THE ASTRONOMICAL JOURNAL VOLUME 105, NUMBER 5 MAY 1993

SURVEY OF A COMPLETE SAMPLE OF SOUTHERN EXTRAGALACTIC RADIO SOURCES

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Received 1992 November 20; revised 1992 December 9

ABSTRACT

We have observed a complete sample of bright Southern (with the declination 0° to −25°) BL Lacertae objects and quasars at 2.3, 4.8, 8.4, 22, 43, 90, and 230 GHz. By using statistical methods we have compared the properties of the different classes of quasars to see if there are significant differences in the radio spectrum and variability of these sources.

1. SAMPLE

The sources in this survey were all the flat spectrum ($\alpha_{2.7\,\mathrm{GHz}-5.0\,\mathrm{GHz}} > -0.5$) bright ($S_{10\,\mathrm{GHz}} > 1$ Jy) sources in the Kühr 1 Jy catalogue (Kühr *et al.* 1981) within the declination range 0° to −25°. The aim was to obtain at least two-epoch spectra of these sources at 22 and 43 GHz at Itapetinga, Brazil and at 90 and 230 GHz at SEST, Chile. Initially we used (Tornikoski *et al.* 1992) the fluxes given in the Kühr catalogue for the 10 GHz data, but these data were later replaced by the 8.4 GHz data obtained at Hartebeesthoek, South Africa.

The aims of this project were to increase our knowledge of these relatively rarely observed sources and of the high-frequency radio sources in general, and to use the sample for statistical studies (variablility versus classification, spectral shape versus classification and variability). Although a number of surveys of radio spectra and variability have been done (see Altschüler 1989 for a list of surveys up to 1987), and data sets at 90 GHz and still higher frequencies have recently become available (e.g., Edelson 1987; Steppe *et al.* 1988; Chini *et al.* 1988, 1989) ours is the first one to study the mm properties of a complete, flux limited sample.

The sample originally consisted of 50 sources. Here we present the results of 8 BL Lac objects (hereafter BLOs), 14 highly polarized quasars (hereafter HPQs) and 24 low polarized quasars (hereafter LPQs). The remaining four sources were either galaxies or without identification. In the main we have followed the classification of Burbidge & Hewitt (1992), complemented by latest optical polarization data. The source list with classifications is shown in Table 1.

2. OBSERVATIONS AND DATA REDUCTION

The observations were done at three different sites: the 230 and 90 GHz observations were done using the Swedish-ESO Submillimetre Telescope (SEST) in Chile, the 43 and 22 GHz at the Itapetinga observatory in Brazil, and the 2.3, 4.8, and 8.4 GHz observations at the Hartebeesthoek Radio Astronomy Observatory (HartRAO) in South Africa.

The SEST telescope is a 15 m Cassegrain-type antenna which is situated on the European Southern Observatory (ESO) site of La Silla, Chile, at an altitude of 2400 m and latitude 29° South. The telescope has been operational since 1987, and observations for this project were done between 1988 April and 1991 December. Because no continuum backend was available at SEST, the 90 GHz observations were done using a wide band (1 GHz) acousto-optic spectrometer as a backend. The 230 GHz observations were initially also done using the wide band AOS, but a bolometer was used for the observations since 1990 August when the SEST bolometer became operational. We obtained at least two-epoch spectra of all the sources at 90 GHz, but only about 25% at 230 GHz. The smaller number of the 230 GHz observations is mainly due to the sensitivity requirements and pointing problems at high frequencies.

The sources were observed using a dual beam switch mode and integrating 10–20 ON–ON pairs of 2*25 s. The result flux density was computed using calibrator sources,

TABLE 1. The classification of the sources and the calculated spectral indices and variability indices. (See text for the definition of the indices.)

