THE REX SURVEY: A SEARCH FOR RADIO-EMITTING X-RAY SOURCES

Alessandro Caccianiga,1 Tommaso Maccacaro, Anna Wolter, and Roberto Della Ceca

Osservatorio Astronomico di Brera, Via Brera 28, I-20121 Milano, Italy

AND

Isabella M. Gioia2

Institute for Astronomy, 2680 Woodlawn Drive, Honolulu, HI 96822

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ABSTRACT

We present the scientific goals, strategy, and first results of the REX project, an effort aimed at creating a sizable and statistically complete sample of radio-emitting X-ray sources (REXs) using the available data from a VLA survey (NVSS) and the ROSAT PSPC archive. Through a positional cross-correlation of the two data sets, we have derived a sample of about 1600 REXs. Among the 393 REXs identified so far (either from literature or from our own spectroscopic observations) a high fraction are active galactic nuclei (AGNs; about 60%-80%), typically radio-loud QSOs, and BL Lac objects. The remaining sources are galaxies, typically radio galaxies isolated or in clusters. Thanks to the low flux limits in the radio (5 mJy at 1.4 GHz) and in the X-ray band (\(~5 \times 10^{-14}\) erg s\(^{-1}\) cm\(^{-2}\), 0.5-2.0 keV) and the large area of sky covered by the survey (2183 deg\(^2\)), we intend to derive a new complete and unbiased sample of BL Lac objects that will contain both radio-selected (RBL) and X-ray–selected (XBL) objects. In this way, the apparent dichotomy resulting from the current samples of BL Lac objects can be directly analyzed in a unique sample. Moreover, the high number of BL Lac objects expected in the REX sample (\(~200\)) will allow an accurate estimate of their statistical properties, such as the X-ray, radio, and optical luminosity functions and the cosmological evolution. For these reasons, the REX sample will be a powerful tool to accurately test the current theoretical models proposed for BL Lac objects. To date, we have discovered 15 new BL Lac objects and 11 BL Lac candidates with optical properties intermediate between those of a typical elliptical galaxy and those of a typical BL Lac object. These objects could harbor weak sources of nonthermal continuum in their nuclei, and if confirmed they could represent the faint tail of the BL Lac population. The existence of such “weak” BL Lac objects has been matter of discussion in recent literature and could lead to a reassessment of the defining criteria of a BL Lac object, and consequently to a revision of their cosmological and statistical properties. Finally, the sample of \(~800\) emission-line AGNs generated by the REX survey will be useful in addressing many of the open questions regarding AGN phenomenology, such as the relationship between radio-loud and radio-quiet AGNs.

Subject headings: BL Lacertae objects: general — galaxies: active — quasars: general — surveys

1. INTRODUCTION

The optical identification of radio or X-ray catalogs has been instrumental in deriving large samples of AGNs (e.g., Stocke et al. 1991; Boyle et al. 1994; Page et al. 1996 for the X-ray band and Gregg et al. 1996 for the radio band). At present, new radio and X-ray surveys characterized by low flux limits and a wide coverage of the sky are in progress. In the radio band, there are two similar projects aimed at creating new catalogs of radio sources at mJy fluxes with accurate radio positions (a few arcseconds of uncertainty or better) based on VLA observations, i.e., the NRAO VLA Sky Survey (NVSS, Condon et al. 1998) and the Faint Image of the Radio Sky at Twenty centimeters survey (FIRST survey, Becker, White, & Helfand 1995). The NVSS survey covers all of the sky north of \(\delta = -40^\circ\) using the VLA D and DnC configurations, with a typical rms of 0.45 mJy; the FIRST survey covers about 10,000 deg\(^2\) around the north Galactic pole plus a southern strip (from R.A. = 21\(^h\)20\(^m\) to 3\(^h\)20\(^m\) and from decl. = -2\(^\circ\)2 to 1\(^\circ\)6) with a higher spatial resolution (B configuration) and a lower flux limit (rms \(~0.15\) mJy) than the NVSS. Eventually, both catalogs will contain more than \(10^6\) radio sources each. In the X-ray band, the ROSAT satellite has produced a great bulk of data, both from the All-Sky Survey (RASS) and from about 4000 PSPC-pointed images gathered in public archives. The first catalog of bright \((f_{0.1-2.4 keV} > 10^{-12}\) erg s\(^{-1}\) cm\(^{-2}\)) X-ray sources produced by the RASS contains about 19,000 sources (Voges et al. 1996), while the catalogs derived from public pointed PSPC images (the WGA [White, Giommi, & Angelini 1994] and ROSATSRC [Voges et al. 1994] catalogs) contain about 70,000 sources each. All these surveys offer a great opportunity to derive sizable new samples of AGNs. In particular, the RASS and VLA surveys will be useful for performing detailed statistical analyses. On the other hand, the large numbers of sources contained in these catalogs draw the attention to the problem of optical identification. Even with the high positional accuracy of the VLA, which guarantees the (almost) univocal identification of the correct optical counterpart (at least for \(m_V \leq 20\)), the number of optical candidates to observe spectroscopically is undoubtedly high. This number increases dramatically in the case of the X-ray catalogs derived from the ROSAT PSPC data, which are characterized by larger positional errors (typically from 14" to 50"; see § 4.3). As a consequence, the completion of
the optical identification process for these surveys will require decades. This fact points out the importance of finding efficient preselection techniques to extract from the whole sample only those candidates of interest for spectroscopic follow-up. Many authors have initiated specific efforts aimed at creating samples of AGNs from VLA data (Gregg et al. 1996) or of BL Lac objects from ROSAT data (Perlman et al. 1998; Laurent-Muehleisen et al. 1998; Nass et al. 1996; Kock et al. 1996) through the application of particular preselection criteria based on radio-to-optical or X-ray-to-optical flux ratios, or using information on optical polarization.

The primary goal of the REX project is the selection of a statistically complete sample of AGNs, in particular radio-loud (RL) QSOs and BL Lac objects, by simultaneously using the information derived from the NVSS survey and that derived from pointed ROSAT PSPC images. Through a positional cross-correlation of sources detected in the NVSS and ROSAT fields, we derive a sample of radio-emitting X-ray sources (REXs) that is expected to contain a high fraction of AGNs (radio-loud QSOs, BL Lac objects, and Seyfert galaxies) and radio galaxies. This method has two fundamental advantages:

1. We are able to minimize a priori the presence in the sample of objects such as stars or normal galaxies, which are not strong radio-emitting X-ray sources, increasing in this way the efficiency with which we can find sources of interest (BL Lac objects and QSOs) to be observed spectroscopically.

2. We can use the accurate VLA positions to pinpoint the optical counterparts of the X-ray sources.

We discuss the main scientific goals of the project in § 2; in §§ 3 and 4 we examine the catalogs of radio and X-ray sources, respectively, used for the cross-correlation. In § 5 we discuss the source-selection criteria and the estimated content of the REX survey. The strategy for optical identification of the sample is described in § 6, while § 7 discusses the content of the REX sample. In § 8 we report preliminary results derived from the study of the sample of BL Lac objects discovered so far. Our conclusions are summarized in § 9.

Throughout the paper, the values of $H_0 = 50$ km s$^{-1}$ Mpc$^{-1}$ and $q_0 = 0$ are used.

2. SCIENTIFIC GOALS

The main goal of the project is the study of RL AGNs and BL Lac objects. These kinds of AGN are either intrinsically few (RL AGNs make up about 10% of the whole class of AGNs, while BL Lac objects represent only few percent) and/or hard to find. BL Lac objects, in particular, lack a UV excess or any other peculiar optical spectral signature, and for these reasons they are found with difficulty in the optical band. Nevertheless, they are both radio loud and X-ray loud (e.g., Stocke et al. 1990), and as a consequence they are typically selected in the X-ray or in the radio band. The small numbers of BL Lac objects or RL AGNs available in current complete samples (e.g., the EMSS catalog contains only 36 BL Lac objects and 43 RL AGNs; Morris et al. 1991; Della Ceca et al. 1994; the 1 Jy catalog contains only 34 BL Lac objects; Stickel et al. 1991) limits any detailed statistical analysis of these objects. On the other hand, accurate statistical studies are needed in order to address many open questions, such as the origin of the differences between radio-loud and radio-quiet AGNs (e.g., Wilson & Colbert 1995), the supposed dichotomy of the BL Lac population (e.g., Giommi & Padovani 1994; Padovani & Giommi 1995), the cosmological properties (evolution, luminosity functions) of BL Lac objects, and the problem of their parent population (e.g., Urry & Padovani 1995 and references therein). Many of these questions, in particular those related to BL Lac objects, require a significant enlargement of the available complete samples. Moreover, many crucial predictions of the current theoretical models, such as the relative number of radio-selected (RBL) and X-ray-selected (XBL) BL Lac objects (Giommi & Padovani 1994; Fossati et al. 1997) could be verified only by reaching low X-ray flux limits (typically a few $10^{-14}$ ergs s$^{-1}$ cm$^{-2}$). The REX sample will satisfy these requirements, since it will contain $\geq 200$ BL Lac objects down to a flux limit of $\sim 5 \times 10^{-14}$ ergs s$^{-1}$ cm$^{-2}$ in the 0.5–2.0 keV energy band.

