WHAT TYPES OF JETS DOES NATURE MAKE? A NEW POPULATION OF RADIO QUASARS

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ABSTRACT

We use statistical results from a large sample of about 500 blazars, based on two surveys, the Deep X-Ray Radio Blazar Survey (DXRBS), nearly complete, and the ROSAT All-Sky Survey–Green Bank Survey (RGB), to provide new constraints on the spectral energy distribution of blazars, particularly flat-spectrum radio quasars (FSRQs). This reassessment is prompted by the discovery of a population of FSRQs with spectral energy distribution similar to that of high-energy-peaked BL Lac objects. The fraction of these sources is sample dependent, being $\sim 10\%$ in DXRBS and $\sim 30\%$ in RGB (and reaching $\sim 80\%$ for the *Einstein* Medium Sensitivity Survey). We show that these "X-ray-strong" radio quasars, which had gone undetected or unnoticed in previous surveys, indeed are the strong-lined counterparts of high-energy-peaked BL Lac objects and have synchrotron peak frequencies, ν_{peak} , much higher than "classical" FSRQs, typically in the UV band for DXRBS. Some of these objects may be 100 GeV to TeV emitters, as are several known BL Lac objects with similar broadband spectra. Our large, deep, and homogeneous DXRBS sample does not show anticorrelations between ν_{peak} and radio, broad-line region, or jet power, as expected in the so-called blazar sequence scenario. However, the fact that FSRQs do not reach X-ray-to-radio flux ratios and ν_{peak} values as extreme as BL Lac objects and the elusiveness of high- ν_{peak} high-power blazars suggest that there might be an intrinsic, physical limit to the synchrotron peak frequency that can be reached by strong-lined, powerful blazars. Our findings have important implications for the study of jet formation and physics and its relationship to other properties of active galactic nuclei.

Subject headings: BL Lacertae objects: general — galaxies: active — quasars: general — radiation mechanisms: nonthermal — radio continuum: galaxies — X-rays: galaxies

1. A PHENOMENOLOGICAL DESCRIPTION OF THE BLAZAR CLASS

Blazars are one of the most extreme classes of active galactic nuclei (AGNs), distinguished by high luminosity, rapid variability, high polarization, radio core dominance, and apparent superluminal speeds (Urry & Padovani 1995). Their broadband emission extends from the radio up to the gamma-ray band and is dominated by nonthermal processes. The blazar class includes BL Lacertae objects, characterized by an almost complete lack of emission lines, and the flat-spectrum radio quasars (FSRQs), which by definition display broad, strong emission lines.

More than 95% of all known blazars have been discovered either in radio or X-ray surveys (Padovani & Giommi 1995a). Previous work has shown that X-ray and radio selection methods yield objects with somewhat different properties at least for BL Lac objects. The energy output of most radio-selected BL Lac objects peaks in the IR/optical (Giommi & Padovani 1994; Padovani & Giommi 1995b, 1996). These objects are more highly polarized (Jannuzi, Smith, & Elston 1994) and are more core dominated in the radio (Perlman & Stocke 1993; Laurent-Muehleisen et al. 1993; Kollgaard et al. 1996; Rector, Stocke, & Perlman 1999) and are now referred to as LBLs (low-energy–peaked BL Lac objects). By contrast, the energy output of most X-ray–selected BL Lac objects peaks in the UV/X-ray; these objects, which are referred to as HBLs (highenergy–peaked BL Lac objects), are less polarized and generally have preferred position angles of polarization in the optical (Jannuzi et al. 1994) and are less core dominant in the radio (Perlman & Stocke 1993; Kollgaard et al. 1996; Rector et al. 2000).

Padovani & Giommi (1995b) have demonstrated that the difference in broadband peaks for HBLs and LBLs is not simply phenomenological. Rather, it represents a fundamental difference between the two subclasses. In this respect, one could expect to find a similar division in the FSRQ class—for which, until recently, no evidence existed. Indeed, it was suggested by some authors (Sambruna, Maraschi, & Urry 1996), based on the similarities of the optical–X-ray broadband spectral characteristics of LBLs and FSRQs, that no FSRQ with synchrotron peak emission in the UV/X-ray band should exist.

The dichotomy that there existed both high- and lowenergy-peaked BL Lac objects (but virtually no intermediate objects) and only low-energy-peaked FSRQs was the state of the art in our knowledge of blazar spectral energy

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distributions (SEDs) in the mid 1990s. Four discoveries have drastically changed this picture:

1. The multifrequency catalog of Padovani, Giommi, & Fiore (1997), which included all FSRQs known before the Deep X-Ray Radio Blazar Survey (DXRBS) and other recent surveys, identified more than 50 FSRQs (\sim 17% of the FSRQs in their catalog) with broadband spectra similar to those of HBLs.

2. About 30% of FSRQs found in DXRBS (Perlman et al. 1998; Landt et al. 2001) were found to have X-ray–to–radio luminosity ratios, L_x/L_r , typical of HBLs $(L_x/L_r \gtrsim 10^{-6} \text{ or } \alpha_{\text{rx}} \lesssim 0.78)$ but broad (FWHM > 2000 km s⁻¹) and luminous ($L > 10^{43} \text{ ergs s}^{-1}$) emission lines typical of FSRQs.

3. Large numbers of "intermediate" BL Lac objects, objects with broadband properties intermediate between HBLs and LBLs, have been discovered in the DXRBS (Perlman et al. 1998; Landt et al. 2001), *ROSAT* All-Sky Survey–Green Bank (RGB; Laurent-Muehleisen et al. 1998), and other samples (Nass et al. 1996; Kock et al. 1996).

4. *BeppoSAX* observations have shown that the X-ray emission of at least one FSRQ is dominated by synchrotron radiation, with a peak frequency $\nu_{\text{peak}} \sim 2 \times 10^{16}$ Hz and steep ($\alpha_x \sim 1.5$) X-ray spectrum (Padovani et al. 2002). Two more FSRQs show evidence of $\nu_{\text{peak}} \approx 10^{15}$ Hz.

The discovery of "X-ray-strong" FSRQs (labeled HFSRQs by Perlman et al. 1998 to parallel the HBL moniker; the "standard" FSRQs would then be the LFSRQs) represents a fundamental change in our perception of the broadband spectrum of FSRQs, similar to that brought about by the X-ray-selected BL Lac objects discovered in the *Einstein* Medium Sensitivity Survey (EMSS; Morris et al. 1991; Stocke et al. 1991; Rector et al. 2000). A preliminary investigation of the properties of HFSRQs in the DXRBS survey was presented in Perlman et al. (1998). The discovery of a large number of intermediate BL Lac objects should have been in many ways expected already in the mid-1990s given our knowledge of the vastly disparate parameter space coverages of X-ray and radio surveys (see § 3).

With these recent discoveries in mind, it is time to once again take stock of the broadband spectral properties of all blazars. Here we utilize updated identifications from DXRBS (most of which were presented by Landt et al. 2001), which result in a much larger sample, combined with a sample of blazars we have extracted from RGB (Laurent-Muehleisen 1996; Laurent-Muehleisen et al. 1998), to attack this problem. A preliminary version of some of these findings was presented previously by Perlman (2000).

The samples are briefly described in § 2. In § 3 we comment on the failure of previous surveys to find X-ray–strong FSRQs. In § 4 we study the SEDs of our sources and discuss the use of the available data to obtain the peak frequency of synchrotron emission and other characteristics of blazars. We discuss the so-called blazar sequence scenario in § 5 and further constraints on blazar emission in § 6, while § 7 summarizes our conclusions. Throughout this paper spectral indices are written $S_{\nu} \propto \nu^{-\alpha}$, and for consistency with previous work the values $H_0 = 50$ km s⁻¹ Mpc⁻¹, $\Omega_M = 0$, and $\Omega_{\Lambda} = 0$ have been adopted. We note that our correlations (or lack of) are basically unchanged for a cosmological model with $H_0 = 65$ km s⁻¹ Mpc⁻¹, $\Omega_M = 0.3$, and $\Omega_{\Lambda} = 0.7$.

2. THE SAMPLES

2.1. The DXRBS Blazar Sample

DXRBS is the result of correlating the *ROSAT* WGACAT database⁵ (N. E. White, P. Giommi, & L. Angelini 1995) with several publicly available radio catalogs (GB6 and PMN at 5 GHz, NORTH20CM at 1.4 GHz), restricting the candidate list to serendipitous flat-spectrum radio sources ($\alpha_r \leq 0.70$). In addition, a snapshot survey with the Australia Telescope Compact Array was conducted for $\delta \leq 0^{\circ}$ to get radio spectral indices unaffected by variability (and arcsecond positions for the sources south of $\delta = -40^{\circ}$, the limit of the NRAO-Very Large Array [VLA] Sky Survey [NVSS]; Condon et al. 1998). The DXRBS X-ray flux limits depend on the exposure time and the distance from the center of the *ROSAT* Position Sensitive Proportional Counter (PSPC) but vary between $\sim 10^{-14}$ and $\sim 10^{-11}$ ergs cm⁻² s⁻¹. Radio 5 GHz fluxes reach down to ~ 50 mJy.

