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Millimeter-wavelength observations of compact steep-spectrum sources

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Abstract. — Using the IRAM 30-m telescope, we have measured 90- and 230-GHz flux densities for a sample of 76 sources, about 70 of which are compact steep-spectrum radio sources (CSSs). These flux densities have been used to extend the radio spectra of the CSSs to millimeter wavelengths, and look for deviations of their high-frequency spectra from the trends established at lower frequencies. Since flat-spectrum, cm-wavelength, nuclear components have been detected in some of these sources, it is possible that such radio cores are self-absorbed at cm wavelengths, but could make their presence felt in the mm range via a flattening of the integrated spectrum. Alternatively, if the nucleus is no longer active and there is no fresh supply of energy to the extended features, one might find high-frequency spectral steepening caused by radiative losses. In this paper we present the results of our observations and discuss their implications.

Key words: galaxies: active — galaxies: nuclei — quasars: general — radio continuum: galaxies

1. Introduction

The compact steep–spectrum sources (CSSs) are of subgalactic dimensions and have steep radio spectra at high frequencies ($\alpha \geq 0.5$, where $S \propto \nu^{-\alpha}$). They account for ≈15% of the objects in the 3CR catalogue, although this fraction could be as large as 30% of the steep–spectrum objects in high–frequency selected samples. The CSSs associated with high-luminosity radio galaxies and quasars exhibit a wide variety of structures reminiscent of those seen in more extended sources (see Sanghera et al. 1995 for a summary). However, since these sources lie within the confines of their host galaxies, they provide us with an opportunity to probe the physical properties of the interstellar media of the galaxies and study the interaction of the radio-emitting plasma with the surrounding environment (e.g. Saikia 1988; Fanti et al. 1990; Spencer et al. 1989, 1991; Akujor et al. 1991; Wilkinson et al. 1991a, b).

We have observed a sample of 76 sources, about 70 of which are CSSs, with the IRAM 30-m telescope to extend their spectra to millimeter wavelengths, and look for deviations in their high-frequency spectra from the trends established at lower frequencies. Although recent, sensitive, multi-frequency, high-resolution observations at cm wavelengths have established the existence of cores, or nuclear components, in about 60% of the quasars and 20% of the radio galaxies from two well-studied samples of CSSs (Sanghera et al. 1995), it might be possible to infer the existence of cores within a large sample of CSSs with relative ease using mm-wavelength observations. Cores which are self-absorbed at cm wavelengths, could reveal themselves at mm wavelengths via a flattening of the integrated spectrum. On the other hand, if some of the CSSs are old and have been confined to small dimensions by a dense interstellar medium, one might find evidence at high frequencies of spectral steepening caused by radiative losses. This could be apparent in an old source where there is no fresh supply of energy from the nucleus to the extended lobes.

The results of our observations are presented in Sect. 2 of this paper, and their relevance to the above issues are described in Sect. 3.

*Hans Steppe died in a tragic hiking accident in Austria on Wednesday, June 30th, 1993

2. Observations and observational results

To investigate the spectral aspects of CSSs as detailed above, we have observed a sample of CSS sources with the IRAM 30-m telescope at 90 and 230 GHz. The observations were carried out in different sessions from 1987 to 1990 using the IRAM 30-m radio telescope at about 90 and 230 GHz. The half-power beamwidth of the telescope at 90 and 230 GHz are about 26 and 12 arcsec respectively. The receivers used in the different sessions are described in Steppe et al. (1988, 1992, 1993). The planets were used as calibrators and the atmospheric optical depth was determined by tipping scans. The planetary disk brightness temperatures assumed at 90 and 230 GHz are from Ulich (1981) and Ulich et al. (1984) respectively. Gain-elevation corrections were applied for each frequency, and the quoted errors in the flux density of each source were estimated from the quadratic sum of the errors of the individual measurements and a calibration error which is estimated to be about 5% at 90 GHz and 10% at 230 GHz. Since CSSs are not usually strongly variable, and we are interested in the overall spectral shape of a source, we have estimated the weighted mean and error for each source at each frequency from the number of observations.

Table 1 lists details of the sources in our sample, and also gives the observational results. The columns are arranged as follows: Col. 1: the IAU name of a source, epoch 1950.0; Col. 2: the most-common alternative name; Col. 3: optical identification where G denotes a galaxy, Q denotes a quasar, EF denotes an empty field, and BL denotes a BL-Lac type object; Col. 4: the source redshift, z; Col. 5: the morphological classification. The sources have been classified as follows based on their overall structures, and bearing in mind that any classification will to some extent be dependent on observing frequency, resolution and observational sensitivity. The sources have been classified as U: unresolved; SR: slightly resolved; R: a well-resolved single source; D: A double–lobed source without evidence of a central component which might be the core or nucleus of the source; CSO: A compact symmetric object (cf. Conway et al. 1994); T: a source with three components, the central one of which is likely to contain the core or nuclear component; MT: misaligned triple sources. If the triple sources are non–colinear with the supplement of the angle formed at the nucleus by the outer components being greater than 15°, they are classified as MTs. CJ: Sources which appear to have a core-jet type of structure; and C: complex sources which do not fit into any of the above categories. Column 6: Status of the identification of the core: c =core identified, – =core unidentified, c? =possible core; the c? cases include sources with very weak cores which require further observational confirmation, sources which have multiple compact components in the central region but do not have additional information to identify the core unambiguously, or a compact component at the base of a one-sided jet-like feature. The c cases generally have a flat-spectrum nuclear component, or in a few cases, a single compact central component located between the two outer lobes of radio emission. Column 7: References for the optical information and radio structures. For sources which are already listed in Sanghera et al. 1995, we have not listed the original references but refer the reader to that paper for further information. The detailed references are listed in Table 2.

