ROSAT OBSERVATIONS OF ACTIVE GALACTIC NUCLEI

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Abstract. The large number of Active Galactive Nuclei detected for the first time through their X-ray emission in the ROSAT All Sky Survey as well as the first measurements of the X-ray emission of many previously known AGN provide a new unprecedented large basis for the statistical and morphological exploration of these objects.
The soft energy range of the X-Ray Telescope, the good energy resolution of the PSPC detector, and the high sensitivity of the instrument further allows an investigation of the spectral properties of sources in this energetically important energy band.
A short overview is given of the actual ongoing research concentrating on the study of the soft X-ray class properties of the various types of AGN.

Key words: Active Galactic Nuclei, X-rays, Unification Schemes

1. Introduction

ROSAT is in orbit for more than three years and it is still working exceptionally well. After performing the first All Sky Survey in the soft X-ray band between August 1990 and February 1991 /1/ it is used for pointed observations in an international PI programme. The fact that about 30% of the proposed targets are Active Galactic Nuclei (AGN) demonstrates the large scientific interest and the observational potential of ROSAT in this field. Two properties make ROSAT especially well suited for the study of AGN:

The soft energy band: The very soft energy band (0.1 – 2.4 keV) together with its high sensitivity and the moderate spectral resolution of the PSPC /2/ allows the spectral study of AGN in a previously unaccessible energy range. Most pointed observations utilize these instrument characteristics. Many results of these investigations on previously known AGN are presented in this volume. In this review I will therefore concentrate on the second main aspect of the ROSAT mission:

The All Sky Survey: The ROSAT All Sky Survey (RASS) provides a large number of new X-ray identifications of AGN of all types and, in particular, it will yield an enormous number of previously unknown AGN.

So far most studies of the class properties of the AGN population are biased by strong selection effects and in many cases data from pointed observations of known objects had to be used. The RASS yields a large number of AGN homogeneously selected all over the sky. However, differences in the Survey exposure as well as spatial variations of the galactic N_H-values introduce some selection biases which have to be taken into account in any statistical study.

The vast majority of these objects remain to be identified. Only about 2000 objects are previously catalogued AGN but mostly without any X-ray detection so far. They will be used for studying the broad band spectral behaviour of these sources

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and form the basis for the study of the evolution of different classes of AGN and their statistical properties.

2. The AGN Content of the Survey

Early estimates predicted that about 40% to 60% of the sources found in the RASS would be AGN, i.e., from the $\sim$ 50000 sources found so far there are $\sim$ 25000 new extragalactic objects, detected for the first time through their X–ray emission. The correctness of these estimates could be confirmed recently in several observational programs in which the complete optical identification of all RASS sources in certain limited areas of the sky was attempted.
The currently most advanced one is an ESO Key Project. 488 of the 688 ROSAT sources in the 'study areas' have been identified up to date. 259 objects turned out to be AGN, 31 were galaxies, only 40 were clusters of galaxies, 2 were CVs, 4 white dwarves, and the rest stars. As the sources are being identified according to their optical brightness it is felt that all stars have been found and the remaining, optically faint unidentified sources are predominantly of extragalactic origin.

From existing catalogues of optically known AGN, for example from the more than 8000 objects listed by Veron-Cetty and Veron /3/ only around 1500 sources were detected in the RASS. Basically, this leaves us with the same number of $\sim$ 25000 objects to be identified optically as AGN.

The above mentioned areas for which the complete identification of RASS sources are attempted cover only a few hundred square degrees of the sky. Other projects try to identify as many sources as possible from existing observational data without pretention to be complete.

2.1. The HAMBURG Quasar Survey

For this project digitized objective prism and direct plates are used obtained with the Calar Alto Schmidt telescope of the northern sky $\delta > 0^o$ and $|b_{II}| > 20^o$ /4/. So far $\sim$ 6200 ROSAT sources have been looked at, of which 63% could be identified. 29% were AGN, 7% galaxies and clusters, and 27% stars. About 30% of the objects were in fields with either too many candidates, with 'implausible' candidates, or on plates with errors. 7% of the fields were 'empty', i.e., no optical counterpart brighter than the plate limit (B $> 18.5^{mag}$) could be found.
This fact highlights one of the observational challenges for optical identification programs: a substantial fraction of the optical counterparts are rather faint. In Fig. 1 I give a histogram for the optically unidentified objects from the ROSAT - Molonglo correlation (see below). Plotted are the magnitudes m_J of those objects for which a 'plausible' optical candidate could be selected from the NRL / ROE digitized finding charts. As seen from figure 1, about half of the objects seem to be fainter than 19^{mag}.

