The SPECFIND V2.0 catalogue of radio cross-identifications and spectra

SPECFIND meets the Virtual Observatory

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ABSTRACT

The new release of the SPECFIND radio cross-identification catalogue, SPECFIND V2.0, is presented. It contains 107488 cross-identified objects with at least three radio sources observed at three independent frequencies. Compared to the previous release the number of entry radio catalogues is increased from 20 to 97 with 115 tables. This large increase was only made possible by the development of four tools at the Centre de Données astronomiques de Strasbourg (CDS) which use the standards and infrastructure of the Virtual Observatory (VO). This was done in the framework of the VO-TECH European Design Study of the Sixth Framework Program. We give an overview of the different classes of radio sources that a user can encounter. Due to the increase of the frequency coverage of the input radio catalogues, this release demonstrates that the SPECFIND algorithm is able to detect spectral breaks around a frequency of ~ 1 GHz.

Key words. astronomical data bases: miscellaneous – radio continuum: general

1. Introduction

The cross-identification of radio sources observed in the centimeter to meter wavelength domain with different instruments is a rather difficult task because of huge differences in sensitivity, spatial resolution, and the non-simultaneous observations of variable sources. Especially the very different spatial resolutions of single dish telescopes and interferometers are difficult to handle. On the other hand, most sources show a power-law spectral energy distribution in these wavelengths due to synchrotron or thermal emission. Synchrotron emission produces a power law spectrum with a possible cut-off or reversal of the spectral index at low frequencies due to self-absorption or comptonisation. The spectrum of thermal electrons is flat in the optically thin domain.

In Vollmer et al. (2005a) we presented the SPECFIND tool for the extraction of cross-identifications and radio continuum spectra from radio source catalogues contained in the Vizier database of the Centre de Données astronomiques de Strasbourg (CDS). The SPECFIND cross-identification tool takes advantage of the power-law shape of the spectra. In addition, it takes into account the angular resolution of the observations, the source size, and the flux densities observed at a given frequency. The SPECFIND tool also ensures that a radio source cannot be assigned to more than one physical object.

In a first release (SPECFIND V1.0; Vollmer et al. 2005a,b) we cross-identified the sources of the 20 largest radio catalogues in Vizier (Ochsenbein et al. 2000), representing 3.5 million sources. Our work led to more than 700 000 independent cross-identifications between sources from different radio catalogues and ~ 67 000 independent radio spectra with more than two independent frequencies.

The information contained in radio catalogues is heterogeneous and contains different entries (e.g. peak flux or integrated

flux) and physical units (e.g. source extent in arcsec, arcmin, or beamsizes). On the other hand, a cross-identification tool needs uniform input: at least a source name, position, and flux density at the measured frequency. The uniformisation of the 20 SPECFIND V1.0 entry catalogues was done by hand. For a significant increase of independent radio cross-identifications, an input of sources from more than a hundred radio catalogues is needed. This goal could only be attained by taking advantage of Virtual Observatory (VO) capabilities, which are described in Sect. 2. The new release of the SPECFIND catalogue is presented in Sect. 3.

2. Table uniformisation using VO tools

The Virtual Observatory offers (i) the standards for an efficient table uniformisation; and (ii) the infrastructure to make new tools available to the astronomical community. The aim of this work is two-fold: 1) the discovery of available resources, i.e. radio catalogues, in the VO world; and 2) the extraction and homogenisation of the relevant information from these resources.

Within the framework of the European VO-TECH Design Study we have developed three VO tools at CDS: (i) TABFIND: a tool to search for useful radio catalogues in the Virtual Observatory; (ii) TABUNIF: a tool to extract relevant information from these catalogues and to uniformise the catalogue information; and (iii) CAMEA: a tool to characterise the data, i.e. to include additional metadata necessary for the full usage of the data in the VO, as required in the VO “characterisation” data model (Louys et al. 2008). For example, the angular resolution of the observations is not provided as a standard parameter in the Vizier catalogue description. During the development the tools were kept as general as possible. They can thus be used in other astronomical contexts. We also plan to include

the extended radio catalogue description gathered by the characterisation tool into Vizier. These tools together with the associated manuals are available at <http://eurovotech.org/twiki/bin/view/VOTech>.