First results from DXRBS were presented in Perlman et al. (1998), while updated identifications were presented in Landt et al. (2001). At the time of writing (2002 November), DXRBS includes 244 blazars: 200 FSRQs (defined as broad-line sources with $\alpha_r \leq 0.50$) and 44 BL Lac objects. Details on our BL Lac classification are given in Landt et al. (2001). Note that Giommi et al. (2002c) have pointed out that sources with optical spectrum typical of a galaxy but nuclear SED typical of a blazar should probably be classified as low-luminosity BL Lac objects. Some of our radio galaxies might fall in that category. We will address this point in future papers.

We include in this work only sources belonging to the complete sample, which fulfills all our selection criteria (see details in Landt et al. 2001). This is necessary because we want to compare in detail the properties (mainly the SED) of DXRBS FSRQs and BL Lac objects, and that requires well-defined samples to avoid introducing any bias. Since we need the sky coverage to deconvolve the observed distributions, we have excluded sources with PSPC center offsets in the range 13'-24', where the sky coverage is difficult to determine because of the effects of the spacecraft wobble and the rib structure. We are then left with 134 FSRQs and 31 BL Lac objects, for a total of 165 blazars. Only about 10 more sources (~5% of the total) with $\alpha_r \leq 0.50$ remain to be identified. The current blazar sample is therefore highly representative.

2.2. The RGB Blazar Sample

Laurent-Muehleisen et al. (1997) have described in depth the procedures undertaken in constructing the RGB catalog of radio- and X-ray–emitting sources. Here we review only the essential points.

The catalog was constructed by correlating the ROSATAll-Sky Survey (RASS) with a radio catalog based on the 1987 Green Bank 5 GHz survey maps (Gregory & Condon 1991; Gregory et al. 1996). VLA observations of all the 2127 radio/X-ray matches within 100" were obtained to derive arcsecond positions (Laurent-Muehleisen et al. 1997). For the 1567 sources with radio/X-ray offset less than 40", optical counterparts were identified using the Automatic Plate Measuring scans (Irwin, Maddox, & McMahon 1994), which give O (blue) and E (red)

⁵ See http://wgacat.gsfc.nasa.gov.

magnitudes. Laurent-Muehleisen et al. (1997, 1998) give many new object identifications based on spectra taken at various optical telescopes. The identifications published by Laurent-Muehleisen et al. (1997, 1998) include a comprehensive list of BL Lac objects, as well as many radio-loud, broad-line objects (i.e., radio-loud quasars); however, since radio spectral index was not included in the search criteria for RGB, no list of FSRQs was compiled there.

Some indication that X-ray-strong FSRQs were being found in the RGB sample could be seen from the distribution of X-ray-to-radio flux ratios of the newly identified objects (Laurent-Muehleisen et al. 1998). We therefore decided to use the information in the RGB along with other public surveys to create a list of all blazars (BL Lac objects and FSRQs) in the full RGB sample. We used Tables 3.3 and 3.4 of Laurent-Muehleisen (1996) and Table 3 of Laurent-Muehleisen et al. (1998) to search for both BL Lac objects and FSRQs as follows. First, the RGB sample was cross-correlated with the AGN catalog of Padovani et al. (1997) to find previously known blazars. Then, we used the identifications given by Laurent-Muehleisen et al. (1998) to include newly identified sources (note that these are limited to objects with $O \leq 18.5$). This resulted in a total of more than 600 classified RGB sources. Being based on the RASS, the RGB covers a very different X-ray flux range: X-ray fluxes range between $\sim 2 \times 10^{-13}$ and $\sim 10^{-10}$ ergs cm⁻² s⁻¹. Radio 5 GHz fluxes reach down to \sim 25 mJy, roughly a factor of 2 fainter than DXRBS at similar declinations.

Radio spectral indices, necessary to determine whether a broad-line radio source is an FSRQ or not, were derived by cross-correlating the RGB with the NVSS. For consistency with DXRBS, we used 5 GHz fluxes from the GB6 survey (and not from the dedicated VLA observations) for the RGB sources. In doing the cross-correlation, then, the 1.4 GHz flux from all NVSS sources within a 3' radius (corresponding roughly to the beam size of the GB6 survey) was summed up (we have already described the rationale connected with doing this in Perlman et al. 1998). We then isolated a sample of FSRQs ($\alpha_r \leq 0.5$).

We checked that the spectral indices derived from the GB6/NVSS radio data were reliable in the following way. Three hundred forty-five radio-loud RGB sources had a value of the radio spectral index in the AGN catalog of Padovani et al. (1997), generally obtained from nonsimultaneous, single-dish measurements around a few GHz. There is a very strong (P > 99.99%) linear correlation with a slope ~ 0.9 between the two spectral indices, with a mean difference $\Delta \alpha = 0.08$ over a range of ~ 2.5 . This shows that the method we used to estimate the radio spectral index for the RGB sample is quite robust.

The RGB blazar sample thus includes 362 blazars: 233 FSRQs and 129 BL Lac objects. To our knowledge the RGB sample is ~44% identified. This fraction goes up to ~76% for the part of the sample with $O \leq 18.5$. Considering only the sources with $\alpha_r \leq 0.5$, we find that these fractions do not change much, being 49% and 73%, respectively.

2.3. The Joint Sample

Overall, the two samples used in this paper include 497 distinct blazars, 342 FSRQs and 155 BL Lac objects (30 objects are in common). In terms of its range of properties, size, depth, and selection criteria this ensemble of objects

represents a unique sample with which to address some of the open questions of blazar research.

As an initial step toward studying the broadband properties of our sources, we first derive their α_{ox} , α_{ro} , and α_{rx} values. These are the usual rest-frame effective spectral indices defined between 5 GHz, 5000 Å, and 1 keV. X-ray and optical fluxes have been corrected for Galactic absorption. The effective spectral indices have been k-corrected using the appropriate radio, optical, and X-ray spectral indices. X-ray spectral indices are available for all DXRBS sources from hardness ratios, as described in Landt et al. (2001). For the RGB objects we obtained X-ray spectral indices from hardness ratios for 73% and 89% of FSRQs and BL Lac objects, respectively, from Brinkmann et al. (1997), Laurent-Muehleisen et al. (1999), Reich et al. (2000), and WGACAT. In the remaining cases we assumed $\alpha_x = 1.2$ following Laurent-Muehleisen et al. (1998). Values for the optical spectral indices were assumed to be the typical ones for the various subclasses. Finally, optical magnitudes for broad-line sources were also corrected for the presence of emission lines according to the prescription of Natali et al. (1998).

It is worth mentioning that, unlike DXRBS, all new RGB identifications have $O \leq 18.5$. This has important selection biases associated with it (§§ 3 and 4). In particular, an optical magnitude limit has the effect of imposing an artificial boundary on the regions of parameter space to which a survey is sensitive. Namely, only sources with $\alpha_{ro} < \alpha_{ro}(\lim)$ and $\alpha_{ox} > \alpha_{ox}(\lim)$, where these limiting values depend on radio and X-ray flux, will be included. At the survey radio limit, for example, only sources with $\alpha_{ro} \leq 0.4$ will be included. We will discuss the effect of this limitation in § 4.

3. THE DISCOVERY OF X-RAY-STRONG FSRQs

The findings of Padovani et al. (1997, 2002) and Perlman et al. (1998) make it clear that detecting X-ray–strong FSRQs requires large and/or deep samples. It was already known in 1995 that radio-selected samples more frequently contain objects with broadband spectra peaking in the IR/ optical. The oft-repeated separation of HBLs and LBLs on the (α_{ox}, α_{ro}) plane (e.g., Padovani & Giommi 1995b) is a direct by-product of these disjoint survey methods.

With this observation in mind, one might expect a similar selection effect to have been present for FSRQs. Yet up until the mid-1990s, no X-ray survey had looked for FSRQs, even though reexaminations of the EMSS and Slew Survey databases have revealed samples of FSRQs in both (Perl-man 2000; Perlman et al. 2001; Wolter & Celotti 2001). The only flux-limited samples of FSRQs that existed prior to that time, in fact, were "classical" high flux limit, radio-selected samples, such as the 1 Jy, produced by surveys that also contained few, if any, HBLs (e.g., the 1 Jy sample has only 2 HBLs out of 34 BL Lac objects total; Padovani & Giommi 1995b). Thus, it was perhaps not a surprise that these radio-selected samples contained very few X-ray-strong FSRQs.