Columns 8 to 13 list the flux density measurements. Column 8: the number of observations at 90 GHz; Col. 9: the flux density in mJy at 90 GHz. For many of the sources, the 90-GHz flux densities were first reported in Steppe et al. (1988). These have been updated for all the sources where further measurements have been made as part of this project, and the average values of all measurements are listed. Column 10: the error on the flux density in mJy at 90 GHz; Col. 11: the number of observations at 230 GHz; Col. 12: the flux density in mJy at 230 GHz; Col. 13: the error on the flux density in mJy at 230 GHz.

Column 14 indicates the spectral type which is classified as follows. For each source we have compiled flux densities at different frequencies from the literature, all values being brought on to the BGPW scale (Baars et al. 1977). Using these values along with our measured flux densities at 90 and 230 GHz we have attempted to fit the integrated spectra using the following functional forms: a) a straight-line fit $\log S = a + b \log\nu$; b) a parabolic fit $\log S = a + b \log\nu + c \log^2\nu$, labelled P; and c) two exponential fits of the form, $\log S = a + b \log\nu + c e^{k \log\nu}$, where $k = +1$ is labelled C+, and $k = -1$ is labelled C–. For each source we fitted these four functional forms and have chosen the one with the minimum χ^2 to represent the spectrum of the source. These spectral types are also indicated in the spectral plots of the sources (Fig. 1). Although none of the sources had a minimum χ^2 for a straight-line fit, a number of sources had spectra which could be reasonably described as being straight. These have been indicated by the letter S in this column; for the sources with P, C+ and C– type of spectra, these correspond to values of the parameter c less than 0.03, 0.035 and 0.2 respectively. In addition, the GHz-Peaked Spectrum (GPS) sources, as well as those whose spectra exhibit a low-frequency turn-over (LFT) at about 100 MHz or less are indicated. Since some of the sources included in our list were based on the value of the two-point spectral index over a relatively narrow frequency range, a few flat-spectrum objects have crept into the list. These have been indicated by the letter F (flat) or Cplx (complex) if none of the above functional forms provide a satisfactory fit.

3. Results and discussion

The spectra of the integrated flux densities for all sources, including those classified as either F or C, are presented in Fig. 1. All the flux densities in these plots are on the BGPW scale (Baars et al. 1977). Excluding the flat-spectrum objects, only a small fraction of the sources show definite signs of a nuclear or core component in their spectra. These are 0858+292, 0906+430 and 1828+487. The radio galaxy 0858+292 has extended large-scale structure (Gregorini et al. 1988), and does not really belong to the class of compact steep-spectrum objects. MERLIN and VLA observations reveal the existence of a compact component (Spencer et al. 1989;