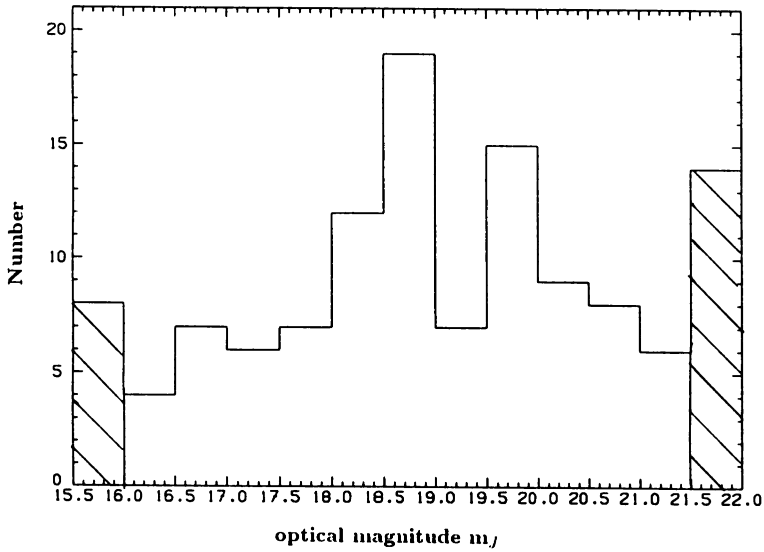

Fig. 1. Histogram of the optically unidentified objects from the ROSAT - MRC correlation. m_J magnitudes from the NRL/ROE digitized finding charts. Hatched areas denote all objects outside the respective magnitude range.

2.2. Radio Surveys

The cross - correlation of the RASS source list with the Molonglo reference catalogue of radio sources (MRC /5/) and a point source catalogue generated from the Condon-Broderick-Seielstad 6cm survey of the northern hemisphere /6/ yielded a total of more than 2500 matches. A large fraction of them (more than 2/3 of the sources) remain optically unidentified. Extensive radio- and optical follow-up observation programs have been initiated to obtain more information on this large sample. First results from the statistical analysis of the optically identified subset of these correlations are presented in /7, 8, 9/ and some of the questions related to the class properties of AGN are discussed below.

To give an impression about the data to be expected, Fig. 2 shows the soft X-ray luminosity as function of redshift z for about 700 ROSAT detected AGN from the Veron-Cetty & Veron catalogue for which all necessary information was readily available. The luminosities are K-corrected according to their group-averaged spectral power law index. Marked with different symbols are different types of AGN. Diamonds represent objects with classifications not strictly belonging to the four mentioned categories or with questionable identification. For an average value of the galactic absorption and a power law index $\Gamma = -2.0$ the full line indicates a flux of 5×10^{-13} erg cm$^{-2}s^{-1}$, representative for the limiting sensitivity

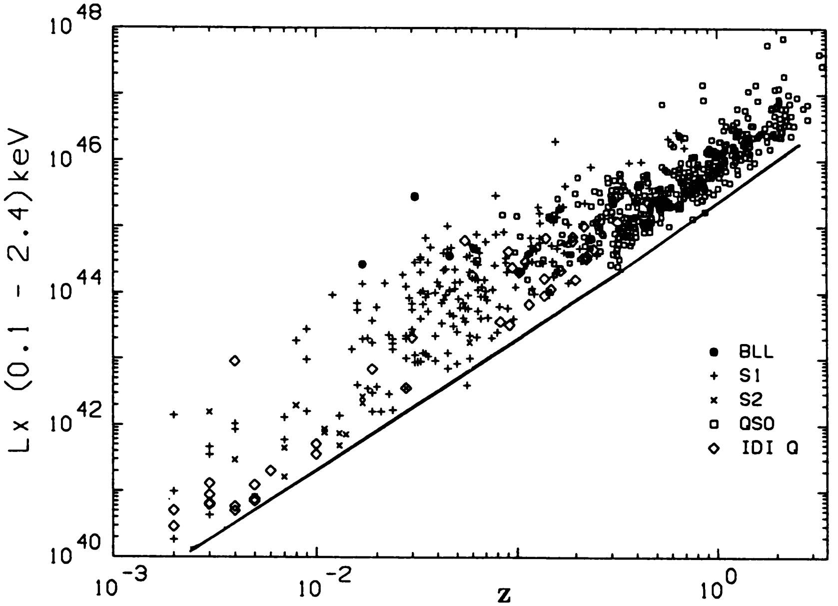

Fig. 2. Soft X-ray luminosities of optically known AGN as function of their redshift. Different types of objects are indicated by different symbols. The full line represents an incident X-ray flux of $5 \times 10^{-13} erg\ cm^{-2} s^{-1}$, characteristic for ROSAT's survey sensitivity.

of the Survey. Clearly visible at low redshifts are 'active galaxies' (like starbursts or radio galaxies), then Seyferts and BL Lac objects. At larger redshifts, z $\gtrsim$ 0.4, the quasar component dominates.

