
233001-00	3.76	7.00±0.19	4.54	6.53±0.12	5.06	6.32±0.12	7.14	5.88±0.18	7.66	5.62±0.21	8.24	5.89±0.21
010733+01	3.76	2.99±0.09	4.54	2.91±0.16	5.06	2.66±0.16	7.14	2.29±0.12	7.66	2.29±0.11	8.24	2.323±0.05
015411-01	3.76	5.39±0.09	4.54	5.55±0.03	5.06	5.39±0.03	7.14	5.07±0.09	7.66	4.98±0.04	8.24	4.96±0.05
020827-00	3.76	5.29±0.68	4.54	5.44±0.30	5.06	4.89±0.49	7.14	4.52±0.19	7.66	4.31±0.17	8.24	4.43±0.18
030533+00	3.76	4.53±0.16	4.54	5.24±0.05	5.06	5.25±0.06	7.14	5.26±0.09	7.66	5.14±0.09	8.24	5.27±0.14
030925+01	3.44	11.74±0.06	4.54	10.51±0.05	6.10	8.33±0.03	7.14	6.76±0.04	7.66	6.41±0.05	8.24	6.07±0.05
031833+00	3.76	5.31±0.24	4.54	5.49±0.08	5.06	4.94±0.09	7.14	3.48±0.08	7.66	3.06±0.09	8.24	2.55±0.17
034526+00	3.76	7.56±0.20	4.54	10.28±0.05	5.06	11.02±0.06	7.14	12.89±0.13	7.66	12.95±0.07	8.24	13.18±0.13
ν_{X2}	S_{X2}	ν_{X3}	S_{X3}	ν_{X4}	S_{X4}	ν_{Ku1}	S_{Ku1}	ν_{Ku2}	S_{Ku2}	ν_{Ku3}	S_{Ku3}	
221650+00	8.76	1.66±0.03	10.643	1.54±0.03	11.16	1.38±0.05	13.24	1.33±0.05	13.76	1.40±0.06	16.24	1.27±0.09
221812-01	8.76	11.49±0.21	10.64	9.27±0.27	11.16	8.72±0.30	13.24	7.55±0.08	13.76	7.09±0.12	16.24	4.83±0.22
223041-00	8.76	6.01±0.13	10.64	5.37±0.18	11.16	5.35±0.21	13.24	4.95±0.09	13.76	4.58±0.11	16.24	3.79±0.15
233001-00	8.76	5.99±0.22	10.64	5.90±0.29	11.16	5.97±0.30	13.24	5.93±0.54	13.76	5.94±0.55	16.24	5.90±0.65
010733+01	8.76	2.15±0.05	10.64	2.06±0.04	11.16	1.92±0.06	13.24	1.73±0.07	13.76	1.64±0.05	16.24	1.51±0.06
015411-01	8.76	4.97±0.05	10.64	4.76±0.07	11.16	4.76±0.05	13.24	4.36±0.06	13.76	4.17±0.10	16.24	3.76±0.12
020827-00	8.76	4.34±0.16	10.64	4.31±0.06	11.16	4.30±0.11	13.24	3.98±0.15	13.76	3.67±0.14	16.24	3.66±0.14
030533+00	8.76	5.07±0.13	10.64	4.66±0.03	11.16	4.44±0.06	13.24	3.97±0.14	13.76	3.93±0.09	16.24	3.46±0.07
030925+01	9.70	5.40±0.03	10.64	4.91±0.05	11.16	4.57±0.05	13.24	4.00±0.05	13.76	3.86±0.05	15.00	3.59±0.03
031833+00	8.76	2.40±0.15	10.64	1.88±0.06	11.16	1.60±0.05	13.24	1.29±0.04	13.76	1.13±0.04	16.24	0.92±0.06
034526+00	8.76	12.78±0.13	10.64	11.94±0.17	11.16	11.60±0.13	13.24	10.08±0.35	13.76	9.86±0.40	16.24	9.04±0.24

