ASTRONOMY & ASTROPHYSICS
SUPPLEMENT SERIES

Astron. Astrophys. Suppl. Ser. **145**, 1–10 (2000)

Long-term monitoring of selected radio sources*

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Received January 27; accepted March 21, 2000

Abstract. The Effelsberg 100 m radio telescope has been used, over a period of 5.5 years, to monitor the flux densities of 40 extragalactic radio sources, including the complete sample of 13 flat spectrum sources from the S5 Survey, and various other active sources. The study of their long-term variability characteristics at several wavelengths, the source light curves, spectra, and a statistical analysis are presented and discussed in this paper.

Key words: galaxies: active — BL Lacertae objects: general — quasars: general — radio continuum: galaxies

1. Introduction

Since the detections of high-frequency variability (Kellermann & Pauliny-Toth 1968) and low–frequency variability (e.g. Hunstead 1972), many extragalactic sources have been found to show significant variability at various frequencies, on time scales of months to a few years (e.g. Dennison et al. 1981), and even of a day (Witzel et al. 1986; Heeschen et al. 1987). Both relativistic bulk motion (Rees 1966a; Jones & Burbidge 1973; Burbidge et al. 1974; Blandford & Königl 1979) and refractive interstellar scintillation (e.g. Rickett 1986) are commonly invoked to explain the various variability phenomena detected.

In order to study the long-term variability behavior of extragalactic radio sources over a range of wavelengths, several monitoring programs have been carried out (Spangler & Cotton 1981; Aller et al. 1985; Padrielli et al. 1987; Salonen et al. 1987; Bregman et al. 1990; Teräsranta et al. 1992; Bloom et al. 1999). We have carried out flux monitoring of selected sources over a wide range of wavelengths with the Effelsberg 100 m radio telescope since 1994. Here we present the results of this long-term monitoring for 40 sources at several wavelengths. Among them, 13 compact extragalactic radio sources, with a declination $\delta \geq 70^{\circ}$, a galactic latitude $|b^{\rm II}| \geq 10^{\circ}$, flux density at 5 GHz $S_{\rm 5GHz} \geq 1$ Jy, and spectral index (between $\lambda = 11$ cm and $\lambda = 6$ cm) $\alpha_6^{11} \leq 0.5$ ($S \sim \nu^{-\alpha}$), form a complete sample of flat spectrum sources from the S5 Survey (Kühr et al. 1981).

In the following section, we briefly introduce the observations and data reduction. In Sect. 3 the results for all 40 extragalactic radio sources are presented, including light curves, spectra and statistics. Subsequently, we make brief comments on individual sources. Observational findings are summarized in Sect. 5. Throughout the paper the radio spectral index is defined by $S_\nu \propto \nu^{-\alpha}$, a deceleration parameter $q_0 = 0.5$ and a Hubble constant of $H_0 = 50\,{\rm km\,s^{-1}\,Mpc^{-1}}$ are used.

2. Observations and data reduction

We present observations performed from January 1994 to July 1999 with the Effelsberg 100 m radio telescope, at wavelengths $\lambda = 21$, 18, 11, 6, 3.6, 2.8, 2, 1.3 cm, 9 and 7 mm. One should note, that both time and frequency coverage are rather irregular, depending on the availability of time slots and receivers. Most observations have been made at wavelengths of 11, 6, 2.8, and 1.3 cm.

All sources monitored are listed in Table 1 with their optical identifications, galactic latitudes, and redshifts (taken from Kühr et al. 1981 and Stickel et al. 1994). Further, we give the estimated spectral indices α_6^{11} and $\alpha_{2.8}^{6}$, and – if available from the literature – the superluminal velocity for the fastest component (see individual references). We also note whether a source showed Intraday variability (IDV, e.g. Wagner & Witzel 1995; Kraus 1997) at least once or not.

Since all target sources are point-like and moderately strong ($\gtrsim 0.2$ Jy) at the frequencies of observation, we were able to perform the measurements with cross-scans (in Azimuth and Elevation). As a first step of the analysis,

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* Figures 1 to 30 are only available in electronic version at http://www.edpsciences.org

Table 1. Source properties: Opt. Id. denotes the optical identification, b^{II} the galactic latitude, z the redshift, α ($\alpha_6^{11}, \alpha_{2.8}^{6}$) spectral indices, β_{a} apparent superluminal speed (in unit of speed of light c), Ref. reference for β_{a}, and IDV or not

