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Variability of Extragalactic Objects in Relation to Redshift, Color, Radio Spectral Index and Absorption Lines

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Abstract. Optical variability of extragalactic objects, viz., QSOs, BL Lacs and Seyfert galaxies has been monitored systematically over an appreciable period of time and a large amount of data have accumulated. The present work reports results of investigations involving statistical analysis of updated data on relationships between variability and various observed properties of the objects, viz., redshift, color indices, radio spectral index and absorption lines. It is found that at high frequencies (rest frame) radio spectral index does not change significantly with the degree of variability. However, the degree of variability depends on redshifts. On the other hand, presence or absence of absorption lines is significantly associated with variability for QSOs with larger redshifts ($z > 1.0$), while no such relationship exists for QSOs at smaller redshifts ($z < 1.0$) or other objects. Correlation between color indices and redshifts depends on the degree of variability and the sample chosen for the color index.

Key words. Galaxies active: galaxies — quasars: general.

1. Introduction

Optical variability is one of the major criteria used in understanding the characteristics of QSOs and related extragalactic objects. Investigations of its association with other properties of different types of closely related objects are expected to throw light on the true nature of such objects and on any possible link between them. Optical variability of extragalactic objects has therefore been monitored systematically over an appreciable period of time.

Accordingly, objects have been classified into three types depending on their degree of variability (V) based on a criteria defined by Penston & Cannon (1970) and Basu (1973, 1980a), viz., $V = 0$ (non-variables, $\Delta m \leq 0^m.2$, the smallest value of Δm that can be detected without any ambiguity), $V = V$ (moderate variables, $0^m.2 < \Delta m < 1^m.0$, on a time scale of few weeks or months) and $V = OVV$ (optically violent variables, $\Delta m \geq 1.0$, over a period of few days or weeks). In the above classification, the magnitude change refers to peak to peak variations and the apparent magnitudes (m) are measured in photographic blue band or Johnson B filter. The degree of variability has been shown earlier to be related to redshifts, colors, radio spectral index, and presence or absence of absorption lines. Thus OVV quasars were found to exhibit flat radio spectra while the other two classes inclined to show steeper

Table 1. The data base.

Source	Name	Type	Var	z_e	z_a	$(B-V)^*$	$(U-B)^*$	α
$0003+158$	PHL 658	Q	OVV?	0.450	N	0.20	−0.83	−0.60
$0007+106$	III Zw2	S	OVV	0.090	-	0.51	−0.83x	0.99
$0017+154$	3C 9	Q	0	2.012	Y	0.46	−0.52	1.05
$0024+349$	OB 338	S	0	0.333	-	-	-	−0.32
$0035+121$		B	V	-	-	-	-	-
$0048-097$	PHL 856	B	V	>0.20	N	0.37x	−0.66x	0.43
$0056-001$	PHL 923	Q	0	0.717	N	0.20x	−0.73x	−0.46
$0058+019$	PHL 938	Q	0	1.961	Y	0.57	−0.66	-
$0106+010$	4C 01.02	Q	0	2.107	N	0.35	−0.53	0.69
$0109+224$		B	V	-	N	0.34x	−0.63x	1.19
$0119-046$	4C 04.04	Q	0	1.969	Y	0.67	−0.49	−0.38
$0127+233$	3C 43	Q	V	1.459	N	-	-	−0.71
$0128+074$	PHL 3375	Q	V	0.39	N	0.32	−0.50	-
$0130+033$	PHL 1027	Q	0	0.363	N	−0.03x	−0.77x	-
$0133+476$	OC 577	Q	V	0.859	N	-	-	-
$0134+329$	3C 48	Q	V	0.367	N	0.40	−0.52	−0.85
$0135-057$	PHL 1078	Q	V	0.308	N	−0.06	−0.65	-
$0137+012$	PHL 1093	Q	V	0.258	N	−0.03	−0.87	−0.37
$0139+061$	PHL 3632	Q	V	1.479	N	0.22	−0.63	-
$0141+339$	4C 33.03	Q	0	1.455	Y	-	-	−1.07
$0147+089$	PHL 1186	Q	V	0.27	N	−0.02x	−0.83x	-
$0148+090$	PHL 1194	Q	V	0.299	N	−0.14	−0.89	-
$0151+048$	PHL 1222	Q	0	1.923	Y	0.67	−0.57	-
$0151+045$	PHL 1226	Q	V	0.404	Y	0.41x	−0.78x	-
$0159-117$	3C 57	Q	V	0.680	N	0.25	−0.84	0.74
$0202-170$		Q	V	1.740	N	-	-	−0.13
$0215+015$		B	OVV	1.715	Y	-	-	0
$0219+428$	3C 66A	B	V	0.444	N	0.33x	−0.58x	-
$0222-234$	MSH $02-27$	Q	V	0.23	-	-	-	-
$0226-038$	PHL 1305	Q	0	2.064	Y	0.29	−0.60	−0.24
$0229+130$	4C 13.14	Q	0	2.065	Y	0.25x	−0.73x	−0.24
$0232-042$	PHL 1377	Q	V	1.434	Y	0.20	−0.66	0.49
$0235+165$	AO	B	OVV	0.94	Y	0.96x	0.14x	1.03
$0237-230$		Q	0	2.225	Y	0.35	−0.81	0.48
$0301-243$		B	V	-	-	-	-	−0.47
$0306+102$	OE 110	B	OVV	0.863	-	0.45x	−0.40x	0.56
$0323+022$		B	0	0.147	-	0.50x	−0.50x	-
$0333+321$	NRAO 140	Q	0	1.258	N	-	-	−0.19
$0336-019$	CTA 26	Q	V	0.852	N	0.55x	−0.82x	0.25
$0338-214$		B	V	-	N	-	-	0.21

Table 1. (*Continued*)

