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Optical and Radio Studies of Radio Sources

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Abstract—We present the classification of optical identifications and radio spectra of six radio sources from a complete (in flux density) sample in the declination range 10° to 12°30′ (J2000.0). The observations were carried out with the 6-m Special Astrophysical Observatory telescope (Russia) in the wavelength range 3600–10000 Å, the 2.1-m Cananea telescope (Mexico) in the range 4200–9000 Å, and the RATAN-600 radio telescope in the frequency range 0.97–21.7 GHz. Three of the six objects under study are classified as quasars, one is a BL Lac object, one is an absorption-line radio galaxy, and one is an emission-line radio galaxy. Five objects have flat radio spectra, and one object has a power-law radio spectrum. All of the radio sources identified as quasars or BL Lac objects show variable flux densities. The spectra of three objects were separated into extended and compact components. *© 2003 MAIK "Nauka/Interperiodica".*

Key words: *nactive galactic nuclei, quasars and radio galaxies, spectra.*

INTRODUCTION

In this paper, we classify the optical objects that were identified with radio sources from a complete (in flux density) sample. The sample contains 154 sources with flux densities from the GB6 catalog (Gregory *et al.* 1996) $S_{4.85} > 200$ mJy in the ranges of declinations 10° to 12°30′ (J2000.0) and right ascensions 0 to 24^{h} and $|b| > 15°$; it has been observed with the RATAN-600 radio telescope since 2000 (Gorshkov *et al.* 2000). One of the goals of studying this sample is to detect the cosmological evolution of quasars. For this purpose, it is necessary to determine the redshifts for most of the objects identified with the radio sources under study. We identified 86% of the sample sources with flat spectra and 60% of the sample sources with normal spectra with optical objects. A large number of identified objects were classified previously; the remaining objects are classified by using the 2.1-m G. Haro Observatory (GHAO) telescope of the National Institute of Astrophysics, Optics, and Electronics (INAOE) in Cananea (Mexico) (Chavushyan *et al.* 2000, 2001, 2002) and the 6-m (BTA) Special Astrophysical Observatory (SAO) telescope of the Russian Academy of Sciences in Nizhnii Arkhyz (Russia) (Afanasiev *et al.* 2003). The redshifts (for some of the BL Lac objects, only the classification is available) of 64 objects with flat spectra and 32 objects with normal spectra are known to date.

OPTICAL AND RADIO OBSERVATIONS

We obtained the spectra of the objects with the 6-m BTA telescope on February 6–8, 2002. We used the SCORPIO spectrograph (http://www.sao.ru/moisav/scorpio/scorpio.html) in a long-slit mode and a 1024 × 1024 pixel TK1024 CCD detector with a readout noise of 3e-. The covered spectral range was 3600–10000 Å with a dispersion of 6 Å pre pixel. The effective instrumental resolution was about 20 Å. We reduced the spectra in a standard way by using the software developed at the Laboratory of Spectroscopy and Photometry of the SAO.

We obtained the spectra of the objects with the 2.1-m GHAO telescope on March 8, 2002. In our observations, we used the LFOSC spectrophotometer equipped with a 600 × 400-pixel CCD array (Zickgraf *et al.* 1997); the detector readout noise was 8e-, and the covered spectral range was 4200–9000 Å with a dispersion of 8.2 Å per pixel. The effective instrumental spectral resolution was about 16 Å. The reduction of our observations was performed with the IRAF package and included cosmic-ray hit removal,

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Table 1. Coordinates and magnitudes of the objects

Object name	Radio coordinates, J2000.0		Optical–radio		Magnitude	
	α	δ	$\Delta\alpha$	$\Delta\delta$	R	B
0946 + 1017	$09^h46^m35\overset{s}{.}069$	$+10°17'06\overset{''}{.}13$	$0\overset{s}{.}011$	$-0\overset{''}{.}15$	18.7	18.7
1015 + 1227	10 15 44.024	+12 27 07.07	−0.001	0.19	18.2	19.2
1103 + 1158	11 03 03.530	+11 58 16.61	0.005	−0.10	18.4	18.9
1207 + 1211	12 07 12.625	+12 11 45.88	0.008	0.05	18.9	19.0
1306 + 1113	13 06 19.248	+11 13 39.79	0.015	−0.01	13.0	15.4
1315 + 1220	13 15 01.853	+12 20 52.63	0.062	0.10	17.8	18.7

flat fielding, wavelength linearization, and flux calibration.