Source	Other name	Opt. Id.	b^{II}	z	α_6^{11}	$\alpha_{2.8}^{6}$	β_{a}	Ref.	IDV
0016+731	*	QSO	+10.7°	1.781	$+0.06 \pm 0.94$	-0.07 ± 0.62	16.6	S92	+
0134+329	3C 48	QSO	−28.7°	0.367	$+0.89 \pm 0.02$	$+1.02 \pm 0.02$			
0153+744	*	QSO	+12.4°	2.338	$+0.72 \pm 0.06$	$+0.97 \pm 0.05$	29.4	W88	+
0212+735	*	QSO	+12.0°	2.367	-0.26 ± 0.18	-0.04 ± 0.14	36.8	W88	−
0235+164		BLL	−39.1°	0.940	$+0.16 \pm 1.39$	-0.57 ± 1.31	54.0	Chu	+
0316+413	3C 84	GAL	−13.3°	0.017	$+0.28 \pm 0.25$	$+0.19 \pm 0.18$	0.4	R84	−
0420−014		QSO	−33.1°	0.915	-0.26 ± 0.19	-0.24 ± 0.19			?
0454+844	*	BLL	+24.7°	0.112	-0.05 ± 0.42	$+0.18 \pm 0.35$	> 3.2	S92	?
0518+165	3C 138	QSO	−11.3°	0.759	$+0.68 \pm 0.02$	$+0.78 \pm 0.02$			
0528+134		QSO	−11.0°	2.060	-0.74 ± 0.53	-0.16 ± 0.67	12.4	B99	?
0538+498	3C 147	QSO	+10.3°	0.545	$+0.88 \pm 0.02$	$+0.91 \pm 0.03$			
0615+820	*	QSO	+26.0°	0.710	$+0.21 \pm 0.09$	$+0.37 \pm 0.10$	< 4.4?	S92	−
0716+714	*	BLL	+28.0°	0.30?	-0.05 ± 0.76	-0.13 ± 0.86	4.6	S92	+
0735+178		BLL	+18.1°	0.424	$+0.30 \pm 0.29$	$+0.58 \pm 0.39$	> 14.4	M90	+
0804+499		QSO	+32.6°	1.433	$+0.03 \pm 0.50$	-0.13 ± 0.70			+
0835+580		QSO	+36.9°	1.534	$+1.09 \pm 0.03$	$+1.20 \pm 0.06$	−0.7	H93	?
0836+710	*	QSO	+34.4°	2.172	$+0.34 \pm 0.20$	$+0.14 \pm 0.38$	21.6	O98	+
0851+202	OJ 287	BLL	+35.8°	0.306	-0.27 ± 0.33	-0.15 ± 0.32	6.4	M90	+
0917+624		QSO	+41.0°	1.446	-0.15 ± 0.17	$+0.02 \pm 0.16$	7.8	S96	+
0923+392	4C 39.25	QSO	+46.2°	0.698	-1.01 ± 0.08	-0.23 ± 0.06	7.1	S87	−
0951+699		GAL	+40.6°	0.001	$+0.69 \pm 0.02$	$+0.76 \pm 0.02$			−
0954+658		BLL	+43.1°	0.367	-0.07 ± 0.58	-0.05 ± 0.49	12.4	G96	+
1039+811	*	QSO	+34.7°	1.254	-0.04 ± 0.19	-0.41 ± 0.14	35.6	W88	?
1150+812	*	QSO	+35.8°	1.250	$+0.07 \pm 0.21$	-0.01 ± 0.10	7.0	W88	+
1226+023	3C 273	QSO	+64.4°	0.158	$+0.23 \pm 0.12$	$+0.19 \pm 0.17$	16.1	C87	−
1253−055	3C 279	QSO	+57.1°	0.536		-0.62 ± 0.43	18.4	C79	−
1328+307	3C 286	QSO	+80.7°	0.849	$+0.59 \pm 0.02$	$+0.68 \pm 0.02$			
1409+524	3C 295	GAL	+60.8°	0.461	$+1.05 \pm 0.02$	$+1.21 \pm 0.02$			
1458+718	3C 309.1	QSO	+42.1°	0.905	$+0.57 \pm 0.09$	$+0.48 \pm 0.11$	13.1	K90	−
1641+399	3C 345	QSO	+40.9°	0.594	-0.03 ± 0.07	$+0.08 \pm 0.11$	18.9	BM	−
1652+398		BLL	+38.9°	0.034	$+0.13 \pm 0.07$	$+0.17 \pm 0.05$			+
1739+522		QSO	+31.7°	1.379	-0.13 ± 0.83	-0.04 ± 0.69			+
1749+701	*	BLL	+30.7°	0.770	$+0.05 \pm 0.17$	$+0.06 \pm 0.23$	4.7	M90	+
1803+784	*	BL?	+29.1°	0.684	-0.18 ± 0.24	-0.05 ± 0.15	7.8	S92	+
1823+568		BLL	+26.1°	0.664	-0.23 ± 0.21	-0.02 ± 0.31	5.1	G89	+
1928+738	*	QSO	+23.5°	0.302	-0.01 ± 0.09	$+0.06 \pm 0.10$	14.1	E85	+
2007+777	*	BLL	+22.7°	0.342	-0.04 ± 0.32	$+0.05 \pm 0.27$	4.7	M90	+
2105+420	NGC 7027	PN	−3.5°		-0.67 ± 0.02	-0.12 ± 0.02			
2200+420	BLLAC	BLL	−10.4°	0.069	-0.08 ± 0.47	-0.04 ± 0.36	7.5	M90	+
2251+158	3C 454.3	QSO	−38.2°	0.859	-0.14 ± 0.19	$+0.29 \pm 0.27$	17.7	PT	−

Notes for columns in Table 1 – for Other name, a $\star$ marks the source which belongs to the S5 survey; for Opt. Id., PN stands for Planetary Nebulae; for z and α_6^{11}, blank if it is not available; for IDV, + if it shows at least once IDV, − if not, ? if unclear yet, blank if it is a primary flux calibrator source.

Notes for references in Table 1 – BM: Biretta et al. 1986, B99: Britzen et al. 1999, C87: Cohen et al. 1987, C79: Cotton et al. 1979, Chu: Chu et al. 1996, E85: Eckart et al. 1985, G89: Gabuzda et al. 1989, G96: Gabuzda et al. 1996, H93: Hough et al. 1993, K90: Kus et al. 1990, M90: Mutel 1990, O98: Otterbein et al. 1998, PT: Pauliny-Toth et al. 1987, R84: Romney et al. 1984, S87: Shaffer et al., 1987, S92: Schalinski et al. 1992, S96: Standke et al. 1996, W88: Witzel et al. 1988.

a Gaussian was fitted to every cross-scan. The average amplitude of these Gaussians (which are the result of the convolution of the point-like source with the antenna-beam) is a measure of the source flux density. Subsequently, we corrected for the elevation-dependence of the gain of the telescope and systematic time-dependent effects. To determine those, we frequently observed steep-spectrum sources (and the primary calibrators) which were known to show no variability on short timescales (cf. Quirrenbach et al. 1992; Kraus 1997; Kraus et al., in preparation).

Finally, we linked our observations to an absolute flux density scale (Baars et al. 1977) by observing primary calibrators such as 3C 286 and 3C 48. The measurement errors are composed of the statistical errors from averaging the individual samples in a scan, and a contribution from the calibration errors, which are reflected by apparent residual fluctuations of the non-variable sources.

3. Results

In the monitoring period of 5.5 years, the flux densities of the primary calibrators, 3C 48, 3C 138, 3C 147, 3C 286, 3C 295, and NGC 7027 (and also few other sources, as reported in Sect. 3.2), remained constant as expected at a level of about 2% at wavelength $\lambda \geq 2.8$ cm, and about 3% at $\lambda = 1.3$ cm.

3.1. Light curves and source spectra

Light curves for each source are plotted in Figs. 1–20 at the four best observed wavelengths 11, 6, 2.8 and 1.3 cm. In case there are less than 3 data points at a given wavelength, the plot has been omitted. We make brief comments on individual sources in Sect. 4.