Source	Name	Type	Var	z_e	z_a	$(B-V)^*$	$(U-B)^*$	α
0340 + 048	3C 93	Q	V	0.357	N	0.35	−0.50	−0.95
0349 − 146	MSH 03−19	Q	0	0.614	N	0.43	−0.72	1.13
0350 − 073	3C 94	Q	0	0.968	N	0.44x	−0.68x	−0.94
0403 − 130		Q	OVV?	0.571	N	0.28x	−0.57x	0.04
0405 − 121	MSH 04−12	Q	V	0.574	N	0.18	−0.60	−0.28
0414 + 009		B	V	0.287	N	0.48x	−0.70x	-
0414 − 060	3C 110	Q	0	0.781	N	0.29	−0.70x	−0.83
0420 − 014	OF O35	Q	OVV	0.915	Y	0.48x	−0.32x	−0.80
0422 + 004	OF 038	B	OVV	-	N	0.10x	−0.49x	0.36
0433 + 052	3C 120	S	OVV	0.033	-	0.67x	−0.77x	0.09
0440 − 033	NRAO 190	Q	OVV	0.844	N	0.37x	−1.05x	−0.64
0454 − 220		Q	V	0.534	Y	0.06x	−0.62x	−0.97
0513 − 002	AKN 120	S	0	0.033	-	0.38x	−0.77x	-
0518 + 165	3C 138	Q	0	0.759	N	−0.04	−0.64	0.57
0538 + 498	3C 147	Q	V	0.545	N	−0.05	−0.82	0.73
0642 + 449	OH 471	Q	V	3.408	Y	1.08x	1.70x	−0.81
0710 + 118	3C 175	Q	V	0.768	N	0.13	−0.78	0.98
0711 + 356	OI 318	Q	V	1.626	N	-	-	−0.32
0725 + 117	3C 181	Q	V	1.382	Y	0.24	−0.88	−0.26
0735 + 170	DA 237	B	OVV	>0.424	Y	0.47x	−0.58x	0.05
0736 + 017	OI 061	Q	V	0.191	N	0.43x	−0.77x	−0.10
0738 + 313	OI 363	S	V	0.631	Y	0.07x	−0.61x	0.24
0740 + 380	3C 186	Q	V	1.063	N	0.19	−0.81	0.67
0752 + 258	OI 287	Q	V	0.456	N	0.55x	−0.35x	−0.27
0754 + 100	OI 090.4	B	V	0.66	N	0.43x	−0.66x	0.58
0802 + 103	3C 191	Q	0	1.952	Y	0.29	−0.72	0.91
0805 + 046	4C 05.34	Q	V	2.88	Y	0.37x	−0.04x	−0.63
0809 + 483	3C 196	Q	V	0.871	Y	0.45	−0.43	0.89
0812 + 020	4C 02.23	Q	V	0.402	N	0.18x	−0.77x	−0.63
0818 − 128	OJ 131	B	OVV	-	N	0.30x	−0.40x	−0.02
0829 + 046	OJ 049	B	OVV	0.18	N	0.70x	−0.37x	0.07
0833 + 654	3C 204	Q	0	1.112	N	0.58	−0.78	0.61
0837 − 120	3C 206	Q	OVV	0.200	N	0.02x	−0.85x	−0.56
0850 + 140	3CR 208	Q	V	1.11	N	0.26	−0.79	−0.93
0851 + 202	OJ 287	B	OVV	0.206	N	0.39x	−0.64x	0.11
0906 + 015	4C 01.24	Q	OVV	1.018	N	0.47x	−0.85x	0.11
0922 + 149	4C 14.31	Q	V	0.896	N	0.37	−0.51	−0.38
0953 + 254	OK 290	Q	V	0.712	N	0.25x	−0.53x	0.80
0955 + 326	3C 232	Q	OVV	0.530	Y	0.08	−0.68	0.22
0957 + 003	OK 096	Q	V	0.907	Y	0.29	−0.69	−0.62

Table 1. (*Continued*)

Source	Name	Type	Var	z_e	z_a	$(B-V)^*$	$(U-B)^*$	α
0957 + 561	A	Q	0	1.413	Y	-	-	-
0957 + 561	B	Q	V	1.425	Y	-	-	-
1004 + 130	OL 331	S	OVV?	0.24	-	0.07	−0.82	−0.70
1019 + 309	OL 333	Q	V	1.319	N	0.26x	−0.77x	−0.64
1021 − 006		Q	V	2.547	N	0.20x	−0.22x	−0.39
1040 + 123	3CR 245	Q	V	1.029	N	0.31	−0.67	−0.67
1048 − 090	3C 246	Q	V	0.344	N	0.09	−0.37	−0.94
1049 + 215	4C 21.28	Q	V	1.300	N	-	-	−0.19
1055 + 018	4C 01.28	Q	V	0.888	N	0.46x	−0.53x	0.13
1055 + 201	4C 20.24	Q	V	1.110	N	0.36	−0.84	0.82
1100 + 772	3C 249.1	Q	V	0.311	N	−0.09	−0.64	−0.97
1101 + 384	Mark 421	B	V	0.031	N	0.51x	−0.55x	0.33
1116 + 128	4C 12.39	Q	V	2.118	Y	0.35	−0.61	−0.33
1119 + 183	OM 133	Q	V	1.040	N	-	-	0.00
1127 − 145	OM 146	Q	0	1.187	N	0.23	−0.73	−0.19
1137 + 660	3C 263	Q	OVV	0.652	Y	0.29	−0.68	0.80
1147 + 245	OM 280	B	0	>0.20	N	0.52x	−0.60x	0.39
1148 − 001	4C 00.47	Q	V	1.980	Y	0.37	−1.20	−0.49
1150 + 497	4C 49.22	Q	0	0.334	N	0.30x	−0.97x	−0.58
1156 + 295	4C 29.45	Q	OVV	0.729	N	0.39x	−0.50x	−0.42
1206 + 439	3C268.4	Q	V	1.400	Y	0.58x	−0.69x	−0.94
1215 + 303	ON 325	B	OVV	0.237	N	0.46x	−0.61x	−0.19
1217 + 023	ON 029	Q	OVV	0.24	Y	−0.06	−0.77	0.04
1218 + 304	RS 4	B	V	-	N	0.65x	−0.50x	-
1218 + 329	3C 270.1	Q	0	1.519	Y	0.34	−0.65	0.85
1219 + 285	ON 231	B	OVV	0.102	N	0.61x	−0.54x	-
1226 + 023	3CR 273	Q	V	0.158	Y	0.13	−0.81	0.08
1229 − 021	4C 02.55	Q	V	1.038	Y	0.55	−0.66	−0.47
1229 + 202		S	V	0.064	-	0.27x	−1.02x	-
1237 − 101	ON 162	Q	V	0.753	N	−0.03x	−0.75x	0.00
1246 + 377	BSO 1	Q	V	1.266	Y	0.34	−0.49	-
1246 + 346	B 46	Q	V	0.271	N	0.35	−0.71	-
1248 + 337	BSO 2	Q	V	0.186	N	0.32	−1.02	-
1252 + 119	ON 187	Q	0	0.870	N	0.20	−0.75	−0.30
1252 + 359	B 114	Q	V	0.210	N	0.08	−0.77	-
1253 − 055	3C 279	Q	OVV	0.536	N	0.35	−0.71	−0.41
1255 + 353	B 154	Q	V	0.183	N	0.27	−0.72	-
1256 + 357	B 194	Q	0	0.894	Y	0.67	−0.58	−2.66
1257 + 346	B 201	Q	0	1.375	N	0.29	−0.53	-
1259 + 344	BSO 6	Q	0	1.956	N	0.29	−0.78	-

Table 1. (*Continued*)

