X-RAY SOURCES OF COSMOLOGICAL RELEVANCE

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1. INTRODUCTION

The imaging and spectroscopic instruments onboard the Einstein Observatory (Giacconi et al. 1979) have been extensively used to study in detail the X-ray properties of a large variety of astronomical objects. In this paper we will briefly discuss some of the most relevant results on extragalactic astronomy obtained mainly with the Imaging Proportional Counter (IPC).

About 2000 different IPC pointings were carried out at high galactic latitude, to study the X-ray behavior of preselected objects or classes of objects. In the great majority of cases, the IPC has provided us with much more information than was asked for. The answer to the observer's enquiry on the target of the observation in fact, can usually be found in a small central region of the IPC image, while the remaining square degree contains important unsolicited information on the soft X-ray universe, through the presence of serendipitous sources. The importance of a systematic search for these sources was immediately realized by several groups, and programs were undertaken to count, identify and study a large number of serendipitous sources.

For each class of objects, we shall consider the results derived from the targeted observations as well as those derived from the survey of serendipitous sources. In Section 2 the X-ray data on Active Galactic Nuclei (AGNs: quasars and Seyfert galaxies) are discussed, BL Lacs are discussed in Section 3, and clusters of galaxies in Section 4. A brief summary is given in Section 5.
A Hubble constant of 50 km/(s Mpc) is used througout the paper.

2. QUASARS AND SEYFERT GALAXIES (AGNs)

From analyses of samples of optically selected and radio selected QSOs (Tananbaum et al. 1979, Ku et al. 1980, Zamorani et al. 1981) it has been shown that:

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1) Quasars are, as a class, powerful X-ray sources.
2) On average, the X-ray luminosity correlates with optical luminosity.
3) Radio loud QSOs show a correlation between radio and X-ray emission.
4) For a given optical luminosity the average X-ray emission of radio loud quasars is ≃ 3 times higher than that of radio quiet quasars.
5) The ratio between X-ray and optical luminosity, Lx/Lo, is possibly a function of Lo and/or redshift.

This last point is extremely important in its implications. It is a key point for the understanding of many QSOs properties and, in particular, the link between optically selected and X-ray selected QSOs. Zamorani (1982) has recently reanalyzed the available X-ray data on optically selected QSOs and Seyfert galaxies, assuming that the dependence of the Lx/Lo is exclusively on Lo and not on redshift. He found that the absence of correlation between Lx/Lo and Lo is rejected at the 6σ level and that the data are best described by:

$$Lx \propto Lo^{\beta} \quad \text{with } \beta = .66 \pm .06 \qquad (1)$$

Namely, Lx/Lo decreases with increasing optical luminosity. More recently Avni and Tananbaum (1982) have analyzed the dependence of Lx/Lo on Lo and redshift. They conclude that the explicit dependence of this ratio is predominantly on Lo.

We shall now summarize the relevant results on X-ray selected AGNs and than show how the above relation between Lx and Lo nicely links the properties of X-ray selected AGNs to those of optically selected AGNs.

The many works devoted to serendipitous X-ray sources (Grindlay et al. 1980, Kriss and Canizares 1982, Maccacaro et al. 1982a, Margon et al. 1982, Reichert et al. 1982, Stocke et al. 1982a) have shown that:

1) The large majority of serendipitous sources are optically identified with AGNs.
2) The increasing detection rate of AGNs as function of the decreasing limiting X-ray flux implies that AGNs, even when selected in the X-rays, show evidence of cosmological evolution.
3) There is a continuity between