Spectra of all sources are presented in Figs. 21–25, by taking all fluxes measured at each wavelength over the 5.5 year monitoring period. Obviously, the flux variations of a source are reflected in its spectrum. Although the reliability of the spectra suffer from flux density variations, it is interesting to note that,

- the spectra of the flat spectrum sources 0153+744 and 1253−055 steepen for $\lambda \leq 11$ cm, and 0735+178 probably steepens for $\lambda \leq 6$ cm;
- the spectra of sources 0316+413 and 0615+820 are inverted at $\lambda \leq 11$ cm, 0212+735, 0454+844, 1641+399, 1928+738, 2007+777 and 2251+158 inverted at $\lambda \leq 6$ cm, 0917+624 at $\lambda \leq 3.6$ cm, 1803+784 at $\lambda \leq 2$ cm;
- sources 0420−014, 0528+134, 0836+710, 0851+202, 1226+023 and 2105+420 (NGC 7027) have flat spectra at $\lambda \leq 6$ cm, and 0923+392 has a flat spectrum at $\lambda \leq 2.8$ cm;
- through the whole range of observing wavelengths, sources 0016+731, 0235+164, 0716+714, 0804+499, 0954+658, 1039+811,1150+812, 1652+398, 1739+522, 1749+701, 1823+568 and 2200+420 have flat spectra. It is further noticeable that most of the steep spectrum sources are not variable with an exceptionally weak variability for 3C 309.1. In other words, variability is a common phenomenon in the flat spectrum sources. This is consistent with previous evidence that most variable sources have flat spectra (Kellermann 1974; Fanti et al. 1981).

We also investigate variations of the spectral indices, by calculating a two-point power law spectrum (6 cm and 2.8 cm, simply derived from $\alpha^{6}_{2.8} = \frac{\ln(S_6/S_{2.8})}{\ln(\lambda_6/\lambda_{2.8})}$), for those sources showing correspondingly at least one pronounced outburst at both wavelengths with enough simultaneous measurements (with more than 8 data points) during the monitoring period. As seen from Figs. 26 and 27, the spectral indices ($\alpha^{6}_{2.8}$) follow the expectations of shock models (Marscher & Gear 1985; Valtaoja et al. 1992; Qian 1996) that shocks propagate from an optically thick to an optically thin regime in each outburst, most evidently seen in sources 0235+164, 0528+165, 0716+714, 0804+499, 0836+710, 1641+399 and 2007+777, so that the variations in these sources were probably intrinsic.

Table 2. Summary of source variabilities at 21 cm. N denotes number of observations during this 5.5 years period, $< S >$ the mean flux in Jy, m the modulation index in % and $\chi^2_{\rm red}$ the reduced χ^2 value (we denote > when the $\chi^2_{\rm red} \geq 100.0$). For the statistical analysis (m and $\chi^2_{\rm red}$), only data sets with $N \geq 8$ are taken into consideration

Source	N	$< S >$ [Jy]	m [%]	$\chi^2_{\rm red}$
0134+329	6	16.14 ± 0.21		
0153+744	5	1.95 ± 0.05		
0212+735	5	2.38 ± 0.03		
0316+413	4	27.28 ± 0.27		
0420−014	2	2.08 ± 0.10		
0454+844	6	0.28 ± 0.05		
0518+165	6	8.65 ± 0.09		
0528+134	4	2.46 ± 0.34		
0538+498	4	21.76 ± 0.14		
0615+820	5	0.69 ± 0.02		
0716+714	7	0.78 ± 0.07		
0804+499	4	0.97 ± 0.08		
0835+580	5	2.26 ± 0.02		
0836+710	7	3.47 ± 0.18		
0851+202	2	1.14 ± 0.07		
0917+624	5	1.24 ± 0.06		
0954+658	5	0.48 ± 0.04		
1039+811	5	0.76 ± 0.02		
1150+812	5	1.64 ± 0.07		
1226+023	1	51.88 ± 0.52		
1253−055	1	9.32 ± 0.09		
1328+307	6	14.65 ± 0.05		
1409+524	6	22.14 ± 0.11		
1641+399	4	7.54 ± 0.15		
1652+398	3	1.82 ± 0.04		
1739+522	3	1.43 ± 0.42		
1749+701	5	0.79 ± 0.02		
1803+784	7	2.07 ± 0.17		
1823+568	3	1.56 ± 0.04		
1928+738	5	3.95 ± 0.05		
2007+777	6	0.95 ± 0.16		
2105+420	4	1.39 ± 0.03		
2200+420	3	4.39 ± 0.34		
2251+158	2	14.35 ± 0.74		

3.2. Statistical analysis

We measure the degree of variability by deriving the modulation index $m[\%] = 100 \times \frac{\sigma_S}{<S>}$, where <> denotes the mean. To see whether a source is variable, we performed a

Table 3. Summary of source variability at 18 cm

Source	N	$< S >$ [Jy]	m [%]	$\chi^2_{\rm red}$
0134+329	6	14.00 ± 0.19		
0153+744	2	2.02 ± 0.01		
0212+735	3	2.33 ± 0.06		
0316+413	7	28.79 ± 0.68		
0420−014	2	2.22 ± 0.30		
0454+844	2	0.25 ± 0.03		
0518+165	6	7.76 ± 0.14		
0528+134	3	2.21 ± 0.05		
0538+498	4	19.79 ± 0.19		
0615+820	2	0.75 ± 0.02		
0716+714	5	0.78 ± 0.11		
0804+499	3	0.92 ± 0.05		
0835+580	2	1.93 ± 0.03		
0836+710	7	3.35 ± 0.15		
0851+202	3	1.41 ± 0.26		
0917+624	8	1.27 ± 0.06	4.6	5.0
0954+658	4	0.48 ± 0.13		
1039+811	2	0.73 ± 0.04		
1150+812	2	1.61 ± 0.13		
1226+023	7	49.30 ± 1.77		
1253−055	5	10.01 ± 0.31		
1328+307	10	13.53 ± 0.11	0.9	0.2
1409+524	9	19.27 ± 0.18	1.0	0.3
1641+399	5	7.46 ± 0.38		
1652+398	1	1.80 ± 0.02		
1749+701	2	0.76 ± 0.02		
1803+784	5	2.25 ± 0.03		
1928+738	8	3.92 ± 0.15	4.0	6.2
2007+777	4	1.01 ± 0.19		
2105+420	7	1.87 ± 0.03		
2200+420	2	3.18 ± 1.10		
2251+158	4	14.27 ± 0.36		

Table 4. Summary of source variabilities at 11 cm. In the last column we denote > when the $\chi^2_{\rm red} \geq 100.0$