The currently most distant object is a ROSAT detected quasar with z = 4.32 /10/ found in the NEP region with its very deep exposure. Correspondingly, it's inferred soft X-ray luminosity $L_{0.1-2.4keV} \sim 2 \times 10^{45}$ erg/s is rather low for a quasar. The second most distant object is, with z = 3.87, the object Q 1745+624, first seen by Einstein /11/, close to the NEP as well. The brightest object is PKS 1937-101 with $L_{0.1-2.4keV} \sim 3 \times 10^{47}$ erg/s at a redshift of z=3.78 /8/.

3. The X-ray AGN - a schematic view

Recently, it has become clear that the wide range of different appearances of AGN is only partially caused by truly different properties of the central machines. A great deal of the observed diversity can be attributed to the actual geometrical viewing conditions of the observer with respect to a preferred direction of emission /12/.

The by far largest number of AGN is radio-quiet. Using the source brightness as additional classification criterium, we find as radio-quiet, low luminosity objects

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the Seyfert galaxies, as high luminosity objects quasars.

The nearby and therefore bright Seyfert I galaxies show a very high detection probability in the Survey. Detailed comparative spectral studies of this class of objects can be found elsewhere in these proceedings. Only very few Seyfert II objects were seen with rather low countrates. This is in accordance with unification schemes which predict the obscuration of the central nuclear region by dense surrounding material.

It should be noted that in this region of the parameter space additional objects like starbursts and IRAS galaxies are found which form, at least with respect to their soft X-ray luminosity, a 'transition' between normal galaxies and AGN. They are detected only due to their relative proximity. Some of them, like NGC 4258, show characteristics which are indicative for a previous Seyfert activity in their nuclei /13/.

3.1. Quasars: radio quiet versus radio loud

About 90% of the quasars are radio quiet /14/ and the available optical information suggests that they form a class quite different from the radio loud objects. Even in X-rays both types of quasars seem to have qualitatively different properties as well.

1. Detection probability: Quasars are the largest group of X-ray detected objects in the survey but with respect to their total number only about 16% of them are seen by ROSAT. However, while $\gtrsim$ 30% of the catalogued radio-loud objects were discovered only $\lesssim$ 7% of the large number of radio-quiet quasars were found.

2. Redshift distribution: Figure 3 shows the relative detection rate as function of redshift, i.e., the number of detected ojects in a redshift bin divided by the total number of objects in that bin. In Fig. 3a the data for the radio-loud quasars are plotted. The detection rate drops roughly like $1/z^2$ (indicated by the dots) due to flux limits of the telescope. Fig 3b shows the equivalent data for the radio-quiet quasars.

These results are in accordance with the well known fact that radio-loud quasars are on the average stronger X-ray emitters than the radio-quiet objects. The detection rate for radio-quiet quasars clearly drops much faster than that for the radio-loud objects. Apart from the different space density of the objects this is indicative for additional differences in the luminosity function of these two classes of objects.

3. Spectral parameters: The ROSAT soft X-ray (0.1 - 2.4 keV) spectra are in general much softer than those found at higher energies and show large intrinsic scatter. While radio-quiet quasars have an average power law photon index of $< \Gamma > \sim -2.4$, radio-loud quasars have a flatter spectrum with $< \Gamma > \sim -2.2$ (see /8/, Schartel et al. and Brunner et al., these proceedings).

4. Luminosity correlations: In figure 4 the soft 0.1-2.4 keV X-ray luminosity is plotted as function of the monochromatic optical luminosity for radio-loud quasars.