Figure 1 shows the distribution of our sources in the $(\alpha_{ox}, \alpha_{ro})$ plane. The figure also shows the 1 Jy FSRQs, which occupy a region of $(\alpha_{ox}, \alpha_{ro})$ parameter space with α_{rx} similar to that typical of LBLs (marked in the figure). FSRQs with low α_{rx} (≤ 0.78 , roughly equivalent to the HBL/LBL division [although see § 4], or $L_x/L_r \gtrsim 10^{-6}$) constitute only ~5% of the 1 Jy sources with X-ray data.



FIG. 1.— $(\alpha_{ro}, \alpha_{ox})$ plane for the DXRBS (*top*) and RGB (*bottom*) samples. Effective spectral indices are defined in the usual way and calculated between the rest-frame frequencies of 5 GHz, 5000 Å, and 1 keV. Filled circles represent the DXRBS and RGB FSRQs, open squares represent the 1 Jy FSRQs, while crosses are the DXRBS and RGB BL Lac objects. The dashed lines represent, from top to bottom, the loci of $\alpha_{rx} = 0.85$, typical of 1 Jy FSRQs and LBLs; $\alpha_{rx} = 0.78$, the dividing line between HBLs and LBLs; and $\alpha_{rx} = 0.70$, typical of RGB BL Lac objects. The regions in the plane within 2 σ from the mean α_{ro} , α_{ox} , and α_{rx} values of LBLs and HBLs are indicated by the solid lines and marked accordingly.

Importantly, none of the 1 Jy FSRQs fall in the region of the plane within 2 σ from the mean α_{ro} , α_{ox} , and α_{rx} values of HBLs, the "HBL box," derived by using all HBLs in the multifrequency AGN catalog of Padovani et al. (1997).⁶ The fainter radio/X-ray-selected DXRBS and RGB FSRQs, on the other hand, reach much lower values of α_{rx} , and many sources "invade" the HBL region. Indeed, as can be seen by comparing the two panels of Figure 1, there is a progression of (α_{ox} , α_{ro}) from 1 Jy to DXRBS to RGB, with the exception of the half of the HBL box to the left of the diagonal line that extends from (0.8, 0.55) to (1.4, 0.2). We will return to this subject in § 4.

Another way of looking at selection effects is to consider Figure 2, which plots α_{ro} versus the 5 GHz radio flux for about 900 FSRQs from the comprehensive multifrequency catalog of Padovani et al. (1997). The observed trend between radio flux and optical-radio spectral index, with stronger radio sources having steeper α_{ro} values, is likely due to two separate effects: First is the relatively bright optical flux limits of the various samples that were included in the catalog, responsible for the lack of sources in the upper left part of the diagram. Indeed, DXRBS FSRQs, which reach $V \gtrsim 23$, start to fill this region (*circles* in Fig. 2). Second is the fact that well-known, "classical" FSRQs, all relatively strong radio sources (3C 273 and 3C 279, for example, have 5 GHz radio fluxes ~16 and 40 Jy, respectively), do have steep $\alpha_{\rm ro} \lesssim 0.5$ (see Fig. 1), they will start to be revealed only at fainter ($\lesssim 200-300$ mJy) radio fluxes, and it is only by conducting relatively faint radio surveys with X-ray information, like ours, that these sources can be identified in reasonable numbers.

There could be two possible reasons for the observations pointed out in the previous two paragraphs. Either some selection effect is at work, perhaps induced by a correlation between the fraction of HFSRQs and flux, with HFSRQs being intrinsically more numerous at fainter fluxes/powers; or these sources are intrinsically rare and their detection in sizeable numbers requires large samples. We will address

⁶ X-ray data are available for ~65% of 1 Jy FSRQs. The sources without X-ray data have $\alpha_{\rm ro} \geq 0.63$ and therefore are all outside the HBL box.



FIG. 2.—Effective radio-optical spectral index α_{ro} vs. the 5 GHz radio flux for about 900 FSRQs from the multifrequency catalog of Padovani et al. (1997; *crosses*) and the DXRBS FSRQs discussed in this paper (*circles*).

this issue in future DXRBS papers. Note that similar questions are perfectly appropriate as well for BL Lac objects, and these are the subject of some debate (see, e.g., Fossati 2001; Giommi et al. 2002b).

4. SEDs AND THE NATURE OF BLAZAR EMISSION

In the previous section we have shown that recent, relatively deep blazar samples with both radio and X-ray information have detected the hitherto unknown class of FSRQs with effective spectral indices typical of HBLs. Based on our knowledge of BL Lac objects, we expect these sources to have a synchrotron peak frequency ν_{peak} in the UV/X-ray band. Similarly, we would expect that the intermediate BL Lac objects in our sample should have synchrotron peak frequencies intermediate between those seen for HBLs and LBLs, as demonstrated for S5 0716+714 by Giommi et al. (1999b). We then need to study the SEDs of our sources.

4.1. α_{rx} Distributions

The HBL/LBL division is generally done in terms of the X-ray-to-radio flux ratio or effective radio-X-ray spectral index α_{rx} (Padovani & Giommi 1995b). While this parameter is broadly related to ν_{peak} (Padovani & Giommi 1996; Fossati et al. 1998; but see \S 6.2), it is much easier to derive. Figure 1 shows that the DXRBS FSRQs and BL Lac objects seem to cluster at the edge of the HBL region, while the RGB FSRQs and BL Lac objects are moving in progressively. This is due at least partly to the different flux limits of the two surveys, which sample different regions of parameter space. It does appear, however, that while the RGB BL Lac objects populate a much larger area of the HBL region than DXRBS BL Lac objects, this is not the case for FSRQs. Inclusion of the unclassified RGB sources with optical information does not alter this conclusion (see also below). Optically fainter sources will have relatively flat α_{ox}



FIG. 3.—Fractional distribution of the X-ray–radio spectral index α_{rx} for FSRQs (*solid lines*) and BL Lac objects (*dashed lines*) for the DXRBS (*top*) and RGB (*bottom*) samples. The dotted line represents the α_{rx} distribution of RGB FSRQs and unclassified radio-loud sources with $\alpha_r \leq 0.5$. The DXRBS distributions have been deconvolved with the appropriate sky coverage. Error bars represent the 1 σ range based on Poisson statistics. See text for details.

but most importantly relatively steep α_{ro} and so will be out of the HBL box.

Figure 3 shows the fractional α_{rx} distribution of all DXRBS and RGB blazars. It is important to note that because of the serendipitous nature of DXRBS (and other, previous serendipitous surveys, including the EMSS), the area in which faint X-ray sources could be detected is smaller than that for brighter X-ray sources. Thus, in order to compare directly distributions of parameters related to X-ray flux, we need to "correct" by using the appropriate sky coverage—a necessary step that is seldom done—otherwise, faint sources would be underrepresented. We have already done this for the redshift distribution in Landt et al. (2001), and we refer the reader to that paper for further details. The α_{rx} is obviously related to X-ray flux, so we have deconvolved its distribution, shown in Figure 3. We follow this practice for all comparisons involving DXRBS and any other serendipitous survey.

A few points can be inferred from Figure 3. The $\langle \alpha_{rx} \rangle$ values for DXRBS FSRQs and BL Lac objects are similar, ~0.83, but the variances are different at the 99.96% level (Student's *t*-test). Moreover, the two distributions are different at the 99.4% level according to a Kolmogorov-Smirnov (KS) test. The BL Lac α_{rx} distribution, in fact, is broader than that of FSRQs, with a peak at $\alpha_{rx} \sim 0.9$ and a tail reaching relatively low values (~0.55). The skewness of the BL Lac distribution is negative and equal to ~3.4 times its standard deviation, unlike the FSRQ distribution, for which the skewness is consistent with being zero (Press et al. 1986). The different nature of the BL Lac and FSRQ α_{rx} distributions is confirmed by the use of the KMM algorithm, developed by Ashman, Bird, & Zepf (1994), which computes for a given distribution the confidence level at which a single

Gaussian fit can be rejected in favor of a double Gaussian fit. While for the DXRBS FSRQs we find that a single Gaussian provides a good fit to the α_{rx} distribution, this possibility is rejected at the 99.9% level for the BL Lac objects. The ~10 still unidentified sources with $\alpha_r \leq 0.5$ are X-ray faint and therefore have relatively large $\langle \alpha_{\rm rx} \rangle \sim 0.9$. Based on our identification statistics, we expect most of them to be FSRQs, thereby somewhat reducing the difference in the α_{rx} distributions at large values in Figure 3. The fraction of sources with $L_{\rm x}/L_r > 10^{-6}$, i.e., $\alpha_{\rm rx} \lesssim 0.78$, is ~28% and $\sim 25\%$ for the BL Lac objects and FSRQs, respectively. More interesting is the fraction of sources that fall into the region typical of HBLs, the HBL box. This is $\sim 15\%$ and $\sim 9\%$ for the BL Lac objects and FSRQs, respectively. For RGB the α_{rx} distributions for FSRQs and BL Lac objects are also significantly different (P > 99.99%), but in this case the mean values are also different, with $\langle \alpha_{\rm rx} \rangle \sim 0.80$ and ~ 0.68 , respectively. The fraction of sources with $L_{\rm x}/L_r > 10^{-6}$ is ~76% and ~35% for the BL Lac objects and FSRQs, respectively. The fraction of sources falling into the "HBL box" is $\sim 60\%$ and $\sim 27\%$ for the BL Lac objects and FSRQs, respectively. While RGB BL Lac objects reach more extreme (i.e., much flatter) α_{rx} values than DXRBS ones, that is not the case for FSRQs.