The radio observations of the sources were carried out with the Northern Sector of RATAN-600 in 2000–2002 at frequencies of 0.97, 2.3, 3.9, 7.7, 11.1, and 21.7 GHz in a fixed-focus mode (Soboleva *et al.* 1986). The observing and reduction techniques were described by Botashev *et al.* (1999). The parameters of the RATAN-600 detectors used for the Northern Sector are presented in Berlin *et al.* (1997). The beam width changed from $11''$ to $235''$ in right ascension and from $1\overset{'}{.}4$ to $30'$ in declination at frequencies from 21.7 GHz to 0.97 GHz. To calibrate the flux densities of the sources, we used the radio source 1347+1217 with a constant flux density, which is a point source for our beams at all frequencies. The adopted flux densities of the calibration source at frequencies 0.97–21.7 GHz are 6.25, 4.12, 3.23, 2.36, 2.00, and 1.46 Jy. The procedure for separating the radio spectra of the sources into extended and compact components was described by Gorshkov *et al.* (2000).

RADIO AND OPTICAL COORDINATES OF THE OBJECTS

Table 1 gives the radio coordinates of the program objects for the equinox J2000.0, the differences between their optical and radio coordinates in right ascension and declination, and their R and B magnitudes. The source names are composed of hours and minutes of right ascension and degrees and arcminutes of declination. For our identifications of the radio sources with optical objects, we used the coordinates from the JVAS catalog[1] at a frequency of 8.4 GHz (Wrobel *et al.* 1998); the rms error of the coordinates in right ascension and declination is 0.014 arcseconds. The optical coordinates and magnitudes were taken from the USNO Astrometric Survey (Monet *et al.* 1996).

[1] JVAS is the Jodrell Bank–VLA Astrometric Survey.

RESULTS

The spectra of the objects taken with the 2.1-m telescope in Mexico and the 6-m BTA telescope are shown in Figs. 1 and 2, respectively. Figure 3 shows the radio spectra of the sources. Table 2 presents the optical observations. Table 3 contains the flux densities of the radio sources and their rms errors in the frequency range 0.97–21.7 GHz. The last column gives the epochs of our observations.

Below we give remarks on each of the program objects. In all of the formulas that fit the spectra, the frequencies are in GHz and the flux densities are in mJy.

The source 0946+1017. The optical spectrum taken with the 2.1-m telescope (Fig. 1a) exhibits one strong line identified with the MgII 2798 Å line at the redshift $z = 0.999$. Two lines, MgII 2798 Å and CIII 1909 Å were identified in the spectrum taken with the 6-m telescope (Fig. 2a). The redshift determined from these lines is $z = 1.007$. This object is a quasar with the mean redshift $z = 1.004$.

The source was observed with RATAN-600 twice, in 2000 and 2001. Using the Texas Survey data at a frequency of 0.365 GHz (Douglas *et al.* 1996), we can separate a power-law component from the spectra with $S = 200\nu^{-0.85}$ mJy. After the subtraction of the power-law component, the spectrum of the compact component for the epoch 09.2000 can be fitted by the logarithmic parabola $\log S = 2.202 + 0.765\log\nu - 0.497\log^2\nu$. The spectrum has a peak at a frequency of 5.9 GHz, with the peak flux density being 313 mJy. In Fig. 3a, the original spectrum and the spectra of the compact and power-law components are indicated by crosses and solid and dashed lines, respectively. The spectrum of the compact component after the subtraction of the power-law component from the data for the epoch 07.2001 can be fitted by the logarithmic parabola $\log S = 2.237 + 0.616\log\nu - 0.483\log^2\nu$; the peak in the spectrum