2.1. Registry query tool TABFIND

This tool identifies VO resources based on unified content descriptors (UCDs). The UCDs are a controlled vocabulary defined by the VO to describe astronomical quantities (Derrière et al. 2004). TABFIND is written in Java and uses XMLDB API¹ to get data from the VO registry of resources. The latter is a kind of telephone book where all web servers are listed who comply with VO standards. The user specifies a required set of UCDs. TABFIND searches the VO registry for all catalogues whose descriptions contain these UCDs. For example, in our project the minimum set of parameters needed for the radio cross-identification are source coordinates and a radio flux.

The result of the query is a list of relevant radio catalogues. The catalogues can then be sorted into useful and not useful catalogues by displaying the catalogue descriptions. A workspace permits us to save and restore all actions performed on the catalogues. At the end, a final list of relevant catalogues is established.

2.2. Data homogenisation tool TABUNIF

The relevant catalogues obtained from TABFIND can be directly loaded into the data homogenisation tool. TABUNIF creates homogenised data from a heterogeneous set of catalogues. It is written in Java and works on XML tables. In a first step the user specifies a set of columns for the output table which can be based on the list of UCDs². In our case we defined the output columns according to the needs of the SPECFIND cross-identification tool (Vollmer et al. 2005a). In a second step the tool generates an interface where a column of the entry radio catalogue is assigned to a user-specified output column.

The user is free to change the input column that he/she wants to assign to an output column. It is also possible to assign an arithmetic combination of different input columns or conditions on input columns to an output column. As a result the tool generates an ASCII output table for each input radio catalogue. The ASCII output tables can be directly used by the SPECFIND cross-identification tool. Alternatively, the output table can be produced in the VO-compliant VOTable format³ for future usage by VO tools.

2.3. Characterisation tool CAMEA

We realised that the description of the radio catalogues in Vizier does not contain all necessary information for the cross-identification. Basic information like the identity of the instrument, frequency, resolution, and observation dates are not included in the catalogue metadata. We therefore decided to develop a third VO tool which permits us to specify this missing information. More generally, it will permit us to create a full description of a VO resource based on the VO characterisation data model (Louys et al. 2008). In the future, CAMEA will help

to provide the input for the data homogenisation tool TABUNIF described above. In this way we plan to complement the Vizier metadata of radio catalogues by adding the frequency, angular resolution, observation dates, etc.

3. SPECFIND V2.0

The use of the registry query tool and data homogenisation tool enabled us to include 97 radio catalogues and 115 tables (a catalogue corresponds to one reference and can contain multiple tables) from Vizier (Ochsenbein et al. 2000) into the SPECFIND radio cross-identification tool (20 catalogues from Vollmer et al. 2005a (Table 1) and the catalogues listed in Table 2). The number of sources from these catalogues is 3.76×10^6 leading to 107 488 cross-identified objects, i.e. objects with at least three flux densities observed at three independent frequencies. Compared to the first release of the SPECFIND V1.0 catalogue this is an increase of available radio sources by $\sim 8\%$. This relatively small increase is caused by the number of catalogues with a given number of radio sources increasing rapidly while the number of radio sources contained in the catalogue decreases. However, the smaller catalogues often provide the missing third flux density to establish a radio spectrum. For example, in the northern hemisphere there is a multitude of radio objects with available NVSS (1.4 GHz; Condon et al. 1998) and WENSS (325 MHz; Rengelink et al. 1997) flux densities. The surveys at higher frequencies, which were included in SPECFIND V1.0, are rather shallow and thus did not detect the majority of the sources. Observations at high frequencies leading to small catalogues are almost always more sensitive than observations which large catalogues consist of, with the drawback that they are made within small areas on the sky. This is the reason why a modest increase of the sources available for the cross-identification ($\sim 8\%$) leads to the significant increase of cross-identified radio objects of $\sim 60\%$. The source coverage of the first and the second release of the SPECFIND catalogues are shown in Fig. 1.