Could this difference between RGB FSRQs and BL Lac objects be explained as a selection effect? A large fraction (~60%) of the most X-ray loud RGB BL Lac objects $(\alpha_{\rm rx} < 0.7)$ were already known because of dedicated surveys (EMSS, Slew, HEAO 1). Given the fact that the identification fraction of the flat-spectrum sources in RGB is quite low (\sim 49%) and that the identified sources in RGB have mostly O < 18.5, it could be that the most extreme RGB FSRQs are still unclassified. We have then included with the RGB FSRQs the ~360 unclassified radio-loud sources with $\alpha_r \leq 0.5$ (assuming z = 1 for the k-correction). Note that this is an extreme assumption because a substantial fraction of these could be BL Lac objects (their current fraction in the $\alpha_r \leq 0.5$ sample is ~30%). Although the α_{rx} distribution now shifts to lower values, with $\langle \alpha_{\rm rx} \rangle \sim 0.74$, it is still significantly different (P > 99.99%) from that of the RGB BL Lac objects. The fraction of sources with $L_{\rm x}/L_r > 10^{-6}$ rises from ~35% to ~62%, while that which falls into the HBL box (among the sources with optical information; $\sim 40\%$ of the unclassified sources are empty fields) rises from $\sim 27\%$ to $\sim 38\%$. As discussed above, this fraction should probably be considered an upper limit.

We point out that the DXRBS and RGB α_{rx} distributions for both FSRQs and BL Lac objects peak at ~0.7–0.8, that is, around the HBL/LBL dividing line. The previously suggested dichotomy in the BL Lac class, then, with most sources at the two ends of the distribution, was simply due to the selection effects induced by combining widely disconnected samples selected in different bands. We can check what happens at even larger X-ray-toradio flux ratios by using two other samples: the EMSS and the Sedentary Survey. The EMSS (e.g., Maccacaro et al. 1994) is an X-ray-selected sample of sources discovered in 1435 *Einstein* Imaging Proportional Counter fields. It reaches $\sim 5 \times 10^{-14}$ ergs cm⁻² s⁻¹ in the 0.3–3.5 keV band, but the area covered is a strong function of X-ray flux (Gioia et al. 1990). The sample is largely identified (completely so down to $\sim 2 \times 10^{-13}$ ergs cm⁻² s⁻¹), and comprehensive, dedicated radio observations provide detections down to ~ 1 mJy levels so that quite high values of X-ray-to-radio flux ratios can be reached.

Two papers have constructed samples of FSRQs within the EMSS. Wolter & Celotti (2001) constructed a sample of EMSS radio-loud quasars by using a cut $\alpha_{ro} > 0.35$. We have used the values for the 13 FSRQs ($\alpha_r \leq 0.5$) given in their paper. Perlman et al. (2001) did a similar search, which yielded those objects plus two more with $0.2 < \alpha_{ro} < 0.35$ (for consistency with the commonly used definition of radio-loud sources; these two sources happen to have the two lowest α_{rx} values). Using these objects, we have constructed the α_{rx} distribution of these EMSS FSRQs, again taking into account the effect of the sky coverage. We have also done the same for the EMSS BL Lac sample, using the revised list and data of Rector et al. (2000). The results are as follows: the α_{rx} distributions for FSRQs and BL Lac objects are still significantly different (P > 99.99%), with mean values $\langle \alpha_{\rm rx} \rangle \sim 0.71$ and ~0.60, respectively. The minimum value reached by EMSS FSRQs is $\alpha_{rx} \sim 0.63$, while that of EMSS BL Lac objects is ~ 0.49 . The fraction of sources with $L_x/L_r > 10^{-6}$, once the effect of the sky coverage is taken into account, is 100% and \sim 78% for the BL Lac objects and FSRQs, respectively. The fraction of sources that fall into the HBL box is the same, namely, 100% and \sim 79% for the BL Lac objects and FSRQs, respectively. Thus, although the α_{rx} gap between the two classes gets narrower, the fact remains that FSRQs do not reach the same values as BL Lac objects.

An even more extreme sample is the Sedentary Survey (Giommi, Menna, & Padovani 1999a), an X-ray/radio–selected sample based on the RASS Bright Source Catalog and the NVSS, which has a cut at $\alpha_{rx} \leq 0.56$. The current sample is ~90% identified, so our conclusions should be relatively stable. The number of radio-loud broad-lined sources in the sample is currently around 20 (or ~12%), but most of these sources are very close to the radio-loud/radio-quiet dividing line, in terms of both their α_{ro} values and their radio powers. Some of these sources could therefore have their X-ray emission dominated by thermal processes and would not be the counterparts of HBLs. We will discuss the presence of HFSRQs in the Sedentary Survey in a future paper (P. Giommi et al. 2003, in preparation). Table 1 summarizes the results of these comparisons, in terms of mean

Т	ABLE	1
α_{rr}	STATIST	TICS

				$\alpha_{ m rx} \le 0.78$		IN HBL BOX		
SAMPLE	FSRQs	$\frac{\langle \alpha_{\rm rx} \rangle}{N}$ BL Lac Objects	N	FSRQs (%)	BL Lac Objects (%)	FSRQs (%)	BL Lac Objects (%)	
DXRBS RGB EMSS	$\begin{array}{c} 0.827 \pm 0.005 \\ 0.803 \pm 0.005 (\gtrsim\!0.74) \\ 0.71 \pm 0.02 \end{array}$	134 233 15	$\begin{array}{c} 0.84 \pm 0.02 \\ 0.68 \pm 0.01 \\ 0.60 \pm 0.01 \end{array}$	31 129 41	25 35 (≲62) 78	28 76 100	9 27 (≲38) 79	15 60 100

 α_{rx} values and fractions of HBLs and HFSRQs in the DXRBS, RGB, and EMSS samples.

Our results reaffirm the fact that the percentage of HBLs/ HFSRQs in a sample is heavily dependent on the survey flux limits or, alternatively, its position on the X-ray-radio flux plane (see Figs. 1 and 2 of Padovani 2002). Table 1 shows very explicitly how these percentages change by moving from DXRBS, a survey whose limits are in the "L" zone, to RGB and EMSS, whose limits move progressively deeper into the "H" zone.

4.2. Synchrotron Peak Frequency

To study in more detail the synchrotron peak frequencies of our sources we have used the multifrequency information at our disposal to extract nonsimultaneous SEDs for our blazars. We restrict ourselves to the DXRBS sample because the determination of ν_{peak} requires a lot more effort than α_{rx} and we did not think it was worth deriving for RGB given its large incompleteness.

We determined ν_{peak} for all 165 DXRBS blazars by applying a homogeneous synchrotron-inverse self-Compton (SSC) model in the $(\log \nu, \log \nu f_{\nu})$ plane to the following data:

1. radio fluxes at two different frequencies (nonsimultaneous 1.4 and 5 GHz data for objects with $\delta > -40^{\circ}$; simultaneous 5 and 8.6 GHz data for objects with $\delta < -40^{\circ}$; see Landt et al. 2001);

2. optical flux, in the V band, derived from Palomar Observatory Sky Survey (POSS I) O and/or E magnitudes as described in Giommi et al. (1999a); fluxes were corrected for Galactic absorption and for the presence of emission lines (for FSRQs) according to the prescription of Natali et al. (1998);

3. unabsorbed *ROSAT* X-ray flux at 1 keV, derived from the broadband flux and the X-ray spectral index α_x ;

4. Two Micron All Sky Survey (2MASS) data (if available; R. M. Cutri et al. 2000, Explanatory Supplement to the 2MASS Second Incremental Data Release);⁷ and

5. any other NASA/IPAC Extragalactic Database (NED) data.

We note that here and in the following we deal with the rest-frame peak frequency, equal to $\nu_{\text{peak}}(\text{obs}) \times (1 + z)$. A redshift of 0.4 was assumed for the BL Lac objects without one.

While we have optical spectra for all objects identified in Perlman et al. (1998) and Landt et al. (2001), we did not use those spectra to estimate peak frequencies for two reasons. First, the DXRBS includes also a significant number of previously known sources (about 40% for the sample used in this paper), for which optical spectra are not necessarily available in digital format. We felt it would be inconsistent to use optical spectra for some objects but not for others. Second, for many objects the spectra were taken with a slit that was not at parallactic angle because of the instrumental setups used (see Perlman et al. 1998 and Landt et al. 2001). This results in a flux loss due to atmospheric differential refraction that is more pronounced in the blue part of the spectrum and would therefore significantly affect the optical/UV slope.