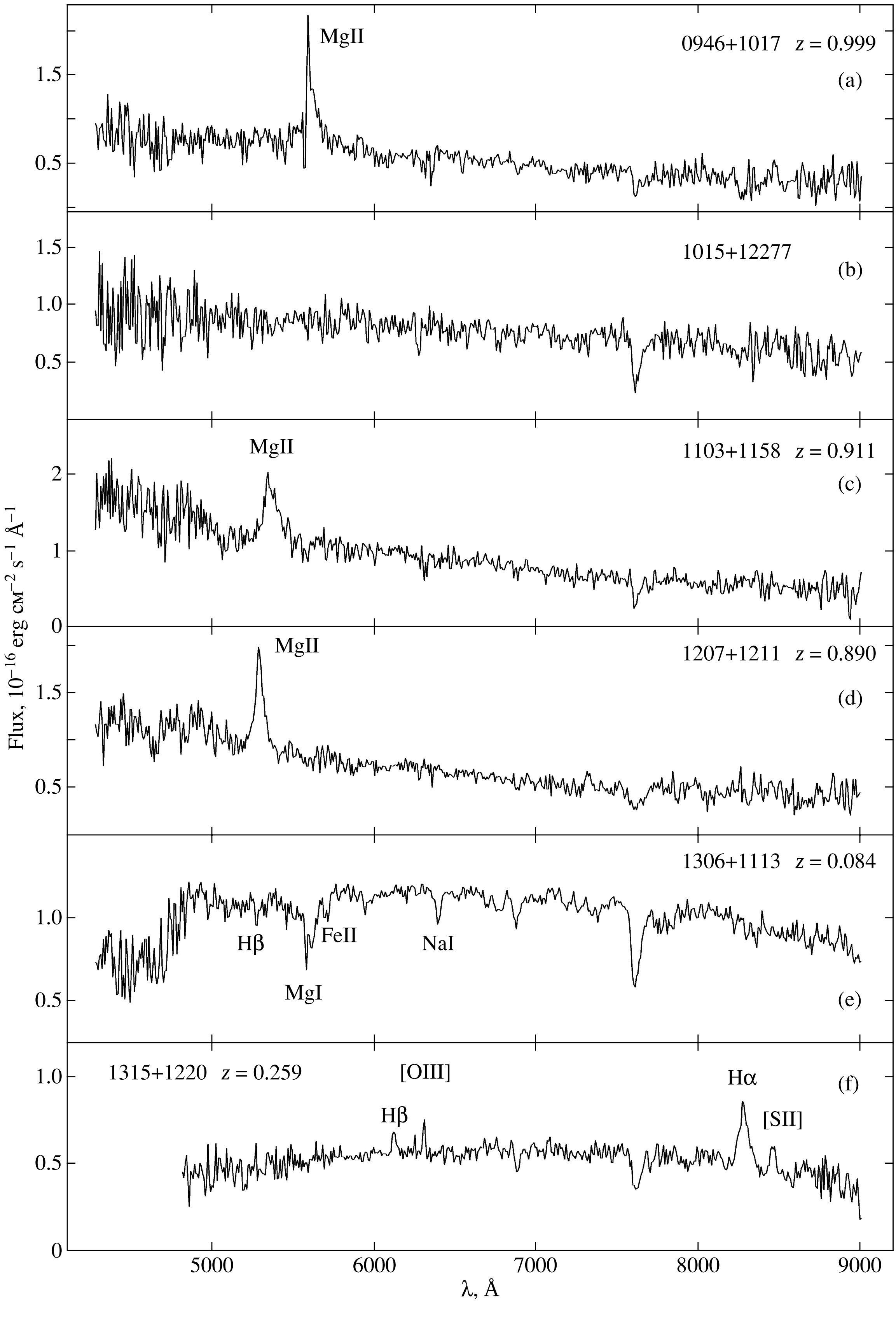

Fig. 1. The optical spectra of the objects taken with the 2.1-m telescope (Mexico).