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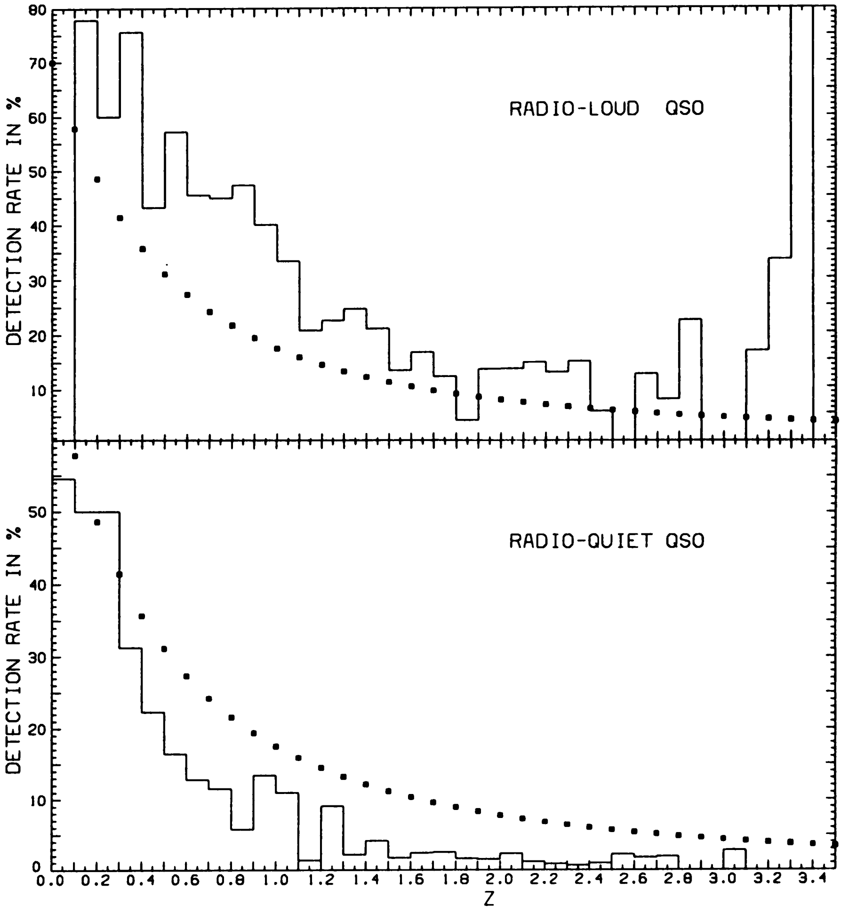

Fig. 3. Relative detection rate (in percent) for quasars in the ROSAT All Sky Survey as function of redshift. Upper panel, radio-loud QSOs, lower panel, radio-quiet objects. Please note the different scaling of the vertical axes. The dotted curves represent a $1/z^2$ sensitivity variation.

A regression analysis gives a correlation of the form $log(L_x) \sim 0.69 log(l_{opt})$ with nearly 100% confidence. A similar analysis for radio-quiet objects results in a different slope $log(L_x) \sim 0.89 log(l_{opt})$. The values for the slopes are securely out of their mutual errors.

5. Selection effects ? Finally, it must be noted that for the ROSAT X-ray selected quasars there seem to be strong selection effects. Even for the radio-brightest quasars the Survey detection rate is only around 50% without obvious exposure, redshift, or galactic absorption dependencies /8/. This indicates that all statistical

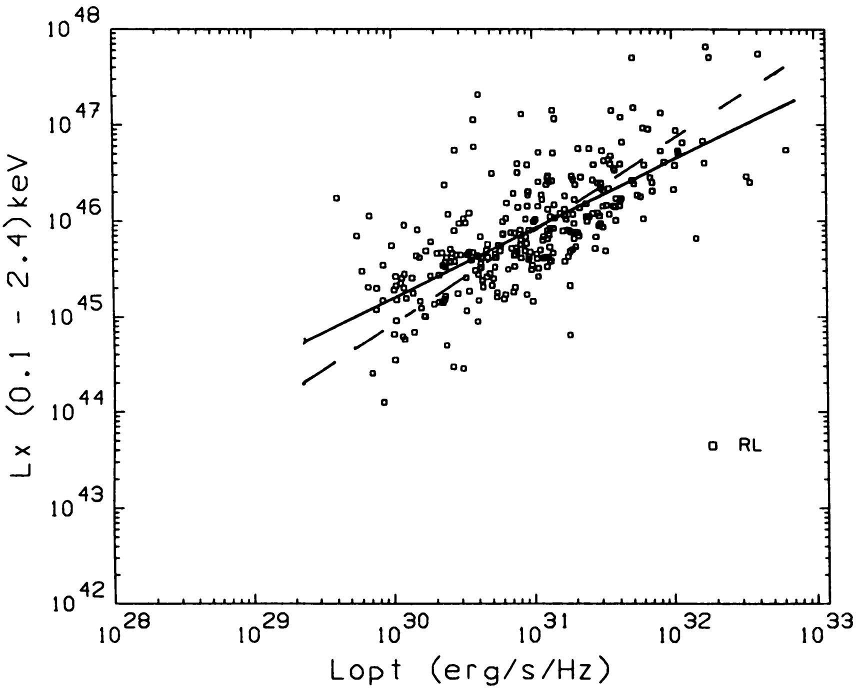

Fig. 4. Integrated soft X-ray luminosity as function of the monochromatic 5500 Å optical luminosity for radio-loud quasars. Full line is the linear regression curve, dashed line that for the radio-quiet quasars.

correlations are valid only for special, X-ray loud sub-samples of the quasar population.