The SSC model has been adapted from Tavecchio, Maraschi, & Ghisellini (1998) and assumes that radiation is produced by a population of relativistic electrons emitting synchrotron radiation in a single zone of a jet that is moving at relativistic speed and at a small angle to the line of sight. These photons are subsequently scattered by the same electrons to higher energies via the inverse Compton process (note that we ignore Comptonization of external photons, which affects the SED only at gamma-ray energies; e.g., Ghisellini et al. 1998). The physical parameters that define the model are the jet radius, the Doppler factor δ , the magnetic field B, and four spectral parameters of the electron population, assumed to follow a power-law distribution that breaks sharply above a given energy: the normalization, the two spectral slopes, and the break energy. The Klein-Nishina cross section is used in the computation of the Compton scattering.

Our aim is to derive a best estimate of ν_{peak} . Given that the SED of most of our sources is not well sampled, we cannot fully constrain the model parameters. However, the available range was limited by physical considerations, namely, $\delta \sim$ 10–20, $B \sim$ 0.1–5 G, jet radius ${\approx}10^{-3}$ pc, and a low-energy slope of the electron distribution, which produces a relatively flat (<0.7) spectral slope in the radio band, consistent with the sample definition. We have also been guided by the work done by some of us using the same model to derive ν_{peak} for a large sample of bright blazars observed by *BeppoSAX* (Giommi et al. 2002a) and from the NVSS-RASS 1 Jy survey (Giommi et al. 2002c). Both samples, in fact, include many "classical" blazars with wellsampled SEDs for which the model parameters were well constrained. In any case, our experience shows that ν_{peak} , a combination of B, δ , and electron break energy, is relatively well constrained even for relatively large variations of these parameters, which affect much more the high-energy/ inverse Compton part of the SED (e.g., Massaro et al. 2003).

FSRQs can have a disk (thermal) component in the optical/UV band, but this, on average, makes up only $\sim 15\%$ of the continuum emission in DXRBS FSRQs (D'Elia, Padovani, & Landt 2003) and therefore should not strongly affect our derivation of ν_{peak} , at least in a statistical sense, although there are individual exceptions. This is also consistent with the relatively steep optical/UV slopes of these objects ($\alpha \sim 1.2$; H. Landt et al. 2003, in preparation). We think it is also unlikely that the thermal component can make a substantial contribution in the X-ray band because our FSRQs have typical redshifts of ~ 1.5 , which implies that the ROSAT band corresponds to a 0.25-6 keV rest frame. By comparison, there is very little evidence for thermal optical/UV emission due to an accretion disk in BL Lac objects, although Corbett et al. (2000) have suggested that accretion disk illumination is responsible for the variations in H α luminosity in BL Lacertae itself. In any case, however, the line luminosity of DXRBS BL Lac objects is much lower than that of FSRQs (H. Landt et al. 2003, in preparation), so any contribution to the total optical/UV flux is negligible for our purposes.

Previous works have derived ν_{peak} by fitting analytical functions, such as a parabola or a third-degree polynomial, to the SEDs of blazars (e.g., Sambruna et al. 1996; Fossati et al. 1998). Although the latter alternative would also allow us to take into account the spectral upturn that is present when the X-ray flux is dominated by inverse Compton

⁷ Available at http://www.ipac.caltech.edu/2mass/releases/second/doc/explsup.html.



FIG. 4.—Representative synchrotron self-Compton fits to the spectral energy distributions of DXRBS FSRQs. Filled circles denote DXRBS data; open circles denote data from NED and 2MASS. The synchrotron peak frequencies for the two sources are $\nu_{\text{peak}} = 5.5 \times 10^{15}$ Hz (WGA J0447.9–0322, z = 0.774; *left*) and $\nu_{\text{peak}} = 1.7 \times 10^{13}$ Hz (WGA J0510.0+1800, z = 0.416; *right*). See text for details.

emission, we chose instead to derive ν_{peak} using a physical model (SSC) that is widely accepted as being responsible for the broadband emission of blazars. We believe that our approach, although more complex and time consuming, is more robust especially when dealing with sparsely sampled SEDs because we are guided by physics rather than just analytical fitting. We also note that our multifrequency data are not simultaneous and therefore our fits are also affected by variability.

As examples, in Figures 4 and 5 we show some representative fits to the SEDs of DXRBS FSRQs and BL Lac objects, spanning a wide range of ν_{peak} . We stress again that the sampling of the SEDs is scanty, being based in many cases on only a few, noncontemporaneous data points, so the precise value of ν_{peak} for a given source can be somewhat uncertain. However, we do believe that its *statistical* use is warranted. This is confirmed by plotting the optical/UV slopes, which are measured for 68 (~51%) of our FSRQs and did not enter in our derivation of the synchrotron peak frequency, versus ν_{peak} . A very strong anticorrelation (P = 99.96%) is observed between the two quantities, as expected if our ν_{peak} estimates were indeed reliable. For relatively small ν_{peak} values, in fact, one expects the optical band to sample the steep tail of the synchrotron component, while when the synchrotron peak moves to progressively larger energies the optical slope becomes flatter as the optical band samples the lower frequency, flatter parts of the synchrotron emission.

Figure 6, which shows the ν_{peak} distribution of all our sources, illustrates the fact that indeed, the SEDs of some DXRBS FSRQs peak in the UV/X-ray band. As in the case of α_{rx} , the ν_{peak} distributions are also corrected for the effect of the sky coverage. The FSRQ distribution ranges between 10^{12} and 10^{16} Hz, with $\langle \nu_{\text{peak}} \rangle = 10^{13.70\pm0.06}$ Hz, while the BL Lac distribution ranges between 6×10^{12} and 8×10^{16} Hz, with $\langle \nu_{\text{peak}} \rangle = 10^{14.1\pm0.1}$ Hz. On average, then, BL Lac objects have a synchrotron peak frequency a factor of ~2.5 larger than that of FSRQs. The two distributions are also different at the 99.97% level according to a KS test. As was the case for α_{rx} , the BL Lac distribution is broader than the FSRQ one, with a tail reaching higher values. For example, while ~64% and ~8% of BL Lac objects have $\nu_{\text{peak}} > 10^{14}$ and 10^{15} Hz, these fractions go down to ~31% and ~4% for FSRQs.



FIG. 5.—Representative synchrotron self-Compton fits to the spectral energy distributions of DXRBS BL Lac objects. Circles denote DXRBS data. The synchrotron peak frequencies for the two sources are $\nu_{\text{peak}} = 1.1 \times 10^{15}$ Hz (WGA J0043.3–2638, z = 1.002; *left*) and $\nu_{\text{peak}} = 2.3 \times 10^{13}$ Hz (WGA J0533.6–4632, z = 0.332; *right*). See text for details.



FIG. 6.—Distribution of the synchrotron peak frequency for FSRQs (*solid line*) and BL Lac objects (*dashed line*) for the DXRBS sample. The distributions have been deconvolved with the appropriate sky coverage. Error bars represent the 1 σ range based on Poisson statistics. See text for details.

We cannot think of any reason why our method should result in lower ν_{peak} for FSRQs. Quite the opposite: both the thermal component (which is small, as discussed above) and the emission lines' contamination of the optical flux (for which we correct anyway) would move the peak to *higher* values (at least with relatively low ν_{peak}). We therefore regard this difference as real.

It is likely that this difference in ν_{peak} , actually, is even larger than shown here. Because of its serendipitous nature, DXRBS is subject to incompleteness at high fluxes, since bright targets are excluded by definition to avoid biasing the sample. We can quantify this in the following way. Approximately 50 BL Lac objects with radio flux above our threshold, mostly from the 1 Jy, Slew, and EMSS samples, and off the Galactic plane have been observed by ROSAT as targets. This corresponds to a surface density $\approx 2 \times 10^{-3} \text{ deg}^{-2}$, i.e., roughly 3-4 sources that could not be included in our survey. This effect is more severe at high ν_{peak} values, where only a few objects have been detected (see Fig. 6) and the loss of even a small number of sources could make a major difference. Note in fact that many of these BL Lac objects are HBLs. As regards FSRQs, although the numbers are somewhat larger, the effect at high ν_{peak} values is zero because none of the previously known (and therefore likely ROSAT targets) FSRQs had high ν_{peak} .

While already in DXRBS, then, there is evidence that FSRQs do not appear to reach the more extreme α_{rx} and ν_{peak} values of BL Lac objects, this tendency is confirmed by studying the RGB and EMSS samples, which sample the blazar population deeper into the region of lower α_{rx} . The fact that the Sedentary Survey, which samples the extreme HBL zone, has found very few, if any, FSRQs also suggests that there might be an intrinsic limit to the ν_{peak} values that can be reached by strong-lined blazars.