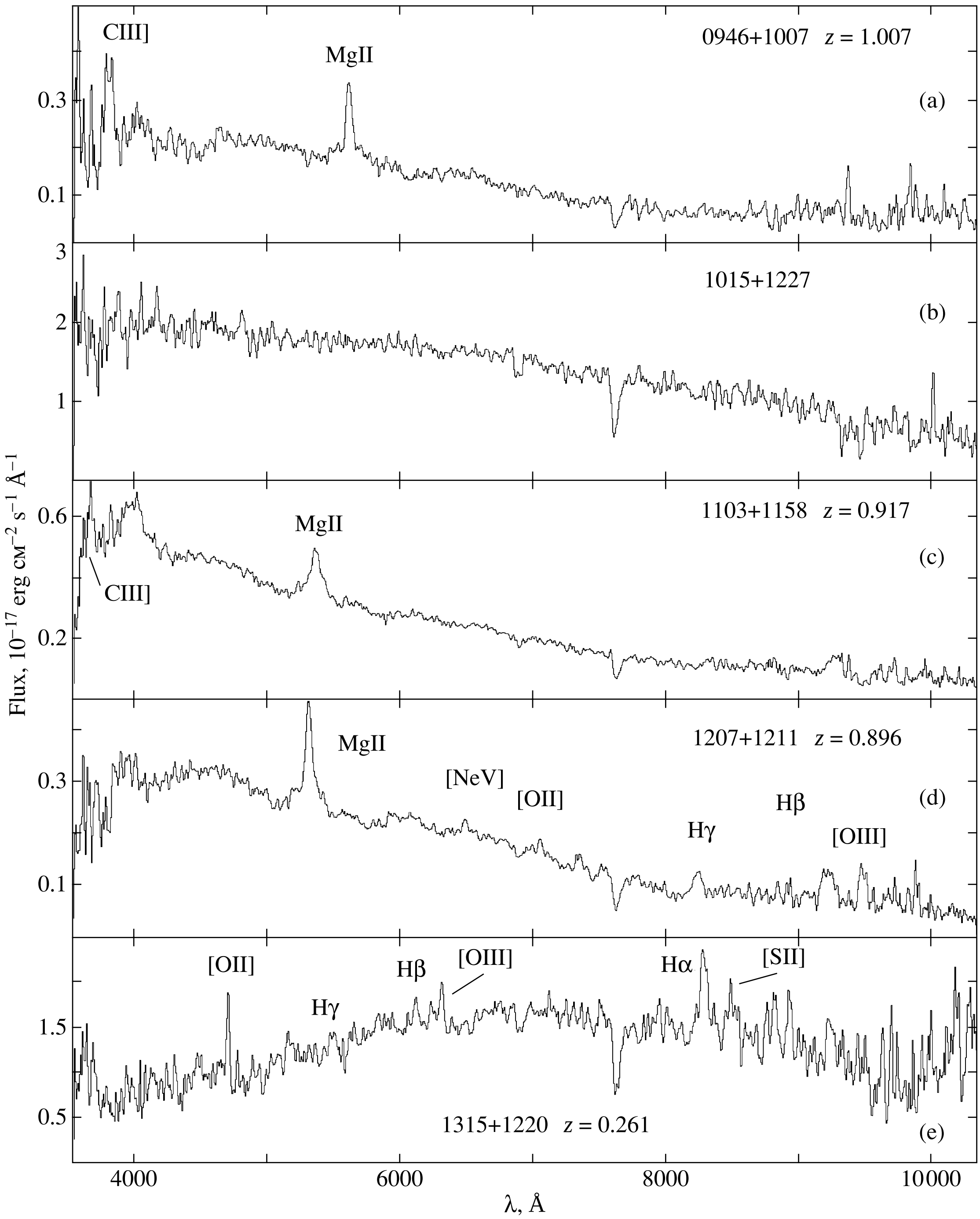

Fig. 2. The optical spectra of the objects taken with the 6-m BTA telescope (Russia).

shifted to a frequency of 4.3 GHz. In this source, we are most likely observing the development of an outburst.

The source 1015+1227. Since both optical spectra (Figs. 1b and 2b) contain no lines, we classified this source as a BL Lac object.