The SPECFIND V2.0 catalogue is available via Vizier at CDS. It has the same data structure as SPECFIND V1.0. Each radio source represents one line of the catalogue. The radio sources from one physical object are linked via a common sequence number. For each radio source SPECFIND V2.0 gives a flag for extended/confused/complex sources (based on the NVSS), the source name, coordinates, flux density, error of the flux density as used in SPECFIND, number of sources with the same sequence number, slope and abscissa of the radio spectrum, positional difference to the NVSS source which is part of the spectrum, and the difference between the interpolated 20 cm and the NVSS flux density. In addition, we provide a link to the plot of the radio spectrum and a link to the Aladin applet in which the NVSS/DSS images and the positions of the SPECFIND V2.0 radio sources together with the beam sizes of the different observations are displayed. Moreover, we provide access to the radio sources that are cross-identified only with respect to their position (overlapping beams or extents), but do not fit the radio spectrum.

The distribution of the spectral indices⁴ is shown in Fig. 2. The distribution peaks at $\alpha \sim -0.9$, which is consistent with the result from the first release (see also Zhang et al. 2003). As in SPECFIND V1.0, there is a wing towards positive spectral indices, which is most probably caused by the flattening of the spectrum at low frequencies due to synchrotron self-absorption and at high frequencies due to the emission of thermal electrons.

⁴ The spectral index α is defined by $S_\nu \propto \nu^\alpha$.

¹ <http://xmldb-org.sourceforge.net/xapi/>

² <http://www.ivoa.net/Documents/latest/UCDlist.html>

³ The VOTable format is an XML standard for the interchange of data represented as a set of tables; <http://www.ivoa.net/Documents/latest/VOT.html>

Table 1. SPECFIND V1.0 catalogue entries.

Catalog name	I/S ¹	Frequency (MHz)	Resolution (arcmin)	$S_{\min}$ (mJy)	Number of sources	Percentage ²	Reference
JVAS	I	8400	5.5×10^{-3}	30	2246	72	Patnaik et al. (1992) Browne et al. (1998) Wilkinson et al. (1998)
GB6	S	4850	3.5	18	75162	59	Gregory et al. (1996)
87GB	S	4850	3.5	25	54 579	64	Gregory & Condon (1991)
BWE	S	4850	3.5	25	53 522	61	Becker et al. (1991)
PMN	S	4850	3.5	20	50 814	30	Wright et al. (1994, 1996) Griffith et al. (1994, 1995)
MITG	S	4850	2.8	40	24 180	52	Bennett et al. (1986) Langston et al. (1990) Griffith et al. (1990, 1991)
PKS	S	2700	8.0	50	8264	65	Otrupcek & Wright (1991)
F3R	S	2700	4.3	40	6495	61	Fürst et al. (1990)
FIRST	I	1400	0.083	1	811 117	1.5	White et al. (1998)
NVSS	I	1400	0.75	2	1773484	3.6	Condon et al. (1998)
WB	S	1400	10.	100	31524	60	White & Becker (1992)
SUMSS	I	843	0.75	8	134 870	1.8	Mauch et al. (2003)
B2	I	408	8.0	250	9929	72	Colla et al. (1970, 1972, 1973) Fanti et al. (1974)
B3	I	408	5.0	100	13 340	66	Ficarra et al. (1985)
MRC	I	408	3.0	700	12 141	73	Douglas et al. (1996)
TXS	I	365	0.1	250	66 841	57	Large et al. (1991)
WISH	I	325	0.9	10	90 357	8.4	de Breuck et al. (2002)
WENSS	I	325	0.9	18	229 420	17	Rengelink et al. (1997)
MIYUN	I	232	3.8	100	34 426	40	Zhang et al. (1997)
4C	I	178	11.5	2000	4844	53	Pilkington & Scott (1965) Gower et al. (1967)
3CR	I	178	6.0	5000	327	31	Bennet (1962)
3C	I	159	10.0	7000	470	3.4	Edge et al. (1959)

Notes. ⁽¹⁾ S: single dish; I: interferometer. ⁽²⁾ Percentage of sources with identified spectrum.

The number of objects as a function of the number of catalogued sources contained in an object is shown in Fig. 3. The shape of the distribution is a broken power law with a break at about 12 sources per object. The maximum number of catalogued sources in a physical object is 30.

The distributions of the spectral indices as a function of the measured or interpolated flux density at 325 MHz from SPECFIND V1.0 and V2.0 are shown in Fig. 4.