5. THE BLAZAR SEQUENCE

Fossati et al. (1998) and Ghisellini et al. (1998) have proposed that some blazar properties can be accounted for by an inverse correlation between intrinsic power and the synchrotron peak frequency, the so-called blazar sequence. The peak of the emission is related to the electron energy, as $\nu_{\text{peak}} \propto B \gamma_{\text{break},e}^2$, with $\gamma_{\text{break},e}$ a characteristic electron energy that is determined by a competition between acceleration and cooling processes. Therefore, less powerful sources (where the energy densities are relatively small) should reach a balance between cooling and acceleration at larger ν_{peak} , while in more powerful sources there is more cooling and the balance is reached at smaller ν_{peak} .

Figure 7 plots radio power at 5 GHz versus ν_{peak} for the DXRBS sources. The dotted lines denote the two quadrants (top left and bottom right) occupied by the sources studied by Fossati et al. (1998), which belonged to the 1 Jy and Slew BL Lac samples and the 2 Jy FSRQ sample.

A few points can be made about this figure. First, as already shown in Figure 6, DXRBS BL Lac objects reach ν_{peak} values slightly higher than DXRBS FSRQs. (Based on the analysis shown in § 4.1 this difference is likely to become more pronounced for more X-ray extreme surveys such as EMSS.) Second, DXRBS sources are starting to occupy regions of this plot (top right and particularly bottom left) that were "empty" in the original plot of Fossati et al. (1998). DXRBS reaches lower radio powers than the 1 Jy sample and therefore detects low-power LBLs. In particular, of the 21 BL Lac objects with $\nu_{\text{peak}} < 10^{15.5}$ Hz and red-shift information, 7 (or 33%) "invade" the low-power part $(L_r < 10^{25.3} \text{ W Hz}^{-1})$ of the plot. Third, no correlation $(P \sim 93\%)$ is present between radio power and ν_{peak} for the whole sample or for the FSRQ and BL Lac samples separately. We also note that the scatter in the plot is very large, reaching 4 orders of magnitude in power for



FIG. 7.—Radio power at 5 GHz vs. the synchrotron peak frequency for FSRQs (*circles*) and BL Lac objects (*crosses*) for the DXRBS sample. The dotted lines denote the two quadrants (top left and bottom right) occupied by the sources studied by Fossati et al. (1998). See text for details.

 $10^{13} \lesssim \nu_{\text{peak}} \lesssim 10^{15}$ Hz. Therefore, by using a homogeneous, well-defined sample that includes both FSRQs and BL Lac objects over a relatively wide region of parameter space, we have not confirmed the Fossati et al. correlation. Fourth, an upper envelope, however, seems to be present in the right part of the diagram. For example, all sources with $L_r > 10^{27.5}$ W Hz⁻¹ have $\nu_{\text{peak}} \lesssim 10^{15}$ Hz while sources with $L_r > 10^{28}$ W Hz⁻¹ have $\nu_{\text{peak}} \lesssim 10^{14}$ Hz.

We have checked the radio power and $\nu_{\rm peak}$ values and distributions for DXRBS blazars in and out of the HBL box. We find that the two classes have indistinguishable radio powers but significantly different synchrotron peak frequencies, with mean values $\langle \nu_{\rm peak} \rangle \sim 10^{15.2\pm0.1}$ and $\sim 10^{13.66\pm0.05}$ Hz, respectively, again in contrast to the proposed correlation.

We note that the lack of high- ν_{peak} high-radio power blazars could also be due to a selection effect, as discussed by Giommi et al. (2002b; see also Padovani et al. 2002). This combination, in fact, implies a dominance of nonthermal emission over the host galaxy and emission-line components, making the redshift determination very hard if not outright impossible. Objects of this kind, which would populate the upper right part of Figure 7, would then be excluded. We note, however, that only four DXRBS BL Lac objects have no redshift and $\nu_{peak} > 10^{14.5}$ Hz.

It is interesting to explore possible correlations between ν_{peak} and other powers. The correlation suggested by Fossati et al. (1998) and Ghisellini et al. (1998) was between synchrotron peak frequency and *intrinsic* power. Because our sources are all flat spectrum, their radio power is strongly affected by beaming, and this could influence the interpretation of Figure 7. We have then evaluated two intrinsic powers for our FSRQs, namely, the broad-line region (BLR) luminosity, L_{BLR} , following Celotti, Padovani, & Ghisellini (1997), and the kinetic jet power, L_{jet} , following D'Elia et al. (2003).

 L_{BLR} is an isotropic quantity, related to the ionizing, disk (thermal) emission via the covering factor f_{cov} , i.e., $L_{disk} =$ $f_{\rm cov}^{-1}L_{\rm BLR}$, with $f_{\rm cov} \approx 10\%$ for FSRQs (D'Elia et al. 2003). Figure 8 plots $L_{\rm BLR}$ versus $\nu_{\rm peak}$ for the 94 (~70%) DXRBS FSRQs for which we could find the relevant BLR line fluxes. We do not include here BL Lac objects because only six of them display the lines needed to derive L_{BLR} and even in those cases the lines are narrow. No hint of an inverse correlation between $L_{\rm BLR}$, proportional to disk power, and $\nu_{\rm peak}$ is present in the figure; rather, the opposite is apparent. There is in fact a strong correlation (P > 99.99%), with a large scatter, between the two quantities, with $L_{\rm BLR} \propto$ $\nu_{\text{neak}}^{0.51\pm0.11}$. It could be argued that the stronger the disk emission, the larger its contribution to the optical/UV flux and the higher the estimated ν_{peak} . However, this is not a very likely explanation. First, as mentioned in § 4.2, D'Elia, Padovani, & Landt (2003) have shown that the disk (thermal) component in DXRBS FSRQs is only ~15% on average. Second, we find no correlation between L_{BLR} or ν_{peak} and the ratio of disk to total emission as defined in D'Elia et al. (2003). This would be expected if larger BLR luminosities and/or larger peak frequencies were due to a stronger disk component.

It is more difficult to estimate the total kinetic jet power L_{jet} because it depends on many uncertain astrophysical parameters. We have derived it according to the prescriptions of D'Elia et al. (2003), which we summarize here briefly. We have used a theoretical relationship obtained by



FIG. 8.—Broad-line region luminosity vs. the synchrotron peak frequency for the DXRBS FSRQs. See text for details.

Willott et al. (1999) to link jet power to extended radio emission at 151 MHz (using c = 20 in eq. [10] of D'Elia et al. 2003, which agrees with another independent method), estimating the latter from the total power at 5 GHz and a correlation between core dominance parameter and radio spectral index. We stress that, although the precise values of L_{jet} for a given source can be somewhat uncertain, we believe that its *statistical* use is warranted.

Figure 9 plots the kinetic jet power versus ν_{peak} for our sources. No correlation is present between the two



FIG. 9.—Kinetic jet power vs. the synchrotron peak frequency for the DXRBS FSRQs (*circles*) and BL Lac objects (*crosses*). See text for details.

quantities. Because $L_{\rm jet}$ is an intrinsic power, again this is in contrast with the blazar sequence of Fossati et al. (1998) and Ghisellini et al. (1998). Similarly to Figure 7, however, in Figure 9 there might be indications of an upper envelope in the right part of the diagram. For example, sources with $L_{\rm jet} > 10^{39}$ W all have $\nu_{\rm peak} \lesssim 10^{15}$ Hz while sources with $L_r > 10^{40}$ W have $\nu_{\rm peak} \lesssim 10^{14}$ Hz.

6. FURTHER CLUES

We have shown the existence of significant numbers of FSRQs with broadband spectra similar to those of HBLs, that is, with synchrotron peak frequencies higher than those of classical FSRQs and reaching the UV band. We now concentrate on DXRBS to further investigate the implications of our findings.