Source	Name	Type	Var	z_e	z_a	$(B-V)^*$	$(U-B)^*$	α
1304 + 374	B 312	Q	0	0.450	N	0.28	−0.81	-
1308 + 3266	OP 313	B	OVV	0.996	Y	-	-	0.20
1311 + 362	BSO 11	Q	0	2.084	Y	0.28	−0.64	-
1318 + 290	Ton 155	Q	0	1.703	Y	0.12x	−0.90x	-
1318 + 290	Ton 156	Q	0	0.549	N	0.08x	−0.66x	-
1328 + 254	3C 287	Q	0	1.055	N	0.51	−0.47	0.54
1347 + 214	UM 614	S	0	0.033	-	0.89x	-	-
1354 + 195	4C 19.44	Q	OVV?	0.720	Y	0.25	−0.64	−0.06
1402 − 012	UM 632	Q	V	2.522	Y	0.21x	−0.27x	0.22
1418 + 546	OQ 530	B	V	0.152	N	0.66x	−0.50x	0.38
1442 + 101	OQ 172	Q	V	3.535	Y	0.80x	−0.37x	−0.71
1458 + 718	3C 309.1	Q	V?	0.905	N	0.29	−0.76	0.54
1502 + 036		Q	0	0.411	N	0.47x	−0.56x	-
1510 − 089	OR 017	Q	OVV?	0.361	Y	0.21	−0.65	-
1514 − 241	Ap Lib	B	OVV	0.048	N	0.80x	−0.29x	−0.16
1526 + 285	Ton 236	Q	0	0.450	N	0.00x	−0.60x	-
1532 + 01E		Q?	V	0.310	N	-	-	-
1532 + 01W	1532+016	Q	V	1.435	N	-	-	−0.26
1538 + 149	4C 14.60	B	V	0.605	N	0.52x	−0.60x	0.34
1545 + 210	3C 323.1	Q	OVV	0.264	N	0.07	−0.68	−0.56
1546 + 027	OR 078	Q	V	0.413	N	0.17x	−0.71x	0.17
1553 + 113		Q	V	0.360	N	-	-	-
1606 + 289		Q	V	2.560	N	-	-	−0.42
1611 + 342	OS 319	Q	V	1.401	N	-	-	0.19
1612 + 261	Ton 256	Q	V	0.131	N	0.65x	−0.78x	−2.29
1615 + 029		Q	0	1.339	N	−0.08x	−1.04x	−0.19
1618 + 177	3CR 334	Q	OVV	0.555	N	0.23	−0.94	1.32
1638 + 398	NRAO 512	Q	OVV	1.666	N	-	-	0.12
1641 + 399	3C 345	Q	OVV	0.594	N	−.39	−0.64	0.26
1652 + 398	MK 501	B	0	0.033	N	0.74x	−0.25x	0.06
1704 + 608	3CR 351	Q	OVV?	0.371	Y	0.11	−0.77	−0.85
1727 + 501	I ZW 187	B	0	0.053	N	0.63x	−0.52x	−0.18
1730 − 130	NRAO 530	Q	OVV	0.902	N	-	-	−0.25
1749 + 701		B	V	0.770	N	0.45x	−0.50x	0.25
1749 + 096	4C 09.57	B	V	0.322	N	0.52x	−0.42x	1.01
1807 + 698	3C 371	B	OVV	0.051	N	0.55x	−0.48x	0.14
1828 + 487	3C 380	Q	V	0.691	N	0.17	−0.79	0.47
1831 + 731		S	0	1.356	-	-	-	-
1845 + 797	3C 390.3	S	V	0.057	-	0.68x	−0.69x	−0.63
1901 + 319	3C 395	Q	V	0.635	N	-	-	−0.58

Table 1. (*Continued*)

Source	Name	Type	Var	z_e	z_a	$(B-V)^*$	$(U-B)^*$	α
1929 − 293	OV 236	Q	OVV	0.352	N	-	-	-
2059 + 034	OW 098	Q	V	1.013	N	0.35x	−0.84x	0.44
2128 − 123	PHL 1598	Q	V	0.501	Y	0.27	−0.82	−0.11
2131 − 021	4C 02.81	B	V	0.557?	N	-	-	0.13
2134 + 004	PHL 61	Q	0	1.936	N	0.30x	−0.94x	-
2135 − 147	PHL 1657	Q	OVV	0.200	Y	−0.03	−0.84	-
2145 + 067	4C 06.69	Q	0	0.990	Y	0.32	−0.76	0.40
2154 − 184		Q	0	0.668	N	-	-	−1.17
2155 − 304		B	V	0.116	Y	0.35x	−0.73x	1.77
2200 + 420	BL LAC	B	OVV	0.069	N	0.97x	−0.10x	−0.13
2201 + 315	4C 31.63	Q	0	0.298	Y	0.09x	−0.76x	-
2209 + 080	4C 08.64	Q	0	0.484	N	-	-	−0.51
2216 − 038	4C 03.79	Q	0	0.901	N	0.63x	−0.71x	−0.61
2223 − 052	3C 446	Q	OVV	1.404	N	0.48	−0.63	−0.08
2223 + 210	DA 580	Q	0	1.935	Y	-	-	-
2230 + 114	CTA 102	Q	V	1.037	N	0.28	−0.63	0.50
2251 + 113	4C 11.72	Q	0	0.323	N	0.15	−0.68	−0.70
2251 + 158	3C 454.3	Q	OVV	0.859	N	0.33	−0.66	−0.79
2251 + 244	4C 24.61	Q	V	2.237	Y	-	-	−0.94
2251 − 178		S	V	0.068	-	0.91x	0.05x	-
2254 + 024	OY 091.3	Q	0	2.091	N	0.083	-	0.17
2254 + 074	OY 091	B	OVV?	0.19	N	0.66	−0.44x	1.19
2304 + 187	4C 18.68	Q	V	0.313	N	0.13x	−0.75x	−0.42
2335 − 181		Q	V	1.441	N	0.07x	−0.91x	−0.18
2344 + 092	4C 09.74	Q	V	0.677	N	0.36	−0.71	−0.06
2345 − 167	OZ 176	Q	OVV	0.600	N	-	-	−1.82
2349 − 014	PB 5564	Q	V	0.174	N	0.12x	−0.90x	−0.60
2354 − 117		Q	0	0.960	N	-	-	−0.18
2354 + 144	4C 14.85	Q	V	1.816	Y	0.14x	−0.90x	1.61

Notes: **Q** = QSO; **S** = Seyfert; **B** = BL Lac; **Var** = degree of variability; z_e = emission line redshift; z_a = absorption line redshift; **N** = No; **Y** = Yes; $\boldsymbol{(U-B)^*}$ and $\boldsymbol{(B-V)^*}$ = continuum color indices; **x** under $(U-B)^*$ and $(B-V)^*$ columns = observed values of color indices; $\boldsymbol{\alpha}$ = radio spectral index between emitted frequencies of approximately 3.0 GHz and 12.0 GHz.

spectra, and a distinct tendency was exhibited by the mean spectral index to approach flatness, while the percentage of quasars showing flat radio spectra was seen to increase with increase in optical variability (Basu 1973). On the other hand, optically variable QSOs demonstrated significant dependence of the degree of variability on the redshift (Basu 1980a). It was further suggested that the very long term variability of QSOs may be caused by changes in the intervening medium over the years along the line of sight through which light travels (Basu 1980b). Variability of QSOs was also shown

Table 2. Breakdown of data in Table 1.

	QSO				BL Lac				Seyfert				
Sec	T	0	V	OVV	T	0	V	OVV	T	0	V	OVV	Total
2	110(74)	27(23)	63(35)	20(16)	28	3	10	15	7	1	2	4	145
3	144(54)	44(19)	76(22)	24(13)	27	4	10	13	11	3	5	3	182
4	145(54)	45(24)	75(30)	25(0)	31	3	14	14	-	-	-	-	176
5(a)	71(48)	22(17)	35(19)	14(12)	-	-	-	-	-	-	-	-	71
5(b)	45	15	24	6	29	4	14	11	7	1	4	2	81

Note:

- Section numbers in the first column refer to the section where the data have been used. 5(a) refers to data for continuum color indices, and 5(b) refers to data for observed color indices.
- Numbers within parentheses under 'QSO' refer to those used in earlier analyses referred to in the text.
- T is 'Total', and 0, V, OVV are degrees of variability.

to be independent of the appearance of absorption lines (Basu 1985). On the other hand, statistically significant relations were found between continuum color indices and redshifts for $V = OVV$ QSOs, while no such relation existed for $V = 0$ and $V = V$ QSOs (Basu 1987).