	ν_{Ku4}	S_{Ku4}											
221650+00	16.76	1.19±0.06											
221812-01	16.76	4.82±0.21											
223041-00	16.76	3.48±0.17											
233001-00	16.76	5.86±0.63											
010733+01	16.76	1.36±0.08											
015411-01	16.76	3.59±0.11											
020827-00	16.76	3.52±0.11											
030533+00	16.76	3.40±0.12											
030925+01	16.76	3.08±0.05											
031833+00	16.76	0.90±0.05											
034526+00	16.76	8.77±0.27											
2015													
	ν_{L1}	S_{L1}	ν_{L2}	S_{L2}	ν_{L3}	S_{L3}	ν_{S1}	S_{S1}	ν_{S2}	S_{S2}	ν_{S3}	S_{S3}	
221812-01	1.64	0.88±0.09	-	-	-	-	2.50	9.15±0.11	-	-	3.50	12.17±0.18	
010733+01	1.42	2.67±0.94	1.62	4.25±1.02	1.81	3.10±0.34	2.63	4.78±1.29	-	-	-	-	
015411-01A	1.32	3.67±0.15	1.71	4.29±0.13	-	-	2.50	4.66±0.10	3.50	4.62±0.07	-	-	
015411-01J	1.51	3.77±0.20	-	-	2.50	4.03±0.06	3.44	4.25±0.13	-	-	-	-	
030533+00	1.32	0.84±0.12	1.52	0.98±0.15	-	-	2.63	3.27±0.11	3.00	3.76±0.10	3.24	4.24±0.08	
030925+01F	1.52	7.72±1.50	-	-	-	-	2.55	15.63±0.60	3.50	17.11±0.11	-	-	
030925+01J	1.51	4.18±0.11	-	-	-	-	2.50	11.53±0.15	-	-	-	-	
031833+00	1.58	0.76±0.17	-	-	-	-	2.50	2.95±0.16	2.74	3.76±0.18	3.37	4.80±0.19	
034526+00	1.64	0.96±0.20	-	-	-	-	2.50	2.12±0.31	2.74	2.84±0.28	3.37	4.37±0.41	
	ν_{C1}	S_{C1}	ν_{C2}	S_{C2}	ν_{C3}	S_{C3}	ν_{C4}	S_{C4}	ν_{C5}	S_{C5}	ν_{X1}	S_{X1}	
221812-01	4.67	14.40±0.15	-	-	6.10	13.29±0.14	7.53	12.03±0.17	-	-	8.55	10.60±0.28	
010733+01	4.74	2.84±0.07	5.26	2.62±0.11	5.50	2.80±0.07	5.74	2.76±0.14	6.26	2.75±0.08	8.24	2.31±0.05	
015411-01A	4.67	3.87±0.08	6.16	3.34±0.08	7.53	2.95±0.10	7.99	2.90±0.15	-	-	8.49	2.83±0.16	
015411-01J	4.80	3.66±0.09	7.40	2.85±0.10	-	-	-	-	-	-	8.55	2.21±0.08	
030533+00	5.25	4.98±0.11	6.55	4.65±0.03	-	-	-	-	-	-	8.80	4.57±0.06	
030925+01F	4.67	18.17±1.00	6.10	15.67±0.18	7.53	13.91±0.25	-	-	-	-	8.49	12.65±0.45	
030925+01J	4.95	12.76±0.11	6.55	11.62±0.06	7.99	10.22±0.17	-	-	-	-	8.49	10.42±0.16	
031833+00	4.95	5.20±0.09	5.97	4.70±0.15	7.40	3.48±0.15	7.99	3.20±0.17	-	-	8.74	2.65±0.17	
034526+00	4.95	7.80±0.48	5.97	9.19±0.31	7.99	9.95±0.46	-	-	-	-	9.07	9.70±0.27	
	ν_{X2}	S_{X2}	ν_{X3}	S_{X3}	ν_{X4}	S_{X4}	ν_{X5}	S_{X5}	ν_{X6}	S_{X6}	ν_{Ku1}	S_{Ku1}	
221812-01	8.75	9.26±0.17	9.83	8.86±0.26	11.05	7.56±0.23	-	-	-	-	14.30	5.88±0.12	
010733+01	8.76	2.05±0.05	9.00	2.22±0.03	9.24	2.21±0.05	9.76	2.08±0.05	-	-	13.99	1.75±0.03	
015411-01A	9.77	2.57±0.13	-	-	-	-	-	-	-	-	13.37	1.95±0.13	
015411-01J	9.83	1.84±0.08	11.05	1.76±0.08	-	-	-	-	-	-	13.50	1.27±0.08	
030533+00	10.73	4.24±0.08	-	-	-	-	-	-	-	-	13.24	1.58±0.06	
030925+01F	9.77	11.53±0.80	-	-	11.05	10.70±0.11	-	-	-	-	14.30	9.00±0.10	
030925+01J	9.83	9.27±0.11	-	-	-	-	-	-	-	-	13.50	6.95±0.13	
031833+00	9.38	2.32±0.18	10.02	2.21±0.19	10.66	1.84±0.19	11.30	1.59±0.09	-	-	12.18	1.34±0.08	
034526+00	10.02	9.50±0.48	10.67	9.30±0.47	11.30	9.10±0.48	-	-	-	-	12.18	9.00±0.49	
	ν_{Ku2}	S_{Ku2}	ν_{Ku3}	S_{Ku3}	ν_{Ku4}	S_{Ku4}							
221812-01	-	-	-	-	16.00	4.71±0.14							
015411-01A	14.75	1.76±0.18	16.13	1.62±0.19	-	-							
015411-01J	15.2	0.59±0.20	-	-	-	-							
030533+00	13.50	3.70±0.09	15.20	3.50±0.11	16.25	3.40±0.06							
030925+01F	16.00	8.38±0.12	-	-	-	-							
030925+01J	15.20	5.52±0.18	-	-	-	-							
031833+00	14.43	0.95±0.09	16.13	0.80±0.06	-	-							
034526+00	13.37	8.51±0.46	14.42	8.12±0.47	16.13	7.03±0.51							
2014													
	ν_{L1}	S_{L1}	ν_{L2}	S_{L2}	ν_{S1}	S_{S1}	ν_{S2}	S_{S2}	ν_{S3}	S_{S3}	ν_{C1}	S_{C1}	
221812-01	1.51	1.82±0.13	-	-	2.55	6.76±0.17	-	-	3.45	11.80±0.20	4.67	13.41±0.17	
233001-00	1.26	2.40±0.18	1.90	4.25±0.24	2.37	7.10±0.19	3.00	7.51±0.11	3.44	7.27±0.09	4.54	7.80±0.07	
030925+01A	1.52	2.39±0.20	-	-	2.37	4.59±0.40	3.00	7.37±0.45	3.63	10.45±0.55	5.65	12.59±0.45	
030925+01J	1.52	4.38±0.10	-	-	2.55	13.41±0.30	3.50	15.97±0.42	-	-	4.67	16.21±0.18	
	ν_{C2}	S_{C2}	ν_{C3}	S_{C3}	ν_{C4}	S_{C4}	ν_{X1}	S_{X1}	ν_{X2}	S_{X2}	ν_{X3}	S_{X3}	
221812-01	6.16	11.27±0.13	7.53	9.88±0.17	-	-	8.55	9.20±0.14	9.83	7.71±0.12	11.05	6.50±0.12	
233001-00	5.06	6.98±0.07	-	-	-	-	8.36	4.98±0.05	9.39	4.56±0.05	10.41	3.96±0.06	
030925+01A	7.40	10.60±0.28	-	-	-	-	8.23	9.40±0.25	9.00	8.23±0.29	9.77	7.55±0.30	
030925+01J	6.04	15.29±0.15	7.53	14.40±0.20	-	-	8.49	13.17±0.07	9.77	11.89±0.06	10.99	10.76±0.10	