Source	Type	$\alpha_{8.4-90}$ quiet	$\alpha_{8.4-90}$ simult.	$\alpha_{8.4-90}$ average	Var ΔS	Var χ^2	α_{90-230}
0003-06	BLO	-0.53	-0.18	-0.39	2.43		
0048-097	BLO	-0.16	0.10	0.00	1.12	0.63	-0.72
0138-097	BLO	-0.15	-0.15	-0.07	0.50	0.23	-0.05
0743-006	BLO	-0.73	-0.73	-0.54	1.05	0.38	
1514-24	BLO	-0.37	-0.18	-0.24	0.83	0.48	-0.57
2131-021	BLO	-0.46	-0.46	-0.36	0.83		-0.94
2155-152	BLO	-0.21	-0.21	-0.16	0.45		
2223-052	BLO	-0.33	-0.27	-0.22	2.39	1.20	0.06
0238-084	HPQ	-0.33	-0.33	-0.30	0.44	0.45	-1.19
0336-019	HPQ	-0.3	0.00	-0.13	1.03	0.43	
0403-132	HPQ	-0.43	-0.43	-0.32	0.44	0.26	-1.37
0420-014	HPQ	-0.06	0.18	0.19	1.63	1.54	-0.55
0454-234	HPQ	-0.38	-0.30	-0.31	1.93	0.69	-0.65
0458-020	HPQ	-0.03	-0.03	0.09	0.59	0.38	-1.06
0605-085	HPQ	-0.14	-0.10	-0.08	0.90	0.38	
1253-055	HPQ	-0.18	0.25	0.03	2.39	1.46	-0.75
1334-127	HPQ	-0.08	0.21	0.1	3.16	1.32	-0.29
1504-167	HPQ	-0.28	-0.28	-0.37	1.41	0.54	
1510-089	HPQ	-0.33	-0.13	-0.16	2.30	1.66	-0.45
1741-038	HPQ	-0.32	0.00	-0.11	1.50	0.64	
2243-123	HPQ	-0.12	-0.12	-0.05	0.88		-0.71
2345-167	HPQ	-0.47	-0.28	-0.34	0.55		-0.33
0112-017	LPQ	-0.36	-0.36	-0.22	0.38		
0122-00	LPQ	-0.40	-0.26	-0.28	0.53	0.33	-1.36
0135-247	LPQ	-0.30	-0.05	-0.17	0.80		
0202-17	LPQ	-0.39	-0.30	-0.35	3.23	0.96	-1.42
0414-189	LPQ	-0.45	-0.14	-0.31	1.10		-0.50
0440-00	LPQ	-0.53	-0.33	-0.41	0.93	0.77	-0.08
0511-220	LPQ	-0.59	-0.38	-0.50	0.54		
0834-20	LPQ	-0.55	-0.47	-0.48	0.19		
1032-199	LPQ	-0.48	-0.39	-0.26	0.8		
1045-18	LPQ	-0.12	-0.12	-0.06	0.23		
1127-14	LPQ	-0.52	-0.37	-0.50	1.03	0.34	
1145-071	LPQ	-0.65	-0.64	-0.54	0.56		
1148-00	LPQ	-0.46	-0.33	-0.39	0.36		
1243-072	LPQ	-0.37	-0.36	-0.34	0.20		
1302-102	LPQ	-0.37	0.16	0.12	2.52		
1354-152	LPQ	-0.42	-0.19	-0.29	0.85		
1406-076	LPQ	-0.27	-0.20	-0.27	0.24		
2008-159	LPQ	-0.27	-0.24	-0.24	0.41	0.24	-1.40
2126-15	LPQ	-0.58	-0.58	-0.58			
2128-123	LPQ	-0.63	-0.41	-0.46	0.76	0.36	
2203-18	LPQ	-0.75	-0.69	-0.72	0.39	0.09	
2216-03	LPQ	-0.50	-0.44	-0.40	0.72		
2227-08	LPQ	-0.62	-0.62	-0.36	7.56	1.10	
2354-11	LPQ	-0.50	-0.50	-0.50			
0539-057	EF	-0.62		-0.55	0.32		
1213-17	_	-0.64		-0.42	1.85		
1936-15	EF	-0.38		-0.03	1.49		
2331-240	Gal	-0.02		0.14	0.63		

mainly planets, for reference. The error of the observation consisted of the rms error of the measurement and an additional error due to pointing and flux calibration uncertainties, which is estimated to be about 4%.

The 2.3, 4.8, and 8.4 GHz data were obtained with the 26 m radio telescope at Hartebeesthoek, South Africa, latitude 26° South. The observations at 4.8 and 8.4 GHz were made in a dual beam Dicke switch mode and with a single beam noise adding radiometer at 2.3 GHz. A five point stepping program was used with the flux from each source corrected for pointing offsets. The measurements were calibrated to the Baars scale of 3C 218. The error of an observation consisted of measurement errors and proportional errors calculated from deviation in observations of 3C 348. All the data were obtained between January and August 1991.

The 22 and 43 GHz observations were made between 1988 February and 1990 November with the 13.7 m radome enclosed Itapetinga radiotelescope in Brazil, using drift scans through the source.

3. ANALYSIS

The analysis was carried out to find out if there are significant differences in the average radio properties of different classes of sources, detectable by statistical analysis. We were looking for correlations between different radio properties to find out how this all fits the orientation dependent scenarios. Only the 90 and 230 GHz SEST data and the 8.4 GHz HartRAO data were used in the statistical analysis, and the sources which had not been identified as HPQs, LPQs, nor BLOs were excluded. Data with $S/\sigma < 4.0$ were discarded from the sample. For the analysis we computed spectral indices, several different variability indices, and time scales of variability.

We used spectral indices α ($S \propto \nu^{\alpha}$) between 8.4 and 90 GHz and between 90 and 230 GHz to measure the overall shape of the spectrum. We calculated three different sets of the 8.4–90 GHz spectral indices: for one of them we used all the 90 GHz data points (the average α), for another one we used the minimum flux values at 90 GHz (the "quiet" α), and for the third set of indices we used the data points obtained at a time closest to the HartRAO observations (the "simultaneous" α).

In order to investigate the variability of the source, we initially computed the fractional variability index $\Delta S = (S_{max} - S_{min})/S_{min}$ which indicates how much the flux changes between observations and is the estimate of the relative strength of the variable and nonvariable components in the source. We had more than four observations of 54% of the sources, in which case we also computed the χ^2 variability index used by Kesteven and others (Kesteven *et al.* 1976).

The statistical tests that we used were the Kruskal–Wallis significance test to evaluate the degree of association between any groups of samples, and the Spearman rank correlation to see if there are any correlations between the variability and the spectral index of any classes of sources.

4. RESULTS

4.1 The Radio Spectrum

The radio spectra of all the sources in the original sample are plotted in Fig. 1. For each source we have included all the available data from the Kühr catalogue, the HartRAO observations at 2.3, 4.8, and 8.4 GHz, the Itapetinga observations at 22 and 43 GHz and the SEST observations at 90 and 230 GHz. The Kühr data are plotted by using filled circles, all the other data are marked by open boxes. The Kühr data have been obtained between the years 1966 and 1980, all of our data have been obtained during or after the year 1988.