3. THE RADIO CATALOG

The NRAO VLA Sky Survey began in 1993 and now covers the whole sky north of $\delta = -40^\circ$ (~10.3 sr, 82% of the total sky). It is performed at 1.4 GHz using the compact D and DnC configurations of the Very Large Array in Socorro, New Mexico. The primary product of this survey is a set of 2324 $4^\circ \times 4^\circ$ maps containing information about total intensity and linear polarization (Stokes parameters $I$, $Q$, and $U$). The size of the restoring beam ($\theta = 45^\prime$ FWHM) allows us to achieve the high surface brightness sensitivity needed for completeness and photometric accuracy. The rms of the Stokes $I$ maps is $\sigma \sim 0.45$ mJy beam$^{-1}$. The final maps have been released electronically by anonymous FTP. Moreover, NRAO has extracted a catalog of discrete sources and components (if the radio source is resolved by the VLA beam) detected in the images, by fitting elliptical Gaussian to all significant peaks. The entries consist of single-Gaussian model fits. The sources (or components) are identified in the Stokes $I$ images, and then the associated polarization information is derived from the Stokes $Q$ and $U$ images. A brief description of this catalog is given on the home page of NVSS. A related program (NVSSlist) is also provided in order to read the catalog (which is released in FITS format) and to browse selected portions of the sky. NVSSlist also corrects the raw catalog for known biases and computes errors associated with the source model parameters (position, flux density, etc.). Both catalog and program are continually updated. For what concerns the REX project, we set the radio limiting flux to 5 mJy (about 10 times the rms of the $I$ maps) in order to achieve accurate positions (95% error circles smaller than $5^\prime$) and to guarantee the completeness of the sample (see Condon et al. 1998 for details). We have used version 2.8 of the NVSSlist program and the version 28 (01/19/98) of the catalog. In that version, the NVSS was plagued by a number of holes, i.e., regions of missing data. We have estimated that in the

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3 This is true in the optically selected samples, while in the X-ray-selected samples, e.g., in the EMSS sample, the fraction of RL AGNs ranges from 3% to 30%, depending on the optical luminosity (e.g., Della Ceca et al. 1994). We consider radio-loud an AGN with $s_{90} > 0.35$ (see Della Ceca et al. 1994), where $s_{90} = \log (I_{5000A}/S_{90})/5.38$.

4 This home page is located at: http://www.cv.nrao.edu/~jcondon/nvss.html.
region of sky covered by the X-ray catalog (see § 4), the area lost because of the holes is about 5%–7%.

4. THE X-RAY CATALOG

The X-ray catalog used for the REX project has been derived from the ROSAT archive of pointed PSPC images. To date, the ROSAT PSPC archive represents the best set of data for deriving a large catalog of X-ray sources covering a wide angle of the sky and reaching faint limiting fluxes (below $10^{-14}$ ergs s$^{-1}$ cm$^{-2}$ in the 0.2–2.4 keV band with the deepest images). We briefly describe the PSPC archive and the existing X-ray catalogs derived from these data. Since these catalogs are not suitable for our purposes, we have undertaken to reanalyze all the PSPC images suitable for this project, with the aim of constructing a new statistically representative catalog of sources. We present the selection of the fields used in this project, the process of source detection, and the source positional uncertainties in the resulting X-ray catalog.

To date, all the pointed ROSAT PSPC observations (~4000 in total) are in the public domain and stored in a public archive. The large field of view of the PSPC (about 2.8 deg$^2$) makes this archive of images particularly useful for building up an X-ray catalog of serendipitous sources. Two different catalogs of X-ray sources detected in a number of ROSAT PSPC images have been made public in the past few years: the WGA catalog (White et al. 1994) and the ROSATSRC catalog (Voges et al. 1994). The detection technique used for the WGA catalog is based on a sliding-box algorithm that is optimized for point-like sources. The inner (0’–19’ off-axis angle) and outer (18’–55’ off-axis angle) regions of the images were processed separately in order to maximize the sensitivity to source detection. The latest version (revision 1) of the catalog contains about 68,000 sources detected in 3007 fields. The ROSATSRC catalog is the first source catalog of pointed observations created at the Max Planck Institut für Extraterrestrische Physik. A maximum-likelihood detection algorithm was used for the central 20’ of the PSPC field, and a sliding-box algorithm of fixed width was used at larger off-axis angles. About 74,000 sources are contained in the latest version of the catalog (revision 1), which is derived from an analysis of 3348 fields. Although the bulk of the images used are the same for both catalogs, there are significant differences, probably related to the different methods and thresholds used for the source detection (see the WGACAT WWW home page$^6$ for a brief description of these differences). Both WGACAT and ROSATSRC catalogs were created principally to quickly derive a list of X-ray sources useful, for instance, for finding peculiar and interesting objects (e.g., sources with anomalous temporal variability or spectral properties) to be re-observed, if necessary, with ROSAT or other telescopes (ASCA, for example). For this reason, they were created without particular attention to the problems of completeness and representativeness. Both catalogs contain, for example, several repetitions, i.e., the same source may appear more than once in the two catalogs; about 4000 sources in the last version of WGACAT are redundant. This problem is related to the fact that many PSPC pointings overlap one another, and a source may thus be detected separately in two different images. Moreover, the algorithms chosen for the source detection work on a fixed scale, while the point-spread function (PSF) of the PSPC changes considerably and continuously with the off-axis angle; this problem still holds even when using different scales in the inner and outer regions of the PSPC. All these problems make the definition of a complete sample and the derivation of the sky coverage very difficult for both catalogs. Finally, WGA and ROSATSRC catalogs are not purely made of serendipitous sources, because they contain all the targets of the PSPC pointings, affecting the representativeness of the two catalogs. For these reasons, WGACAT and ROSATSRC, although useful for some specific purposes, are not suitable for statistical studies, and in particular not for our project, which requires completeness and representativeness in addition to a precise estimate of the sky coverage.

Thus, we have reanalyzed a well-defined subset (see § 4.1) of the public PSPC observations with the purpose of constructing a complete and well-defined sample of X-ray sources. In particular, we are interested in:

1. Resolving the problem of overlapping PSPC images.
2. Eliminating all the targets and the target-related sources from the catalog.
3. Using a detection algorithm sensitive to the changes in the PSF over the PSPC field.
4. Computing the appropriate sky coverage.

4.1. Selection of ROSAT PSPC Fields

From the ~4000 PSPC images in the public archive, we have selected all the fields that fulfill the following criteria:

1. $\delta \geq -40^o$ (to match the NVSS sky coverage).
2. $|b| \geq 10^o$ (to avoid the Galactic plane).
3. Exposure time $\geq 1000$ s.
4. The field is processed with revision 7 of the SASS as of 1997 December (to obtain data with an improved aspect solution).

We have also excluded intrinsically “confused” regions, such as those with a high stellar density (e.g., images pointed at Pleiades or Hyades), or regions near extended dark or molecular clouds, which could create problems in the process of source optical identification or in the computation of the limiting sensitivity of the field.

The distribution in the sky of all the PSPC pointings clearly shows that there are several overlapping images (deep surveys, targets that cover a wide area of sky, fields pointed to close targets). Combining these images in single frames would create several problems during the process of source detection. Typically, the presence of strong gradients in the sensitivity profile of the final image, induced by the edges of the individual fields, creates difficulties in the background determination and the detection algorithm, and may yield spurious sources. We avoided this problem simply by excluding from the analysis the outer region of one of the overlapping fields in order to obtain a mosaic of separated fields. Figure 1 illustrates this “cleaning” procedure.

Finally, in the case of an exact overlap in the sky coordinates of two or more distinct pointings, we summed them

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5 The RASS, although it covers the whole sky, reaches limiting fluxes of about $10^{-12}$ ergs s$^{-1}$ cm$^{-2}$ (in the Bright RASS catalog) or fluxes of about $1.5 \times 10^{-12}$ ergs s$^{-1}$ cm$^{-2}$ (in the total catalog of 60,000 sources presented in Voges 1993); for this reason, it is not optimal for studying the faint tail of the log $N$–log $S$ of BL Lac objects and RL AGNs.

6 WGACAT WWW home page is available at: http://heawww.gsfc.nasa.gov/users/white/wgacat/wgacat.html.
and consider these fields as a single image with an exposure time that is the sum of the individual exposures. In this case, the name of the resulting field is formed by the lowest ROSAT Observation Request (ROR) sequence number with the suffix "sum."

In order to achieve a catalog of purely serendipitous sources, we have eliminated from the survey the area containing the target of the observation (since it is, by definition, not chosen randomly) and all the target-related sources. In the majority of the PSPC pointings, the target falls in the center of the field, and its extent is typically included in a circle of 4’ radius. In the case of images pointed toward rich or nearby clusters of galaxies, the radius of the circle around the target can be considerably larger (from 10’ to 20’). The few fields that contain very extended targets (dimension $\gtrsim 25'$) have been fully excluded from the survey. In the few cases in which the target object was deliberately offset from the center (e.g., for variability studies), we excluded a circle of radius $r_t$ centered on the target position. Furthermore, in the case of PSPC images centered on an optically very bright object (e.g., $\alpha$ Ari or $\beta$ CMa), we have excluded the area "blinded" by the optical image. In these cases, in fact, it would be extremely difficult, if not impossible, to optically identify a serendipitous source close to the target.