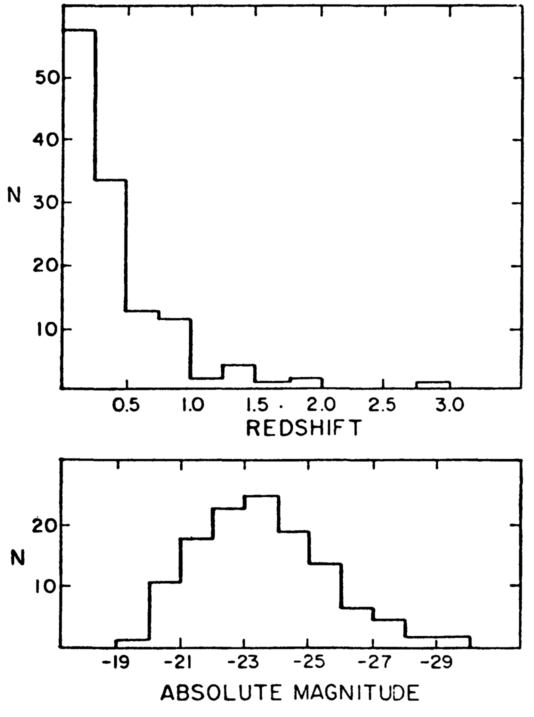

Figure 1. Redshift and absolute magnitude distribution for a sample of 127 X-ray selected AGNs.

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the X-ray properties of Seyfert galaxies and quasars.

4) Most of these newly discovered AGNs are characterized by low redshift and low absolute luminosity.

Figure 1 shows the redshift and absolute magnitude distributions of a sample of 127 AGNs taken from the work of Grindlay et al. 1980, Kriss and Canizares 1982, Gioia et al. 1982a, Margon et al. 1982, and Stocke et al. 1982a. As pointed out by Margon et al. (1982), high redshift and high optical luminosity objects are almost totally absent from X-ray selected samples. About 90% of these objects in fact, have a redshift smaller than 1 and an absolute magnitude fainter than -26.

Recently the first complete sample of AGNs extracted from a fully identified sample of X-ray sources and thus exclusively defined by its X-ray properties became available. It consists of 31 AGNs extracted from the Einstein Observatory Medium Sensitivity Survey (Maccacaro et al. 1982a, Stocke et al. 1982a). The analysis of this sample has confirmed the previous findings and has further shown that X-ray selected AGNs do indeed evolve (Maccacaro et al. 1982b). In the framework of pure luminosity evolution of the form:

$$L(z) = L(0)\exp(Cz/(1+z)) \quad (2)$$

their evolution is best described by the parameter C = 5.1. Figure 2 shows the result of the Ve/Va test (a generalized V/Vmax test) used to determine the best value of C.

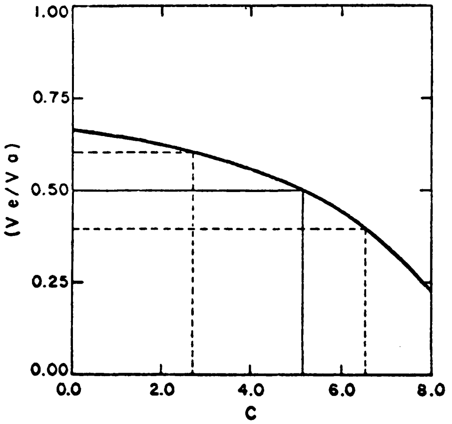

Figure 2. The resulting <Ve/Va> for different trial values of the evolution rate. Dashed lines: 95% confidence region, thin line: best fit value (adapted from Maccacaro et al. 1982b).

A significant difference exists between the X-ray and optical evolution rates. For optically selected samples, in fact, higher values are derived (cf. Schmidt 1978, Marshall et al. 1982).
It can be shown that the dependence of Lx/Lo on the optical luminosity can explain the difference in the evolution rate and in the redshift distribution between optically selected and X-ray selected AGNs.