In general, the old catalogue data and our new measurements agree quite well, the differences being comparable to the range of variations we observe in our own monitoring data. Thus, the overall shape of a spectrum shows constancy over 10–20 years; flat-spectrum sources still remain flat-spectrum sources, and sources with basically straight spectra (for example, 0403−132) still have straight spectra.

In an effort to derive typical cm-to-mm spectra for the different classes of sources we have also calculated the median minimum fluxes at each observing frequency for the HPQ, LPQ, and BL Lac subsamples. In order to demonstrate the range of variation within a class we have scaled the quiet spectrum of each source by using the median values between 1.4 and 10.7 GHz for each class of sources and then superposed the spectra (Fig. 2). According to these plots the HPQs have a flat radio spectrum up to 40–90 GHz, whereas the spectra of the LPQs and BLOs steepens at lower frequencies, around 20 and 30 GHz, respectively. These differences are also reflected in the calculated spectral index distributions (see below).

4.2 Spectrum Versus Classification

The 8.4–90 GHz and 90–230 GHz average spectral index distributions of different classes of sources are shown in Figs. 3 and 4, respectively. It can be seen that the flattest spectra are found among the HPQs, and the steepness tends to increase when proceeding towards the BLOs and LPQs. The results were basically the same when using the assumed quiet spectral index or the spectral index calculated from the semi-simultaneous observations.

When comparing the classes it is evident that the LPQs and HPQs are clearly distinguishable ($P=99.6\%$) from each other, whereas the BLOs cannot be distinguished ($P=87\%$) from the other two classes.

Due to relatively few observations at 230 GHz no statistical analysis was done for the 90–230 GHz spectral indices of the different classes of sources.

The median 8.4–90 GHz average spectral index is

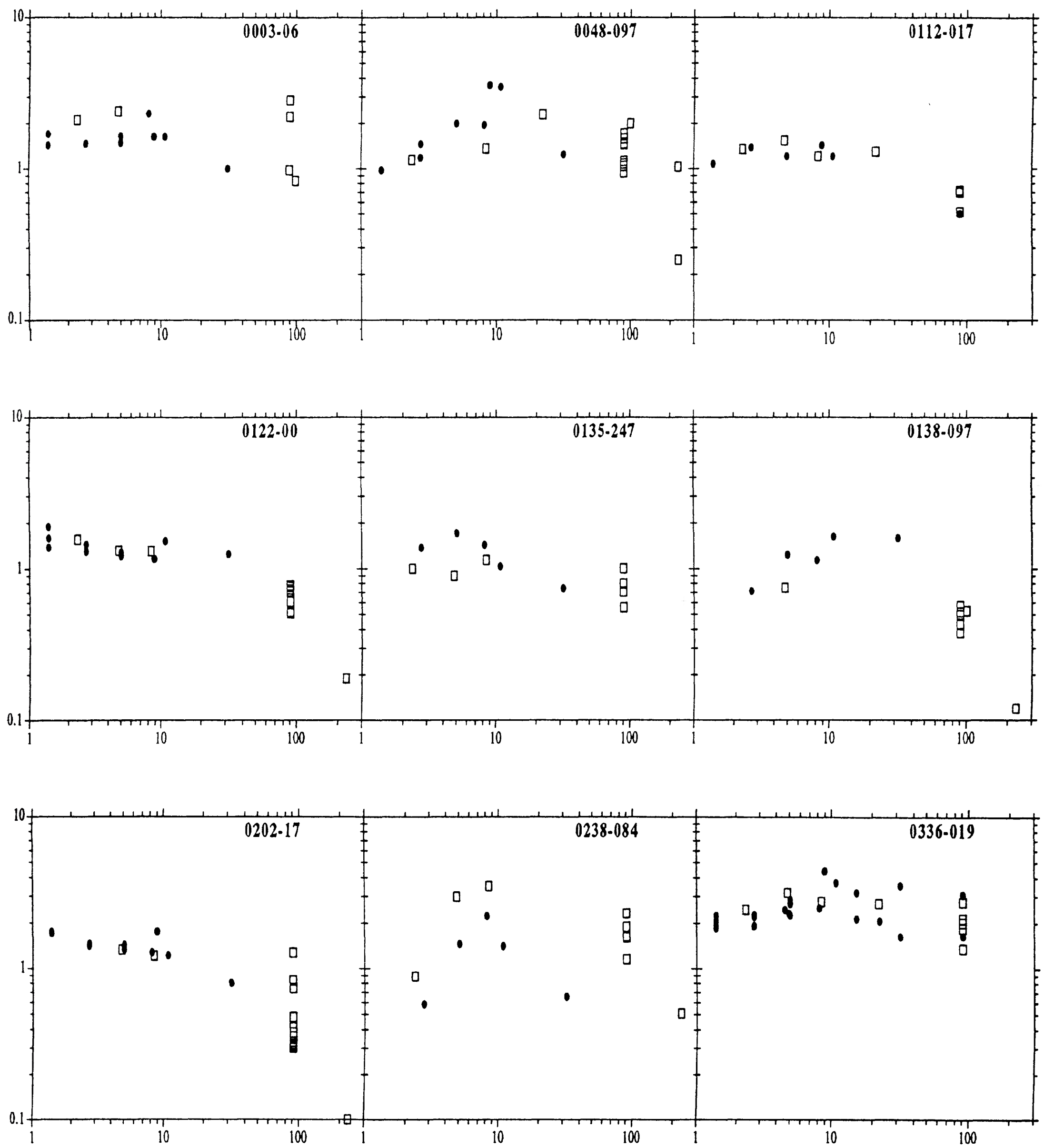

FIG. 1. The radio spectra, flux (Jy) vs frequency (GHz). The data from the Kühr catalogue are plotted by using filled circles and the data obtained for this survey at HartRAO, Itapetinga, and SEST are marked by open boxes.