However, the volume of data has increased enormously since the above analyses were performed. Furthermore, while the earlier works reported above were carried out mostly with QSOs, extensive data are now available for other types of extragalactic objects as well, viz., BL Lacs and Seyferts, which provide an opportunity to compare properties of these three types of objects. The importance of these objects in such studies will be appreciated as they exhibit many similar characteristics and also due to the possibility of existence of continuity in their properties (Thakur & Sapre 1980; Basu 1986). We were therefore prompted to re-examine the relationships mentioned above with the help of updated data involving the three types of extragalactic objects, viz., QSOs, BL Lacs and Seyferts, collectively known as Active Galactic Nuclei (AGNs). It may be mentioned in this connection that various aspects of AGN variability have been reviewed recently by Ulrich *et al* (1997).

Our data base presented in Table 1 has been prepared from Evans (1972); Basu (1973, 1980a); Burbidge *et al* (1997); Pica *et al* (1988); Webb *et al* (1988); Stickel *et al* (1991); Elvis *et al* (1994); Hewitt & Burbidge (1993); Padovani & Giommi (1995); Veron-Cetti & Veron (1996); Fan (1997) and Hall *et al* (1998). A breakdown of the number of different types of objects in different classes in the present analysis compared to the same in the earlier work is shown in Table 2. The purpose of this paper is to draw attention of researchers in the field to certain relationships that exist and/or do not exist although expected to exist, between various properties stated above of different types of extragalactic objects in relation to their variability. Throughout the work it has been assumed that the samples used are representative of their classes, even though the samples of different AGN classes are actually heterogeneously selected. Further, the samples comprising the three classes combined, viz., QSOs, BL Lacs and Seyferts, are hereinafter called Active Galaxies (AGs).

2. Optical variability and radio spectral index

A major contribution of optical monitoring of extragalactic objects has been the discovery of the OVVs which are now thought to possibly represent a separate class of objects that includes QSOs along with BL Lacs (the so called "Blazars") which are believed to be beaming their radiation toward the observer (Angel & Stockman 1980). One of the important properties of OVVs is that they show flat radio spectra, as mentioned above, based on which models have been proposed for these objects. Special attention is therefore needed as to how do OVVs particularly distinguish themselves, if at all, in respect of radio spectra from objects with $V = 0$ and $V = V$.

We calculated radio spectral index (α) from data at observed frequencies of 2.695 GHz and 5.0 GHz. The observed frequencies (ν_{ob}) are converted to emitted frequencies (ν_{em}) as $\nu_{em} = \nu_{ob}(1 + z)$, where z is the redshift of the object. α is defined as $S_\nu = \nu^\alpha$, where S_ν is the flux value at the frequency ν. This provided us with α values between emitted frequencies of approximately 3.0 GHz to 12.0 GHz for redshift values of the sample used here. α_2 values of Basu (1973) are used as α in the present analysis, and additional values of α have been calculated and/or obtained from data available in Stickel *et al*. (1991), Veron-Cetti & Veron (1996) and Hall *et al*. (1998).

Results are shown in Fig. 1 as the distribution of the radio spectral index for the three variability classes. For each class, individual samples of QSOs, BL Lacs, Seyferts and AGs are shown. The mean value of each distribution and the standard deviation (σ_n) are presented in Table 3.

Several features are seen in Table 3 and Fig. 1. The way the quantity α has been defined, a spectra will be called flat if α is more negative than 0.5 or more positive than -0.5, i.e., if α remains between ± 0.5. Based on this criteria, all the spectra are flat from consideration of the mean values of their distributions (with the exception of BL Lacs for $V = V$ which is also actually nearly flat). This is in contrast to earlier findings where flatness was found to be related to the degree of variability (Basu 1973). Furthermore, the present analysis indicates no statistically significant change in mean values of the radio spectral index at the high frequencies with the degree of variability, in either of the individual samples viz., QSOs, BL Lacs or Seyferts, or AGs. It is, however, noted in Table 3 that the standard deviation is quite high in all cases, as in the previous analysis.

Results presented in Table 4 demonstrates that almost the same proportion of objects in each of the three variability classes exhibit flat radio spectra, viz., 50 to 60 per cent of AGs, 40 to 50 per cent of QSOs and 70 to 80 per cent of BL Lacs, while the sample is too small for consideration for Seyferts.

The analysis confirms earlier findings (Basu 1973) that, contrary to the currently existing view, in which OVV objects are regarded as exhibiting flat radio spectra, this is really not a unique property of OVV objects, but the property is almost equally shared by objects of moderate variablity and non-variables as well.

3. Optical variability and redshift

The dependence of variability on redshift is complicated by the dependence of variability on absolute luminosity as well, while at the same time the absolute luminosity

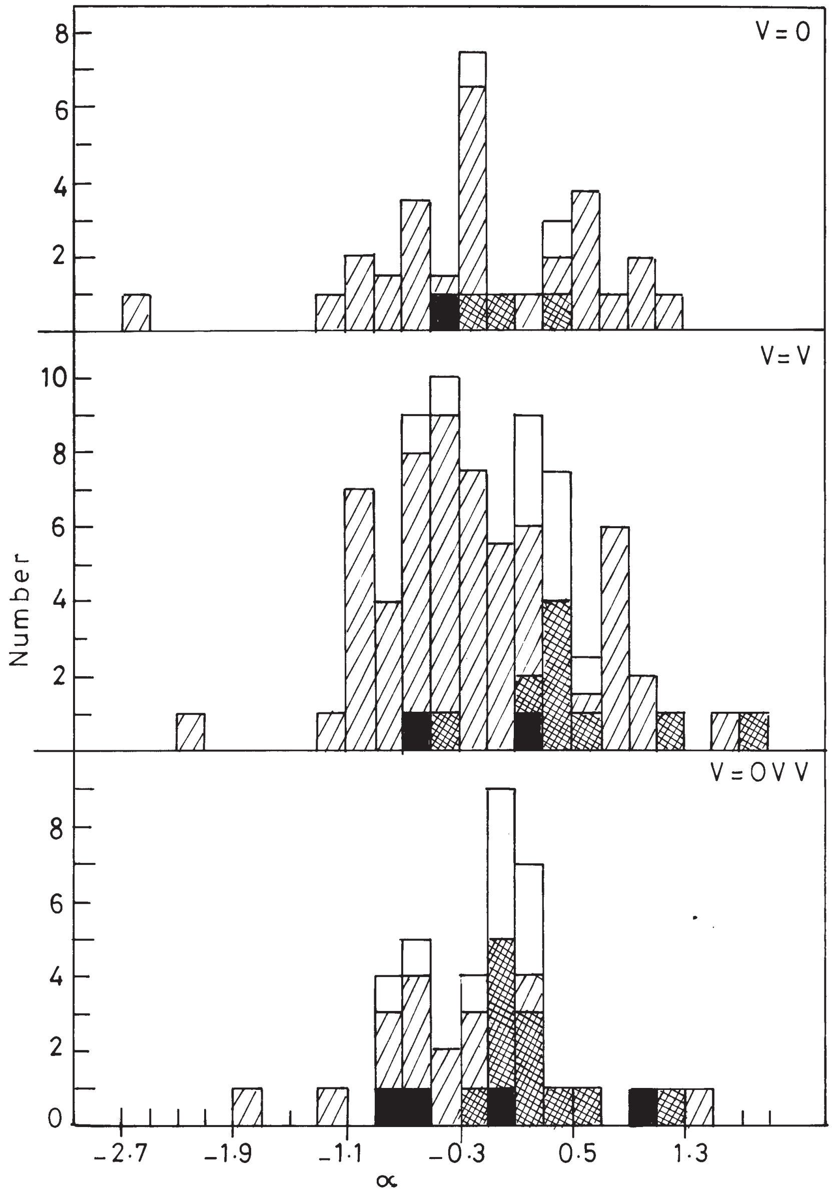

Figure 1. Distribution of mean radio spectral index (α) at high frequencies (rest frame) for three variability classes. White = AGs; Hatches = QSOs; Crossed hatches = BL Lacs; Dark = Seyferts.