Table 1. The sample of sources

IAU name	Alt. name	Opt. Id.	z	Morph.	core	References	n_{90}	$S(90)$ mJy	$\Delta S(90)$ mJy	n_{230}	$S(230)$ mJy	$\Delta S(230)$ mJy	Sp. Type
0003–003	3C2	Q	1.037	T	c	2,5,6	4	230	20	2	56	7	C+,S
0019–000	4C00.02	G		D	–	4,3,7,8,9				8	7	3	P,GPS?
0023–263	PKS	G	0.322	D	–	4,28,29	3	268	33				C–
0108+388		G	0.323	CSO	c?	8,10,11,30	3	160	43				C–,GPS
0116+319	4C31.04	G	0.059	T	c?	1				1	55	13	C+
0127+233	3C43	Q	1.459	MT	c	1	2	189	42	1	64	10	C–,S
0134+329	3C48	Q	0.367	CJ/C	c	1	2	292	41	1	89	10	C–,LFT
0138+136	3C49	G	0.621	MT	c	1				8	14	3	C–,LFT
0221+276	3C67	G	0.310	T	c?	1				8	9	2	P
0223+341	4C34.07	Q?		T	c	1				2	65	8	P
0237–233	PKS	Q	2.225	D?	–	3,4,5,6,7,12	2	350	58	1	95	19	C–,GPS
0248+430	S4	Q	1.316	D?	–	4,5,6,7	1	319	74	1	77	10	C+,GPS
0316+162	4C16.09	G?		D	–	1	7	27	7	2	17	5	C–,GPS
0319+121	OE131	Q	2.67	D	–	1	2	315	66	1	75	12	P
0400+258	OF200	Q	2.109	U	–	4,5,6	4	245	17	1	76	8	P,GPS
0400–319		EF		D?	–	4,36				1	213	22	C–,S,F
0403+768	4C76.03	G	0.599	T	c?	1	2	374	66				C+,S
0428+205	OF247	G	0.219	T	c?	1	4	240	20				C–,GPS
0429+415	3C119	G	1.023	C	c	1	5	256	16	1	47	10	C+
0457+024	PKS	Q	2.384	U	–	4,5,6	3	371	36	1	75	9	C–,GPS
0500+019		Q?		U	–	3,7,13,29	2	322	52				C–,GPS
0511–220	PKS	Q	1.296	D?	–	4,5,6	4	531	22	1	307	17	C–,F
0518+165	3C138	Q	0.759	T	c	1	2	327	46	1	191	26	C–,LFT
0528+134		Q	2.07	D?	–	4,6,14	2	896	43	1	707	115	P,GPS
0531+194		G		SR	–	4	4	107	14	2	34	8	P
0538+498	3C147	Q	0.545	MT	c	1	2	426	44	1	280	28	C–,LFT
0552+398	DA193	Q	2.365	D/CH?	–	5,6,15,16,17	29	2358	29	1	901	38	P,GPS
0615+820	S5	Q	0.71	SR/C	–	5,6,18,19	3	258	23	1	265	21	C–,F
0624–058	3C161	G		C	–	4	1	254	47	1	71	13	P
0646+600	S4	Q	0.455	U	–	4,6,30	1	73	55				C–,GPS
0710+439	S4	G	0.518	CSO	c?	7,11,20	5	136	24				C–,GPS
0711+356	OI318	Q	1.626	T	c	5,6,11,21,22	3	89	31	2	29	6	C–,GPS
0738+313	OI363	Q	0.631	U	–	4,5,6,23	3	273	30	1	97	13	P,GPS
0741–063	4C–06.18			SR	–	4	5	108	15	2	17	5	C–,GPS
0742+103		EF		U?	–	4,7,13	2	518	46	1	133	24	P,GPS
0743–006	4C00.28	Q	0.998	U	–	4,5,6,23	1	506	76	1	157	14	C–,GPS
0802+212		EF				7	3	118	29				C+,F?
0834–201	PKS	Q	2.752	U	–	4,5,6	1	846	50	1	281	28	Cplx
0858+292	3C213.1	G	0.194	T	c	1	1	516	55				C+
0858–279	PKS	Q	2.152			5,6	8	76	7	2	28	5	C+
0906+430	3C216	Q	0.67	MT	c	1	2	436	39	1	267	15	P
0941–080		G		U	–	4,7,8,23	6	≤42		2	21	5	C–,GPS?
1117+146	4C14.41	Q?		D	–	1	3	≤117		10	10	2	P
1127–145	PKS	Q	1.187	D/T?	–	4,5,6,23,31,32	1	631	163	1	726	91	C–,GPS
1143–245	PKS	Q	1.95	U	–	4,5,6,23	2	107	61	8	18	3	C+
1151–348	PKS	Q	0.258	SR	–	4,6,23,28,29	2	102	59	1	99	16	C–,LFT
1225+368	ON343	Q	1.975	T	c?	1	6	≤60					C–,GPS
1237–101	PKS	Q	0.750	D?	–	4,6	1	248	64	1	105	8	C–,GPS
1245–197	PKS	Q	1.275	SR	–	4,6,33				9	8	3	P,GPS?
1250+568	3C277.1	Q	0.321	T	c	1	4	≤129		7	24	4	P
1311+678	4C67.22			SR	–	4	3	≤201					C–,S
1323+321	4C32.44	G	0.369	D	–	1	4	219	21	1	122	22	C–
1328+254	3C287	Q	1.055	C	c?	1	1	512	90	1	116	20	P
1328+307	3C286	Q	0.849	MT	c	1	2	746	15	1	334	29	C+
1345+125	4C12.50	G	0.1218	CJ?	c?	1	3	558	28	1	167	18	C–,GPS?
1351–018	PKS	Q	3.710	U	–	4,5	5	177	19	4	65	7	C–,GPS
1416+067	3C298	Q	1.439	T	c	1	3	68	38	2	≤33		C–,LFT?
1419+419	3C299	G	0.367	T	c	1	10	39	9				C–
1442+101	OQ172	Q	3.5305	D	–	1	5	58	23	4	18	6	P
1443+773	3C303.1	G	0.267	D	–	1	8	17	1	6	15	5	C–,S
1458+718	3C309.1	Q	0.904	MT	c	1	1	364	71	1	119	21	C–
1519–273		BL		R	–	6,7,24	1	540	45	1	485	61	C+,F
1524–136	PKS	Q	1.687	SR	–	4,5,25,33,34	2	168	48	2	40	8	C–
1543+005		G	0.550	U	–	4,7,35	7	173	17	1	95	10	C–
1600+335	OS300	G?		D	–	1	3	487	32	1	304	34	C–,GPS?
1607+268	CTD93	G	0.473	D	–	1				8	11	3	C–,GPS
1634+628	3C343	Q	0.988	C	c?	1	4	≤129		8	≤9		C–
1641+173	3C346	G	0.161	T	c	1	4	306	27	1	166	17	C+,S
1828+487	3C380	Q	0.691	C	c	1	9	1573	14	1	400	18	C+
1848+283		Q?		R	–	4,7,16,26	4	138	29	1	81	11	P,GPS
2126–158	PKS	Q	3.266	U	–	4,5,6	8	294	18	1	80	8	C+
2128+048		G	0.990	D?	–	3,4,7,23,37	8	152	18	2	46	10	C–,GPS
2134+004	PKS	Q	1.936	U	–	4,5,6	12	1601	30	1	833	33	P,GPS
2223+210	PKS	Q	1.953	T	c	5,6,27,38	1	301	55	2	132	14	C–
2230+114	4C11.69	Q	1.037	T	c	1	16	1677	23	2	952	72	Cplx
2342+821		Q	0.735	T	c?	1	2	156	40	4	≤15		C+