Source	N	$< S >$ [Jy]	m [%]	$\chi^2_{\rm red}$
0016+731	3	1.35 ± 0.58		
0134+329	24	9.44 ± 0.09	0.9	0.5
0153+744	2	1.86 ± 0.02		
0212+735	3	2.64 ± 0.24		
0235+164	8	1.31 ± 0.56	45.7	>
0316+413	7	30.37 ± 2.46		
0420−014	7	2.35 ± 0.08		
0454+844	15	0.31 ± 0.06	19.4	>
0518+165	12	5.71 ± 0.03	0.5	0.3
0528+134	15	2.76 ± 0.23	8.5	26.8
0538+498	4	13.34 ± 0.04		
0615+820	2	0.87 ± 0.03		
0716+714	43	0.64 ± 0.16	25.1	>
0735+178	2	2.28 ± 0.01		
0804+499	15	1.02 ± 0.11	10.6	47.1
0835+580	8	1.15 ± 0.01	0.4	0.2
0836+710	39	2.60 ± 0.16	6.2	22.3
0851+202	17	1.38 ± 0.18	13.2	94.0
0917+624	15	1.40 ± 0.12	8.5	17.7
0923+392	15	6.01 ± 0.20	3.5	5.2
0951+699	13	5.03 ± 0.01	0.3	0.1
0954+658	20	0.48 ± 0.11	23.6	>
1039+811	3	0.79 ± 0.07		
1150+812	6	1.56 ± 0.16		
1226+023	4	45.20 ± 1.79		
1328+307	31	10.62 ± 0.07	0.7	0.3
1409+524	20	12.28 ± 0.11	0.9	0.2
1458+718	6	4.71 ± 0.09		
1641+399	7	8.34 ± 0.22		
1652+398	8	1.72 ± 0.05	3.1	3.8
1739+522	9	1.37 ± 0.51	39.3	>
1749+701	4	0.71 ± 0.04		
1803+784	15	2.34 ± 0.26	11.5	66.6
1823+568	1	1.43 ± 0.01		
1928+738	14	3.91 ± 0.14	3.6	6.9
2007+777	13	1.36 ± 0.15	11.1	79.6
2105+420	30	3.69 ± 0.04	1.0	0.7
2200+420	14	3.71 ± 0.63	17.6	>
2251+158	5	13.77 ± 0.46		

χ^2 test, $\chi^2 \equiv \sum(\frac{S_i - <S>}{\sigma_i^2})^2$, (similarly to, e.g. Fanti et al. 1981 and Bondi et al. 1996), where the uncertainties σ_i are a combination of the experimental uncertainties $\sigma_{\rm e\it i}$ and the statistical uncertainties $\sigma_{\rm s\it i}$ at the i-th epoch, i.e., $\sigma_i^2 = \sigma_{\rm e\it i}^2 + \sigma_{\rm s\it i}^2$ (Eqs. (6-1) in Bevington 1969).

Our data were not obtained under identical conditions but rather comprised various observations during such a long-term monitoring period. For each calibrator source, $\sigma_{\rm s\it i}$ is taken to be the standard deviation of the data set during the monitoring period, and for each target source, $\sigma_{\rm s\it i}$ is approximated by taking the value of the $m_{0,\rm max} \times < S >$, where $m_{0,\rm max}$ is the maximum of the m_0 (the modulation index of a non-variable source) from calibrators at each wavelength. We take $m_{0,\rm max}$ as 1.0% at $\lambda \geq 11$ cm, as 1.2, 2.0, 2.3 and 3.1% at $\lambda = 6$, 3.6, 2.8 and 1.3 cm, and as 4.6% at $\lambda \leq 9$ mm respectively.

The statistical results (only for data sets with $N \geq 8$ at each wavelength) are presented in Tables 2–11 for all sources at wavelengths of 21, 18, 11, 6, 3.6, 2.8, 2 and 1.3 cm, 9 and 7 mm respectively, with the source name, number of observations, the mean flux density with estimated error, the modulation index, and the reduced $\chi^2_{\rm red}$. Obviously, the statistical results confirm that nearly all sources, with the exception of 0835+580 and 0951+699 and the six primary flux calibrators, are variable at a confidence level of more than 99.95% at most of the radio wavelengths over this 5.5 years period.

3.3. Variability dependence

We investigate whether there is any dependence of the degree of variability on either source galactic latitude ($b^{\rm II}$), redshift (z), spectral indices (α_6^{11} and $\alpha_{2.8}^6$ only), or superluminal motions by taking the modulation index of each

Table 5. Summary of source variabilities at 6 cm. In the last column we denote $>$ when the $\chi^2_{\rm red} \geq 100.0$

Source	N	$< S >$ [Jy]	m [%]	$\chi^2_{\rm red}$
0016+731	15	1.30 ± 0.47	37.5	$>$
0134+329	68	5.53 ± 0.07	1.2	0.6
0153+744	12	1.21 ± 0.04	3.8	6.0
0212+735	14	3.08 ± 0.19	6.5	19.3
0235+164	19	1.19 ± 0.84	72.3	$>$
0316+413	29	25.71 ± 3.19	12.6	88.3
0420−014	14	2.75 ± 0.30	11.5	51.9
0454+844	31	0.32 ± 0.05	17.4	$>$
0518+165	35	3.79 ± 0.04	1.2	0.6
0528+134	37	4.29 ± 1.31	30.9	$>$
0538+498	13	7.92 ± 0.08	1.0	0.5
0615+820	10	0.77 ± 0.03	4.2	6.0
0716+714	74	0.66 ± 0.25	37.7	$>$
0735+178	8	1.91 ± 0.33	18.3	$>$
0804+499	35	1.00 ± 0.28	28.4	$>$
0835+580	30	0.60 ± 0.01	1.0	0.4
0836+710	75	2.12 ± 0.21	10.2	45.2
0851+202	33	1.62 ± 0.24	15.0	78.0
0917+624	45	1.53 ± 0.09	5.8	10.1
0923+392	29	10.98 ± 0.35	3.3	4.2
0951+699	32	3.33 ± 0.03	0.8	0.3
0954+658	39	0.50 ± 0.13	26.8	$>$
1039+811	12	0.81 ± 0.06	7.9	22.6
1150+812	14	1.50 ± 0.11	7.9	20.3
1226+023	20	39.48 ± 2.32	6.0	11.8
1253−055	11	14.40 ± 2.82	20.5	$>$
1328+307	74	7.49 ± 0.07	0.9	0.7
1409+524	39	6.58 ± 0.08	1.1	0.7
1458+718	10	3.36 ± 0.16	5.1	9.6
1641+399	27	8.47 ± 0.29	3.4	3.8
1652+398	13	1.59 ± 0.04	2.4	2.2
1739+522	21	1.48 ± 0.48	33.1	$>$
1749+701	14	0.69 ± 0.06	8.6	22.2
1803+784	40	2.60 ± 0.23	9.1	31.8
1823+568	6	1.64 ± 0.20		
1928+738	36	3.92 ± 0.16	4.2	6.8
2007+777	34	1.39 ± 0.22	16.4	96.1
2105+420	66	5.48 ± 0.06	1.0	0.5
2200+420	23	3.90 ± 0.89	23.3	$>$
2251+158	26	14.97 ± 1.65	11.3	49.4