itself is anti-correlated with redshift, and this "has resulted in a complex situation" (Cristiani *et al*. 1996). Cristiani *et al*. (1996) have developed a 'variability index' (IDX) which is a measure of the intrinsic variance and takes also photometric errors into consideration. They found that the IDX is anti-correlated with redshift, although correlated with absolute magnitude. However, since absolute magnitude, in its turn, is anti-correlated with redshift, these relations may not be real. In practice, it is difficult

Table 3. Mean values of α and corresponding σ_n.

Sample	Variability	No. of objects	α	σ_n
AG	0	51	−0.1484	0.7586
	V	91	−0.1681	0.6674
	OVV	40	−0.1263	0.6094
QSO	0	44	−0.1286	0.8093
	V	76	−0.1841	0.6674
	OVV	24	−0.3143	0.6342
BL Lac	0	4	0.0667	0.2494
	V	10	0.5200	0.5671
	OVV	13	0.2133	0.4097

Table 4. Percentage of objects with $\alpha = \pm 0.5$.

Sample/Variability	No. of objects	0	V	OVV
QSO	144	41	50	50
BL Lac	27	75	70	80
Seyfert	11	100	50	25
AG	182	47	53	59

to know the relative dependence of variability on redshift and on absolute luminosity, individually, and to separate the two from each other. No such attempt has been made in the present analysis.

Figure 2 shows the redshift distribution of the entire sample for the three different degrees of optical variability. As in the previous analysis, the striking feature of the diagram is that while the non-variable and, to some extent, the moderate variable objects are spread more or less uniformly along the redshift scale up to $z = 2.50$ to $z = 3.0$, OVV objects are concentrated at the lower range of the scale, mostly at $z < 1.0$.

Mathematically, χ^2 test is performed to determine any significant dependency of the degree of variability on the lower redshift range ($z < 1.0$) versus the higher redshift range ($z > 1.0$) (there is no object in Table 1 with $z = 1.0$) for AGs, QSOs and BL Lacs, the sample being too small for Seyferts for any such test. 2×3 contingency tables for three degrees of variability against redshifts of lower and higher ranges are shown in Table 5. The analysis is repeated with 2×2 contingency tables for nonvariables ($V = 0$) and variables ($V = V$ plus $V = OVV$) against lower and higher redshift ranges (Table 6). Results given in Table 7 show that the hypothesis of dependency is statistically significant at high levels for all samples, except for BL Lacs where the significance is marginal for variables against non-variables. This confirms the earlier result that optically variable QSOs exhibit statistically significant dependency of the

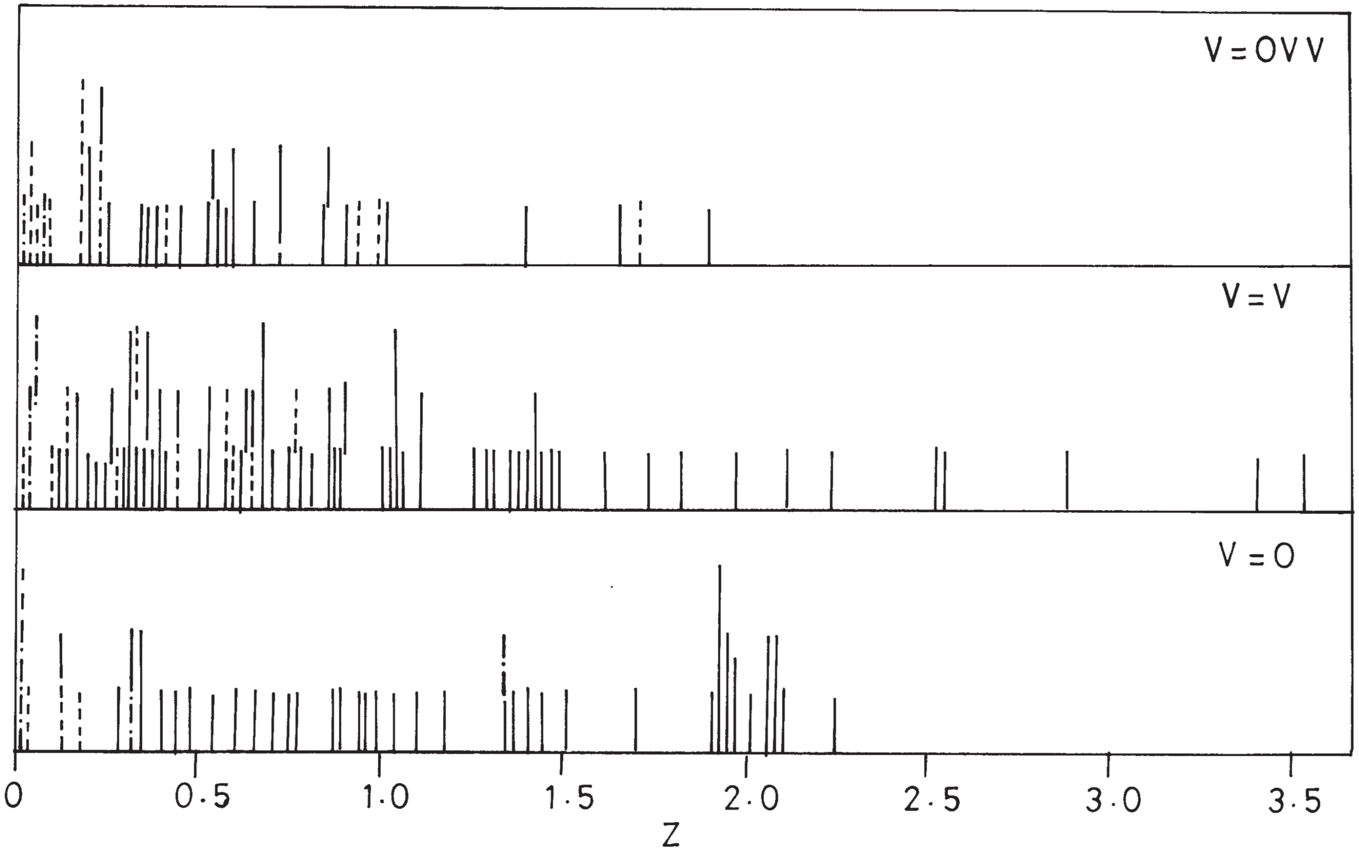

Figure 2. Distribution of redshifts for three variability classes. Each small bar represents an object with the corresponding redshift value. Solid line = QSOs; Dashed line = BL Lacs; Dashes and dots = Seyferts.

Table 5. 2 × 3 tables for variability against z.