Table 2. References for Table 1

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28. Tadhunter et al. 1993	29. Morganti et al. 1993	30. Stickel et al. 1994
31. Wehrle et al. 1992	32. Rusk 1988	33. Mantovani et al. 1992
34. Mantovani et al. 1988	35. Heckman et al. 1994	36. Saikia et al. 1987a
37. Stickel et al. 1994	38. Lonsdale et al. 1993	

Akujor et al. 1991) which has a flux density of 149 mJy at 5 GHz (Akujor et al. 1991). The radio sources 0906+430 and 1828+487 are associated with quasars and are known to have prominent compact components which also exhibit superluminal motion (Barthel et al. 1988a; Wilkinson et al. 1990, 1991a; Vermeulen & Cohen 1994).

Additional CSSs which could show evidence for a flat-spectrum component at mm wavelengths are 0108+388, 0237−233 and 1127−145, all of which are GPS sources. The integrated spectrum of the radio galaxy 0108+388 (Baum et al. 1990) is dominated by the compact core component. It is possible that this feature has a flat-spectrum nuclear component. High-frequency *VLBI* observations should permit evaluation of this possibility. The radio source 0237−233 is associated with a quasar at a redshift of 2.225 and has a possible 10% variability at 2.3 GHz over a timescale of 1 yr (Preston et al. 1989). If 0237−233 has a high-frequency component, its spectrum suggests that this peaks between 30 and 100 GHz. The Australian SHEVE data show a complex structure, but Preston et al. (1989) obtained a reasonable fit to the data using two unequal point sources separated by 18 mas. The third source, 1127−145, is also associated with a quasar, whose radio flux density is variable. Its *VLBI* structure shows a nearly-equal resolved double with weak extended emission to the north-east (Wehrle et al. 1992), while VLA observations at 1375 MHz reveal a weak jet extending to about 30 arcsec along a PA of about 40° (Rusk 1988). In both these sources, multi-frequency *VLBI* observations are needed to identify the location of the possible nuclear or flat-spectrum component. There are a few other sources such as 0538+498, 1225+368, 1443+773 and 2134+004, which show even weaker evidence for a possible flat-spectrum nuclear component at mm wavelengths and require further observations.

An earlier attempt to determine the spectra of CSSs at mm wavelengths was made by Schilizzi et al. (1990) who, with the Nobeyama telescope at 43 and 92 GHz, observed 18 CSSs from the list of 26 compiled by Fanti et al. (1985, 1986). They detected 13 objects, and found 5 of them, all quasars to exhibit a flattening at high frequencies. We have observed 10 of these 13, and there is clear evidence of spectral flattening at high frequencies only for 0906+430 (3C216).

Although more than half of our objects are quasars, clear evidence of a core component via flattening of the integrated spectra at millimeter wavelengths is seen in only a few of them. The median value of the fraction of emission from the core at an emitted frequency of 8 GHz, f_c, is about 0.002 and 0.05 for the high-luminosity 3CR radio galaxies and quasars respectively (Saikia & Kulkarni 1994). While examining the consistency of the CSSs with the unified scheme (cf. Barthel 1989), Saikia et al. (1995) find similar values of f_c for the CSS radio galaxies and quasars with detected cores from high-resolution cm-wavelength observations. This suggests that for many quasars, the core spectra do not continue to be flat but steepen at mm wavelengths. Interferometric observations in the millimeter region would enable us to determine the spectra of the cores at these wavelengths.

We have also examined our spectra for possible signatures of spectral ageing. Since many of these sources are small with multiple components, the overall spectral shape is often governed by the effects of opacity due to synchrotron self-absorption, plus possible thermal free-free absorption by the interstellar media in their host galaxies. While a detailed study would require the determination of the spectra of individual components, rough estimates are sometimes possible. For example, 5-GHz MERLIN observations of the radio galaxy 0221+276 (3C67) by Sanghera et al. (1995) show that the hot-spots which contribute most of the flux density at these frequencies are well resolved and should not become optically thick in the observed frequency range of the source. The source has a weak nuclear component with a flux density of only a few mJy. Thus, the curved spectrum of the source could be due to radiative losses.