In the framework of pure luminosity evolution, and with the very important assumption that X-ray surveys and optical surveys select from the same parent population of objects, one can easily derive the amount of evolution expected to characterize X-ray selected AGNs from the amount of evolution required to describe optically selected QSOs, if the relation between their optical and X-ray properties is known.
Combining an optical evolution law of the form of Eq. (2) with the relation between X-ray and optical luminosities of Eq. (1), one obtains:

$$Lx(z) = Lx(0)\exp(\beta Co \cdot z/(1+z)) \qquad (3)$$

where β is from Eq. (1) and Co is the parameter which describe the optical evolution. We can define $Cx = \beta \cdot Co$ and therefore, since β is smaller than 1, Cx is smaller than Co. In particular, for values of Co between 7 and 8, one expects Cx to be between 4.7 and 5.3 since $\beta = .66$, (cf. Avni and Tananbaum 1982 for a more detailed discussion of the link between optical and X-ray evolution rate).
The lack of high redshift, high luminosity objects among X-ray selected AGNs detected in a flux-limited survey, can also be explained by the dependence of Lx/Lo on Lo.
Figure 3a shows the expected redshift distribution of X-ray selected AGNs in a survey with limiting sensitivity of 10^{-14}ergs/(cm^{2}s), a few times better than the Einstein Deep Surveys. The expected redshift distribution is very similar to the redshift distribution of optically selected objects. Such a survey in fact is deep enough to allow an almost uniform sampling, at all redshift, of the optical luminosity function. If we now increase the limiting X-ray flux of the survey to 10^{-13}ergs/(cm^{2}s) we see that we loose objects at high redshifts (Figure 3b). Again the reason for this is easily understood: in a flux limited sample, objects at high redshifts can be detected only if they have high luminosities. When the limiting flux is increased the objects which disappear first are the high luminosity objects since for them the production of X-rays is relatively less efficient as indicated by the decreasing dependence of Lx/Lo on Lo.

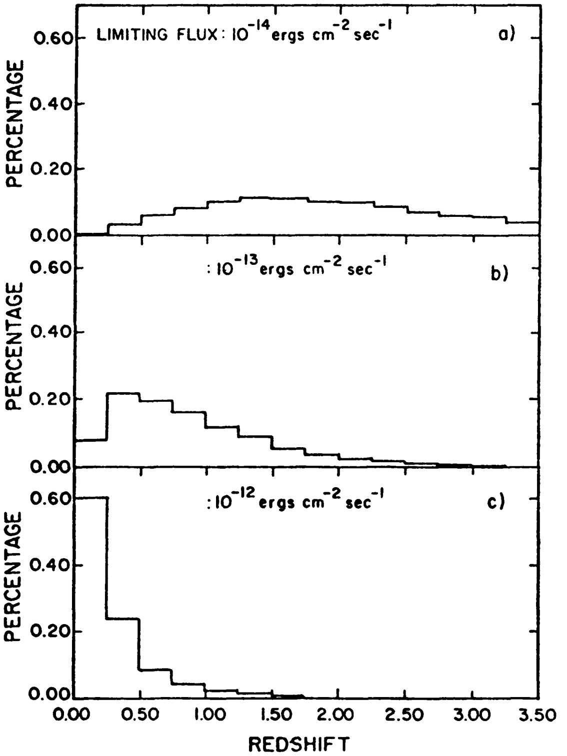

Figure 3. Expected redshift distribution for a sample of X-ray selected AGNs (see text for details).

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If we further increase the limiting flux by another factor of 10, (we are now dealing with a sensitivity comparable to that of a 1000 seconds IPC observation), the redshift distribution is remarkably weighted toward very low redshifts (Figure 3c), and is now similar to the observed redshift distribution (Figure 1). These expected redshift distributions (done in collaboration with P. Giommi) have been derived integrating the optical luminosity function of quasars, assuming pure luminosity evolution and converting optical luminosities into X-ray luminosities according to Eq. (1). In a recent work, Zamorani (1982) has independently reached these same conclusions.

It is worth mentioning that if instead of the Einstein Observatory, AXAF (the Advanced X-ray Astronomical Facility, a 1.2 meter X-ray telescope under study) had been launched, the whole issue of the apparent anomalous redshift distribution of X-ray selected AGNs would probably never have arisen. The AXAF capability to detect sources at 10^{-14}ergs/(cm^{2}s) in a few thousand seconds (Murray 1980, Zombeck 1982) would have in fact allowed us to easily detect virtually all QSOs, including the high redshift, high luminosity ones.