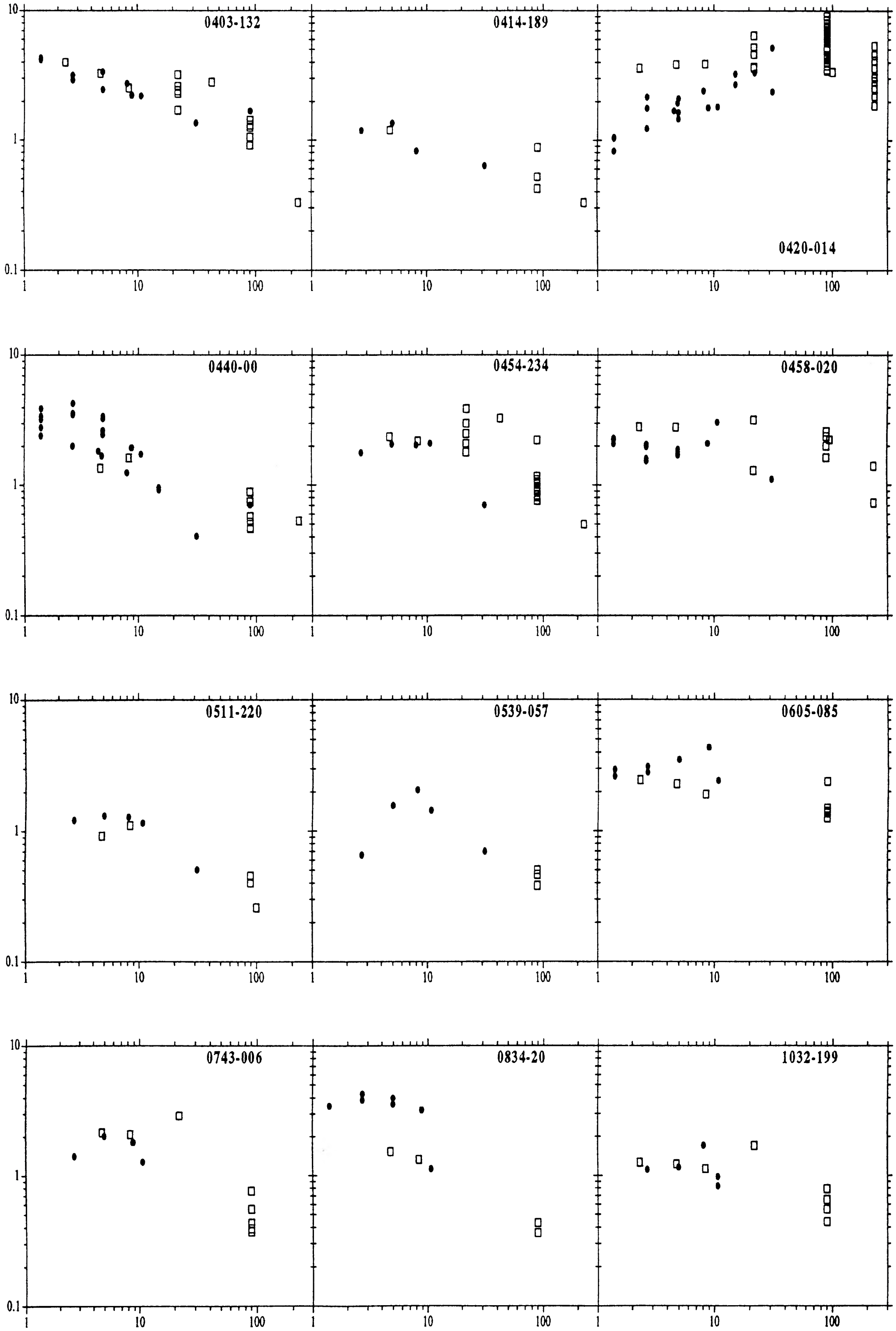

FIG. 1. (continued)