In SPECFIND V1.0 the straight, almost horizontal edge of the distribution in the left part of the plot (marked as (a) in the upper panel of Fig. 4) is due to a selection effect. For these low flux density sources with a steep spectrum, SPECFIND found a source at 20 cm (NVSS) and 50 cm (WENSS), but none at 6 cm, where the sensitivity of the surveys (~ 20 mJy) is insufficient. The inclusion of the new radio catalogues at 4850 MHz into SPECFIND V2.0 improved this situation only mildly.

The vertical edge in the lower left part of the plot (marked as (b) in the upper panel of Fig. 4) is mainly due to the limiting flux density of the B3 survey. Here the inclusion of a significant number of new sources at low frequencies ($\nu < 1$ GHz, mainly the 6C and 7C catalogues) leads to a significant increase of objects with 325 MHz flux densities smaller than 100 mJy and spectral indices smaller than 0.

4. Compatibility with SPECFIND V1.0

The cross-identification of radio sources observed at different frequencies and with considerably different angular resolutions (see Table 2) is a complex task. The details of the SPECFIND cross-identification algorithm are described in Vollmer et al. (2005a). In a first step SPECFIND makes a positional cross-identification accounting for the source extent and resolution of the survey. In a second step the flux densities and associated errors observed at the same frequency are compared and in a third step, a power law is fitted to the flux densities at different frequencies. The cross-identification is done for each catalogued radio source separately, which results in different spectral indices of sources belonging to the same object. In crowded fields with a high source density the cross-identification might not be unique and depends on the weight given to each source in the physical object. The resulting degeneracy in the cross-identification is solved by a self-consistency check of all physical objects found by SPECFIND (for details see Vollmer et al. 2005a). This procedure ensures that a radio source cannot be associated with two different physical objects.

Once sources of new catalogues are added to the input of the SPECFIND cross-identification tool, sources in crowded fields can be redistributed among physical objects, former objects can disappear and new ones can be created. To ensure

Table 2. Additional SPECFIND V2.0 catalogue entries.