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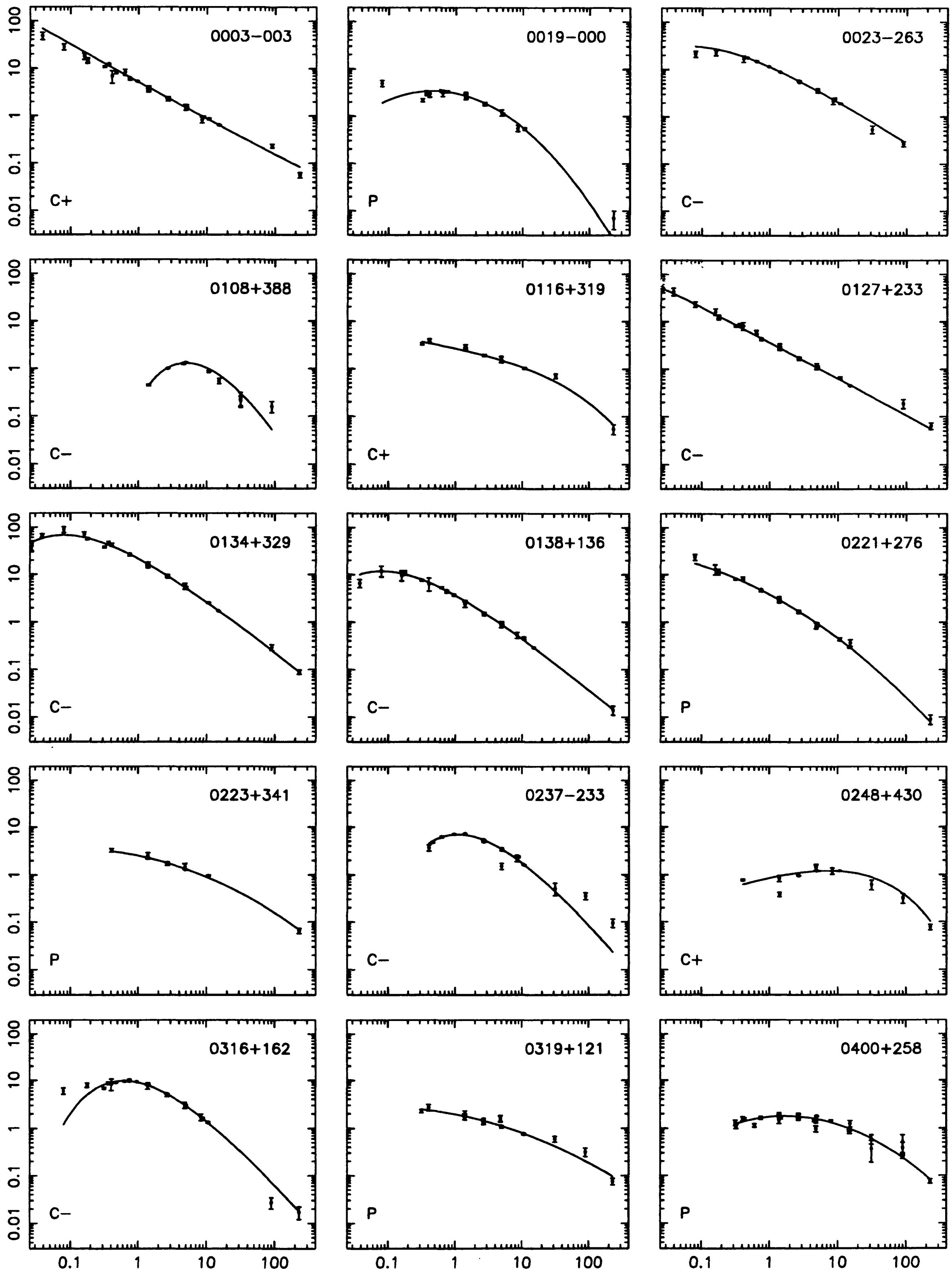
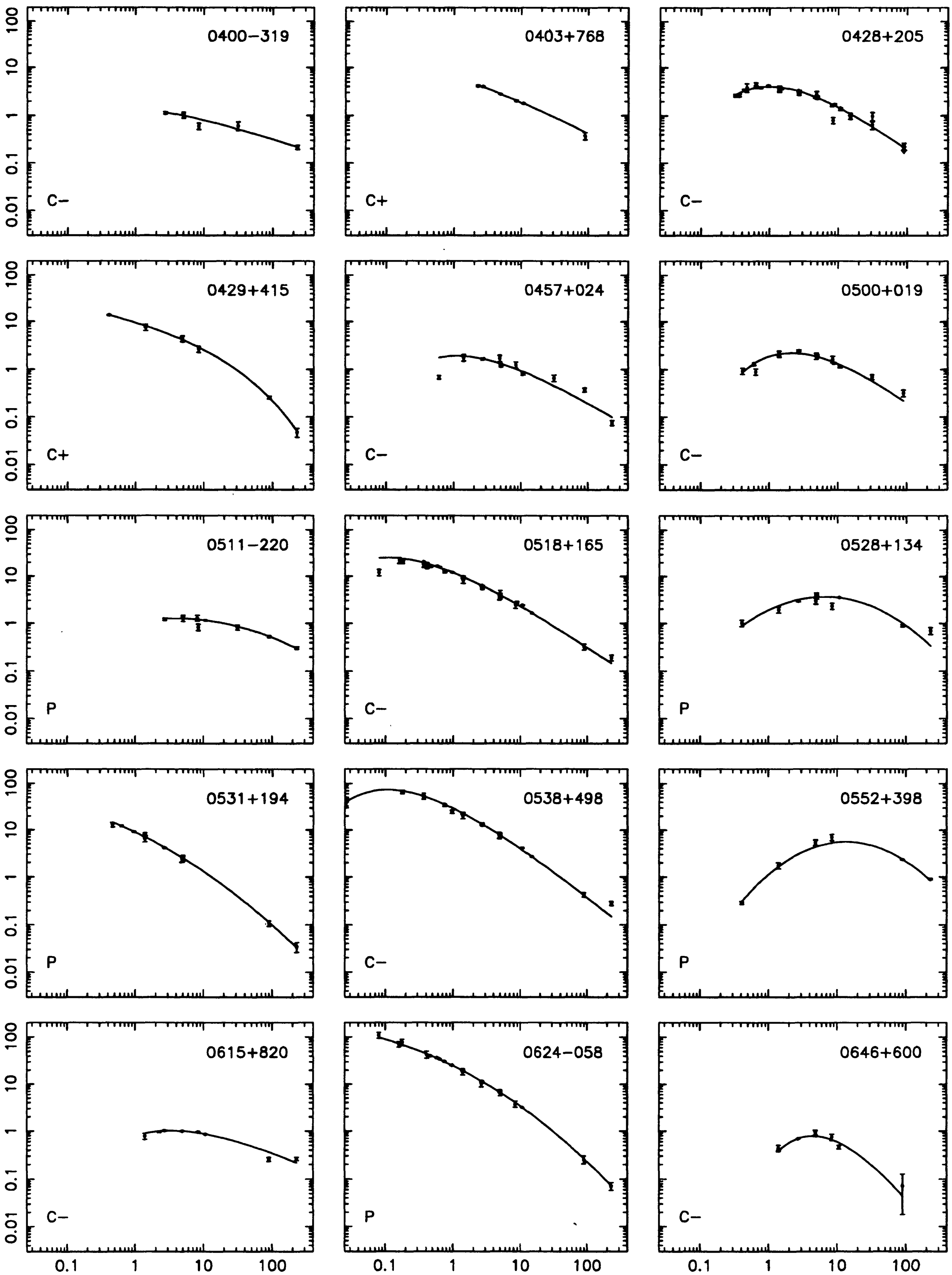