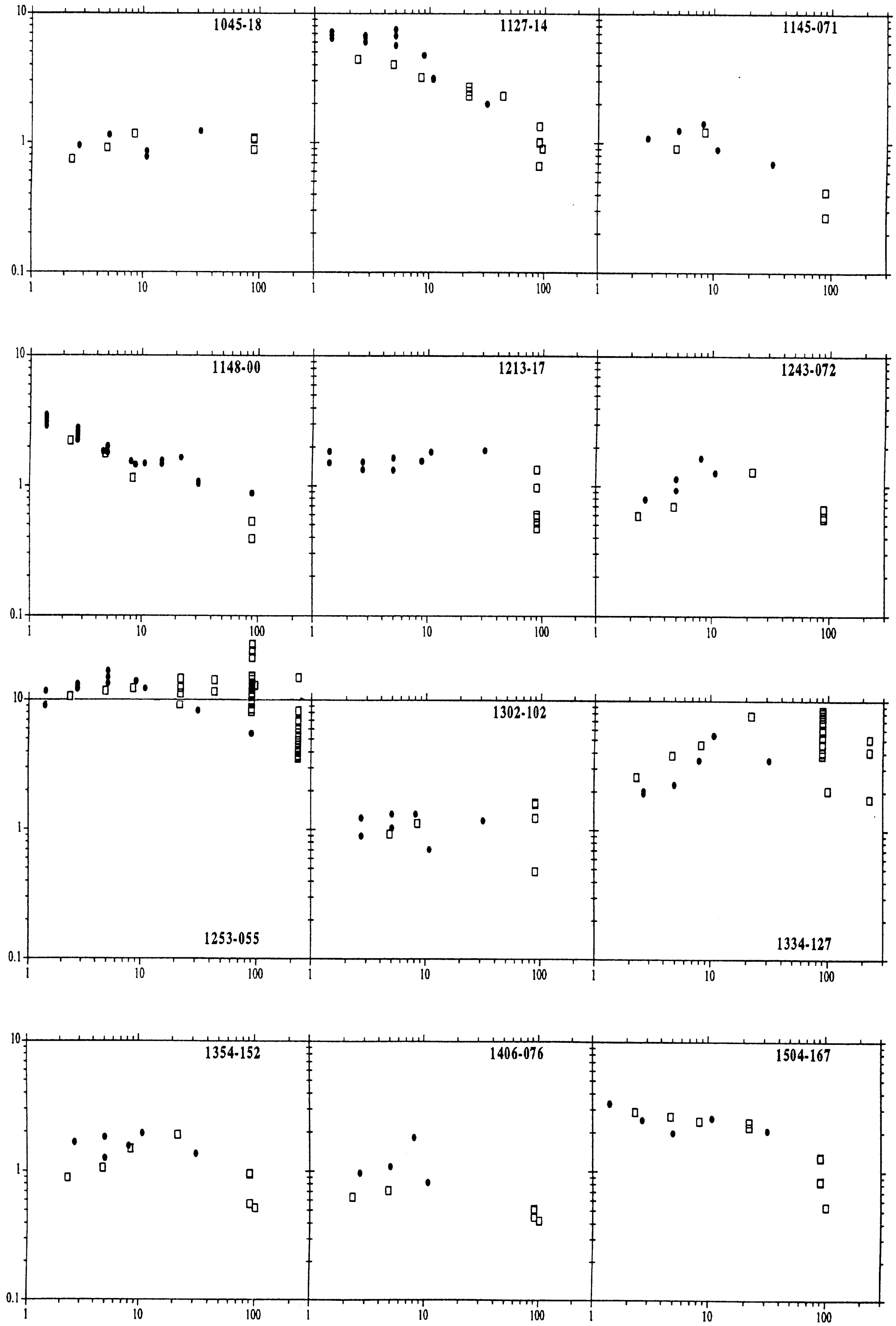

FIG. 1. (continued)