In total, we have selected 1202 distinct PSPC fields. For reference, we have made electronically available a table containing the complete list of PSPC images used for this survey, covering a total area of 2183 deg$^2$. In particular, we have reported for each PSPC field the ROR sequence number, the sky coordinates (J2000), the exposure time (which is the total exposure time in the cases of summed fields), the inner ($r_i$) and outer ($r_o$) radii of the PSPC region used, the position of the target in detector coordinates, the radius of the excluded area ($X_o$, $Y_o$, and $r_o$) if the target is offset, and the Galactic hydrogen column density (in units of $10^{20}$ cm$^{-2}$), derived from Dickey & Lockman (1990). When there were no targets (e.g., surveys or mispointed fields), both $r_i$ and $r_o$ are zero. The maximum value of the outer radius has been set to 47’ (although the "standard" radius for a PSPC field is 55’), in order to exclude the part of the PSPC where PSF degradation is severe and the positional uncertainties are too large (>50’).

We report in Figure 2 the distribution on the sky of the total set of selected PSPC fields, while in Figure 3 we show the histogram of their exposure times.

### 4.2. The Detection Algorithm

The detection algorithm used for this project was developed at the Palermo Astronomical Observatory; it is described in detail in Damiani et al. (1997a). The method is based on wavelet transforms, which are well suited to the case in which the PSF varies across the image (see also Rosati et al. 1995). This detection technique outperforms that used to produce the WGA and the ROSATSRC catalogs in terms of reliability and efficiency.

For the REX project, we have applied the detection algorithm to the selected set of PSPC fields using the “hard” images (0.5–2.0 keV) to reduce the intensity of the background and to minimize the effects due to Galactic absorption. Moreover, the choice of the hard band minimizes the uncertainties related to the conversion from count rate to flux due to the unknown spectral shape of the sources, as discussed in Vikhlinin et al. (1995). The images used all have a 15” pixel size. The final catalog contains 16,275 X-ray sources detected with a confidence level $\geq 6$σ (see Damiani et al. 1997a for a discussion of the determination of the probability associated with a given source detection threshold) and a count rate of $\geq 3 \times 10^{-3}$ counts s$^{-1}$. The high threshold on significance guarantees a very low number of spurious X-ray sources (see Fig. 3 of Damiani et al. 1997b); the limit on the count rate was chosen to avoid very faint sources that could be very difficult to identify spectroscopically. Assuming a power-law spectrum with an energy index $\alpha_x = 1.0 (f_x \propto E^{-\alpha})$, this count-rate limit corresponds to a limiting flux in the 0.5–2.0 keV band of $\sim 3.5 \times 10^{-14}$ ergs s$^{-1}$ cm$^{-2}$ for $N_H = 7 \times 10^{19}$ cm$^{-2}$ (the lowest value for the PSPC fields used in the REX survey) and of $\sim 6 \times 10^{-14}$ ergs s$^{-1}$ cm$^{-2}$ for $N_H = 2 \times 10^{21}$ cm$^{-2}$ (the highest value).

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[7] The table pspc_table.txt can be retrieved by anonymous ftp at ftp.brera.mi.astro.it. The table (in ASCII format) is in the directory /pub/REX/tables/. A description of the table is found in the file pspc_table.doc in the same directory.
4.3. The Positional Accuracy of the X-Ray Catalog

Before cross-correlating the X-ray catalog with that derived from the NVSS survey, it is crucial to accurately assess the positional uncertainties. The error circle of the sources detected in the ROSAT PSPC images is typically of the order of tens of arcseconds, while the error circles associated with the NVSS positions are an order of magnitude smaller (a few arcseconds). Therefore, the impact parameter, which is the square combination of the two error circles, depends mainly on the X-ray positional accuracy.

To determine the uncertainties associated with the X-ray positions, we have cross-correlated the X-ray sources against two catalogs: the Hipparcos Input Catalog of stars (HIC, Perryman et al. 1997) and the V&V96 catalog of AGNs (Véron-Cetty & Véron 1996).

The HIC catalog contains 118,000 stars with a positional accuracy of ~0.3. In the case of the V&V96 catalog, we have used only the 8272 sources with a good estimate of the position (accuracy better than 1°).

By using an impact parameter of 4', we found 960 X-V&V96 correlations and 525 X-HIC correlations, for a total of 1485 sources. The distribution of the offsets in right ascension (Δα) and declination (Δδ) between the X-ray and the V&V96 or HIC positions is shown in Figure 4. We have divided the sources in three groups, corresponding to different ranges of the off-axis angle (θ): from 0° to 19° (Fig. 4a); from 19° to 35° (Fig. 4b); and from 35° to 47° (Fig. 4c).

Using two different methods, we have estimated from these data the positional errors of the X-ray sources as a function of the off-axis angle.

In the first method we compute, from the three panels presented in Figure 4, the radius of the circle that includes 90% of the real positional correlations (the total correlations minus the expected chance coincidences), i.e., the radius (r₉₀) of the circle that contains 90% of the points is defined by

\[
\frac{N(\leq r_{90}) - N_{sp}(\leq r_{90})}{N_{tot} - N_{spTOT}} = 0.90, \tag{1}
\]

where \(N(\leq r_{90})\) is the number of correlations with offset \(\leq r_{90}\), \(N_{sp}(\leq r_{90})\) is the number of expected spurious corre-
Fig. 4.—Distribution of the offsets between the position of AGNs and stars in the V&V96 and HIC catalogs and the X-ray position from our catalog. The first three panels correspond to three different ranges of the off-axis angle in the ROSAT PSPC field: (a) from 0° to 19°, (b) from 19° to 35°, and (c) from 35° to 47°. In (d), all the 1485 correlations are shown. The circles of radius 40 arcsec, and 50 arcsec plotted in (a), (b), and (c), respectively, represent the 90% X-ray error circles derived from the analysis presented in the text.

relations with offset ≤r_{90}, N_{int} is the total number of correlations within the 4° radius, and N_{TOT} is the total number of expected spurious correlations within the 4° radius. We have estimated N_{sp} and N_{TOT} by assuming that all the sources with an offset >r_{sp} were of spurious origin. The value of r_{sp} ranges from 50° for θ ≤ 19° to 100° for 35° ≤ θ ≤ 47°. This analysis indicates that the error circles at the 90% confidence level are at 14° for θ < 19°, 40° for 19° ≤ θ < 35°, and 50° for 35° ≤ θ ≤ 47°.

We have also studied the differential distribution of the number of correlations found, defined as

$$d(r) = \frac{N(r, r + Δr)}{\pi[(r + Δr)^2 - r^2]}$$

where N(r, r + Δr) is the number of correlations with offset between r and r + Δr, and Δr is the width of the bin used (=2°).

We then performed a fit to this distribution using a Gaussian profile, assumed to represent the real coincidences, plus a constant, representing the spurious matches. The radius of the 90% error circle is then obtained by the σ of the Gaussian fit. The problem with this method is that the observed profiles typically are not Gaussian, showing a systematic excess (wings) at large values of r. Moreover, the first bins contain few objects, so that the uncertainties are large. By excluding the first three bins from the analysis, we have found values of r_{90} in good agreement with those estimated with the first method.

In conclusion, for the positional cross-correlation, we use an X-ray error circle of radius 14°, 40°, and 50° for θ < 19°, 19° ≤ θ < 35°, and 35° ≤ θ ≤ 47°, respectively.

5. THE REX SELECTION

5.1. Criteria for the Cross-Correlation

Given the estimate of the X-ray and radio positional error circles, the impact parameter (b) to be used during the cross-correlation to achieve the 90% completeness level can be determined simply by summing quadratically the two positional uncertainties (σ_x and σ_y) corresponding to the 90% confidence level for the radio and the X-ray positions,
i.e.,

\[ b = \sqrt{\sigma_R^2 + \sigma_X^2} \]  \hspace{1cm} (3)

In practice, \( \sigma_R^2 \ll \sigma_X^2 \) (see Condon et al. 1998 and § 4.3), and thus \( b \sim \sigma_X \). Since we use the 90% confidence level error circles, we expect to lose about 10% of the REXs using the impact parameter given by equation (3). This represents a compromise between reliability and completeness, since a larger value of \( b \) would increase the number of spurious radio/X-ray correlations, while a smaller value of \( b \) would increase the number of missed REXs. Clearly, the loss of 10% of the REXs must be considered when deriving statistical properties such as the log \( N \)-log \( S \) relation or the luminosity function.

A positional cross-correlation between the radio and the X-ray catalogs using the impact parameter \( b \) given in equation (3) is the correct way to find REXs that are unresolved in the radio band. However, a large number of radio sources (e.g., radio galaxies and RL QSOs) show characteristic extended structures (radio lobes, cores, jets) that are often well resolved in VLA images, even with the compact D and DnC configuration used for the NVSS. In these cases, the X-ray emission is centered corresponding to the radio core and may be distant from the emission of the other structures (radio lobes). In a number of cases, only the emission produced by the lobes is visible on the radio map, and the object appears as a double radio source. As a consequence, several REXs (typically quasars and radio galaxies) could be lost in a “blind” positional cross-correlation. The absence of a radio core in RL QSOs is a well-known possible cause of incompleteness, which may affect in particular the highly resolved VLA surveys. This effect, for example, may be one of the principal sources of incompleteness for the FIRST bright QSO survey (Gregg et al. 1996). The existence of double radio sources may also introduce an erroneous identification of the optical counterpart of the REXs in the case in which only one radio component falls inside the X-ray error circle; in this case, the REX is not lost but the optical counterpart, if it is supposed to be coincident with the radio position, could be misidentified or spurious.