We observed the source with RATAN-600 three times, in 2000–2002. All of the spectra obtained rise toward higher frequencies. Figure 3b shows the spectra for the epochs 09.2000 (upper spectrum) and 06.2002 after the subtraction of a small power-law component with $S = 45\nu^{-0.8}$ mJy from the original spectra. The spectrum taken at the epoch 07.2001 (Gorshkov *et al.* 2002) is located between the shown spectra. The flux densities at frequencies of 0.97–2.3 GHz were constant within the limits of the mea-

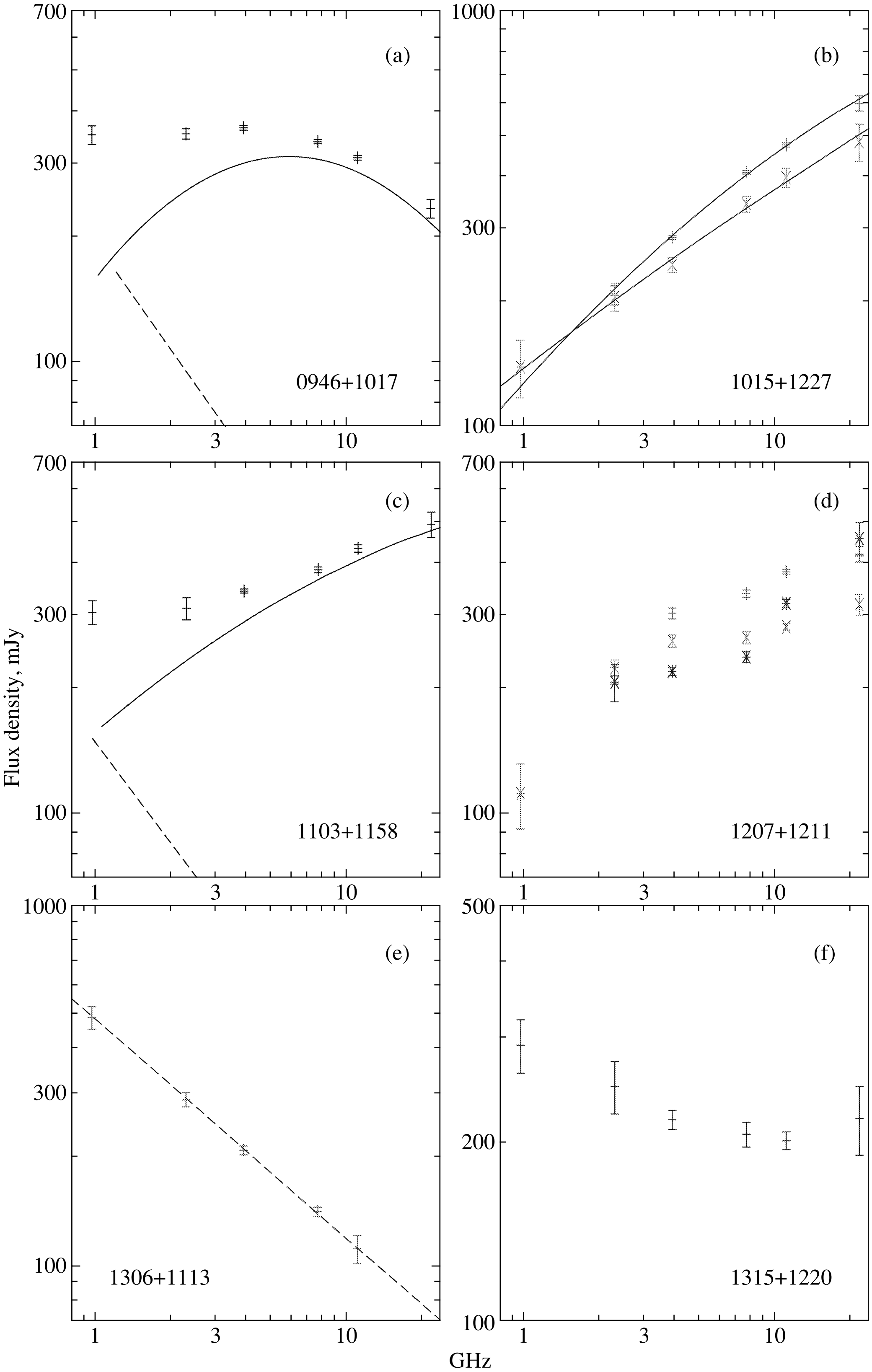

Fig. 3. The radio spectra of the sources. The spectra of the sources 0946+1017 and 1103+1158 (a, b) were separated into components: the original spectra are indicated by crosses, the spectra of the extended components are indicated by dashed lines, and the spectra of the compact components are indicated by solid lines. The spectrum of the source 1207+1211 (d) is indicated by pluses, crosses, and asterisks for the epochs 09.2000, 07.2001, and 06.2002, respectively.