Table 6. Summary of source variability at 3.6 cm. In the last column we denote $>$ when the $\chi^2_{\rm red} \geq 100.0$

Source	N	$< S >$ [Jy]	m [%]	$\chi^2_{\rm red}$
0016+731	6	1.39 ± 0.40		
0134+329	9	3.22 ± 0.04	1.2	0.4
0153+744	1	0.64 ± 0.01		
0212+735	1	3.08 ± 0.04		
0235+164	2	2.48 ± 1.67		
0316+413	21	24.53 ± 2.39	10.0	14.0
0420−014	1	3.00 ± 0.15		
0454+844	5	0.29 ± 0.06		
0518+165	6	2.37 ± 0.07		
0528+134	7	3.49 ± 0.70		
0538+498	5	4.67 ± 0.19		
0615+820	1	0.64 ± 0.01		
0716+714	16	0.82 ± 0.35	44.4	$>$
0735+178	1	2.15 ± 0.03		
0804+499	6	1.36 ± 0.46		
0835+580	5	0.31 ± 0.01		
0836+710	19	1.84 ± 0.41	22.9	77.5
0851+202	8	2.01 ± 0.26	13.9	30.0
0917+624	14	1.71 ± 0.21	12.7	29.5
0923+392	11	13.29 ± 0.41	3.2	1.1
0951+699	4	2.12 ± 0.03		
0954+658	8	0.45 ± 0.16	38.5	$>$
1039+811	2	0.95 ± 0.24		
1226+023	5	38.79 ± 3.14		
1253−055	6	14.66 ± 0.57		
1328+307	20	5.11 ± 0.07	1.5	0.4
1409+524	11	3.38 ± 0.04	1.2	0.2
1458+718	2	2.55 ± 0.04		
1641+399	11	8.45 ± 0.44	5.4	4.3
1652+398	3	1.53 ± 0.04		
1739+522	4	1.20 ± 0.62		
1749+701	3	0.59 ± 0.05		
1803+784	11	2.51 ± 0.23	9.5	12.8
1928+738	5	3.71 ± 0.22		
2007+777	4	1.31 ± 0.13		
2105+420	12	6.02 ± 0.12	2.0	0.3
2200+420	7	3.17 ± 0.64		
2251+158	3	13.91 ± 1.05		

source at 6 cm, where the sources have been observed most frequently.

As shown in Fig. 28, there is no obvious dependence of the degree of variability on most of the above mentioned quantities. This is confirmed by the formal estimates of the correlation probabilities (coefficients are less than 0.26) of these relationships with an exception, that is a weak correlation (coefficient is 0.48) between the degree of variability and the 6 to 2.8 cm spectral index. Both the degree of variability and its rate of occurrence appear to be higher when the source spectra are flatter. This is consistent with previous findings: sources with flat spectra are small, and are variable, while sources with steep spectra are less variable (Heeschen et al. 1987). Furthermore, there is a trend showing that the degree of variability decreases with increasing wavelength, as seen in Fig. 29 by taking only the derived m of the common 16 sources at the four wavelengths of 11, 6, 2.8 and 1.3 cm, which has been shown in other variability studies (e.g. Peng et al. 2000). The maximum values for m are derived to be 25.1, 37.7, 54.0 and 60.9% respectively at the four wavelengths sequenced above. This is contrary to the expectations of the interstellar scintillation (ISS, e.g. Rickett 1990), but in favor of shock models (e.g. Marscher & Gear 1985).

Table 7. Summary of source variabilities at 2.8 cm. In the last column we denote > when the $\chi^2_{\rm red} \geq 100.0$

Source	N	$< S >$ [Jy]	m [%]	$\chi^2_{\rm red}$
0016+731	5	1.37 ± 0.41		
0134+329	37	2.58 ± 0.05	2.1	0.6
0153+744	7	0.58 ± 0.01		
0212+735	13	3.18 ± 0.28	9.1	10.1
0235+164	15	1.83 ± 1.29	73.0	>
0316+413	13	22.23 ± 1.13	5.3	3.3
0420−014	14	3.31 ± 0.30	9.3	12.7
0454+844	22	0.28 ± 0.06	21.1	49.1
0518+165	28	2.08 ± 0.05	2.3	0.5
0528+134	29	4.84 ± 1.96	41.3	>
0538+498	6	3.95 ± 0.08		
0615+820	5	0.58 ± 0.04		
0716+714	59	0.73 ± 0.39	54.0	>
0735+178	3	1.23 ± 0.30		
0804+499	23	1.10 ± 0.50	46.4	>
0835+580	13	0.24 ± 0.01	2.0	0.5
0836+710	58	1.91 ± 0.52	27.3	>
0851+202	21	1.82 ± 0.35	19.9	45.9
0917+624	29	1.51 ± 0.16	10.8	9.4
0923+392	20	13.11 ± 0.42	3.3	1.5
0951+699	12	1.87 ± 0.03	1.8	0.4
0954+658	22	0.52 ± 0.14	28.4	90.6
1039+811	11	1.11 ± 0.08	7.4	7.8
1150+812	4	1.51 ± 0.06		
1226+023	6	34.09 ± 4.03		
1253−055	3	23.14 ± 6.02		
1328+307	44	4.45 ± 0.06	1.3	0.3
1409+524	31	2.60 ± 0.03	1.1	0.6
1458+718	12	2.34 ± 0.17	7.6	8.4
1641+399	15	7.96 ± 0.60	7.8	5.4
1652+398	13	1.40 ± 0.04	2.7	0.9
1739+522	14	1.52 ± 0.63	43.1	>
1749+701	4	0.66 ± 0.10		
1803+784	25	2.70 ± 0.20	7.4	7.1
1823+568	8	1.67 ± 0.33	21.0	62.4
1928+738	17	3.76 ± 0.25	6.7	4.1
2007+777	23	1.34 ± 0.17	13.2	22.0
2105+420	44	6.05 ± 0.10	1.7	0.5
2200+420	20	4.02 ± 0.63	16.1	28.8
2251+158	15	12.03 ± 2.04	17.6	48.1