Figure 5 presents four cases of two NVSS components (small circles) close to the X-ray position (large circle). We note that the size of the X-ray error circles depends on the off-axis angle, as described in § 4.3, while for clarity the

![Diagram](diagram.png)

Fig. 5.—(a) Example of REX that would be totally lost in a “blind” cross-correlation between radio (small circles) and X-ray (large circle) positions; (b) An example of an extended radio source that might introduce an erroneous identification of the optical counterpart; (c) An example of an extended radio source that might induce a spurious radio/X-ray correlation; (d) An example of a “false” double radio source.
radio error circles are all plotted with a fixed size of 6°. Figure 5a is an example of a possible double radio galaxy whose lobes lie just outside of an X-ray error circle that contains the optical galaxy. If we cross-correlate using the impact parameter $b$ defined above (eq. [3]), this source would be lost. Figures 5b and 5c show similar cases of possible double radio galaxies in which one of the two components lies inside the X-ray error circle. In both cases the source would be selected as a REX, but a search for the optical counterpart at the radio position of the component consistent with the X-ray position would fail to produce the correct identification. In the case of Figure 5b, the REX is correctly retained in the sample, while in Figure 5c the match would be spurious, since the optical counterpart of the radio source is not consistent with the X-ray position. Finally, Figure 5d shows a false case of a double radio source: one of the two components is a radio source consistent with the X-ray position, while the other is an unrelated radio source. Given this complex situation, instead of cross-correlating with the parameter $b$, we use the following procedure. We cross-correlate the two catalogs using a large impact parameter (2.5); this yields a large list of positional coincidences, most of which of spurious origin. At this stage, double radio sources are not missed (if their sizes are less than $\sim 5$'), but we must deal with the problem of separating the real coincidences from the spurious ones. The possible cases can be divided in three categories, schematically represented in Figure 6:

Case 1.—Only one radio source falls closer than 2.5 to an X-ray source.

Case 2.—Two radio sources fall closer than 2.5 to an X-ray source.

Case 3.—Three or more radio sources fall closer than 2.5 to an X-ray source.

The first case is the simplest to deal with: if the radio and X-ray positions are consistent within the impact parameter defined by equation (3), we consider this object a REX; otherwise we eliminate the source.

We call the other two cases T-REX, for Temporary REX. The number of T-REX is very large, because of the large impact parameter used for the cross-correlation, and for this reason we automatically filter some obvious cases of chance coincidences. In particular, we can exclude a priori situations in which the line joining the two radio positions does not intersect the X-ray error circle, i.e., where the optical counterpart of the presumed double source falls outside the X-ray error circle (see Fig. 6, case 2d) or, if it intersects the X-ray error circle, where both the radio components are on the same side. By excluding all these situations (in case 2), we reduce significantly the number of T-REXs that must be considered. For the remaining cases, we inspect the $5' \times 5'$ optical finding chart from the Digitized Sky Survey (DSS) and the $5' \times 5'$ radio map produced from the NVSS images, and we try to detect all the possible cases of radio-extended REXs and to recognize sources that are clearly chance coincidences (considering the position of the plausible optical counterparts and the morphology of the radio emission). We have analyzed the sample of $\sim 1000$ T-REXs resulting from the cross-correlation, and we have found that, on the basis of the radio and optical maps, we are able to distinguish a real REX from a chance coincidence in $\sim 80\%$ of the cases. The

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**Fig. 6.**—Possible configurations resulting from the cross-correlation between radio sources (stars) and X-ray sources (circles), using an impact parameter of 2.5 (box). There are three possible cases: (1) only one radio source falls closer than 2.5 to an X-ray source; (2) two radio sources fall closer than 2.5 to a X-ray source; and (3) three or more sources fall closer than 2.5 to an X-ray source.
other 20% of T-REXs will be correctly classified only after gathering further information, including the spectroscopic data for the possible optical counterparts. Of the T-REXs that we have already classified, 90 are real double or triple radio sources (see Fig. 5a), 443 are represented by normal REXs, i.e., the radio source consistent with the X-ray position is not related to the other radio component(s) found within 2.5 (see Fig. 5d), and 318 are chance coincidences, i.e., the radio and the X-ray sources are not related.

The source catalog containing the relevant information on the REXs (position, X-ray and radio flux, relative errors, etc.) will be made available electronically as soon as the NVSS data become stable and the REX quality check is completed. At the time of writing, the NVSS catalog is still an evolving entity because of the existence of a few snapshot fields lacking total intensity images (corresponding to about 5%–7% of the area covered by the X-ray data). These gaps are being filled by the NVSS group either by reprocessing existing data or by new observations. We anticipate that we will release a REX catalog obtained using the latest NVSS version, and that thus the total number of sources will differ marginally from that presented in this paper. Furthermore, for each REX we intend to make available an optical finding chart derived from the DSS.

5.2. Estimate of the Number of Radio/X-Ray Chance Coincidences

We can evaluate the number of chance coincidences produced by the X-ray/radio cross-correlation in two different ways. One possibility is to calculate the number of spurious REXs analytically, i.e., by computing the number of radio sources expected by chance within a circle of radius \( b \) centered on an X-ray position. If \( N_1, N_2, \) and \( N_3 \) are the number of X-ray sources with \( \theta < 19' \), \( 19' \leq \theta < 35' \), and \( 35' \leq \theta \leq 47' \), respectively, and \( b_1, b_2, \) and \( b_3 \) are the corresponding impact parameters used for the cross-correlation, the total number of expected chance coincidences is

\[
N_{\text{chance}} = (N_1 \pi b_1^2 + N_2 \pi b_2^2 + N_3 \pi b_3^2) \rho ,
\]

where \( \rho \) is the number of radio sources per unit area with a radio flux greater than 5 mJy. We have \( N_1 = 4943, N_2 = 7674, N_3 = 3658, \) and \( \rho \sim 31 \text{ deg}^{-2} \), and consequently \( N_{\text{chance}} = 170, \) that is, about 10% of the total number of the REXs.

Alternatively, the number of chance coincidences can be derived by cross-correlating the two catalogs after applying a relative shift in position to one catalog: if this offset is significantly greater than the impact parameter \( b \), we expect that all the results of the cross-correlation will be pure chance coincidences. By using this second approach, we have derived an expected percentage of chance coincidences in the REX sample of 11.5% ± 2%, in agreement with the result of the other (independent) method.

For double or triple REXs, the computation of the spurious matches is not so straightforward as for single-component REXs. On the other hand, these complex sources represent a small fraction (about ~6%) of the total number of REXs, and thus the overall percentage of chance coincidences is practically determined by the single-component REX.

Finally, we note that the estimated percentage of chance coincidences is a function of the off-axis angle, since the size of the impact parameter used for the cross-correlation depends on the position of the source in the PSPC field. If we consider the three ranges of off-axis angle independently, we find that the percentage of chance coincidences is 2.6% in the inner part of the PSPC field (\( \theta \leq 19' \)), 12% between 19' and 35', and 16% for \( \theta \geq 35' \). Thus, upon completion of the identification program, a comparison of the identification content as a function of the off-axis angle will provide information useful for the recognition of the spurious matches.

Moreover, if during the identification process we find within the X-ray error circle a source that is a good candidate as an optical counterpart of the X-ray source, but which is not positionally consistent with the radio source, we flag this REX as a possible spurious match.

5.3. Expected Composition of the REX Sample

The expected composition of the REX sample depends on the radio, X-ray, and optical limits. We estimate that the main constituents of the sample will be RL AGNs and BL Lac objects. Nevertheless, a number of radio-quiet (RQ) AGNs is also expected if their magnitudes are sufficiently bright. For instance, a RQ AGN with \( z_{\text{opt}} = 0.3 \) will be included in the REX survey (i.e., it will have a radio flux \( \geq 5 \text{ mJy} \) only if its magnitude is brighter than \( \sim 18 \). In addition, clusters of galaxies will be present in the REX sample if they contain at least one bright (\( \geq 5 \text{ mJy} \)) radio galaxy. In this case the term “REX” is somewhat improper, because the radio and the X-ray emissions come from physically disjointed (although related) sources: from the hot diffuse plasma in the X-ray band, and from the radio galaxy in the radio band. The number of clusters of galaxies expected in the REX sample is difficult to compute. First of all, there is a strong bias against clusters that do not contain bright radio galaxies. Moreover, even in the case of a cluster containing a powerful radio galaxy, the position of such a radio source must be consistent within the impact parameter \( b \) with the position of the center of the X-ray source, which has no relation to the physical dimension of the cluster. Since neither the fraction of clusters containing a bright radio galaxy nor the positional distribution of such radio galaxies within the cluster itself are known accurately, a quantification of these biases is hard to compute. We stress that these considerations imply that the sample of clusters of galaxies selected in this project cannot be used for statistical purposes. On the other hand, the REX sample could be very useful in finding individual high-redshift clusters of galaxies. For the same reasons discussed above, it is difficult to predict the expected number of radio galaxies in the REX survey, since a significant fraction of them are found in clusters. Thus, in this section we will assess the predicted properties only of AGNs and BL Lac objects. To this end, we have used the current knowledge of the statistical properties of these classes of objects (i.e., luminosity functions, evolution, and X-ray/optical/radio relationships).