On the other hand, there is a substantial number of objects without optical counterparts brighter than $\sim 20^{mag}$ but relatively luminous at radio- and X-ray wavelengths. It remains to be seen what the nature of these radio / X-ray bright but optically faint objects is. So far they have been regarded as being relatively rare as only very few of them have been found /15/.

4. Unification schemes

Only a small fraction of the order of 10% of known quasars are strong radio emitters /14/ and only very few radio galaxies have been detected in X-rays /16/. However, extragalactic radio sources have been studied in great detail with unsurpassed sensitivity and spatial resolution and they represent an important subgroup of

X-ray detected AGN. Further, radio quasars are the most luminous objects in the Universe and thus the distances and look back times are large enough that cosmological and evolutionary effects can be studied.

The largest sub-group of the cross - correlation of the ROSAT All Sky Survey source list with catalogues of radio sources (see sect. 2.2) with about 40% of the objects are quasars, followed by galaxies (17%), clusters of galaxies (3%), and BL Lacs (1%).

These samples are sufficiently large to allow to test current AGN unification models over a broad energy range. For more than a decade unification schemes have been proposed, which try to relate the various types of extragalactic objects /17, 18/, and references therein. In none of these schemes the X-ray properties of the various classes were taken into account. Therefore, a comparison of the properties of the above samples of radio selected extragalactic X-ray sources can give new information about the applicability of these schemes. First results indicate, that schemes based on purely "geometrically different" viewing conditions might be questionable:

i) Radio galaxies have an average photon index $\Gamma \sim 1.8$ in the soft X-ray range, quasars an index of $\Gamma \sim 2.25$

ii) About 25% of the radio galaxies of the MRC are in clusters or groups of galaxies. But from the more than 200 quasars only one object is found in a cluster.

iii) Quite a fraction of the objects in the various subclasses of AGN can be found in the IRAS catalog, i.e., they are infrared sources as well, but none of these sources is associated with a cluster environment.

At present it seems to be premature to draw strong conclusions from these observational facts. The influences of the various selection effects have not been evaluated yet and so far we have to rely on rather 'inhomogenous' catalogued data. Even more, we don't know what 'special' properties of the sources in an object class lead to their detection in the ROSAT All Sky Survey. These X-ray detected objects certainly form some not yet defined 'sub-groups' of their corresponding classes. Nevertheless, the above X-ray results strongly indicate an additional environmental or/and evolutionary difference between different types of objects. The real question to ask is perhaps not whether certain unification schemes are correct or not, but more, what fraction of the apparent source properties can be related to orientation dependent 'viewing conditions'.

Another question raised in the study of associations of galaxies with clusters is whether the X-ray emission attributed to the radio galaxies is predominantly cluster emission or whether the cluster environment is the evolutionary cause for active galaxies with strong X-ray and radio emission. In this case X-ray studies of distant clusters might be severely biased by a galaxy contribution. The spatial resolution of the PSPC in the Survey is usually insufficient to separate these two components and there seem to be examples for both possibilities /19/.

5. Conclusions

The ROSAT mission changed our approach of studying the AGN phenomenon considerably: The soft energy band allows an examination of the energetically vital region between the 'canonical power law' and the 'big blue bump' where spectral diversity promises new insights in the source conditions. The large number of newly detected AGN provide statistically sufficiently large samples for all classes of AGN. The results obtained from the ROSAT All Sky Survey presented in this paper must still be regarded as somehow preliminary as they are based on data obtained from the first processings of the Survey when the data were not complete.

Qualitatively, the results are not expected to change drastically, although the quantitative properties of individual sources might have to be revised slightly after a reprocessing of the data.

The following main findings and open questions will, however, remain unaffected:

* ROSAT multiplied the number of known X-ray emitting AGN
* Most AGN have a considerably **steeper** spectral slope in the ROSAT band than the canonical $\Gamma \sim 1.7$ found in the medium energy band
* The number of known X-ray emitting radio sources has been greatly increased
* What is the nature of the "unknown" radio sources ?
* What are the X-ray / radio - loud but optically "dull" objects ?
* X-ray observations provide new tests for Quasar/radio galaxy unification schemes

And, finally, the $\gtrsim$ 25000 unidentified X-ray sources from the ROSAT All Sky Survey form an invaluable source of information both for observers and theoretical astronomers.

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