Table 8. Summary of source variability at 2 cm

Source	N	$< S >$ [Jy]	m [%]	$\chi^2_{\rm red}$
0538+498	4	2.88 ± 0.14		
1409+524	7	1.69 ± 0.05		
1641+399	6	7.73 ± 0.52		
2105+420	6	5.82 ± 0.13		

Table 9. Summary of source variabilities at 1.3 cm

Source	N	$< S >$ [Jy]	m [%]	$\chi^2_{\rm red}$
0016+731	2	0.66 ± 0.19		
0134+329	10	1.11 ± 0.03	2.8	0.4
0153+744	2	0.42 ± 0.02		
0212+735	3	2.25 ± 0.28		
0235+164	4	2.04 ± 1.78		
0316+413	12	17.23 ± 1.89	11.4	5.8
0420−014	9	3.57 ± 0.44	12.9	3.4
0454+844	6	0.33 ± 0.13		
0518+165	10	1.10 ± 0.03	3.1	0.3
0528+134	14	4.17 ± 1.58	39.3	49.5
0538+498	5	1.91 ± 0.11		
0615+820	1	0.40 ± 0.02		
0716+714	19	0.92 ± 0.55	60.9	92.3
0804+499	8	1.10 ± 0.33	32.5	30.1
0836+710	49	1.74 ± 0.38	22.2	23.9
0851+202	10	1.92 ± 0.30	16.3	9.8
0917+624	10	1.19 ± 0.09	7.5	3.2
0923+392	5	11.13 ± 0.62		
0951+699	2	1.00 ± 0.06		
0954+658	7	0.55 ± 0.19		
1150+812	1	1.06 ± 0.06		
1226+023	3	34.27 ± 9.55		
1328+307	16	2.46 ± 0.05	1.9	0.2
1409+524	12	0.92 ± 0.02	2.8	0.3
1458+718	2	1.42 ± 0.22		
1641+399	10	7.45 ± 0.75	10.7	5.4
1652+398	8	1.13 ± 0.07	6.5	1.6
1739+522	6	1.64 ± 0.64		
1749+701	1	0.62 ± 0.05		
1803+784	12	2.27 ± 0.12	5.6	1.5
1928+738	9	3.27 ± 0.27	8.8	3.0
2007+777	12	1.16 ± 0.10	9.0	3.0
2105+420	22	5.58 ± 0.10	1.8	0.2
2200+420	8	4.00 ± 0.62	16.5	10.6
2251+158	6	10.26 ± 3.44		

Table 10. Summary of source variability at 9 mm

Source	N	$< S >$ [Jy]	m [%]	$\chi^2_{\rm red}$
0134+329	10	0.81 ± 0.02	2.2	0.3
0518+165	6	0.76 ± 0.07		
0716+714	21	0.88 ± 0.53	60.9	54.5
0851+202	4	2.03 ± 0.37		
0917+624	10	1.01 ± 0.07	6.9	0.6
0954+658	5	0.45 ± 0.19		
1328+307	15	1.92 ± 0.03	1.7	0.1
1409+524	10	0.56 ± 0.02	4.6	0.3
1652+398	4	1.00 ± 0.03		
1739+522	4	1.57 ± 0.51		
1928+738	4	2.73 ± 0.29		
2007+777	8	1.05 ± 0.16	16.0	3.5
2105+420	15	5.25 ± 0.14	2.7	0.3
2200+420	11	3.61 ± 0.58	16.8	7.0
2251+158	3	8.01 ± 1.14		

Table 11. Summary of source variability at 7 mm

Source	N	$< S >$ [Jy]	m [%]	$\chi^2_{\rm red}$
0134+329	7	0.55 ± 0.07		
0316+413	4	11.87 ± 2.51		
0518+165	5	0.63 ± 0.05		
0528+134	7	4.39 ± 1.76		
0716+714	6	0.92 ± 0.53		
0804+499	5	1.08 ± 0.30		
0836+710	25	1.63 ± 0.32	20.2	7.7
0851+202	5	1.52 ± 0.35		
1328+307	7	1.49 ± 0.03		
1409+524	5	0.44 ± 0.08		
1641+399	6	6.79 ± 0.74		
1803+784	5	1.89 ± 0.27		
1928+738	4	2.86 ± 0.32		
2105+420	10	5.01 ± 0.22	4.6	0.3

4. Comments on individual sources

In the context, the apparent brightness temperature is given by Gopal-Krishna et al. (1984),

$$T_{\rm app} \geq \frac{2c^2 \triangle S}{\pi \kappa \nu^2 \theta^2_{\rm app}} \ {\rm K}, \tag{1}$$

when transforming to the co-moving frame of the source it becomes,

$$T'_{\rm app} \geq T_{\rm app}(1+z)^3 \delta^{-3} \ {\rm K}, \tag{2}$$

where $\triangle S$ is the flux change during a period τ, $\theta_{\rm app} \leq 2c\tau/D_{\rm a}$ the apparent diameter of the variable component based on the causality argument, $D_{\rm a}$ (Lang 1974) the angular distance of the source, and δ the Doppler factor.