5.3.1. RL AGNs

The X-ray luminosity function (XLF) and the cosmological evolution of this class of objects have been adapted from Della Ceca et al. (1994). The XLF has first been
rescaled from the 0.3–3.5 keV energy band to the 0.5–2.0 keV energy band and then integrated over the luminosity range $10^{42}$ to $10^{47}$ ergs s$^{-1}$ and from $z = 0$ to $z = 4$. We have assumed the best-fit evolutionary model until $z = 2$, and no evolution at higher redshift. Given the shape of the XLF (flat at low luminosities and steep at high luminosities), the results of the integration are not particularly sensitive to the choice of the luminosity limits. By convolving the results with the X-ray sky coverage, we have derived a synthetic sample of sources characterized by an X-ray flux and a redshift. We have then assumed a relationship between radio and X-ray luminosities and between optical and X-ray luminosities, and we have associated with each object a corresponding radio and optical flux. For this purpose we have used the correlation between the total (extended plus core) radio luminosities at 1.4 GHz and the luminosities at 2 keV, and the relationship between the luminosities at 2500 Å and the luminosities at 2 keV, derived by Brinkmann, Yuan, & Siebert (1997) for the RL QSOs detected in the RASS. We have added a synthetic noise to the relationships to mimic the spread of the observed distributions. Finally, we have imposed the radio limit ($\text{flux}_{1.4 \text{ GHz}} \geq 5 \text{ mJy}$), obtaining an expected sample of $\sim 1200$ RL AGNs. As previously discussed (§ 5.1), we expect to lose about 10% of the real REXs because of the impact parameter used in the cross-correlation. As a consequence, the predicted number of RL AGNs in the REX sample is about 1100. In Figure 7 we show the distributions of radio, X-ray, and optical monochromatic luminosities and the redshift distribution for this sample.

5.3.2. BL Lac Objects

We have considered the two populations of BL Lac objects (i.e., XBL and RBL; see § 8.2) separately. For both the XBLs and the RBLs we have used the X-ray LFs and the evolutionary parameters presented in Wolter et al. (1994). After rescaling the XLFs to the 0.5–2.0 keV energy band, we have integrated them from $10^{42}$ to $10^{47}$ ergs s$^{-1}$ and from $z = 0$ to $z = 4$. We have assumed no evolution after $z = 2$. From Wolter et al. (1994) we have used the relationships between the radio and X-ray luminosities and between the optical and X-ray luminosities. Then, as for the RL AGNs, we have imposed the radio limit ($\text{flux}_{1.4 \text{ GHz}} \geq 5 \text{ mJy}$) to derive the expected sample of BL Lac objects. We have obtained a simulated sample of about 290 BL Lac objects; 120 of these are XBL and 170 are RBL. Taking into

![Graphs showing distributions of redshift, optical, radio, and X-ray monochromatic luminosities for simulated RL AGNs.](image-url)
account that 10% of BL Lac objects will be lost during the cross-correlation, the effective number of BL Lac objects expected in the REX sample is about 260. The properties of the simulated sample of XBL-type and RBL-type objects are presented in Figure 8. We note that these results are sensitive to the evolutionary parameters and to the luminosity ranges used in the integration of the luminosity functions. Of course, the dependence of the results on the parameters used implies that the final composition of the REX sample will provide strong constraints on the evolutionary properties of BL Lac objects as well as on the XBL/RBL ratio.

5.3.3. RQ AGNs

As stated previously, we do not expect a high number of RQ AGNs ($z_{\text{RO}} < 0.35$) in the REX sample because of the presence of a relatively high radio flux limit. For comparison, in the EMSS sample (Maccacaro et al. 1994) only six of the 382 RQ AGNs ($\sim 2\%$) have a radio flux (at 5 GHz) above 5 mJy, and most are not detected even at 1 mJy. To quantify the number of expected RQ AGNs, we have used the XLF and evolution model of the RQ AGN population as given in Della Ceca et al. (1994), adapted to the 0.5–2.0 keV energy band, and we have integrated the derived XLF from $L_X = 10^{31}$ to $10^{46}$ ergs s$^{-1}$ and from $z = 0$ to $z = 4$. We have assumed the best-fit evolutionary model until $z = 2$ and no evolution afterward. The radio (or radio upper limit) and optical flux to be associated with each simulated X-ray source has been computed under the hypothesis that the $z_{\text{RX}}$ and $z_{\text{RO}}$ distributions of the RQ AGNs in the EMSS sample are representative of the class. The expected number of RQ AGNs in the REX survey obtained after imposing the radio constraint is $\lesssim 100$.

In Figure 9 we show the total number of AGNs (both RL and RQ; solid line) and BL Lac objects (XBL + RBL types; dashed line) expected in the REX sample as a function of the limiting magnitude, $m_B$. We note that 70%–80% of the expected BL Lac objects and AGNs are brighter than $m_B = 21$, and thus observable with 4 m class telescopes.

6. OPTICAL IDENTIFICATION OF REXS

The positional accuracy of the VLA data guarantees that there is, in general, only one possible optical counterpart for each REX, at least for $m_B \leq 21$. In the case of a T-REX the situation is slightly different, but in general the objects for spectroscopic observation are at most two. This represents
a great advantage over similar projects requiring optical identification of X-ray catalogs derived from PSPC observations, and makes the complete identification of the REX sample a feasible endeavor. The importance of dealing with a fully identified sample of sources is fundamental, as clearly demonstrated by previous surveys (e.g., the Einstein EMSS). Even with a VLA position, however, one should pay attention to the possibility of finding spurious optical candidates falling within the error circle, in particular at faint magnitudes. We have assessed the expected probability of finding interlopers in error circles of 5" and 2" radius (95% confidence for a NVSS source of 5 mJy and ≥10 mJy, respectively) using the surface density of stars, galaxies, and QSOs at the POSS II limit, as given by Condon et al. (1998). The results are extremely encouraging, since the number of spurious objects of all kinds expected is of the order of a few percent (with a radius of 5") or <1% (with a radius of 2").

For each REX, we create a 5' × 5' finding chart from the DSS material and search for the probable optical counterpart. Using the NED facility, we have identified a number of sources from the literature. At the same time, we have initiated spectroscopic observations at the 88" telescope of the University of Hawaii (UH) in Mauna Kea (USA), at the 2.1 m telescope of UNAM in San Pedro Martir (Mexico) and at the 2.2 m and 3.6 m telescopes of ESO (Chile).

The spectroscopic observations have been carried out during 1995/1998 using a long-slit and low-dispersion (from 3.7 Å pixel⁻¹ to 13.2 Å pixel⁻¹) setup to maximize the wavelength coverage. The details of the setup used during the observing runs are summarized in Table 1. Details about the individual sources observed at the San Pedro Martir 2.1 m telescope in the period 1995 April–September have been presented in Wolter, Ruscica, & Caccianiga (1998).

For the reduction of the data, we have used the IRAF LONGSLIT package. The spectra have been wavelength calibrated using an He-Ar (UNAM, ESO) or a Hg-Cd-Zn (UH) reference spectrum. The photometric standard stars observed for the flux calibration are: Feige 34 (UNAM, UH), BD+284211 (UNAM), HD 194445 (UH), SAO 098781 (UH), LTT 377 (ESO), and HD 84937 (UH). No attempt has been made to perform an absolute photometric calibration.

In total, at the time of writing, we have observed and identified 125 REXs. We have classified the objects on the basis of the features observed in their optical spectra. We classify a source as an emission-line object if at least one strong (EW ≥ 5 Å in the source rest frame) emission line is present in the spectrum. Then, on the basis of the width of the observed line(s), we call the object a broad emission line AGN if the FWHM of at least one emission line is greater than 1000 km s⁻¹ (in the rest frame of the source) or a narrow emission line object if all the observed lines have FWHM < 1000 km s⁻¹. In this last case we have applied, when possible, the diagnostic criteria presented in Veilleux & Osterbrock (1987) to distinguish a starburst galaxy from an AGN.