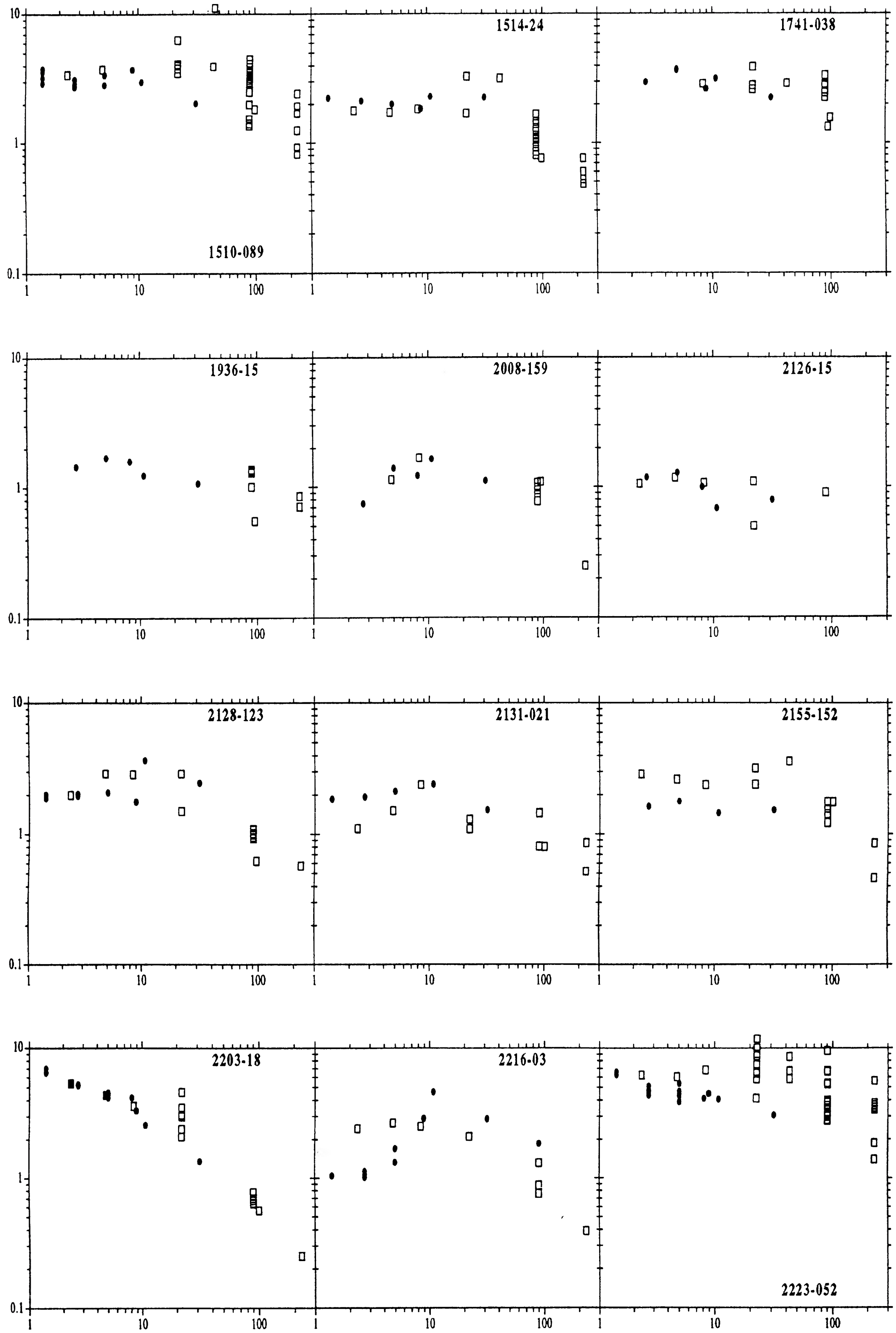

FIG. 1. (continued)

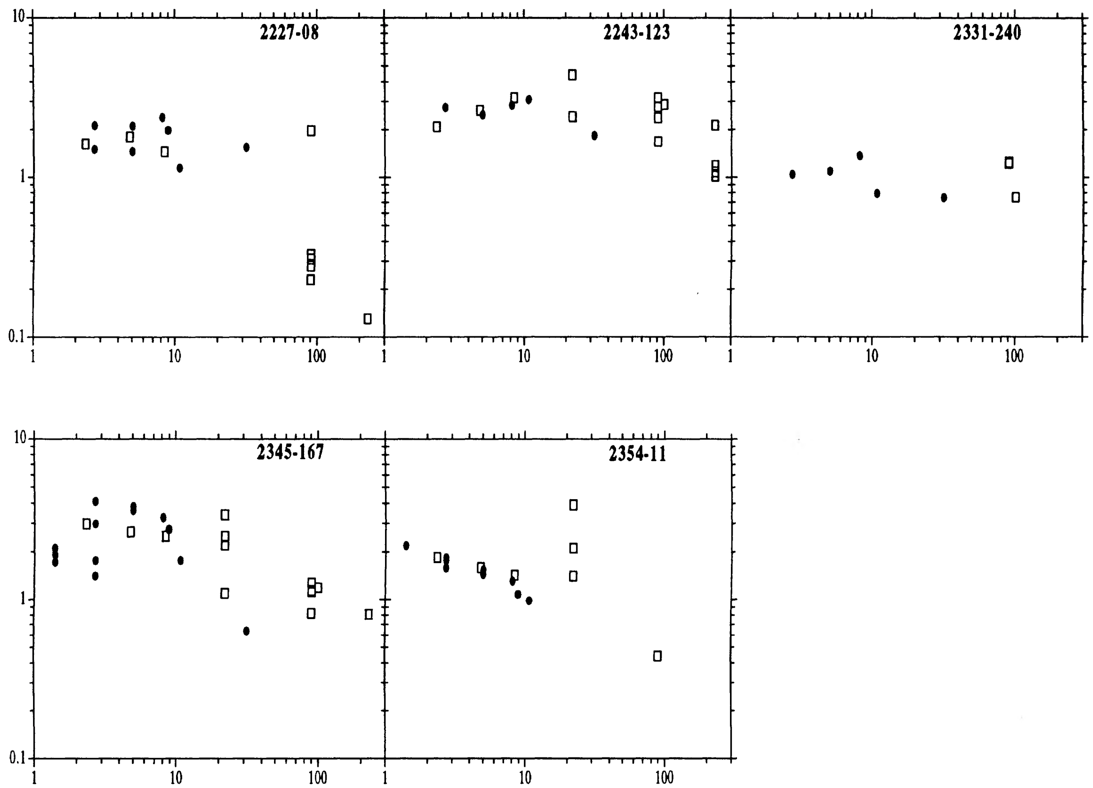

FIG. 1. (continued)

−0.25 and for the 90–230 GHz −0.7. If we exclude outbursts which tend to flatten the spectra, the median indices are even steeper (−0.45 and −0.85, respectively). The lack of flat high frequency quiet spectra (also apparent in Fig. 1) indicates that there are no persistent strong components peaking at mm/submm regions.

The innermost radio "core" seen unresolved even in high-resolution *VLBI* maps, sometimes called the core-jet or the milliarcsecond jet, appears to be the most compact major radio structure in quasars. Judging from our mm-spectra, even the most compact of these become optically thin in the vicinity of 100 GHz.

4.3 Variability Versus Classification

In order to examine the differences in the variability between the three classes, we used the fractional variability index ΔS and for the sources with more than four observations also the χ^2 index. The ΔS vs classification plot is shown in Fig. 5.

In the case of the ΔS index the range of distribution is wide, the most variable source according to this index being an LPQ (2227−08), the variation of which has occurred in a relatively long time scale, approximately three years. On the other hand it can be seen that the low end of the variability is mainly occupied by the LPQs. Only the HPQ and LPQ classes are marginally distinguishable ($P = 93\%$) from each other.

When using the χ^2 index the tendencies were similar. We must notice however that only the sources with more than four observations were used for these calculations, and because we in general had more observations of the HPQs than the LPQs the source distribution is now different from the other calculations.

4.4 Variability Versus Spectrum

We examined the possible correlation between the variability and the spectral indices by calculating both variability indices (the ΔS and χ^2 indices) and all the three spectral indices (average, quiet, simultaneous) for different sets of analysis.