Fig. 1. The integrated spectra of the sources. The x-axis is the frequency in GHz while the y-axis is the flux density in Jy. The continuous line represents the least-squares fit to the data. The functional form which yields the minimum χ^2 for each source, as discussed in the text, is indicated in the bottom left hand corner



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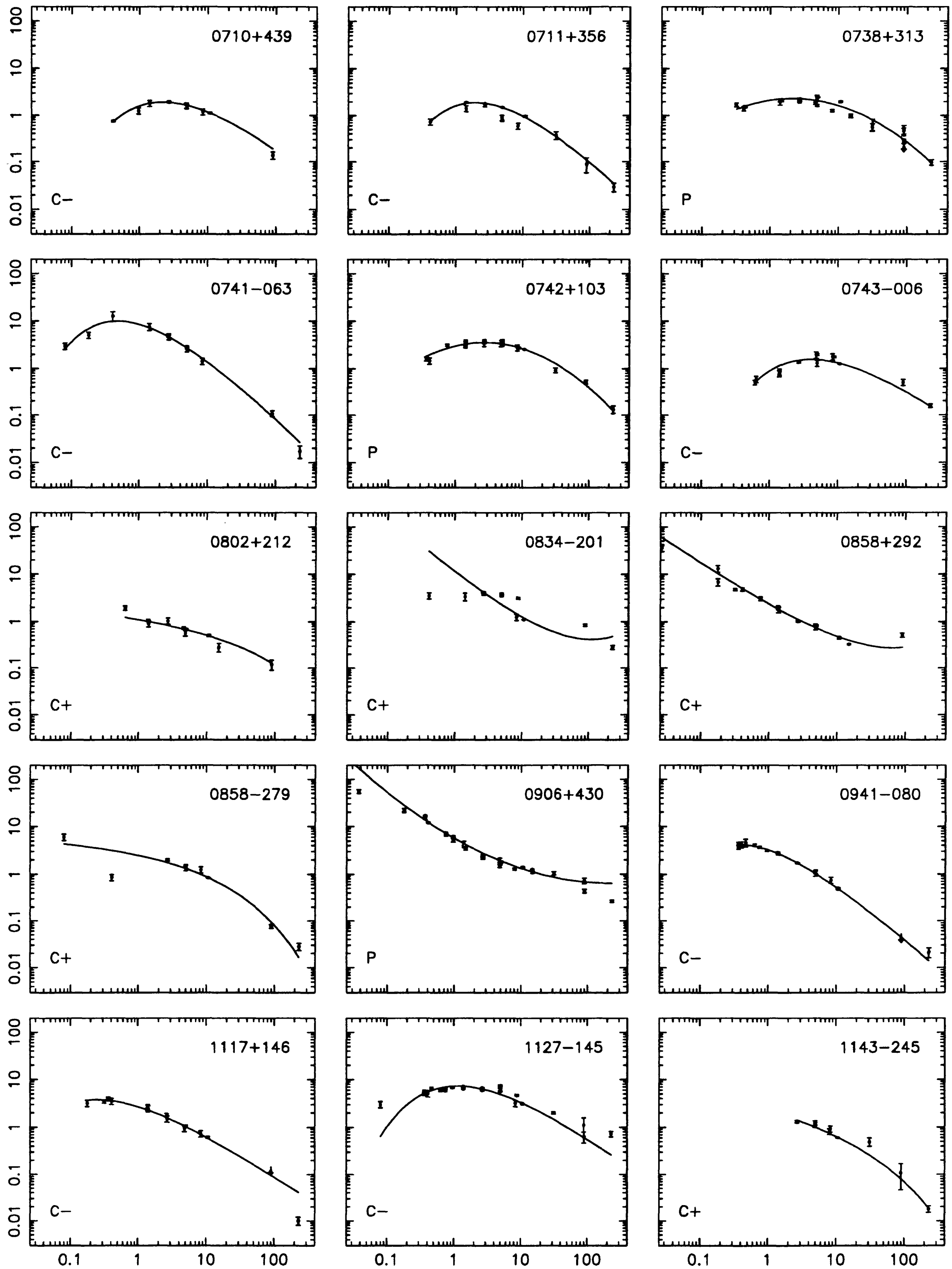

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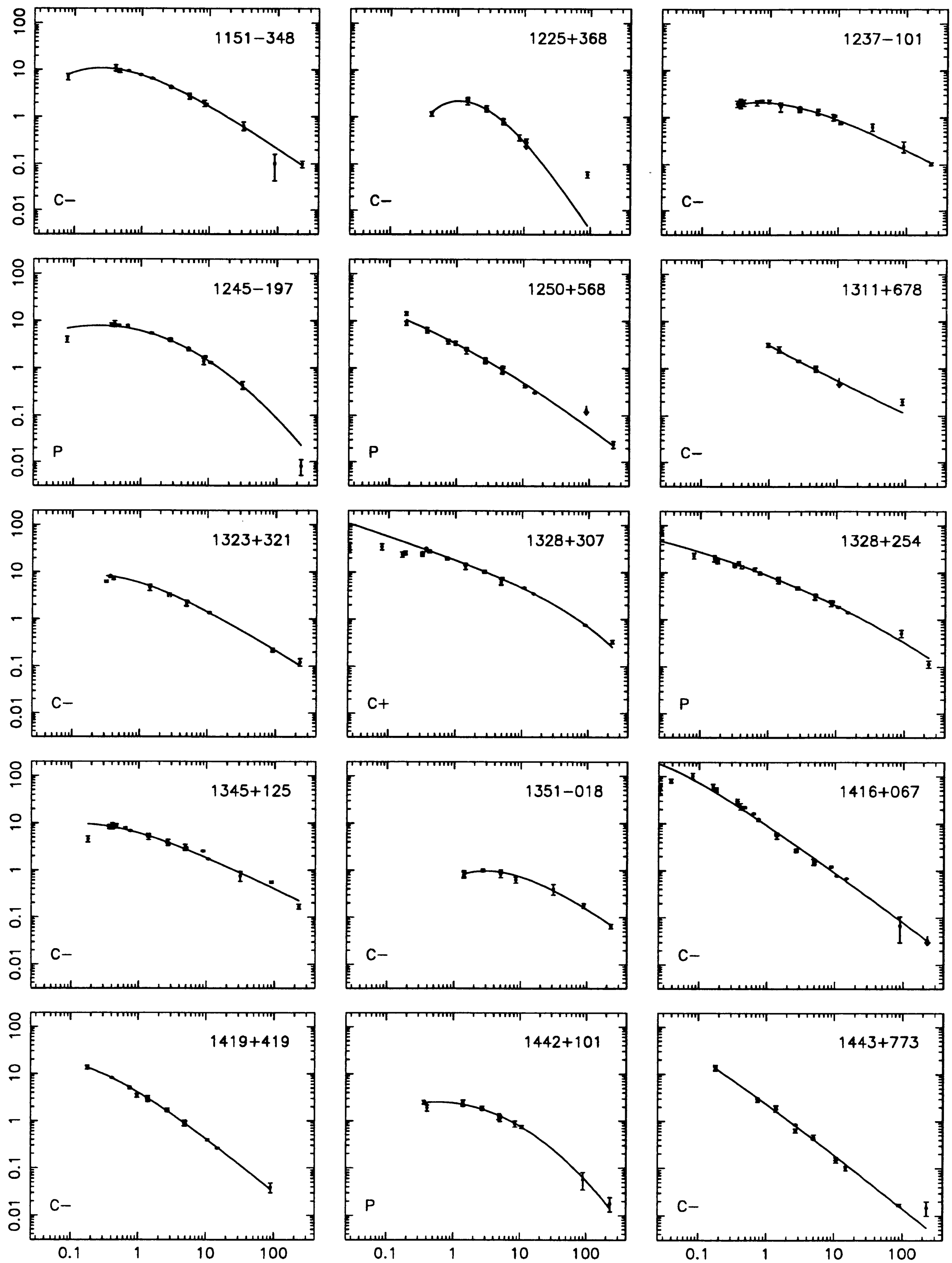