In the case of objects without any strong emission line (EW < 5 Å), we have used the relative depression of the continuum across λ = 4000 Å (the “Ca II contrast”) as an indicator of the presence of a nuclear nonthermal component (a BL Lac nucleus) in the host galaxy. We have computed its amplitude following Dressler & Shectman (1987), i.e., by estimating the average fluxes (expressed in units of frequency) between 3750 and 3950 Å (f⁺) and between 4050 and 4250 Å (f⁻) in the rest frame of the source; the contrast is then defined by

\[ K(\text{Ca II}) = \frac{f^+ - f^-}{f^+}. \]  

If this feature is absent or if it has an intensity of less than 25%, the optical emission of the source is dominated by the

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**Table 1: Observing Setup**

| Telescope/Instrument | Grism Name (g mm⁻¹) | Slit (arcsec) | Dispersion (Å pixel⁻¹) | Observing Period |
|----------------------|---------------------|--------------|------------------------|------------------|
| UNAM 2.1m + BC       | (300)               | 1.6          | 3.9                    | 1995 Apr 25-27   |
| UNAM 2.1m + BC       | (300)               | 1.6          | 3.9                    | 1995 Sep 22-24   |
| UH 88" + WFGS        | blue (400)          | 1.5          | 4.2                    | 1996 Jan 14-15   |
| UH 88" + WFGS        | green (420)         | 2.3          | 3.7                    | 1996 Aug 7-11    |
| UNAM 2.1 m + BC      | (300)               | 1.6          | 3.9                    | 1996 Dec 6-10    |
| ESO 2.2 m + EFOSC2   | n.1 (100), n.6 (300)| 1.5          | 13.2, 4.1              | 1996 Dec 11-12   |
| ESO 3.6 m + EFOSC1   | B300 (300), R300 (300)| 1.5 | 6.3, 7.5              | 1996 Dec 9-10    |
| UH 88" + WFGS        | blue (400)          | 1.5          | 4.2                    | 1997 Mar 3-5     |
| UH 88" + WFGS        | blue (400)          | 1.5          | 4.2                    | 1998 Feb 26-Mar 1|
ness only the objects with a "firm estimate of redshift. Stocke et al. (1991) pointed out that only 1.2% of the galaxies contained in the Dressler & Shectman sample have \( K(\text{Ca} \, \text{II}) \leq 25\% \) (and no emission lines with \( EW > 5 \, \text{Å} \)) and that, consequently, it is extremely unlikely that normal elliptical galaxies would be classified by mistake as BL Lac objects using these definition criteria. Moreover, the adopted classification is supported by the absence, in the EMSS sample, of objects without emission lines (\( EW < 5 \, \text{Å} \)) and with a Ca II contrast between 30% and 40% (see Fig. 4 of Stocke et al. 1991). In the last years, however, the discovery of a large number of new BL Lac objects from the ROSAT All-Sky Survey catalog (Laurent-Muehleisen et al. 1998) or from a sample of optically bright flat-spectrum radio sources (Marcha et al. 1996), this "gap" has been partially filled up, and the distinction between a normal elliptical galaxy and a BL Lac object has become blurred, at least in the optical band. Therefore, it is necessary to redefine the classification criteria used to distinguish a BL Lac from an elliptical galaxy.

To this end, we have studied the objects found in the REX sample without optical emission lines and with a measurable Ca II contrast. In Figure 10 we have reported the observed distribution of the values of the Ca II contrast for this sample of sources. The histogram is peaked around \( K(\text{Ca} \, \text{II}) \sim 50\% \), which is consistent with the mean value found by Dressler & Shectman (1987) for a population of elliptical galaxies. However, unlike the Dressler & Shectman sample, where only 5% of galaxies have a \( K(\text{Ca} \, \text{II}) \leq 40\% \), our sample contains 18 objects out of 46 (39%) with a \( K(\text{Ca} \, \text{II}) \leq 40\% \). This excess is statistically significant (\( \geq 5 \, \sigma \)), and it is also present in the samples studied by Laurent-Muehleisen et al. (1998) and Marcha et al. (1996). We consider this excess as evidence of the presence, at least in objects with \( K(\text{Ca} \, \text{II}) < 40\% \), of an extra source of continuum emission that significantly lowers the values of the Ca II contrast. In addition, objects with \( K(\text{Ca} \, \text{II}) > 40\% \) could, in principle, harbor an optically weak BL Lac nucleus, whose intensity is not sufficient to significantly reduce the value of the Ca II contrast. We are not able to distinguish these cases using only our optical discovery spectra. The lack of a sharp bimodality in the Ca II contrast distribution makes the problem of the definition of a BL Lac a somewhat arbitrary task (at least using only optical spectroscopy). On the other hand, as discussed in \\S 8.1, the existence of objects intermediate between a typical BL Lac and a typical radio galaxy is of fundamental importance in the context of the "beaming model," and should be investigated with attention.

Nevertheless, a limit on the value of the Ca II contrast that can distinguish a BL Lac from a galaxy is needed, at least from an operative point of view. While it is now clear that the usual limit of 25% fails to find a significant fraction of BL Lac objects, a new higher limit could classify as BL Lac some normal elliptical galaxies. If we assume that all the objects in our sample with \( K(\text{Ca} \, \text{II}) > 45\% \) are normal elliptical galaxies and that these objects are distributed, in terms of values of the Ca II contrast, as the elliptical galaxies studied by Dressler & Shectman (1987), we expect that only 1–2 objects among those with a Ca II contrast less than 40% (18 in total) are normal galaxies (i.e., \( \sim 10\% \)). Therefore, we call BL Lac candidates all the objects without emission lines (\( EW \leq 5 \, \text{Å} \)) and \( 25\% < K(\text{Ca} \, \text{II}) \leq 40\% \). Further observations will be necessary to distinguish galaxies harboring a BL Lac nucleus from normal galaxies. In \\S 8.1 we will present a study of the X-ray luminosities of BL Lac candidates that supports the hypothesis of the presence of a non-thermal nucleus at least in a fraction of these objects.

Finally, Marcha et al. (1996) also proposed a revision of the limit of 5 Å usually imposed on the equivalent width of the emission lines present in the optical spectrum. Basically, they point out that the observed equivalent width of an emission line is relative to the total continuum composed of the thermal emission from the host galaxy plus the non-thermal contribution from the active nucleus. Since the nonthermal nucleus is strongly dependent on the viewing angle, they proposed to refer the intensity of the emission lines to the galaxy starlight. This means that, given a defining limit on the equivalent width of the emission lines (relative to the starlight), the observed equivalent width (i.e., relative to the total emission) depends on the Ca II contrast strength (see Fig. 6 of Marcha et al. 1996). We note that a criterion based on the strength of any emission lines relative to the brightness of the host galaxy may introduce a bias in the sample, since the same BL Lac nucleus could be differently classified on the basis of the luminosity of the elliptical galaxy that harbors it.

In any case, at present, we have found only one object that fulfills the defining criteria proposed by Marcha et al. (1996) (\( K(\text{Ca} \, \text{II}) \sim 30\% \) and an emission line, \([\text{O II}] \, \text{Z}3727\), with \( EW \sim 30 \, \text{Å} \)). The spectrum of this source resembles that of a spiral Sb or Sc galaxy, such as NGC 4750 or NGC 6643 (see Kennicutt 1992). Thus, we define this object as a possible BL Lac, but we do not consider it in the analysis of BL Lac candidates presented here.
In summary, we classify an object without strong optical emission lines (EW \leq 5 \ang) as a firm BL Lac if the Ca II contrast is absent or below 25\%, as a BL Lac candidate if the Ca II contrast is between 25\% and 40\%, and as an elliptical galaxy (usually a radio galaxy, given the high luminosity in the radio band, as described below) if the Ca II contrast is above 40\%.

We note that the definition of an object “without emission lines” could be dependent on the observing setup, since the capability to detect an emission line depends on, among other things, the actual wavelength coverage. Our spectra cover the range between \sim 4000 and \sim 8000 \ang, extended, in some cases, blueward to 3500 \ang and/or redward to 9000 \ang. An object without emission lines in this range is, in general, a real featureless object. Nevertheless, some objects may show, in a low signal-to-noise ratio spectrum, only a strong H\alpha (see, e.g., MS0007.1–0231 in Stocke et al. 1991). If the redshift of the source is such that the H\alpha emission line falls outside the observed wavelength range, the object could be erroneously classified as a no emission line object. A fraction (\sim 20\%) of the objects in the REX survey without emission lines have not been observed in the spectral region where the possible H\alpha is expected. The reobservation of these objects with an adequate wavelength coverage is planned. A similar follow-up will also be necessary for the objects classified from the literature (NED).

7. THE COMPOSITION AND GENERAL PROPERTIES OF THE REX SAMPLE

The spectroscopic observations carried out so far have led to the identification of 125 REXes. Another 268 REXs have been identified from the literature (NED). Among the 393 REXs identified we have found 202 emission-line AGNs (67 new), 136 galaxies (32 new), and 55 BL Lac objects or BL Lac candidates (26 new). However, we stress here that the subsample of identified REXs is not expected to reflect the global composition of the REX sample, since it is not a well-defined, representative subset.

At present, the percentage of BL Lac objects in the REX survey is about 14\%, and it should be considered only as indicative of the efficiency of the REX survey in finding BL Lac objects. Altogether, this number is high compared to the radio or the X-ray selections. By extrapolating this number, we predict a total of \sim 200 BL Lac objects, which is in fair agreement with the number predicted by our simulations (§5.3).

In Figure 11 we report the radio-optical (\alpha_{\text{RO}}) versus the X-ray–optical (\alpha_{\text{OX}}) spectral indices of the 393 REXs identified so far. Emission-line AGNs have been represented as open circles, firm BL Lac objects as filled circles, BL Lac candidates as filled triangles, and galaxies as stars. The values of \alpha_{\text{OX}} and \alpha_{\text{RO}} have been computed as in Stocke et al. (1991), using the monochromatic fluxes at 5 GHz, 2500 \ang, and 2 keV.