	ν_{X4}	S_{X4}	ν_{Ku1}	S_{Ku1}	ν_{Ku2}	S_{Ku2}	ν_{Ku3}	S_{Ku3}	ν_{Ku4}	S_{Ku4}	ν_{Ku5}	S_{Ku5}
221812-01	-	-	-	-	14.3	5.5±0.14	15.2	4.99±0.17	-	-	-	-
233001-00	11.43	3.47±0.08	13.24	3.30±0.07	13.76	3.51±0.07	15.74	2.94±0.08	16.26	2.95±0.08	-	-
030925+01A	10.92	6.56±0.33	13.37	4.92±0.32	14.88	4.17±0.46	16.13	3.66±0.39	21.85	3.70±0.45	24.37	3.30±0.43
030925+01J	-	-	14.30	9.29±0.11	15.19	8.62±0.14	-	-	-	-	-	-
2012												
	ν_{S1}	S_{S1}	ν_{S2}	S_{S2}	ν_{S3}	S_{S3}	ν_{C1}	S_{C1}	ν_{C2}	S_{C2}	ν_{C3}	S_{C3}
233001-00	2.40	6.85±0.95	3.20	9.29±0.71	3.80	9.64±1.08	4.50	10.52±0.73	5.10	10.56±0.71	7.10	9.61±0.70
	ν_{C4}	S_{C4}	ν_{Ku1}	S_{Ku1}	ν_{Ku2}	S_{Ku2}	ν_{Ku3}	S_{Ku3}	ν_{Ku4}	S_{Ku4}		
233001-00	7.70	9.38±0.73	13.20	7.27±1.02	13.80	6.84±0.97	14.20	6.49±1.03	14.80	6.22±0.98	-	-

NOTE—In case of the sources that have been observed more than once a year, a letter indicates the month of observation.

Table 8. GMRT measurement points

Name	ν_{Band4_1} [MHz]	S_{Band4_1} [mJy]	ν_{Band4_2} [MHz]	S_{Band4_2} [mJy]	ν_{Band4_3} [MHz]	S_{Band4_3} [mJy]
	(1)	(2)	(3)	(4)	(5)	(6)
221812-01	595	0.73±0.10	677	0.79±0.10	-	-
223041-00	593	0.31±0.02	673	0.36±0.02	757	0.48±0.01
233001-00	593	0.97±0.10	673	1.11±0.10	757	1.21±0.10
010733+01	593	2.70±0.20	-	-	715	2.80±0.20
015411-01	-	-	673	2.60±0.25	757	2.70±0.25
030925+01	-	-	670	0.50±0.10	757	0.60±0.10
031833+00	-	-	670	0.11±0.03	-	-