Sample	z/Var	0	V	OVV
AG	$z < 1.0$	26	58	36
	$z > 1.0$	25	32	4
QSO + BL Lac	$z < 1.0$	24	53	33
	$z > 1.0$	24	32	4
QSO	$z < 1.0$	20	43	21
	$z > 1.0$	24	32	3
BL Lac	$z < 1.0$	4	10	12
	$z > 1.0$	0	0	1
Seyfert	$z < 1.0$	2	5	3
	$z > 1.0$	1	0	0

Table 6. 2 × 2 tables for variability against z.

Sample	z/Var	0	V + OVV
AG	$z < 1.0$	26	94
	$z > 1.0$	25	36
QSO + BL Lac	$z < 1.0$	24	86
	$z > 1.0$	24	36
QSO	$z < 1.0$	20	64
	$z > 1.0$	24	35
BL Lac	$z < 1.0$	4	22
	$z > 1.0$	0	1

degree of variability on redshift (Basu 1980a), and the finding is now extended to other objects like BL Lacs and possibly to Seyferts, and AGs, i.e., extragalactic objects in general.

This is of course expected, as $\Delta t_{\text{observed}} = (1 + z)\Delta t_{\text{intrinsic}}$, and observed high redshift sources will tend to be less variable in the observer's reference frame. This also explains why OVV objects seem to concentrate at low redshift regions. Moreover, the known correlation between variability time scales and luminosity (see e.g., Netzer *et al*. 1996) would support having less variable sources at higher redshift regions.

4. Optical variability and absorption features

Variability is measured as a change in optical magnitude of the object over a certain period of time. Such changes may result from physical phenomena occurring in the

Table 7. Results of χ^2 tests for var against z.

Sample	Table	χ^2	Sig level
AG	2 × 3	15.07	99.0
QSO + BL Lac	2 × 3	14.39	99.0
QSO	2 × 3	11.2	99.0
AG	2 × 2	7.62	99.5
QSO + BL Lac	2 × 2	6.52	99.0
QSO	2 × 2	4.83	95.0
BL Lac	2 × 2	1.09*	75.0
BL Lac	2 × 3	36.0	99.9

* Yeates correction applied.

source itself (intrinsic) or from changes occurring in the intervening medium along the line of sight. It is known that absorption lines may also originate intrinsically to the object itself or at the intervening medium. Thus the intervening medium may be the common cause associated with the occurrence of both variability and absorption lines, at least in some cases, in extragalactic objects.

Analysis of a sample of 54 QSOs taken out of 64 objects, "probably complete" to $m \leq 18.0$, demonstrated (Basu 1985) that optical variability is not associated with the presence or absence of absorption lines in QSOs. Thus, χ^2 test performed for the absence or presence of absorption lines against non-variable ($V = 0$) and variable ($V = V$ plus $V = OVV$) QSOs did not show any association of variability with the appearance of absorption features, even though Borra (1975) claimed optical variability to be more frequent among QSOs with absorption lines than those without any absorption feature.

Table 8. 2 × 3 tables for Abs lines against var.

Sample	Abs lines/Var	0	V	OVV
QSO + BL Lac	Yes	18	21	12
	No	30	68	27
QSO	Yes	18	20	8
	No	27	55	17
BL Lac	Yes	0	1	4
	No	3	13	10

Table 8 shows the 2×3 contingency tables for the presence and absence of absorption lines against the three degrees of variability for different samples. We also performed the χ^2 test with 2 × 2 contingency table for the presence or absence of absorption lines against non-variables ($V = 0$) and variables ($V = V$ plus $V = OVV$) with the same sample, and this is shown in Table 9.

As in the earlier work, we repeated the latter analysis by eliminating the objects with $z < 1.0$ from the sample, which left us with 59 QSOs (Table 9), in order to look

Table 9. 2 × 2 tables for Abs lines against var.

Sample	Abs lines/Var	0	0 + OVV
QSO + BL Lac	Yes	18	33
	No	30	95
QSO	Yes	18	28
	No	27	72
QSO ($z > 1.0$)	Yes	15	13
	No	9	21
BL Lac	Yes	0	5
	No	3	23

Table 10. Results of χ^2 tests for Abs lines against var.

Sample	Table	χ^2	Sig level
QSO + BL Lac	2 × 3	−20.95	0
QSO	2 × 3	1.94	< 75
BL Lac	2 × 3	−1.90	0
QSO + BL Lac	2 × 2	2.33	< 75
QSO	2 × 2	2.06	< 90
QSO ($z > 1.0$)	2 × 2	10.25	99.9
BL Lac	2 × 2	0.64	50

for any selection effect, as it has been pointed out (Basu 1982) that relatively more absorption lines are seen at $z > 1.0$.

Table 10 shows the χ^2 values and corresponding significance levels for these analyses. It will be seen that none of the samples considered is statistically significant, except QSOs with $z > 1.0$. Thus the presence or absence of absorption lines in extragalactic objects is, in general, independent of the variability of the object, and this confirms the earlier findings for QSOs in this respect (Basu 1985).

However, it also appears that the above mentioned selection effect may have influenced the result for the current sample of QSOs with $z > 1.0$, in which the presence or absence of absorption lines is significantly associated with the degree of variability. More observations are therefore needed.

On the other hand, BL Lac objects individually or in combination with QSOs, i. e., extragalactic objects in general (QSOs plus BL Lacs) exhibit absorption features in their spectra independent of their optical variability. The reason may be the low redshifts ($z < 1.0$) of the BL Lacs. No test was performed for BL Lacs with $z > 1.00$ as almost all BL Lacs have $z < 1.00$.

The number of Seyfert galaxies in the sample is too small for a separate analysis. Furthermore, there is no data available for their absorption features. Also, redshifts of Seyferts are even smaller than those of BL Lacs, and hence it is very unlikely that Seyferts will influence the conclusion reached above in connection with extragalactic objects in general.

Assuming redshift is cosmological, $z > 1.0$ corresponds to objects at very large distances implying a larger light path through the intervening medium. It may be worth investigating (which is of course beyond the scope of the present work) whether the two phenomena, viz., variability and absorption lines for objects with $z > 1.0$, if there is no selection effect for the close association between the two, may have a common origin in the intervening medium, as was pointed out by Basu (1987). It is known that variability is observed at other wavelength bands as well, e.g., hard x-ray and infra-red, which are much less affected by absorption. Variability in such cases may be assigned to be an intrinsic phenomenon.

5. Optical variability and color-redshift relation

Variation of color indices with redshifts is known to be complex and does not exhibit any correlation (McCrea 1966; Strittmatter & Burbidge 1967; Goldsmith 1972; Basu 1981, 1986, 1990). The importance of such study lies in the fact that a simple relationship between the redshift and color indices may lead to the prediction of redshifts from photometric observations, a rather much easier way of determination of redshifts. Derivation of energy distribution function is another possibility, although continuum color indices have to be used for the purpose. The effect of variability, if any, in such investigations would certainly throw more light on the phenomena involved.

Basu (1980b) analysed continuum color indices (Evans 1972) and found a statistically significant correlation between redshift and continuum color indices for OVV QSOs, although no such correlation was exhibited by the other two classes, viz., $V = 0$ and $V = V$. As was indicated in Basu (1974, 1980b, 1986), continuum color indices are better suited for such analyses since observed indices are contaminated with the presence of emission lines.