As expected, the majority (84\%) of AGNs are RL (\alpha_{\text{RO}} \geq 0.35), but we find also a fraction (16\%) of RQ AGNs, selected thanks to the low radio flux limit. The percentage of RQ AGNs is high compared to our simulations (§ 5.3), but we recall that the sample of identified REXs is not representative of the whole population, and, in particular, that it is strongly biased toward the bright magnitudes, where the percentage of RQ AGNs is expected to be significantly higher. Galaxies are more widely distributed in the \alpha_{\text{RO}}/\alpha_{\text{OX}} plane; on the other hand, in the case of galaxies in a cluster, a substantial fraction of the X-ray flux probably comes from the intracluster gas.

Figure 11 shows that BL Lac objects occupy a unique area in the \alpha_{\text{RO}}/\alpha_{\text{OX}} plane compared to the other classes of sources, as firstly noted by Stocke et al. (1991). Thus, a further selection in terms of \alpha_{\text{RO}} and \alpha_{\text{OX}} could increase the efficiency of the search for BL Lac objects up to 25\%–30\%. On the other hand, a sample obtained in this way may be biased toward selecting the most extreme subset of the whole population.

8. THE REX SAMPLE OF BL LAC OBJECTS: PRELIMINARY RESULTS

Although the principal aim of this paper is to present the scientific goals and the selection criteria of the REX survey, two preliminary results can be drawn from the analysis of the current sample of BL Lac objects. Since this sample is not complete and representative, given the low rate of identifications, the conclusions must be considered as general indications of the potential of this survey.

8.1. The Connection between BL Lac Objects and Radio Galaxies

In the context of the beaming model, BL Lac objects and FR I radio galaxies are thought to be the same class of sources seen at different viewing angles (e.g., Urry & Padovani 1995). If this picture is correct, we expect to find some transition objects with intermediate properties between BL Lac objects and FR I radio galaxies. Up to now, this intermediate population of objects was missed, probably...
because of the limiting fluxes of the current X-ray/radio surveys and/or to the criteria adopted to classify BL Lac objects. For example, in the Deep X-ray and Radio Blazar Survey (DXRBS; Perlman et al. 1998), which is the result of a positional cross-correlation between the WGA catalog and a number of radio catalogs, an additional constraint on the radio spectral index (i.e., $\alpha_{\text{R}} \leq 0.7, f \propto v^{-\alpha}$) is imposed to further increase the efficiency of the selection. This constraint excludes from the DXRBS sample most of the normal radio galaxies. On the other hand, the presence of both radio galaxies and BL Lac objects in the same sample is of fundamental importance in addressing the problem of the existence of a population of “transition” objects between normal radio galaxies and BL Lac objects. The existence of such a population of sources is predicted by the beaming model, and has been matter of discussion in recent literature (e.g., Browne & Marchâ 1993).

In the REX survey we do not impose any further conditions other than the presence of the source in a radio and an X-ray catalog. Moreover, as described above, we have developed a technique of cross-correlation that allows us to select double radio sources (such as radio galaxies) as well. For these reasons, we expect that the REX sample will contain both FR I galaxies and BL Lac objects, as well as intermediate objects.

In § 6 we have presented the discovery of low-luminosity BL Lac objects that show a Ca II contrast value intermediate between BL Lac objects and elliptical galaxies. To assess whether these sources represent the connection between beamed objects (i.e., BL Lac objects) and non-beamed objects (i.e., FR I galaxies), we have studied in the X-ray and radio band the properties of all the objects for which we detect a Ca II contrast in the optical spectrum (i.e., elliptical galaxies, BL Lac candidates, and a fraction of BL Lac objects).

The information available for these objects comes from the ROSAT PSPC images and from the NVSS data used to select the REX sample.

8.1.1. Radio Properties

The luminosities at 1.4 GHz of the BL Lac candidates and of the elliptical galaxies newly discovered in the REX survey range from $10^{31}$ to $10^{33}$ ergs s$^{-1}$ Hz$^{-1}$, consistent with those of FR I galaxies and BL Lac objects ($L_{\text{R}} \geq 10^{30}$ ergs s$^{-1}$ Hz$^{-1}$). Given this range of luminosity, the elliptical galaxies, which do not show any emission line in the optical spectrum, can be classified as radio galaxies, probably FR I. For a fraction of objects we have information on the radio flux at 5 GHz, since they are included in the Green Bank catalog (Gregory et al. 1996) or in the PMN catalog (Wright et al. 1994). All the BL Lac objects and BL Lac candidates present a slope $\alpha_{\text{R}} \leq 0.6 (f \propto v^{-\alpha})$, while the radio galaxies cover a wider range of values, from $-0.2$ to $1.2$. The overall distribution of the slopes does not reveal any bimodality.

Radio galaxies and BL Lac objects are expected to be different in radio morphology. Typically, a radio galaxy with a radio luminosity between $10^{31}$ and $10^{33}$ ergs s$^{-1}$ Hz$^{-1}$ and a redshift between 0.1 and 0.5 (such as the objects discussed here) shows extended radio structures of 100–500 kpc (Singal 1993), while BL Lac objects show more compact radio morphologies (Perlman & Stocke 1993; Kollgaard, Gabuzda, & Feigelson 1996). These differences cannot be well established with the NVSS data, which are characterized by a large beam (FWHM = 45′′) that corresponds to a linear size of 100–300 kpc for redshifts of 0.1–0.5. Specific observations with a better resolution are needed to study the differences between radio galaxies, BL Lac objects, and BL Lac candidates from the viewpoint of the radio morphology. For the sources falling in the area of sky covered by the FIRST survey, we will be able to study the radio morphology with a resolution a factor of 10 better than that achieved by the NVSS.

8.1.2. X-Ray Properties

The X-ray luminosities in the 0.5–2.0 keV band of the radio galaxies and BL Lac candidates are above $3 \times 10^{42}$ ergs s$^{-1}$. The objects with $K(\text{Ca II}) \geq 40\%$ (radio galaxies) show X-ray luminosities up to $10^{44}$ ergs s$^{-1}$, while some of the objects with $K(\text{Ca II}) \leq 40\%$ (BL Lac objects and BL Lac candidates) reach luminosities of $5 \times 10^{42}$–$10^{45}$ ergs s$^{-1}$, consistent (but at the low luminosity end) with the range of luminosities shared by BL Lac objects ($10^{44} < L_X < 10^{47}$ ergs s$^{-1}$). We recall that a typical FR I galaxy (without emission lines in the optical spectrum) barely reaches X-ray luminosities of $10^{44}$ ergs s$^{-1}$ (Fabbiano et al. 1984). There are only few cases of objects (Silverman, Harris, & Junior 1998; Tananbaum et al. 1997; Caccianiga & Maccacaro 1997) showing high X-ray luminosities ($3 \times 10^{43}$ ergs s$^{-1}$) and an optical spectrum without any signature of the presence of an active nucleus (i.e., strong emission lines and/or a reduced value of the Ca II contrast). There are strong evidences that these objects must be considered BL Lac objects whose optical emission is overwhelmed by the light of the host galaxy.

We note that some of the objects discussed here probably reside in clusters of galaxies, and that thus the X-ray emission could be produced in part or completely by the intracluster gas. We have distinguished some of these cases on the basis of CCD observations of the optical field and/or on the basis of spectroscopic observations of other galaxies in the same field. In Figure 12 we have reported the values of the Ca II contrast versus the monochromatic luminosities at 1 keV for the REXs for which we have no evidence of the presence of an overdensity of objects in the optical field (Fig. 12a) and for the REXs in clusters (Fig. 12b). Figure 12a shows that the two quantities are anticorrelated (at the $>95\%$ confidence level), while clusters of galaxies (Fig. 12b) do not show any correlation. The correlation found for the isolated objects suggests a common origin for the high X-ray luminosity and the low value of the Ca II contrast, probably related to the presence of a nonthermal nucleus in the host galaxy; the stronger the nonthermal emission is, the lower the Ca II contrast and the higher the X-ray luminosity. In the case of clusters of galaxies, the strong X-ray luminosities are mainly related to the intracluster gas and not to the activity of the nucleus, and thus the values of the Ca II contrast and the X-ray luminosities are not expected to be correlated.