For the HPQs we, in general, found a positive correlation between spectral flatness and variability. The most significant correlations were found between the ΔS index and the simultaneous spectral index and the χ^2 index and the simultaneous spectral index (99.2% and 94%, respectively). The ΔS vs simultaneous spectral index correlation is shown in Fig. 6.

For the LPQs we found earlier (Tornikoski *et al.* 1992) a rather surprising *negative* correlation between the variability and the spectral index. When using the now avail-

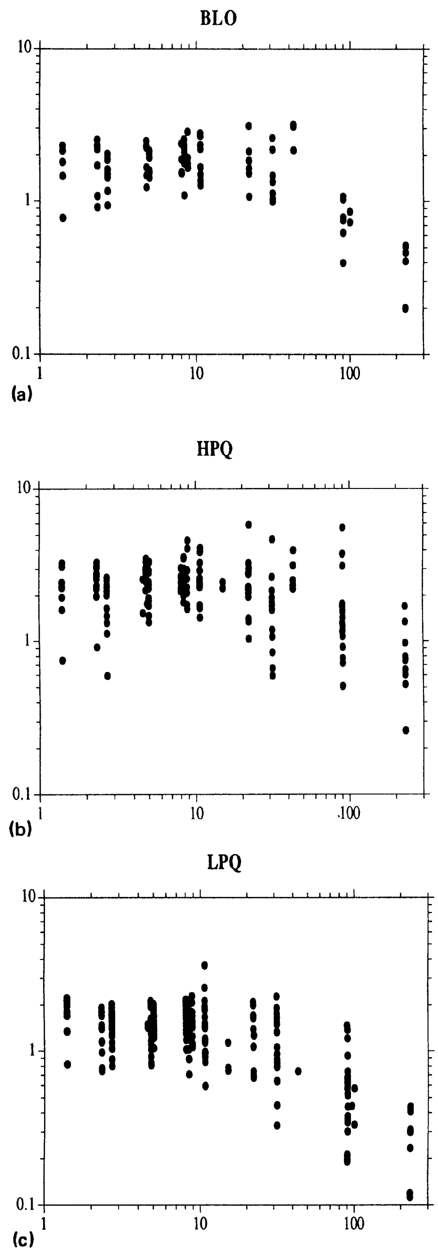

FIG. 2. (a)–(c) The general spectral shapes of the three different classes of sources. For each source the quiet spectrum is used and the data points are scaled according to the 1.4–10.7 GHz data of the median spectrum of each class.

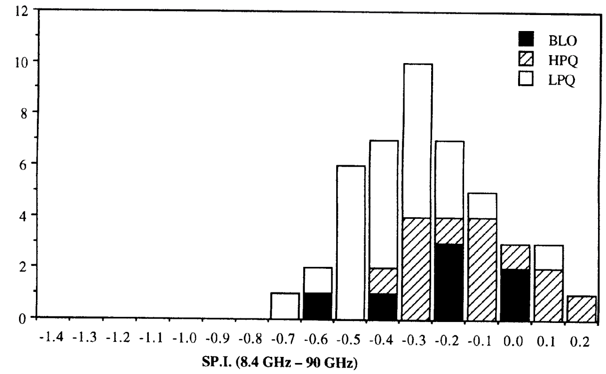

FIG. 3. The average spectral index α(8.4–90 GHz) distribution of the different classes of sources.

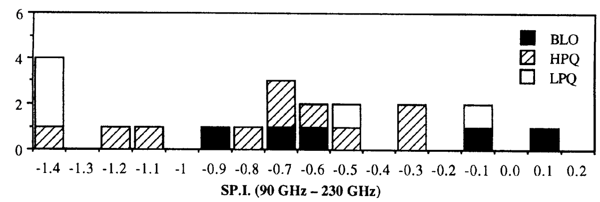

FIG. 4. The average spectral index α(90–230 GHz) distribution of the different classes of sources.

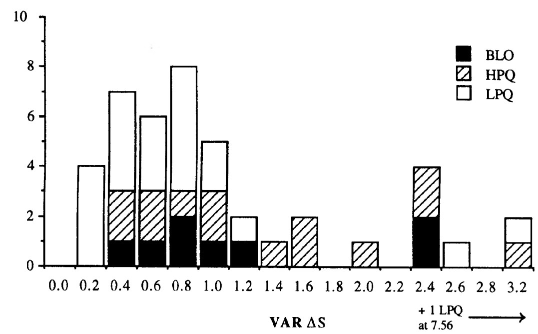

FIG. 5. The variability ΔS distribution of the different classes of sources.

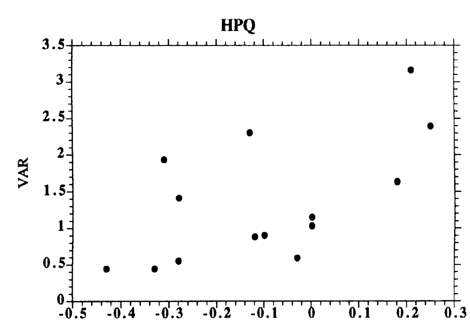

FIG. 6. The variability ΔS vs the simultaneous spectral index correlation of the HPQs.

able additional data, the negative correlation between the ΔS index and the quiet spectral index is not statistically significant ($P=84\%$) any more.