- 0016+734: This quasar ($z = 1.781$, in which highly superluminal motion is observed, SLM hereafter) shows a monotonic flux decrease at 6, 3.6 and 2.8 cm. Its modulation index is 38% at 6 cm. It belongs to a complete sample of flat spectrum sources in the S5 survey (S5 sample hereafter);
- 0134+329 (3C 48): This quasar ($z = 0.367$) shows no flux variations as expected. It has been used as a primary flux calibrator;
- 0153+744: In this quasar ($z = 2.338$, showing highly SLM), the modulation index is 3.8% at 6 cm. It belongs to the S5 sample;
- 0212+735: In this quasar ($z = 2.367$, highly SLM), the modulation index increases with decreasing wavelength from 6.5% at 6 cm to 9.1% at 2.8 cm. Its spectrum at 6 and 2.8 cm has been inverted since around late 1996. It belongs to the S5 sample;
- 0235+164: In this BL Lac object ($z = 0.940$, highly SLM), a pronounced outburst started at early 1997 and lasted to the end of our monitoring period at all observing wavelengths. Its modulation index increases with decreasing wavelength at 11, 6 and 2.8 cm. It is a IDV source discussed recently by Kraus et al (1999a). Its angular-diameter distance $D_{\rm a}$ is 1.72 10^3 Mpc. Because of the flux change $\triangle S = 2.88$ Jy at 2.8 cm during $\tau \sim 229$ days (which corresponds to the fastest flux change in the lightcurve), this corresponds to an apparent brightness temperature in the co-moving frame of the quasar, $T'_{\rm app} \geq 1.59\ 10^{14} \delta^{-3}$ K. If the large excess of the brightness temperature over the inverse Compton limit of 10^{12} K (Kellermann & Pauliny-Toth 1969) is due to a relativistic bulk motion (as suggested by Rees 1966b and by Woltjer 1966) of the variable component, a Doppler factor $\delta \geq 5.4$ is needed. The resultant δ is well within the "canonical" value of 10, derived from VLBI and X-ray observations (see Ghisellini et al. 1993; Zensus 1997; Wagner & Witzel 1995);
- 0316+413 (3C 84): This galaxy ($z = 0.017$, showing subluminal motion, Sub-LM hereafter) mostly shows a slow, monotonic flux decrease (with an exception at 21 cm where it is not variable), but with an increase in the middle of 1998 at 3.6 cm and a significant increase at 7 mm since 1994. Its modulation index at the level of $5-13$% varies irregularly with wavelength;
- 0420−014: In this quasar ($z = 0.915$), two outbursts cover the whole monitoring period at all observing wavelengths. Its modulation index decreases firstly from 11.5% at 6 cm to 9.3% at 2.8 cm, then increases to 12.9% at 1.3 cm;
- 0454+844: This BL Lac object ($z = 0.112$, SLM), shows firstly a monotonic flux increase till the middle of 1995, then a monotonic decrease. Its modulation index at the level of $17-21$% varies up and down with decreasing wavelength. It belongs to the S5 sample;
- 0518+165 (3C 138): This quasar ($z = 0.759$) shows no flux variations as expected. It has been used as a primary flux calibrator;
- 0528+134: In this quasar ($z = 2.060$, SLM), two pronounced outbursts covered the whole monitoring period at most of the observing wavelengths, but measurements were not available at 11 and 1.3 cm during the outbursts. The modulation index increases with decreasing wavelength at 11, 6 and 2.8 cm, but decreases by about 2% at 1.3 cm. The angular distance $D_{\rm a}$ is 1.63 10^3 Mpc. The flux change $\triangle S = 2.18$ Jy at 6 cm during $\tau \sim 167.8$ days (the fastest flux change in the lightcurve) corresponds to an apparent brightness temperature $T'_{\rm app} \geq 3.48\ 10^{15}\ \delta^{-3}$ K in the co-moving frame of the quasar. A Doppler factor $\delta \geq 15$ is needed in terms of a relativistic bulk motion, which is higher than the "canonical" value of 10. However this agrees well with the suggested Doppler boosting (Krichbaum et al. 1995) and the observed superluminal motion (Krichbaum et al. 1995; Britzen et al. 1999) in this source, which is one of the strongest gamma-active blazars (Britzen et al. 1999);
- 0538+498 (3C 147): This quasar ($z = 0.545$) shows no flux variations as expected. It has been used as a primary flux calibrator;

- 0615+820: In this quasar ($z = 0.710$, SLM), the modulation index is 4.2% at 6 cm. It belongs to the S5 sample;
- 0716+714: In this BL Lac object (at uncertain redshift $z = 0.30$, SLM), (quasi-)periodic flux variations appear simultaneously at all observing wavelengths. Remarkably, its modulation index at the level of about $25-61\%$ increases with decreasing wavelength, but has the same value at both 1.3 cm and 9 mm. It belongs to the S5 sample, showing close radio-optical IDV correlations (Quirrenbach et al. 1992; Wagner et al. 1996). Rapid variations on time scales of a few hours have been observed at 5 GHz (Quirrenbach et al. 1989). It is the only blazar showing the IDV phenomenon throughout the entire wavelength regime;
- 0735+178: In this BL Lac object ($z = 0.424$, highly SLM), a monotonic flux decrease appears with a modulation index of 18.3% at 6 cm;
- 0804+499: In this quasar ($z = 1.433$), a pronounced outburst started at early 1997 and continued to the end of the monitoring period at all observing wavelengths. Its modulation index increases by about 18% interval at wavelengths 11, 6 and 2.8 cm, then decreases by about 14% at 1.3 cm;
- 0835+580: This quasar ($z = 1.534$, sub-SLM) shows no flux variations at all. Therefore it can be used as a secondary flux calibrator;
- 0836+710: In this quasar ($z = 2.172$, highly SLM), a few outbursts appear with time delays at increasing wavelengths of 7 mm, 1.3, 2.8 and 6 cm. Its modulation index increases with decreasing wavelength till 2.8 cm, then decreases to about 20.2% at 7 mm. VLBI monitoring observations during 1993–1996 revealed the ejection of a new jet component, and gamma to radio variations of the flux density were observed in the first half of 1992, indicating a correlation of the jet activity with the variability of the broad-band electromagnetic spectrum of the source (Otterbein et al. 1998). It belongs to the S5 sample, and once showed weak IDV at a very low level (Kraus 1997). No variations were seen by Quirrenbach et al. (2000), and it has been further suggested to serve as a polarization calibrator because of its high degree of polarization;
- 0851+202 (OJ287): In this BL Lac object ($z = 0.306$, SLM), significant variations appear. Its modulation index increases with decreasing wavelength till 2.8 cm, then decreases to 16.3% at 1.3 cm;
- 0917+624: In this quasar ($z = 1.446$, SLM), smooth variations appear. Its modulation index varies with wavelength. It is an IDV source with a change in the variability properties (Kraus et al. 1999b);
- 0923+392 (4C 39.25): In this quasar ($z = 0.698$, SLM), smooth flux variations appear with a wavelength-independent modulation index of 3.3%;
- 0951+699: This galaxy ($z = 0.001$) shows no flux variations at all. It can be used as a secondary flux calibrator;
- 0954+658: In this BL Lac object ($z = 0.367$), a pronounced outburst appears. Its modulation index increases with decreasing wavelength till 3.6 cm, but decreases to 28.4% at 2.8 cm;
- 1039+811: In this quasar ($z = 1.254$, highly SLM), a flux increase appeared since early 1997 at 6 and 2.8 cm. Its modulation index is almost the same at 6 cm and 2.8 cm. It belongs to the S5 sample;
- 1150+812: In this quasar ($z = 1.250$, SLM), a monotonic flux increase appears at 21, 11, and 6 cm since 1994. Its modulation index is 8% at 6 cm. It belongs to the S5 sample;
- 1226+023 (3C 273): In this quasar ($z = 0.158$, highly SLM), smooth flux variations appear. Its modulation index is 6% at 6 cm;
- 1253−055 (3C 279): In this quasar ($z = 0.536$, highly SLM), smooth flux variation appears with a modulation index of 21% at 6 cm.
- 1328+307 (3C 286): This quasar ($z = 0.849$) shows no flux variations as expected. It has been used as a primary flux calibrator;
- 1409+524 (3C 295): This galaxy ($z = 0.461$) shows no flux variations as expected. It has been used as a primary flux calibrator;
- 1458+718 (3C 309.1): This quasar ($z = 0.905$, highly SLM) has modulation indices of 5% at 6 cm and 7.6% at 2.8 cm;
- 1641+399 (3C 345): In this quasar ($z = 0.594$, highly SLM), smooth flux variations appear. Its modulation index increases with decreasing wavelength;
- 1652+398: In this BL Lac object ($z = 0.034$), very slow and weak flux variations appear. Its modulation index is 3% at 11 cm, then increases with decreasing wavelength;
- 1739+522: In this quasar ($z = 1.379$), two (adjacent) continuous outbursts appear at 6 and 2.8 cm. Its modulation index varies with wavelength;
- 1749+701: In this BL Lac object ($z = 0.770$, SLM), a pronounced outburst appeared at 6 cm since mid-1996. But there were no measurements available at other wavelengths during the outburst. Its modulation index is about 9% at 6 cm. It belongs to the S5 sample;
- 1803+784: In this superluminal source, classified variously as a BL Lac object or quasar ($z = 0.684$), significant flux variations appear at 6 cm. Its modulation index decreases from 11.5% to 5.6% between wavelengths of 11 cm and 1.3 cm, but is almost the same at 6 and 3.6 cm. It belongs to the S5 sample;
- 1823+568: In this BL Lac object ($z = 0.664$, SLM), a monotonic flux decrease appears at both 6 and 2.8 cm. Its modulation index is 21% at 2.8 cm;
- 1928+738: In this quasar ($z = 0.302$, highly SLM), weak flux fluctuations appeared at most wavelengths