Catalog name	I/S ¹	Frequency (MHz)	Resolution (arcmin)	$S_{\min}$ (mJy)	Number of sources	Percentage ²	Reference
NEK	I	31	12.0	2000	703	4	Kassim (1988)
8C	I	38	4.5	700	5859	66	Hales et al. (1995)
CRJ2004	I	74	0.42	150	949	63	Cohen et al. (2004)
VLSS	I	74	1.33	400	68 308	66	Cohen et al. (2007)
TRC2006b	I	74	0.5	0.3	725	0.2	Tasse et al. (2006)
Cula	I	80	3.7	2000	2173	49	Slee (1995)
6C	I	151	4.2	300	27 666	84	Baldwin et al. (1985)
							Hales et al. (1988/80/91/93)
7C	I	151	1.17	200	43 683	77	Hales et al. (2007)
Culb	I	160	1.85	1000	2042	66	Slee (1995)
TRB2007a	I	240	0.25	6	466	63	Tasse et al. (2007)
TRC2006a	I	325	0.12	2.5	843	47	Tasse et al. (2006)
WSTB90	I	327	1.5	3	407		Oort et al. (1988)
W93a	I	327	1.0	1	4157	32	Wieringa (1993)
WSTB2	I	327	1.5	10	309		Righetti et al. (1988)
WSRTGP	I	327	1.0	5	3984	14	Taylor et al. (1996)
PSRa		400	1.0	0.1	561	0.4	Taylor et al. (1993)
32P	I	408	4.0	30	494	61	Leahy & Roger (1996)
5C5	I	408	1.5	10	214	60	Pearson (1975)
5C6	I	408	1.5	6	267	68	Pearson (1978)
5C7	I	408	1.5	10	235	41	Pearson (1978)
5C12	I	408	1.5	2	308	70	Benn et al. (1982)
5C13	I	408	1.5	12	238	60	Benn (1995)
51P	I	408	4.0	80	383	31	Green & Riley (1995)
5C12a	I	408	1.33	5	680	49	Benn & Kenderdine (1991)
DRAOP	I	408	3.5		915	62	Landecker & Caswell (1983)
							VizieR VIII/55 ³
CGPSEa	I	408	3.0	10	140	24	Kerton et al. (2007)
PSRb		600	1.0	0.4	352	0.4	Taylor et al. (1993)
W93b	I	608	0.5	1	1693	62	Wieringa (1993)
TRB2007b	I	610	0.11	1	1037	35	Tasse et al. (2007)
FLSGMRT	I	610	0.1	0.1	3944	1	Garn et al. (2007)
NAIC	S	611	12.6	350	3122	45	Durbin et al. (1975)
MOST	I	843	0.733	40	348	59	Jones & McAdam (1992)
MGPS2	I	843	0.75	10	48 850	3	Murphy et al. (2007)
ATESP	I	1400	0.23	0.3	3370	1	Wieringa & Ekers (2000)
PSRc		1400	1.0	0.1	445	0.4	Taylor et al. (1993)
OWH82	S	1400	10.0	100	487	63	Owen et al. (1982)
GPSR	I	1400	0.083	5	1992	11	Zoonematkermani et al. (1990)
LO95	I	1400	0.25	10	375		Ledlow & Owen (1995)
PDF	I	1400	0.15	0.1	1079	0.1	Hopkins et al. (1998)
VIRMOS	I	1400	0.1	0.1	1103	4	Bondi et al. (2003)
FHW95a	S	1400	15.2	40	192	45	Filipovic et al. (1995)
WST32	I	1400	1.2	10	215	29	Fanti et al. (1981)
37W	I	1400	0.6	1	53	28	Walterbos et al. (1985)
ELAISR	I	1400	0.25	0.1	965	1	Ciliegi et al. (1999)
MGC2004	I	1400	0.23	0.03	1048	1	Morganti et al. (2004)
WBH2005	I	1400	0.1	2	6919	4	White et al. (2005)
RRF1	S	1410	9.4	100	884		Reich et al. (1990)
RRF	S	1410	9.4	80	1830		Reich et al. (1997)
QC93	S	1410	10.0	400	171	57	Quiniento & Cersosimo (1993)
CCH85	I	1411	0.33	5	208	9	Coleman et al. (1985)
WSTB	I	1412	0.385	1	536		Windhorst et al. (1984)
WSTB1	I	1412	0.385	1	359		Oort (1987)
33P	I	1420	1.0	3	255	36	Leahy & Roger (1996)

Notes. ⁽¹⁾ S: single dish; I: interferometer. ⁽²⁾ Percentage of sources with identified spectrum. Only unambiguous source names could be counted.

⁽³⁾ This catalogue is a compilation of tables in 27 articles. Landecker & Caswell (1983) is the first reference.

Table 2. continued.