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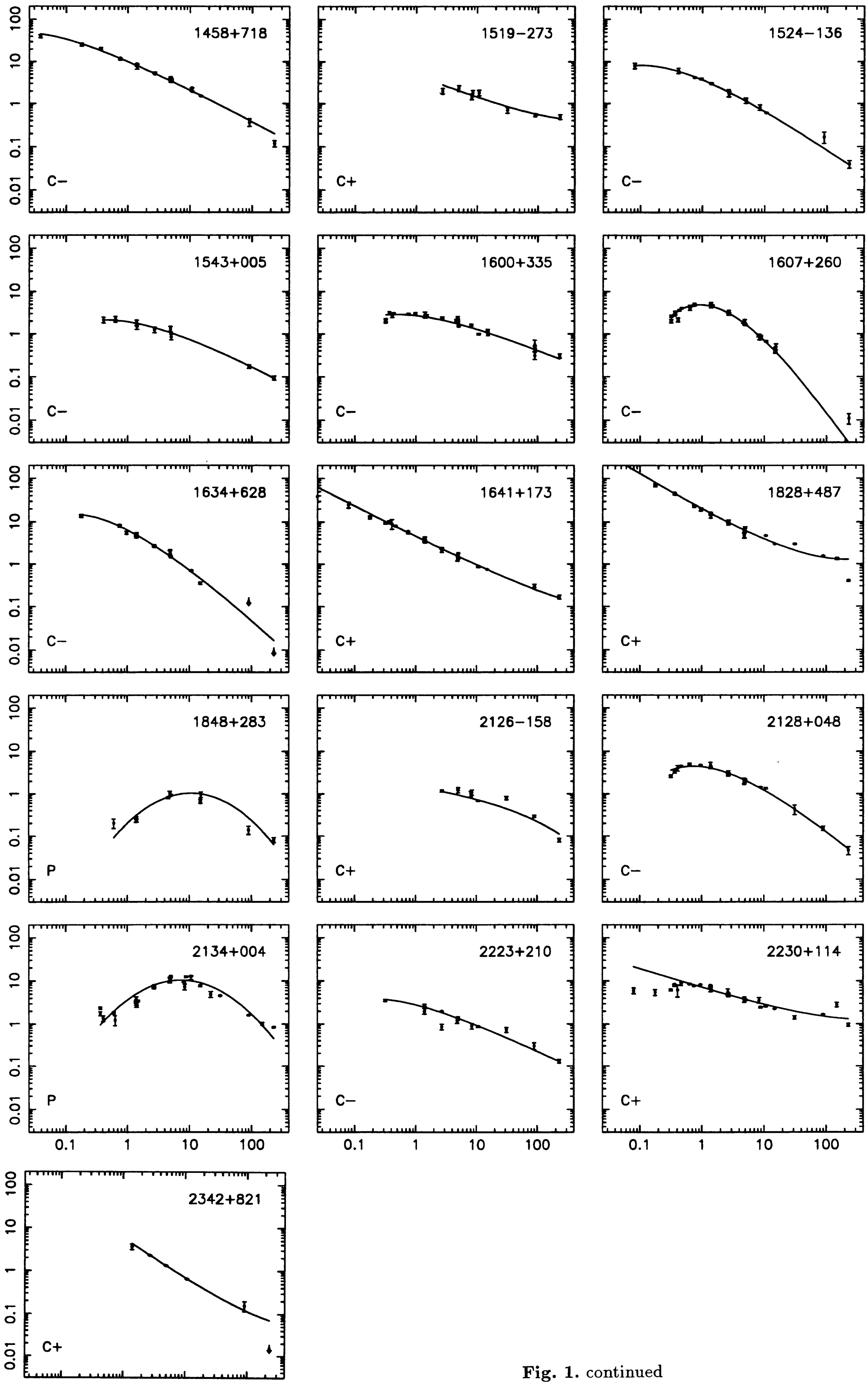

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