3. BL LACS OBJECTS

The Hewitt and Burbidge (1980) catalogue of quasi stellar objects contains about 1500 QSOs but only 60 BL Lacs. Of these not more than a third have a measured redshift. This huge difference between the number of QSOs and BL Lacs known, reflects the elusive nature of BL Lacs and limits our capability of a systematic study of their properties. Nonetheless a number of BL Lacs have been observed with the Einstein Observatory (e.g. Ku 1979, Schwartz and Ku, 1980, Maccagni and Tarenghi 1981). From the results of these observations we know that BL Lacs, in many respects, are similar to QSOs in the X-ray band. They are, as a class, powerful X-ray emitters with an X-ray to optical flux ratio similar to those of QSOs.

BL Lacs, however, show a more frequent and more pronounced X-ray variability. If one believes that optical, radio and X-ray emission are related, this is not surprising since BL Lacs are, by definition, characterized by strong flux variations. More noticeable is the difference between the X-ray spectra of AGNs and BL Lacs.
Figure 4 shows a histogram of X-ray (2-10 keV) spectral indexes for a sample of 23 AGNs, and for 7 BL Lacs. The data on AGNs are taken from Halpern and Grindlay (1982), those on BL Lacs from Worral et al. (1981), Maccagni and Tarenghi (1982) and Maccagni et al. (1982). The distribution is very narrow for the AGNs suggesting that these objects may be characterized, in the X-rays, by a unique power low spectrum with an energy slope of 0.7. BL Lacs instead do not show any preference for a particular spectral index and they seem to be characterized by a steeper spectrum with no evidence for a low energy cut-off. In several cases variations of the slope of the spectrum have been reported (e.g. Worral et al. 1981, Kondo et al. 1981, Maccagni et al. 1982).

The most surprising result however, is probably the almost total absence of BL Lacs from samples of serendipitous sources. Only one source, 1E1402+0416 has been reported in the literature as positively identified with a BL Lac object (Maccacaro et al. 1982a, Stocke et al. 1982b), despite the many serendipitous X-ray sources which have been identified. This result implies a further significant difference between the X-ray properties of BL Lacs and QSOs.

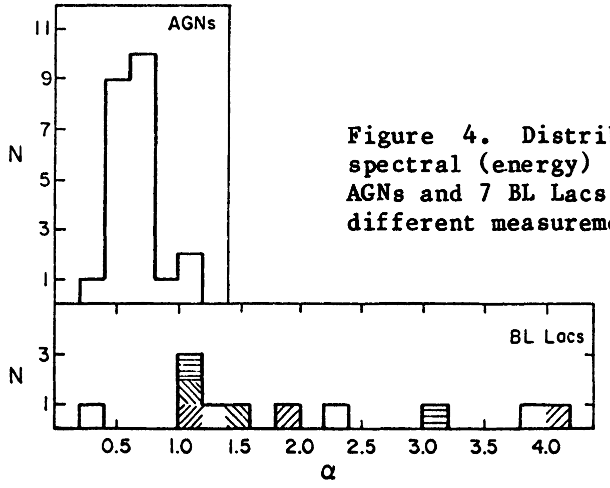

Figure 4. Distribution of the X-ray spectral (energy) index for a sample of 23 AGNs and 7 BL Lacs. Shaded areas represent different measurements of the same objects.

Let us compare, as a function of the X-ray flux, the detection rate of these two classes of objects. For the comparison we are considering two X-ray surveys: the HEA01-A2 all sky survey (Piccinotti et al. 1982) and the Einstein Observatory Medium Survey (Maccacaro et al. 1982a). The former covers the entire high galactic latitude sky with a sensitivity of $\simeq 3\times10^{-11}$ergs/(cm^{2}s) (2-10 keV). The latter covers 50 square degrees of high galactic latitude sky with sensitivities in the range 10^{-13} - 10^{-12} ergs/(cm^{2}s) in a softer (0.3 - 3.5 keV) band. The numbers of extragalactic sources detected in the two surveys are similar, 61 in the HEA01-A2 survey and 49 in the Medium Survey.