Nevertheless we have also added observed color indices in Table 1 for objects for which continuum indices are not available. As far as is known to us, continuum color indices have not been determined other than the work of Evans (1972), and more recently, that of Elvis *et al* (1994), used in the present analysis. Published data and work with observed color indices are actually more common in catalogues and literature (e.g., McCrea 1966; Strittmatter & Burbidge 1967; Goldsmith 1972; Hewitt & Burbidge 1993; Veron-Cetti & Veron 1996). The present study with observed color indices may provide a comparison.

Figures 3 to 5 show plots of color indices, both observed ($(U - B)x,\ (B - V)x$) and continuum ($(U - B)^*,\ (B - V)^*$), against redshifts for QSOs, BL Lacs and Seyferts separately, for the three degrees of variability. The plots may appear random distribution of points, but following up individual symbols would demonstrate some significant correlations, and these are presented in Table 11 (we did not consider any correlation for samples with total number of objects less than 15).

In case of AGs, significant correlation is established for redshift against $(U - B)^*$ for $V = 0$ and $V = OVV$, and $(B - V)^*$ for $V = V$. As for QSOs, whereas the previous analysis showed significant correlation for $(U - B)^*$ and $(B - V)^*$ against redshifts only for OVVs, the present analysis demonstrates such relation for $(U - B)^*$ for $V = 0$, and $(B - V)^*$ for $V = V$ and $V = OVV$.

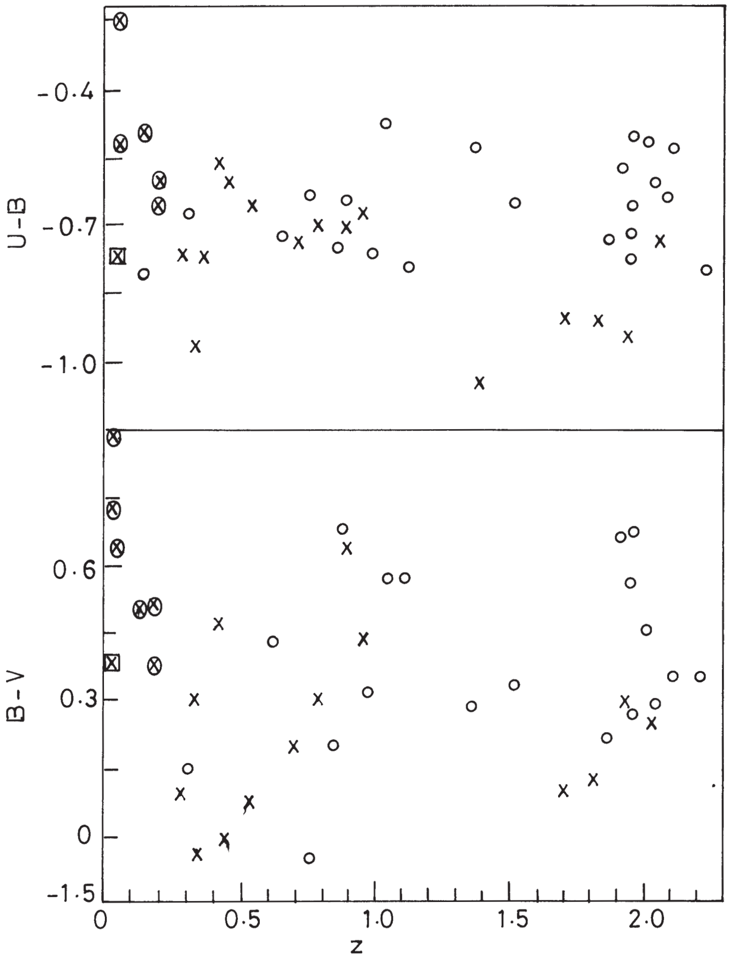

Figure 3. Plots of color indices against redshifts for variability class $V = 0$. Circles and crosses = QSOs; filled circles and crossed circles = BL Lacs; squares and crossed squares = Seyferts. Crossed symbols = $(U - B)x$ or $(B - V)x$; Non-crossed symbols = $(U - B)^*$ or $(B - V)^*$.

On the other hand, observed color indices $(U - B)x$ and $(B - V)x$ show significant correlation for $V = V$ and $V = 0$ (latter, although negative) respectively for AGs. As for QSOs, such relations are demonstrated by both $(U - B)x$ and $(B - V)x$ for $V = V$, and $(B - V)x$ for $V = OVV$.

Significant correlation of color indices against redshift is therefore not limited to OVV objects only, as was found in the earlier analysis (Basu 1986).

The relationships shown by the observed color indices against redshifts are important from the practical point of view in the sense that redshifts can be predicted and/or determined from photometric observations. A statistically significant relationship between the two quantities has long been sought for in the past (see Basu 1986, in this respect). In general, extragalactic objects do not show such a relation. However, Table 11 would demonstrate that for non-variable ($V = 0$) and moderate variable ($V = V$) objects highly significant linear relations do exist for the observed color indices $(U - B)x$

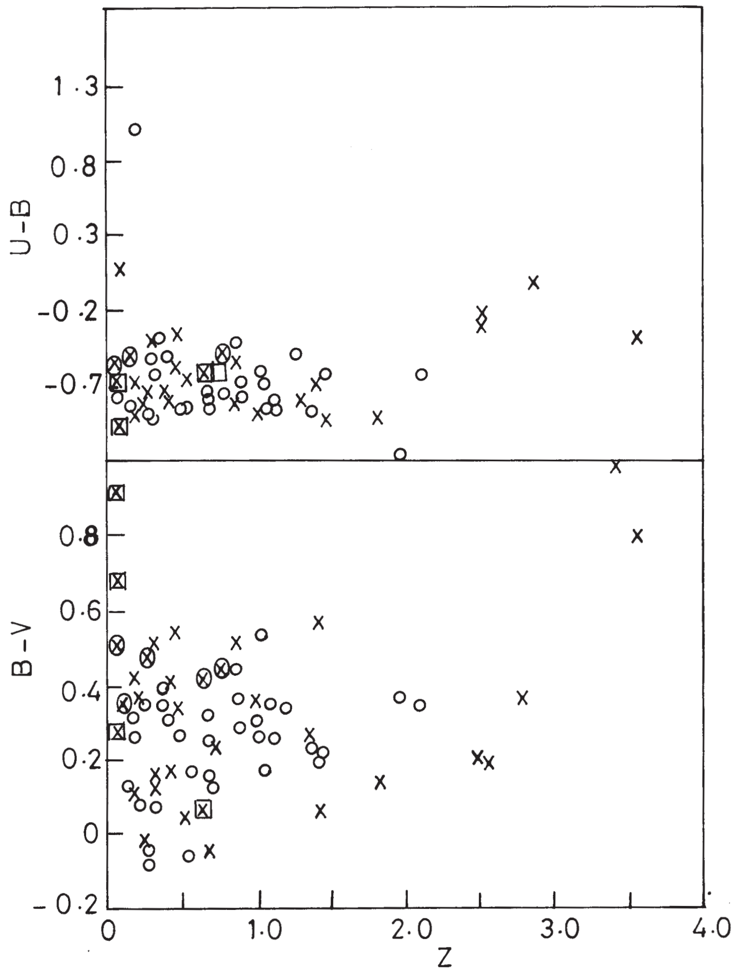

Figure 4. Same as Fig. 3, for variability class $V = V$.

and $(B - V)x$. As mentioned earlier, such prediction and/or determination of redshifts from photometric measurements is a much simpler and easier method and should be exploited.