6.1. X-Ray Spectral Slopes

The study of the X-ray emission of the FSRQs with synchrotron peak frequencies in the UV/X-ray band is vital. The X-ray emission of HFSRQs, in fact, should be synchrotron in nature, in contrast to that of most FSRQs, where it is dominated by inverse-Compton emission (e.g., Sambruna et al. 1996), a dichotomy similar to that exhibited by LBLs and HBLs. In BL Lac objects, in fact, observational evidence points to a different origin for the X-ray emission of HBLs and LBLs (e.g., Padovani & Giommi 1996). In HBLs, the X-ray continuum appears to be an extension of the synchrotron emission seen at lower energies, consistent with their steep ($\alpha_x \sim 1.5$) X-ray spectra in the *ROSAT* band. In LBLs, the X-ray continuum is more likely due to inverse Compton emission, consistent with their harder ($\alpha_x \sim 1$) spectra. BeppoSAX observations of BL Lac objects are confirming this picture (Wolter et al. 1998; Padovani et al. 2001). Indeed, Padovani et al. (2002) have presented evidence for at least one HFSRQ with relatively high $\nu_{\rm peak} \sim 2 \times 10^{16}$ Hz and steep ($\alpha_{\rm x} \sim 1.5$) synchrotron X-ray spectrum and two possible "intermediate" sources with $\nu_{\text{peak}} \approx 10^{15} \text{ Hz}.$

We have derived X-ray spectral indices in the 0.4–2.0 keV range for the DXRBS FSRQs using hardness ratios following Padovani & Giommi (1996). This method, when applied to relatively bright X-ray sources, is relatively robust and compares well with the results of a proper spectral fit to the full pulse-height analyzer spectrum. One important limitation of this method is the effect of the PSPC background, which is not subtracted off the WGACAT hardness ratios and becomes more and more important close to the sensitivity limit, especially at large off-axis angles. Fiore et al. (1998) have discussed this at length and shown that for sources with signal-to-noise ratio (S/N) > 7 background contamination is not important. However, many of the Fiore et al. (1998) sources were targets and therefore at relatively small PSPC offsets. Because DXRBS is a serendipitous survey, we have excluded all targets, and therefore, on average, our sources are at larger PSPC offsets, where the PSPC pointspread function degrades significantly, increasing the seriousness of the background contamination. We have then conservatively chosen a higher S/N cut of 10, which reduces our sample to 54 sources, 39 FSRQs and 15 BL Lac objects. We stress that these effective spectral indices should still be regarded as an estimate of the "average" X-ray spectral shape and are therefore most suitable for statistical studies.



FIG. 10.—*ROSAT* X-ray spectral index vs. the synchrotron peak frequency for DXRBS FSRQs (*circles*) and BL Lac objects (*crosses*). Error bars represent 1 σ uncertainties.

Errors on these spectral indices (1σ) were derived as described in Padovani & Giommi (1996) and are typically ~0.2.

Figure 10 shows the *ROSAT* X-ray spectral index versus the synchrotron peak frequency for DXRBS FSRQs (*circles*) and BL Lac objects (*crosses*). We note that α_x is relatively flat (~1–1.5) and constant for $\nu_{peak} \leq 10^{14}$ Hz. For $10^{14} \leq \nu_{peak} \leq 10^{15}$ Hz, α_x steepens to reach values up to ~2.5. Above $\nu_{peak} \sim 10^{15}$ Hz α_x flattens again to reach values of ~1–1.5. Figure 10 shows a trend similar to that displayed by the BL Lac objects included in Figure 6 of Padovani & Giommi (1996), despite the fact that ~70% of the sources are FSRQs. We then infer that the interpretation put forward for BL Lac objects applies to our FSRQs as well. Namely, at low ν_{peak} values flat inverse Compton emission dominates. For "intermediate" values the steep tail of the synchrotron component enters the *ROSAT* band. Finally, when ν_{peak} gets even closer to the X-ray band, the X-ray spectrum will flatten out again because the *ROSAT* band is now sampling the top of the synchrotron emission.

We note that *BeppoSAX* observations of four HFSRQ candidates have given mixed results: one source is clearly synchrotron dominated, another one is clearly inverse Compton dominated, while two others have a flat X-ray spectrum with evidence of steepening at low energies, similar to intermediate BL Lac objects (Padovani et al. 2002). It is, however, worth noting that the synchrotron-dominated source is the one with the lowest α_{rx} and right in the middle of the HBL box, while the Compton-dominated object has the largest α_{rx} and is at the edge of the box. *BeppoSAX* spectra of classical (2 Jy) FSRQs, on the other hand, are all consistently flat, with $\alpha_x \sim 0.7$, perfectly explained by inverse Compton emission (Tavecchio et al. 2002; Giommi et al. 2002a). Sambruna, Chou, & Urry (2000) reported on *ASCA* observations of four FSRQs characterized by steep *ROSAT*

spectra ($\alpha_x \sim 1.3$). The sources were all found to have flat hard X-ray spectra, with $\alpha_x \sim 0.8$. Sambruna et al. discuss their results in terms of relatively high synchrotron peaks and thermal emission extending into the X-ray band. Importantly, their sources sample a region of parameter space widely different from ours. Their effective spectral indices place them firmly in the LBL region, unlike ours, so they should not have been expected to show high ν_{peak} values and steep *ASCA* spectra.

As shown in § 4.2, the ν_{peak} distributions are continuous and peak at $\approx 10^{14}$ Hz for both FSRQs and BL Lac objects. While on this basis there appears to be no need for dividing blazars into H (high-energy) and L (low-energy) subclasses, the picture that comes out for FSRQs is the same as that already known for BL Lac objects (e.g., Padovani & Giommi 1996), that is, one of a division that can be based on physical grounds with H sources as those whose X-ray band is dominated by synchrotron emission and L sources as those in which inverse Compton dominates.

6.2. Synchrotron Peak Frequency versus Effective Spectral Indices

It has been suggested in the literature (e.g., Padovani & Giommi 1995b, 1996; Fossati et al. 1998) that the blazar synchrotron peak frequency can be estimated from the values of the effective spectral indices. We address this point here by using for the first time a large, homogeneous, and well-defined sample of blazars.

Figure 11 plots α_{rx} versus ν_{peak} . As can be seen, the two parameters correlate quite well (the correlation is significant at the greater than 99.9% level for the whole sample and the FSRQs and at the 98% level for BL Lac objects). However, there is considerable scatter—for any given value of α_{rx} the scatter in ν_{peak} is more than a decade. This is much more



FIG. 11.—Radio–X-ray spectral index α_{rx} vs. synchrotron peak frequency ν_{peak} for FSRQs (*circles*) and BL Lac objects (*crosses*) for the DXRBS sample. The dotted lines at $\alpha_{rx} = 0.725$ and $\log \nu_{peak} = 15.3$ denote the two quadrants (top left and bottom right) occupied by the sources studied by Fossati et al. (1998). See text for details.

than reported in this relationship by Fossati et al. (1998), whose Figure 8 shows a correlation with typically less than a decade of scatter, particularly for $\nu_{\text{peak}} \gtrsim 10^{14}$ Hz. A careful comparison shows that the major difference between the two plots occurs at low α_{rx} . The plot in Fossati et al. shows that for $\nu_{\text{peak}} \leq 10^{15.3}$ Hz there are no objects with $\alpha_{\text{rx}} \leq 0.75$, while for $\nu_{\text{peak}} \gtrsim 10^{15.3}$ Hz the exact opposite is the case. We have drawn these regions on Figure 11 (dotted horizontal and vertical lines). With DXRBS, however, we see a different picture. As Figure 11 shows, DXRBS has effectively expanded the accessible region of parameter space by making accessible the region $0.65 \leq \alpha_{rx} \leq 0.75$ in the bottom left quadrant. The resulting increase in accessible parameter space is huge: while for objects with $10^{12} \leq \nu_{\text{peak}} \leq 10^{13}$ Hz this is only about 20%, it is more than 50% for objects with $10^{14} \leq \nu_{\text{peak}} \leq 10^{15}$ Hz. A look at Figure 11 shows that while the correlation is still highly significant, the plot looks very different at the high- α_{rx} end than it does at low α_{rx} . At high $\alpha_{\rm rx}$ we see a clear envelope, while it is obvious that we do not see an envelope at low α_{rx} . In other words, a DXRBS blazar with $\alpha_{\rm rx} \sim 0.7$ is just as likely to have $\nu_{\rm peak} \sim 10^{12}$ Hz as it is to have $\nu_{\text{peak}} \sim 10^{16}$ Hz. We note that the sources with relatively low α_{rx} and ν_{peak} values are the DXRBS sources in the upper left part of Figure 1, which have low α_{rx} but are outside of the HBL box.

What is the reason behind this difference? In the first place the models are different: Fossati et al. (1998) used a simple third-degree polynomial fit, while the model we use is based on a calculation of synchrotron and inverse-Compton spectra for reasonable physical parameters. More importantly, however, all the samples used by Fossati et al.—the 1 Jy, 2 Jy and Slew surveys-are classic, high flux limit surveys in the radio and X-rays, respectively. As shown in \S 3, this type of survey has the effect of imposing what amounts to severe selection biases. This can in fact be seen in Figure 8 of Fossati et al. (1998), where both their ν_{peak} - α_{rx} and ν_{peak} - α_{ro} plots are seen to be discontinuous, hardly surprising considering that all but one of the objects with $\nu_{\text{peak}} > 10^{15.3}$ Hz in the Fossati et al. study are found in the Einstein Slew Survey but not the 1 Jy (only 2 of 34 1 Jy BL Lac objects fall in the lower right-hand quadrant of our Fig. 11 as denoted by the two dotted lines, compared to 50 of 60 Slew BL Lac objects), while the vast majority of the objects with $\nu_{\text{peak}} < 10^{15.3} \text{ Hz}$ come from the 1 Jy (33 of 34 1 Jy BL Lac objects are in this range compared to 10 of 60 Slew BL Lac objects).