Table 2. Optical observations

Object name	Spectral lines	Wavelengths, in rest frame and observed, Å	z	Object type	Date of observation	Exposure time, min	Telescope	$\bar{z}$
0946+1017	CIII	1909/3830	1.007	QSO	Feb. 07, 2002	10	BTA	
	MgII	2798/5615						1.004
	MgII	2798/5592	0.999	QSO	Mar. 08, 2002	90	GHAO	
1015+1227					Feb. 07, 2002	20	BTA	
					Mar. 08, 2002	60	GHAO	
1103+1158	CIII]	1909/3660	0.917	QSO	Feb. 08, 2002	20	BTA	
	MgII	2798/5364						0.915
	MgII	2798/5346	0.911	QSO	Mar. 08, 2002	60	GHAO	
1207+1211	MgII	2798/5300	0.896	QSO	Feb. 08, 2002	20	BTA	
	[NeV]	3426/6495						0.895
	[OII]	3727/7065						
	Hγ	4340/8230						
	Hβ	4861/9220						
	[OIII]	5007/9490						
	MgII	2798/5288	0.890	QSO	Mar. 08, 2002	30	GHAO	
1306+1113	Hβ	4861/5269	0.084	Abs.G	Mar. 08, 2002	30	GHAO	
	MgI	5175/5610						0.084
	FeII	5270/5706						
	NaI	5896/6396						
1315+1220	[OII]	3727/4700	0.261	Em.G	Feb. 06, 2002	20	BTA	
	Hγ	4340/5473						0.260
	Hβ	4861/6130						
	[OIII]	5007/6310						
	Hα	6563/8280						
	[SII]	6724/8480						
	Hβ	4861/6120	0.259	Em.G	Mar. 08, 2002	90	GHAO	
	[OIII]	4959/6249						
	[OIII]	5007/6306						
	Hα	6563/8272						
	[SII]	6724/8455						

surement errors; the largest change in flux density, from 490 ± 44 to 605 ± 25 mJy, was recorded at a frequency of 21.7 GHz.

The spectra of the compact components shown in Fig. 3b were fitted by the logarithmic parabolas $\log S = 2.110 + 0.670 \log \nu - 0.120 \log^2 \nu$ (09.2000) and $\log S = 2.103 + 0.573 \log \nu - 0.098 \log^2 \nu$ (06.2002). We see all of the spectra in an optically thick region; the flux density peaks at frequencies much higher than the range under study.

The Source 1103+1158. The optical spectra shown in Figs. 1c and 2c exhibit a broad line identified

Table 3. Radio observations

Object name	Flux densities and errors, mJy						Epoch
	0.97 GHz	2.3 GHz	3.9 GHz	7.7 GHz	11.1 GHz	21.7 GHz	
0946+1017	353 18	355 10	367 05	340 04	311 04	235 12	09.2000
	358 20	352 10	338 04	280 03	250 03	181 16	07.2001
1015+1227	185 20	231 11	302 03	420 04	483 05	605 25	09.2000
		230 26	263 07	354 15	406 21	490 44	06.2002
1103+1158	310 21	305 15	312 05	350 04	396 07	490 17	09.2000
	305 20	293 07	320 04	345 06	388 05	474 20	07.2001
		312 19	343 04	386 06	434 09	496 35	06.2002
1207+1211	112 19	215 10	303 09	338 07	381 05	420 16	09.2000
	112 20	224 10	260 09	265 09	281 05	318 18	07.2001
		207 21	220 05	238 07	320 07	458 42	06.2002
1306+1113	498 35	290 13	210 06	142 04	112 10		11.2001
1315+1220	298 20	245 18	219 08	205 10	210 07	215 20	06.2001

with MgII 2798 Å. The line width is FWHM ≈ 90 Å. The CII 1909 Å line was additionally identified in the BTA spectrum. We measured the redshift from these lines, $z = 0.915$. The object is a quasar.