Catalog name	I/S ¹	Frequency (MHz)	Resolution (arcmin)	$S_{\min}$ (mJy)	Number of sources	percentage ²	Reference
FBR2002	I	1420	1.633	3	534	43	Filipovic et al. (2002)
CGPSEb	I	1420	1.0	3	140	27	Kerton et al. (2007)
RLM94	I	1465	0.075	5	725	42	Roettgering et al. (1994)
P82_1	I	1465	0.43	200	404	71	Perley (1982)
NEP	I	1490	0.333	1	2435	16	Kollgaard et al. (1994)
DC78	S	2370	2.7	1	858	29	Dressel & Condon (1978)
FBR2002a	I	2370	0.667	1	697	33	Filipovic et al. (2002)
FHW95b	S	2450	8.85	30	334	54	Filipovic et al. (1995)
FORa	S	2695	4.78	20	221	81	Forkert & Altschuler (1987)
RFS	S	2695	4.9	30	1212	27	Reich et al. (1984)
RGB11	S	2700	4.3	50	697	50	Reich et al. (2000)
PBD2003	S	2700	8.0	100	1432	9	Paladini et al. (2003)
KMP90	S	4730	2.8	15	752	85	Kulkarni et al. (1990)
FORb	S	4750	2.71	25	227	85	Forkert & Altschuler (1987)
FHW95c	S	4750	4.8	15	368	53	Filipovic et al. (1995)
NAICGB	S	4775	2.8	8	2453	65	Lawrence et al. (1983)
A86	S	4760	2.8	15	882	74	Altschuler (1986)
FBR2002b	I	4800	0.5	1	75	40	Filipovic et al. (2002)
GDP	I	4850	0.5	0.3	253	8	Gregorini et al. (1994)
CAB95	S	4850	3.5	25	351	76	Condon et al. (1995)
JRB99	I	4860	0.03	1	298	28	Jackson et al. (1999)
FPD2001a	I	4860	6.7e-3	1	213	36	Fanti et al. (2001)
ADP79	S	4875	2.6	100	569	19	Altenhoff et al. (1979)
RGB	I	4885	0.067	13	1861	56	Laurent-Muehleisen et al. (1997)
P82_2	I	4885	0.1	200	404	82	Perley (1982)
KR	I	4890	0.07	10	195	41	Fich (1986)
GPSR5	I	4900	0.067	1	1286	3	Becker et al. (1994)
Slee	I	4900	0.67	0.2	177	21	Slee et al. (1998)
HCS79		5000	0.54	240	702	3	Haynes et al. (1979)
RGB6	S	5000	2.4	40	729	56	Reich et al. (2000)
GPA2	S	8350	9.7	900	555	6	Langston et al. (2000)
CLASS	I	8400	5.5e-3	0.1	21486	39	Myers et al. (2003)
FPD2001b	I	8460	3.3e-3	0.2	199	33	Fanti et al. (2001)
FHW95d	S	8550	2.7	20	205	47	Filipovic et al. (1995)
FBR2002c	I	8640	0.27	1	54	41	Filipovic et al. (2002)
NKB95	S	10 550	1.15	3	202	57	Niklas et al. (1995)
B3VLA	S	10 600	1.15	10	981	80	Gregorini et al. (1998)
RGB2	S	10 700	1.2	30	698	53	Reich et al. (2000)
GPA1	S	14 350	6.6	2000	365	7	Langston et al. (2000)
9C	I	15 000	0.42	25	242	71	Waldram et al. (2003)

Notes. ⁽¹⁾ S: single dish; I: interferometer. ⁽²⁾ Percentage of sources with identified spectrum. Only unambiguous source names could be counted.

the compatibility between the SPECFIND V1.0 and V2.0 catalogues, we developed a tool to check the coherence between these catalogues. This tool searches for (i) radio sources of SPECFIND V1.0 which are not found in V2.0; and (ii) radio sources of a physical object in SPECFIND V1.0 which are found in different physical objects in V2.0. The tool displays the V1.0 and V2.0 object lists together with the V1.0 and V2.0 spectra. As an additional step the user can display the NVSS 20 cm image within Aladin (Bonnarel et al. 2000) together with the source positions and the beam sizes (angular resolution) (Figs. 5–9). This information allowed us to either (i) merge both spectra or to keep the (ii) the V1.0; or (iii) V2.0 spectrum. In this way we visualised and modified about 1000 physical objects in the SPECFIND V2.0 catalogue.

This procedure also allowed us to detect complicated cases of the radio cross-identification. Below we present the five major classes of physical objects that a user finds in the SPECFIND V2.0 catalogue: (i) well-behaved; (ii) extended; (iii) complex; (iv) physical double; and (v) unphysical double sources. Sources of class (ii)–(v) can be recognised by a spread of the spectral indices α of the sources contained in a physical object which is larger than the uncertainty due to the flux density errors ($\Delta\alpha > 0.3$; Vollmer et al. 2005b). We decided to leave all these sources in the catalogue. *We therefore caution the user against a blind use of the SPECFIND V2.0 catalogue.* To help the user, we provide flags for sources which (i) have at least one neighbouring NVSS source within a radius of $2'$ (possible confusion); (ii) have deconvolved sizes larger than $45''$ in the NVSS

Fig. 1. Sky coverage of radio sources. In both images black/blue/red corresponds to 0/27/64 objects per pixel. *Upper panel:* from the first release; *lower panel:* from the SPECFIND V2.0 catalogue.

Fig. 2. Number distribution of spectral indices.

catalogue (extended sources), and (iii) are marked as complex in the NVSS catalogue.