Figure 12 shows a continuity between the X-ray/optical properties of the radio galaxies and the BL Lac candidates discovered in the REX survey. This continuity suggests that the BL Lac candidates represent the connection between BL Lac objects and their parent populations. In the context of the beaming model, these sources could be less beamed than the usual BL Lac objects i.e., they are seen at viewing angles intermediate between those of FR I galaxies (~90°) and BL Lac objects (~0°–30°).
that the contribution of the nonthermal emission coming from the nucleus (or the jet) is not strong enough to cancel completely the stellar emission from the host galaxy. The existence of two distinct populations of BL Lac objects has been tentatively attributed to a difference in the width of the emission cones of the radio and X-radiation (Ghisellini & Maraschi 1989; Celotti et al. 1993); in this framework, the X-radiation is less beamed than the radio, and consequently XBLs are seen at larger angles than the RBLs. Nevertheless, Sambruna, Maraschi, & Urry (1996) have shown that the typical radio-to-X-ray spectrum of an XBL cannot be obtained from the spectrum of an RBL simply by changing the viewing angle alone, and they suggested that other physical parameters, such as the intensity of the magnetic fields, must be considered. Moreover, XBLs and RBLs show significant differences in the slope of their X-ray spectra (Comastri, Molendi, & Ghisellini 1995; Urry et al. 1996; Padovani & Giommi 1996; Lamer, Brunner, & Staubert 1996) that are difficult to explain in terms of a different viewing angle. Giommi & Padovani (1994) have suggested the existence of a unique class of BL Lac objects, characterized by a wide range of different overall spectral properties. The X-ray and radio surveys have sampled the extreme ends of this distribution, thus creating an apparent dichotomy: the class of high-energy peaked BL Lac objects (HBL ~ XBL) and the class of low-energy peaked BL Lac objects (LBL ~ RBL). In this framework, the intermediate objects between HBL and LBL were missed in previous X-ray and radio surveys. Recently, Fossati et al. (1997) have further elaborated the idea proposed by Giommi & Padovani (1994), suggesting that the physical parameter that governs the shape of the spectral distribution is the bolometric luminosity.

The most compelling and straightforward way to test these competing hypotheses is to select a new sizable sample of BL Lac objects containing both HBLs and LBLs, in order to directly compare their properties. At present, the only existing statistically complete samples of BL Lac objects contain only few tens of objects each. Since the REX survey reaches radio fluxes 200 times fainter than the limiting flux of the 1 Jy sample and X-ray fluxes about 10 times below the EMSS limits, we expect to find both kinds of BL Lac objects, as well as objects with intermediate properties. We have shown the results of numerical simulations to evaluate the capability of the REX survey to select LBLs and HBLs and, as described above, we have found that both kinds of objects are expected to be sampled.

In Figure 13 we show the \( \alpha_{\text{X}} \) distribution for the 55 BL Lac objects (or BL Lac candidates) discovered in the REX survey. The shaded histogram represents only the firm BL Lac objects. This figure does not reveal any bimodality. Nearly all the BL Lac objects of this sample (47/55) fall below the limit on \( \alpha_{\text{X}} \) frequently used to discriminate between HBLs and LBLs (\( \alpha_{\text{X}} = 0.8 \), e.g., Padovani & Giommi 1996). Apparently, the number of HBLs largely exceeds that of LBLs, as suggested by the “viewing angles hypothesis” or the “bolometric” scenario proposed by Fossati et al. (1997). Moreover, Figure 13 shows that several BL Lac objects (13) are intermediate (0.70 \( \leq \alpha_{\text{X}} \leq 0.80 \)) between the BL Lac objects of the EMSS (\( \alpha_{\text{X}} \geq 0.70 \)) and those of the 1 Jy sample (\( \alpha_{\text{X}} \geq 0.8 \)). This result seems to rule out the models proposed by Ghisellini & Maraschi (1989) or by Celotti et al. (1993), which predict a sharp separation between LBLs and HBLs, and to support those

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**Figure 12.** Value of the Ca ii contrast vs. the monochromatic X-ray luminosity at 1 keV for the elliptical galaxies and BL Lac candidates newly discovered in the REX survey. We have distinguished, on the basis of the optical images, the objects for which there is no evidence for the presence of a cluster of galaxies (a) from possible clusters (b). Only objects with a firm estimate of redshift have been considered.

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8.2. XBL versus RBL

Up to now, radio and X-ray surveys have selected different types of BL Lac objects, RBLs and XBLs, respectively. Typically, XBLs are less variable and less polarized than RBLs. The overall spectral distribution of the two classes is strongly bimodal, and their cosmological evolution differs significantly (Morris et al. 1991; Stickel et al. 1991; Wolter et al. 1994; Bade et al. 1998). Moreover, XBLs frequently show absorption features in their optical spectrum similar to those of normal elliptical galaxies. This is an indication of the presence of a pointlike source among the BL Lac candidates newly discovered in the REX survey. We have distinguished, on the basis of the optical images, the objects for which there is no evidence for the presence of a cluster of galaxies (a) from possible clusters (b). Only objects with a firm estimate of redshift have been considered.
models that predict a smooth passage between LBLs and HBLs, such as those proposed by Giommi & Padovani (1994) or by Fossati et al. (1997). However, the incidence of both the radio and the X-ray limits in the selection must be considered before drawing any firm conclusion about the relative number of HBLs and LBLs. The sky coverage of the REX survey, in fact, is the combination of the limiting fluxes in the X-ray and radio bands. Other projects, similar to the REX survey, find samples of BL Lac objects with very different HBL/LBL ratios; for example, the DXRBS (Perlman et al. 1998) finds a low number of HBL objects (16%) compared to intermediate and LBL objects (84%). Conversely, the RASS–Green Bank sample (RGB; Laurent-Muehleisen et al. 1998) contains mostly HBL (∼60%) and intermediate (∼23%) objects, while only ∼17% are LBLs. Finally, about half of the RC sample (Kock et al. 1996) are HBLs, and about half are intermediate objects.

These results clearly show the importance of the radio/X-ray limits in sampling the BL Lac population; the DXRBS is characterized by a high ratio between the radio and the X-ray limiting fluxes ($\alpha_{\text{RX}} \sim 0.8–0.9$), and thus it favors the selection of LBLs, while the RGB and the REX surveys are more shifted toward a lower ratio between the radio and X-ray limiting fluxes ($\alpha_{\text{RX}} \sim 0.6–0.7$), and for this reason are able to sample the HBL population.

One way to take into account these selection effects is to compare the spatial densities of the two populations of BL Lac objects, i.e., the number of objects divided by the volume of universe sampled (which must be computed by taking into account the limiting fluxes in the two selection bands). Alternatively, it is possible to use the competing theoretical models proposed and the radio and X-ray sky coverage of the REX sample to predict the number of BL Lac objects expected in the survey. Then, through a comparison of the predicted and observed numbers of HBLs and LBLs, it will be possible to draw some interesting conclusions about the origin of the BL Lac dichotomy. At this stage, however, given the low identification rate of the sample, we cannot perform any detailed statistical analysis of the HBL/LBL ratio.

9. SUMMARY AND CONCLUSIONS

We have presented and discussed in detail the scientific goals and the selection criteria of the REX survey, a project optimized for the selection of new, large samples of BL Lac objects and radio-loud AGNs over a large area of sky (2183 deg$^2$). Since the existing X-ray catalogs obtained from the pointed PSPC observations are not suitable for statistical studies, we have produced our own X-ray catalog from the analysis of a well-defined subset of all the public PSPC images, using a source detection and characterization algorithm based on wavelet transforms (Damiani et al. 1997a, 1997b). An elaborate positional cross-correlation between this newly compiled catalog of X-ray sources and the NVSS (Condon et al. 1998) radio catalog has led to the definition of about 1450 single-component REXs, 90 REXs that show a radio double or triple morphology, and about 180 T-REXs that still need to be correctly classified. Upon classification of the remaining T-REXs, the final number of REXs will be close to 1600 (including the objects with a complex radio morphology). The positional accuracy of the VLA allows us, in the very large majority of cases, to unambiguously identify the optical counterpart of the REX, making feasible a program aimed at the complete identification of the whole sample.

The REX sample contains a very high fraction of RL AGNs and BL Lac objects, as indicated by preliminary results of the optical identification program.

The high number of BL Lac objects expected in the survey (≥200) will significantly increase our knowledge of their nature and statistical properties, which is currently based on samples of a few tens of objects. Moreover, the possibility of comparing directly in the same sample the properties of XBLs and RBLs will be instrumental in testing existing theoretical emission models.

Finally, unlike other similar projects (e.g., the DXRBS), in the REX survey we do not impose any constraint on the slope of the radio spectrum. In this way we will be able to compare directly radio galaxies and BL Lac objects in the same sample and to test the transition between a normal radio galaxy and a BL Lac object. The importance of this characteristic is confirmed by the preliminary results presented in this paper. We have analyzed a sample of newly discovered BL Lac and elliptical galaxies for which we have an homogeneous set of optical spectra. Given the high luminosities at 1.4 GHz (∼10$^{43}$ ergs s$^{-1}$), the elliptical galaxies, which do not show any emission line in their optical spectrum, can be considered as radio galaxies, probably FR I. In the optical band, we have found that the distinction between BL Lac objects and elliptical galaxies is quite blurred. In the X-ray band, both radio galaxies and BL Lac objects show a significant anticorrelation between the X-ray luminosity and the value of the Ca II contrast (which is an indicator of the ratio of stellar and nuclear emission in the optical band). The radio galaxies show higher values of the Ca II contrast (∼50%) and lower X-ray luminosities (∼5 × 10$^{43}$ ergs s$^{-1}$), while BL Lac objects show lower values of the Ca II contrast (≤40%) and higher X-ray luminosities (∼5 × 10$^{43}$ ergs s$^{-1}$). This behavior could be interpreted as being due to an increasing importance of the nuclear nonthermal components in these sources. This can be connected either to the intrinsic power of the nonthermal radiation.
nucleus or to the effect of orientation in the framework of the beaming model.

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