We observed the object with RATAN-600 three times, in 09.2000, 07.2001, and 06.2002. A power-law component of the source's extended part with $S = 180\nu^{-0.78}$ mJy was separated from the original spectra. After the subtraction of the power-law component, the spectrum of the compact component in the frequency range 0.97–21.7 GHz can be fitted by the parabolas $\log S = 2.151 + 0.433\log\nu - 0.035\log^2\nu$ (09.2000), $\log S = 2.128 + 0.509\log\nu - 0.092\log^2\nu$ (07.2001), and $\log S = 2.135 + 0.618\log\nu - 0.161\log^2\nu$ (06.2002). The peak in these spectra successively shifted toward lower frequencies; the development of an outburst is observed. We observed all of the spectra of the compact components in an optically thick region. Figure 3c shows the original spectrum of the source for the epoch 06.2002 (crosses), the spectrum of the extended component (dashed line), and the spectrum of the compact component (solid line).

The source 1207+1211. One strong emission line that was interpreted as MgII 2798 Å at the redshift $z = 0.890$ can be identified in the object's optical spectrum taken with the 2.1-m telescope (Fig. 1d). The line width is FWHM ≈ 55 Å. In addition to the magnesium line, five more weaker lines can be identified in the BTA spectrum (Fig. 2d): [NeV] 3426 Å, [OII] 3727 Å, Hγ 4340 Å, Hβ 4861 Å, and [OIII] 5007 Å. The object's redshift was estimated from all of these lines to be $z = 0.896$. We classify the object as a quasar with the mean redshift $z = 0.895$.

We observed the source with RATAN-600 in 09.2000, 07.2001, and 06.2002. Figure 3d shows the source's spectra for these epochs. The source has a variable flux density. All of the spectra are complex and are poorly fitted by logarithmic parabolas. Simultaneously several outbursts probably occur in this source. The extended component is weak in the frequency range under consideration. The largest change in flux density, from 318 ± 18 to 458 ± 42 mJy, was observed at a frequency of 21.7 GHz.

The source 1306+1113. We identified the Hβ 4861 Å, MgI 5175 Å, FeII 5270 Å, and NaI 5896 Å absorption lines in the source's optical spectrum taken with the 2.1-m telescope (Fig. 1e). The redshift was estimated from all of these lines to be $z = 0.084$. The object is an absorption-line elliptical galaxy.

The radio source has a power-law spectrum in the frequency range 0.97–11.2 GHz: $S = 484\nu^{-0.606}$ mJy (Fig. 3e).

The source 1315+1220. Five emission lines classified as two hydrogen lines (Hα 6563 Å and Hβ 4861 Å), two forbidden oxygen lines ([OIII] 4959 Å and 5007 Å), and one forbidden silicon line ([SII] 6717 Å) can be identified in the object's optical spectrum obtained with the 2.1-m telescope (Fig. 1f). In addition to these lines, a strong [OII] 3727 Å line and the Hγ 4340 Å line can be identified in the BTA spectrum (Fig. 2e). We classify this object as an emission-line galaxy. The object's redshift was estimated from all of these lines to be $z = 0.260$.

The source was observed with RATAN-600 in 09.2000 and 06.2001. Within the limits of the measurement errors, the flux density was constant at all frequencies. The spectrum is shown in Fig. 3f. The flattening of the spectrum toward higher frequencies is probably caused by the compact component, but we cannot separate the components in terms of the model under consideration.

CONCLUSIONS

Three of the six objects under study were classified as quasars with similar redshift, 0.895, 0.915, and 1.004; one object exhibits no lines in its optical spectra, and we classified it as a BL Lac object. All of these objects show variable radio flux densities. The spectra of the objects 0946+1017, 1015+1227, and 1103+1158 were separated into two components: an extended component with a power-law spectrum and a compact component fitted by a logarithmic parabola. In the source 1207+1211, the extended component is weak in the frequency range under consideration.

We classified one object as an absorption-line galaxy with a redshift of 0.084 and a power-law radio spectrum and one object as an emission-line galaxy with the redshift $z = 0.260$ whose radio spectrum flattens toward higher frequencies.

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