We can represent a significant linear relation between a color index (CI) and redshift (z) by CI = A + Bz, where CI can be $(U - B)x$ or $(B - V)x$ and A, B are constants. Determination of A and B from data in Table 1 shown in Figs. 3 and 4 leads to

$$(U - B)x = -0.7955 + 0.2678z \text{ for AGs for } V = V, \quad (1)$$

$$(B - V)x = 0.4365 + 0.1578z \text{ for AGs for } V = 0, \quad (2)$$

$$(U - B)x = -0.9453 + 0.3343z \text{ for QSOs for } V = V, \quad (3)$$

$$(B - V)x = 0.1981 + 0.1133z \text{ for QSOs for } V = V. \quad (4)$$

Equations (1) to (4) can be used for prediction and/or determination of redshifts from values of color indices obtained by photometric measurements. This can be demon-

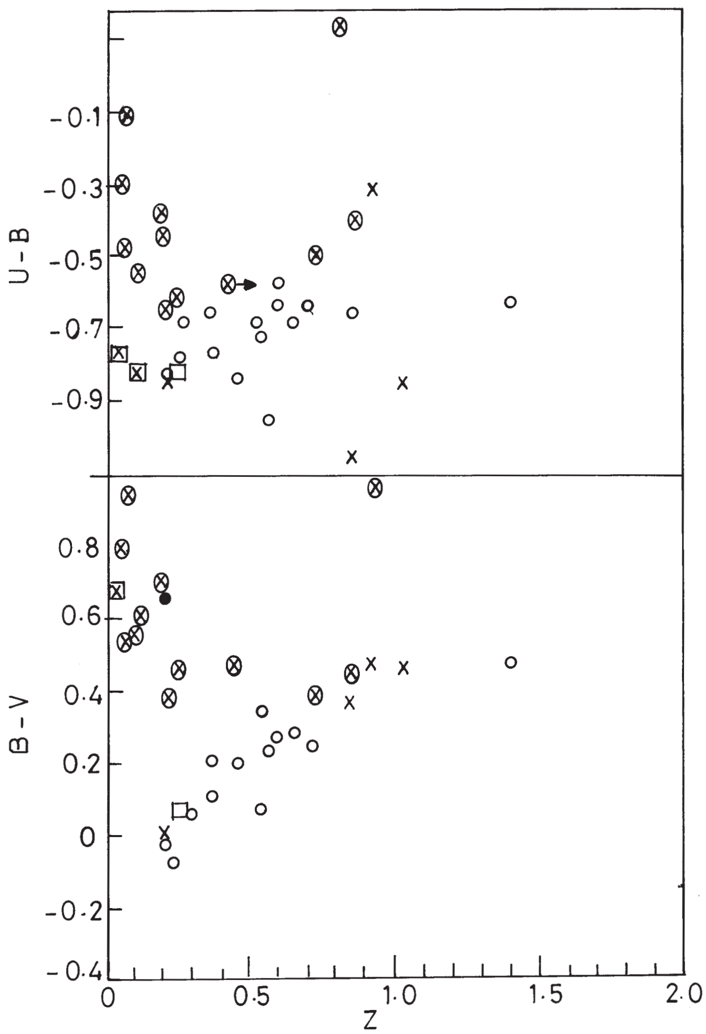

Figure 5. Same as Fig. 3, for variability class $V = OVV$.

strated for individual objects of our own sample. Thus redshifts computed from the above equations are 0.9914 (object 1055 + 018), 2.0057 (object 1328 + 290), 2.708 (object 0805 + 046) and 1.3407 (object 2059 + 034), the spectroscopic values being 0.888, 1.703, 2.88 and 1.013, and hence accuracies 11.6, 17.8, 6.4 and 32.3pc respectively. Accuracies appear reasonable and better for $(U - B)x$ values than those for $(B - V)x$ values, which can also be seen from the relatively larger correlation coefficients of $(U - B)x$ versus z than those for $(B - V)x$ versus z.

It is, however, admitted that although the statistical significance levels are high, appreciable scatters are present in Figs. 3 and 4. More data obtained from future observations would probably make less scatters in the diagrams, and hence better prediction and/or determination of redshifts from such relations. Furthermore, equations (1) to (4) obtained for the present sample can be used for prediction and/or determination of

Table 11. Correlation coefficients with redshift.

Sample	Parameter	Var = 0			Var = V			Var = OVV		
		r	L	Sig?	r	L	Sig?	r	L	Sig?
AG	$(U-B)^*$	0.3554	95	Y	0.1056	0	N	0.4832	> 95	Y
	$(B-V)^*$	0.2859	90	M	0.4089	99	Y	0.2923	85	N
	$(U-B)x$	−0.3306	93	M	0.5714	99	Y	−0.0071	0	N
	$(B-V)x$	−0.4012	97	Y	0.1791	88	N	−0.1814	< 80	N
QSO	$(U-B)^*$	0.3554	95	Y	0.1056	0	N	0.4443	99.9	Y
	$(B-V)^*$	0.2851	90	M	0.4089	99	Y	0.5600	99.9	Y
	$(U-B)x$	−0.4182	92	M	0.6664	99	Y	0.1171	0	N
	$(B-V)x$	0.0667	0	N	0.4061	98	Y	0.9748	99.9	Y

Notes: **r** = Correlation coefficient; **L** = Level of significance; **Sig?** = whether significant; **Y** = Yes; **N** = No; **M** = Marginal.

redshifts from photometric measurements for $(U-B)x > -0.7955$, $(B-V)x < 0.4365$, $(U-B)x > -0.9453$ and $(B-V)x > 0.1981$ respectively.

6. Conclusion

The foregoing analyses lead us to make the following important conclusions with respect to optical variability of extragalactic objects in relation to their redshifts and other properties. It is, however, admitted that some selection effects have not been taken into consideration. As an example, low redshift objects are likely to be nearer and brighter and hence better studied than high redshift ones which are expected to be fainter. Some degree of caution is therefore suggested with respect to the conclusions stated below.

• Radio spectral index at high frequencies (rest frame) does not change significantly with the degree of variability of extragalactic objects. OVV objects which have drawn special attention in this respect exhibit flat radio spectra at high frequencies (rest frame), but this is not an exclusive property of OVVs only, as has so far been considered, since objects of lower categories of variability and non-variables also show such spectra.

• The degree of variability of AGs depend significantly on redshifts in the sense that smaller redshift objects exhibit a higher degree of variablity.

• Presence or absence of absorption lines in AGs does not depend on the degree of variability except for QSOs at larger redshifts (> 1.0).

• Correlation between color indices and redshift depends on the degree of variability and the sample considered. Thus:

(a) For AGs, in general, continuum color index $(U-B)^*$ exhibit significant correlation for non-variables and violent variables and $(B-V)^*$ for moderate variables. For QSOs, $(U-B)^*$ is significantly correlated for non-variables while $(B-V)^*$ for moderate and violent variables.

(b) Observed color indices $(U-B)x$ and $(B-V)x$ exhibit significant correlations with redshifts for moderate variable and non-variable AGs respectively, and moderate variable QSOs. This is an important property and can be utilized for predicting/determining redshifts from photometric observations.

In view of the above findings with respect to variability, continued observations involving monitoring of all types of extragalactic objects is suggested and the relationships checked as more and more data are available.

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