since 1994. Its modulation index mostly increases with decreasing wavelength. It belongs to the S5 sample, sometimes showing weak IDV (Heeschen et al. 1987; Kraus 1997), but no variations were seen by Quirrenbach et al. (2000);

- 2007+777: In this BL Lac object ($z = 0.342$, SLM), outbursts appeared at wavelengths longer than 2.8 cm. Its modulation index at the level of about $9 - 16\%$ varies irregularly with wavelength. It belongs to the S5 sample. Simultaneous variability on time scales of a few days was found at radio, infrared and optical regimes (Peng et al. 2000);
- 2105+420 (NGC 7027): This planetary nebula (denote PN in Table 1), shows no flux variations as expected. It has been used as a primary flux calibrator;
- 2200+420: In this BL Lac object ($z = 0.069$, SLM), a long-term (of more than 4 years at least) outburst on which many small flares are superimposed appeared. Its modulation index goes up by about 6% from 11 to 6 cm, then appears almost wavelength-independent at shorter wavelengths;
- 2251+158 (3C 454.3): In this quasar ($z = 0.859$, highly SLM), two small outbursts appeared since 1994. Its modulation index increases with decreasing wavelength.

5. Summary

We have presented the data from a long-term flux monitoring project carried out with the Effelsberg radio telescope, on a complete sample of 13 flat spectrum sources from the S5 Survey and 27 other sources. Our observational findings can be summarized as follows:

- Nearly all but the two steep spectrum sources 0835+580 and 0951+699 (excluding the six primary calibrator sources), are variable at most of the observing wavelengths in this 5.5 years monitoring period;
- Among the 32 variable sources, 15 of the 19 IDV sources (79%) show a relatively strong degree of variability (of above $\sim 7\%$ at 6 cm) and pronounced outbursts or significant flux variations. The rest 4 of the 19, 0153+744, 0917+624, 1652+398 and 1928+738, do not show strong long-term variability. On the other hand, most of the non-IDV sources (6 of the 9 sources, i.e. 67%) show a relatively weak variability (of below $\sim 7\%$ at 6 cm), but 2 sources 0212+735 and 1226+023 show different variability behavior at different wavelengths. This implies that IDV sources vary more strongly. Therefore we suggest that, one might identify an IDV source by its long-term variability characteristics (degree of variability and outbursts);
- As seen from Fig. 28, there is no dependence of the degree of variability on either source galactic latitude, or redshift, or superluminal motions; but both the degree of variability and the rate of occurrence of variability are higher when source spectra are flatter. It appears that there is a weak correlation between the degree of variability and the 6 to 2.8 cm spectral index;
- There is a trend showing that the degree of variability decreases with increasing wavelength, as demonstrated in Fig. 29, which is contrary to the expectations of ISS models, but consistent with shock models;
- The variability in BL Lac objects is stronger than that in quasars, as demonstrated in Fig. 30. Statistically, the mean variability at each wavelength in BL Lacs is about 2 times larger than that in QSOs. This is consistent with the unified scheme of the AGNs.

From this large although not complete sample, we conclude that, the long-term variability behavior does not follow the expectations of the ISS theory: the wavelength dependence and independence of the degree of variability on galactic latitude. Although it is generally accepted that the long term variations discussed here are intrinsic to the source, this result is a useful confirmation.

Acknowledgements. We thank I. Pauliny-Toth for critically reading the manuscript, the referee Dr. M.F. Aller for her valuable comments, R. Nan and Y. Han for helpful discussions, and A.P. Lobanov, E. Ros, J. Klare for helping with the observations. B. Peng thanks the NSF of China for supporting this research. This research has made use of the NASA's Astrophysics Data System Abstract Service and of the NASA/IPAC Extragalactic Database (NED) which is operated by the Jet Propulsion Laboratory, Caltech, under contract with the National Aeronautics and Space Administration.

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