4.5 Variability Time Scales

In order to determine the typical time scales of variability, we computed for each source the variability $V=(S1-S2)/[0.5*(S1+S2)]$ between all epochs of observations

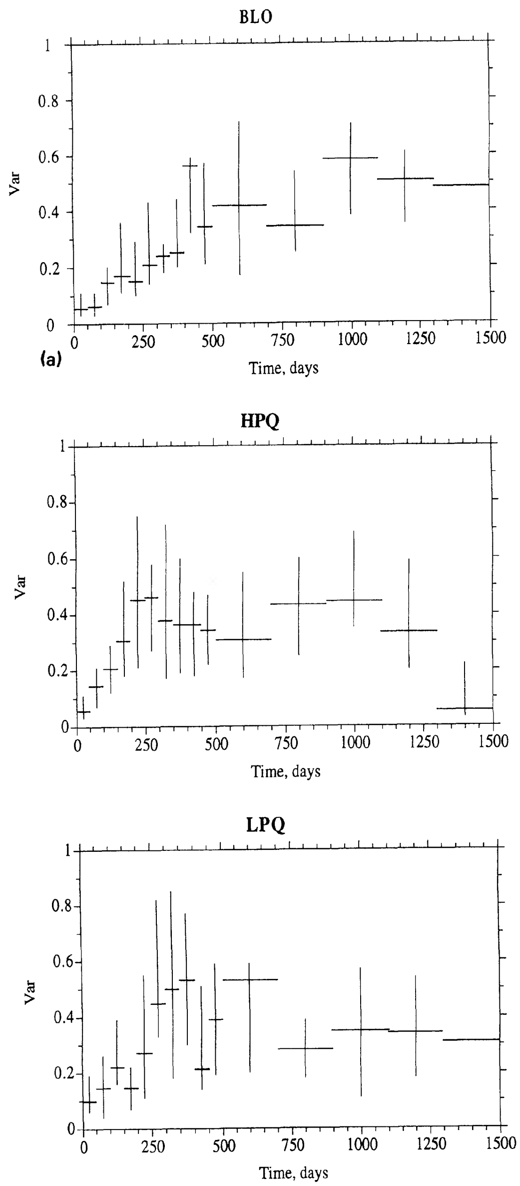

FIG. 7. The variability V of the different classes of sources (a) to (c), divided into bins of 50–200 days. The width of the horizontal bars shows the width of each bin, the position of the horizontal bar is the median variability, and the vertical bar shows the variability limits (1st to 3rd quartile).

and plotted it against the time between the observations by using time bins of 50 to 200 days. The results are plotted in Fig. 7.

It can be seen that the variability of the HPQs and LPQs increases more rapidly than the variability of the BLOs. The HPQs and LPQs reach their peak variabilities at 200–300 days, whereas in the case of the BLOs the peak variabilities are reached at around 500 days, resulting in longer total time scales of variation.

On the other hand we can see that even in shorter time scales, in the order of 100–200 days, there are already significant changes in the fluxes of several sources among all the classes.

5. DISCUSSION

This paper extends the survey described in Tornikoski *et al.* (1992). Now we had more data points for most of the sources, used several different indices in order to approach the problem in different ways, and we had replaced the 10.7 GHz data from the Kühr catalogue by the 8.4 GHz HartRAO data, thus having data which are, if still not quite simultaneous, at least closer in time at different frequencies.

The general trend in our analysis is that the HPQs and LPQs seem to fall into two classes, which can be distinguished from each other by the means of statistical analysis of their radio properties. Thus, the purely observational optical HPQ/LPQ division is also reflected in the radio properties and must be an indication of some fundamental property of these sources.

The result from comparing the spectral index with the classification comes as no surprise; the flattest spectra are found among the HPQs and the steepest among the LPQs. We have earlier found the same result in our lower frequency studies (Valtaoja *et al.* 1988, 1992; Wiren *et al.* 1992).

The variability versus spectrum analysis has shown a positive correlation between the variability and the spectral index in the case of the HPQs. This agrees with the orientation-dependent models (cf. Eckart *et al.* 1989; Valtaoja *et al.* 1992).

When comparing the variability with the classification it seems that the LPQs have the smallest variabilities and the HPQs tend to have the greatest variabilities, even though the latter conclusion is somewhat blurred by occasional highly variable LPQs. Again this can be understood if the HPQs have smaller viewing angles than the LPQs and are therefore more relativistically boosted.

In the earlier analysis we concluded that the variability of the BLOs is not very strong at higher frequencies. This still seems to hold true to the point that the BLOs are not found among the most variable sources, but they do not have the smallest variability indices either. On the whole the unfortunately small sample of BLOs makes it very difficult to draw precise conclusions of their variability behavior in general, even though the rather large number of observations of some BLOs leads us to conclude that the greatest variability indices are not to be found among them. In any case it is clear that neither especially rapid nor strong radio variability are characteristic of BLOs as a class (cf. Altschüler 1982, 1983; Valtaoja *et al.* 1992; Wirén *et al.* 1992).

The variability time scales show us that the variability seems to increase in time only up to some months. The explanation to this may be that the high frequency variations are dominated by repeated outbursts of duration of 200–400 days. It seems that the BLOs have longer time scales of variation than the HPQs and LPQs, the greatest variability seen between epochs which are more than two years apart. We must, however, also notice that already in relatively short time scales, approximately 100 days, rather drastic variations ($V_{max} \approx 0.4$) can be seen in all classes of sources. These results suggest that in order to notice the short-scale variations we must monitor the sources frequently enough, that is, the observations should not be much more than a month apart from each other. On the other hand in some sources the greatest variations occur in time scales of several years, which means that the monitoring should be patiently continued for a period of time sufficiently long, at least 2 to 3 years, in order to observe the different kinds of variations.

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