A tighter correlation appears to be present between $\alpha_{\rm ro}$ and $\nu_{\rm peak}$, shown in Figure 12. The correlation is significant at the greater than 99.99% level (~97% for BL Lac objects only), with $\alpha_{\rm ro} \propto \nu_{\rm peak}^{-0.12}$. This correlation is expected to break down for $\nu_{\rm peak} \gtrsim 10^{16}$ Hz or $\alpha_{\rm ro} \lesssim 0.4$ (Padovani & Giommi 1995b; Fossati et al. 1998), but most of our sources are outside of this range, which explains why the correlation looks almost linear. Apart from the lack of objects with $\alpha_{\rm ro} \gtrsim 0.8$ and the paucity of objects with intermediate values of $\nu_{\rm peak}$, Figure 8 of Fossati et al. (1998) does not look too different from Figure 12 in the overlapping range of $\nu_{\rm peak}$.

We note that Figure 11 shows that a definition based solely on X-ray-to-radio flux ratio or α_{rx} is not optimal because we have found blazars with low α_{rx} and low ν_{peak} values. The position of the sources on the (α_{ox} , α_{ro}) plane, which means using two (instead of one) effective spectral indices, on the other hand, appears to be more sensitive to the synchrotron peak frequency, with a difference of a factor of ~35 in the mean ν_{peak} values for blazars in and out of the



FIG. 12.—Radio-optical spectral index α_{ro} vs. synchrotron peak frequency ν_{peak} for FSRQs (*circles*) and BL Lac objects (*crosses*) for the DXRBS sample. The dotted line at $\alpha_{ro} = 0.825$ denotes the limit of the sources studied by Fossati et al. (1998). See text for details.

HBL box. This is true especially for FSRQs. Figure 1 shows, in fact, that most of the blazars with $\alpha_{rx} \leq 0.78$ but outside the HBL box are strong lined. Table 1 shows also that, taking into account the sky coverage, while ~54% of BL Lac objects with $\alpha_{rx} \leq 0.78$ are in the HBL box, this is true only for ~36% of the FSRQs.

6.3. Other Properties of HBLs/LBLs and HFSRQs/LFSRQs

We have studied the properties of blazars in and out of the HBL box not addressed in \S 4, namely, radio, optical, and X-ray powers and redshift. As before, distributions are "corrected" by using the sky coverage. HFSRQs have slightly smaller radio powers and slightly larger X-ray powers than LFSRQs, by factors of ~ 2 , but not significantly so $(P \sim 90\%)$. HFSRQs, on the other hand, have significantly (P > 99.99%) larger (factor of \sim 7) optical powers, due to the fact that for these sources $\langle \nu_{\text{peak}} \rangle \sim$ 7×10^{14} Hz. Both classes have similar mean redshifts, ~ 1.6 and \sim 1.7, respectively, with redshift distributions that are different at the 96% level. The same comparison in the case of BL Lac objects is hampered by the relatively small number statistics (18 LBLs and 4 HBLs with redshift). With this caveat, we find that HBLs have slightly larger radio and optical powers than LBLs, by factors of $\sim 2-5$, but not significantly so ($P \sim 50\%$ and $\sim 90\%$, respectively), while they have significantly ($P \sim 98.7\%$) larger (factor of ~ 35) X-ray powers. The redshift distributions for the two classes are similar with $\langle z \rangle \sim 0.4$.

If indeed all blazars that lie within the HBL box have radio-to-X-ray continua produced by synchrotron emission, one might expect a significant population of HFSRQs to be 100 GeV to TeV emitters. An example of such an object might be RGB J1629+4008 (Padovani et al. 2002), which has a synchrotron peak ~2 × 10¹⁶ Hz and a predicted νF_{ν} at 10²⁵ Hz of nearly 10⁻¹⁰ ergs cm⁻² s⁻¹. A similar point was also made by Perlman (2000), albeit without the aid of *BeppoSAX* spectral data, who also listed five FSRQs with $\alpha_{rx} < 0.78$ and $z \le 0.1$ derived from the RGB and *Einstein* Slew Survey. Thus, the discovery of a new, X-ray–loud population of FSRQs predicts the existence of a new class of 100 GeV to TeV–emitting sources that could be particularly helpful for probing the diffuse infrared background at higher redshifts.

7. SUMMARY AND CONCLUSIONS

We have used the results of two recent surveys, DXRBS and RGB, to study the spectral energy distribution of about 500 blazars. Never before had this been done with a sample even remotely close to ours in terms of size, depth, and welldefined selection criteria. DXRBS, in particular, is ~95% complete and reaches fluxes ~ 20 times lower than previously available blazar radio surveys. We have first derived the effective spectral indices α_{ox} , α_{ro} , and α_{rx} . We have then studied the α_{rx} distributions for DXRBS, RGB, and even the EMSS samples for both FSRQs and BL Lac objects. The serendipitous nature of DXRBS and the EMSS has been taken into account by "correcting" these and other distributions using the appropriate sky coverage. The synchrotron peak frequencies for DXRBS blazars have also been derived by using multifrequency information and a homogeneous synchrotron-inverse self-Compton model. BLR and jet powers were also estimated. One of the main aims of this work was to look for the strong-lined counterparts of high-energy-peaked (HBL) BL Lac objects, the HFSRQs, that is, FSRQs with high-energy synchrotron peaks. We have found them. Our main results can be summarized as follows.

1. About 10% of DXRBS FSRQs have effective spectral indices typical of HBLs (to be compared with 15% for BL Lac objects) and can therefore be called HFSRQs. The fractions of HFSRQs and HBLs increase to \sim 30% and \sim 60% for RGB and to \sim 80% and 100% for the EMSS, respectively. Although HFSRQs have X-ray-to-radio flux ratios larger than previously known FSRQs, in none of the samples do they manage to reach values as high as those of HBLs.

2. The synchrotron peak frequency distribution of DXRBS FSRQs and BL Lac objects is continuous and peaks at $\approx 10^{14}$ Hz, with the former sources having an average $\nu_{\text{peak}} \sim 2.5$ times smaller than the latter. We have verified that blazars with effective spectral indices typical of HBLs indeed have larger ν_{peak} values (by a factor of ~ 35) than other blazars. About 60% and more than 8% of DXRBS BL Lac objects have $\nu_{\text{peak}} > 10^{14}$ and 10^{15} Hz, respectively, to be compared with $\sim 30\%$ and $\sim 5\%$ for FSRQs.

3. These results, together with the dependence we find of the X-ray spectral index, estimated from the hardness ratios, on ν_{peak} , confirm the existence of strong-lined counterparts of high-energy-peaked BL Lac objects. As is the case for HBLs, we would expect a significant fraction of these sources to emit at 100 GeV to TeV energies.

4. We find no anticorrelation between synchrotron peak frequency and radio, BLR, and jet powers, contrary to the

predictions of the so-called blazar sequence scenario, which calls for an inverse dependence of ν_{peak} on intrinsic power due to the effects of the more severe electron cooling in more powerful sources. On the other hand, available data from DXRBS and other surveys suggest that high- ν_{peak} highpower blazars have not been found yet and that HFSRQs do not reach the extreme synchrotron peak frequencies of BL Lac objects. This indicates that after all there might be an intrinsic, physical limit to the synchrotron peak frequencies and therefore electron energies that can be reached by powerful blazars.

The discovery of HFSRQs and the study of their properties have important implications for our understanding of jet formation and physics. Since $\nu_{\text{peak}} \propto \gamma_{\text{peak}}^2 \delta B$, where γ_{peak} is the Lorentz factor of the electrons emitting most of the radiation, we have shown that powerful jets with large magnetic fields and electron Lorentz factors can indeed existregardless of whether or not they have strong emission lines—albeit only up to a point. This provides an important challenge for existing models that advocate that the spectral energy distribution of relativistic jets is strongly affected by the external radiation field. We have also shown that selection effects are very strong and that, in particular, the HBL/ HFSRQ fraction is sample dependent. Can we separate selection effects from physics? We think we can. By using DXRBS we have sampled a region of parameter space that should be largely unbiased in terms of ν_{peak} (unlike that covered by the EMSS, for example). We have found that HBLs/HFSRQs make up a minority of the blazar population, $\sim 10\%$ -15%. We then believe that the available evidence suggests that nature preferentially makes jets that peak at IR/optical energies. We will address this issue in detail in a future paper.

It is also clear that, although a consistent picture comes out of our results, we need more information on these sources. We are planning dedicated X-ray observations of our newly discovered HFSRQs to further constrain their X-ray emission processes.

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