4.1. Well-behaved sources

The vast majority of the SPECFIND V2.0 objects are well-behaved (Fig. 5), i.e. they are unresolved or marginally resolved in most of the surveys and exhibit consistent spectral indices for all sources (the uncertainty of the spectral index is ± 0.3 ; Vollmer et al. 2005a). In the case of sources which are only present in one of the catalogues SPECFIND V1.0 or V2.0, we merged the spectra of all these well-behaved sources.

Fig. 3. The number of sources as a function of the number of independent points in the radio spectrum.

Fig. 4. Spectral index as a function of 325 MHz flux density. *Upper panel:* SPECFIND V1.0 (Vollmer et al. 2005a). *Lower panel:* SPECFIND V2.0.

4.2. Extended sources

The second class of sources are those which are extended with respect to the mean resolution of the input catalogues, which is $\sim 1-2'$. An example for such a source is shown in Fig. 6. At low frequencies these objects have radio fluxes from low resolution

SPECFIND spectrum #107144

Fig. 5. Well-behaved sources – TXS 2112+158. *Upper panel:* Aladin view of the NVSS image, the positions of the radio sources and the beamsizes of the radio surveys. *Lower panel:* Vizier view of the radio spectrum. Red symbols: Specfind V2.0; green symbols: waste, i.e. source with overlapping beams that do not fit the radio spectrum.

SPECFIND spectrum #96349

Fig. 6. Extended sources – TXS 2300-189. *Upper panel:* Aladin view of the NVSS image, the positions of the radio sources and the beamsizes of the radio surveys. *Lower panel:* Vizier view of the radio spectrum. Red symbols: Specfind V2.0; green symbols: waste, i.e. source with overlapping beams that do not fit the radio spectrum.

surveys in which the source is unresolved. However, at high frequencies the radio fluxes are provided by high resolution surveys. The source is thus resolved leading to a flux density which is smaller than the total flux density. The spectrum of the physical object has two different slopes: one which is fitted to the flux density of the unresolved sources and one which is fitted to the flux density of the resolved sources. In these cases the user has to verify the resolutions of the data points and to make a choice to which points he or she wants to fit a power law. Extended sources thus exhibit different spectral indices ($\Delta\alpha > 0.3$) within the same

frequency range (between 100 and 500 MHz in the example of Fig. 6).

4.3. Complex sources

Nearby large Galactic radio sources often display a complex structure (Fig. 7). In the presence of a sufficient number of observations at different frequencies the SPECFIND algorithm identifies power laws, but as for the extended sources, there are multiple spectral indices within the same frequency range (here between 100 MHz and 10 GHz). In the case of such complex

Fig. 7. Complex sources – WN B2040.8+4246. *Upper panel:* Aladin view of the NVSS image, the positions of the radio sources and the beamsizes of the radio surveys. *Lower panel:* vizier view of the radio spectrum. Red symbols: Specfind V2.0; green symbols: waste, i.e. source with overlapping beams that do not fit the radio spectrum.

Fig. 8. Possibly physical double sources – WN B1853.1+6226A. *Upper panel:* Aladin view of the NVSS image, the positions of the radio sources and the beamsizes of the radio surveys. *Lower panel:* Vizier view of the radio spectrum. Red symbols: Specfind V2.0; green symbols: waste, i.e. source with overlapping beams that do not fit the radio spectrum.

sources the user has to carefully inspect all resolutions and, if necessary, all source extents in the original catalogues in VizierR.

4.4. Physical double sources

Since the typical resolution of the SPECFIND entry surveys is $\sim 2'$ (Table 2), radio sources which are separated by less than this distance will most frequently end up in one object in the SPECFIND catalogue (Fig. 8). There are observations with large

beamwidths which comprise the two sources and observations with higher resolution which resolve the two sources. In a physical double source, i.e. the radio lobes of an active galactic nucleus, the two sources often differ in flux density, size, and spectrum. Many double lobe radio sources show an intrinsic asymmetry in their lobes, probably due to Doppler-boosting and jet inclination. The different resolutions of the surveys and the detection of different source components leads to a dispersion of the spectral indices in the composite spectrum.

Fig. 9. Unphysical double sources – WN B2228.2+5940A. *Upper panel:* Aladin view of the NVSS image, the positions of the radio sources and the beamsizes of the radio surveys. *Lower panel:* VizieR view of the radio spectrum. Red symbols: Specfind V2.0; green symbols: waste, i.e. source with overlapping beams that do not fit the radio spectrum.

4.5. Unphysical multiple sources

Other sources which are separated by less than $2'$ are not physically related, i.e. the sources are only close in projection (Fig. 9). When these sources exhibit two largely different spectral indices, they can be separated easily with the help of the radio spectrum. If these sources have about the same spectral index, the user has to rely on the NVSS image.

5. Spectral breaks

As described in Vollmer et al. (2005a) the SPECFIND algorithm is able to detect a spectral break if enough data points at independent frequencies are available. Due to the increased number of input frequencies in the SPECFIND V2.0 catalogue, we could identify 18 sources which show a spectral break (Fig. 10). Since the frequency coverage of the input survey ranges between ~ 100 MHz and ~ 10 GHz, the break is located in the middle of this interval around 1 GHz. These giga Hertz peaked sources (GPS) are powerful ($\log P_{1.4 \text{ GHz}} > 25 \text{ W Hz}^{-1}$) and compact ($< 1 \text{ kpc}$) extragalactic radio sources, which show a convex radio spectrum peaking between 500 MHz and 10 GHz in the observer's frame (for a review see O'Dea 1998). The physical mechanism responsible for the turnover of the spectrum is still unclear and two competing models are proposed: the synchrotron self-absorption caused by dense plasma within the source or the free-free absorption caused by a screen external to the source. GPS sources are associated with either quasars or galaxies. All but one object of Fig. 10 were already included in the SPECFIND V1.0 catalogue, but the limited frequency range often prevented the detection of the spectral break. Four objects are included in the GPS sample of Vollmer et al. (2008) which was based on SPECFIND V1.0 objects showing an inverted radio spectrum.

6. Accuracy of radio catalogues

The cross-identification realised for SPECFIND V2.0 allowed us to evaluate the accuracy in position and flux density of the 97 radio catalogues with respect to the NVSS source catalogue. We do not find significant systematic offset in position or flux densities between the entry catalogues (Table 2) and the NVSS catalogue.

7. Summary

We present the second release of the SPECFIND catalogue, SPECFIND V2.0, which is available at CDS's VizieR⁵. The catalogue contains 107488 cross-identified objects with at least three radio sources observed at three independent frequencies. The cross-identification algorithm is based on proximity, source extent, survey resolution, flux density at the same frequency, and power law spectra at different frequencies (Vollmer et al. 2005a). We increased the number of entry catalogues from 20 to 97 with 115 tables (Table 2). This large increase was only made possible by the development of four tools at CDS which use the standards and infrastructure of the Virtual Observatory (VO). This was done in the framework of the VO-TECH Design Study. The first three tools described below are not specifically designed for radio data and can be used for other purposes. Together with the associated manuals they are available at <http://eurovotech.org/twiki/bin/view/VOtech>. These tools are:

1. TABFIND: discovery of relevant resources based on unified content descriptors (see Sect. 2.1).
2. TABUNIF: Uniformisation of a heterogeneous set of catalogues (see Sect. 2.2).
3. CAMEA: Description of the catalogue data (see Sect. 2.3).
4. A SPECFIND-specific tool to insure the compatibility between two successive releases of the SPECFIND catalogue.

⁵ <http://vizier.u-strasbg.fr/viz-bin/VizieR>

Fig. 10. Radio objects with spectral breaks identified by SPECFIND. The different lines correspond to fits of different parts of the radio spectrum. The SPECFIND V2.0 sequence number from Vizier and the name of one of the radio sources are marked in each box.

With a modest increase in the number of input sources ($\sim 8\%$) we could increase the number of cross-identified objects by $\sim 60\%$. We decided not to remove extended and complex sources from SPECFIND V2.0 and therefore caution the user against a blind use of the catalogue. Typical source geometries and subsequent radio spectra are given in Sect. 4. Most frequently, the user can separate the underlying objects with the help of the SPECFIND radio spectrum and the NVSS image. Due to the larger frequency coverage of the SPECFIND entry catalogues with respect to that of the previous release spectral breaks are present in the SPECFIND V2.0 catalogue.

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