If we now define as a QSO any AGN with absolute optical magnitude brighter than -24 we have 3 QSO and 4 BL Lacs detected in the HEA01-A2 survey. The ratio of detections between QSOs and BL Lacs is therefore of the order of the unity. In the Medium Survey, about 100 times more sensitive, 16 QSOs, but only 1 BL Lac, are detected.

Why do we find so few BL Lac objects? Since their spectra are predominantly steeper than those of QSOs the different energy band of the two surveys cannot account for the lack of objects among serendipitous Einstein sources. Just the the opposite would be expected, a steep spectrum should favour their discovery in soft X-ray surveys. The explanation we favour is that BL Lacs do not show, at least at X-ray wavelengths, the same amount of cosmological evolution observed for QSOs.

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4. CLUSTER OF GALAXIES

The IPC, with its moderate angular resolution is an extremely powerful instrument to study the X-ray emission from cluster of galaxies. Observations with the Einstein Observatory have shown a large variety of structures in the X-ray surface brightness distribution of cluster of galaxies, from smooth and centrally peaked to highly clumped emission. An extensive review of the X-ray properties of clusters is given in Forman and Jones (1982). Here, we shall very briefly summarize some of the results on a specific class of clusters, those which show double or multiple structures.
The issue of the presence of sub-structure in clusters of galaxies was addressed by Abell and coworkers as early as in 1964 and then investigated by others. Recently, however, interest on this topic has very much revived, due largely to the X-ray images taken with the Einstein Observatory (Forman et al. 1981, Henry et al. 1981, Beers et al. 1982, Gioia et al. 1982b)

Since the X-rays mainly come from diffuse intracluster gas and not from individual galaxies, an X-ray image of the cluster can give us immediate information on the overall cluster morphology. At optical wavelengths, the capability to easily recognize substructures is often limited by the presence of background and foreground galaxies and, in the case of distant clusters even by stellar contamination. Figure 5 shows the X-ray isointensity contours for the clusters of galaxies A98, A115, A1750, and SC0627-54, superposed on optical photographs. The double structure of these cluster can be immediately seen.

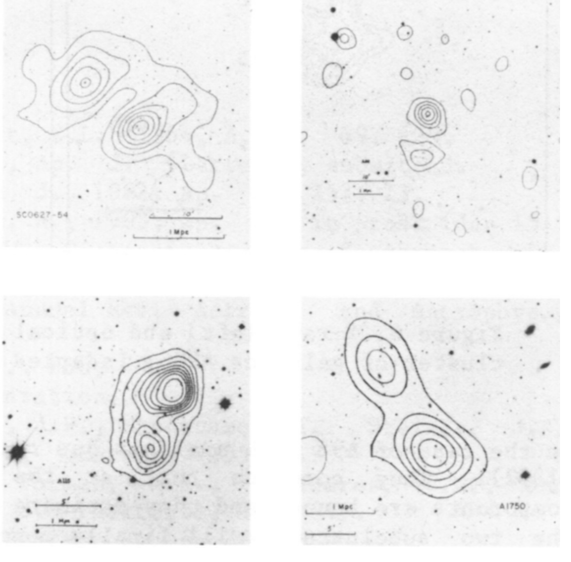

Figure 5. X-ray isointensity contours for the four cluster of galaxies A98, A115, A1750 and SC0627-54 (adapted from Forman et al. 1981).

Optical contour maps for these 4 clusters, are presented by Geller and Beers (this volume) along with a discussion of the comparison between X-ray and optical data.

A cluster which shows multiple subcondensations both in the X-rays and in the optical is shown in Figure 6. The cluster is A2069 and was discovered as an X-ray source by Gioia et al. (1982b) while extending the CFA survey of serendipitous sources. The similarity between the X-ray and the optical contours is striking. This close correspondence between the gas and the galaxy distribution indicates that the galaxies in this system do indeed map the mass distribution.

Obvious questions are whether these subsystems are gravitationally bound and whether these clusters represent an intermediate stage of cluster evolution in the sense that the two or more subcondensations will eventually merge. The answer comes only from a detailed dynamical analysis of the cluster itself.

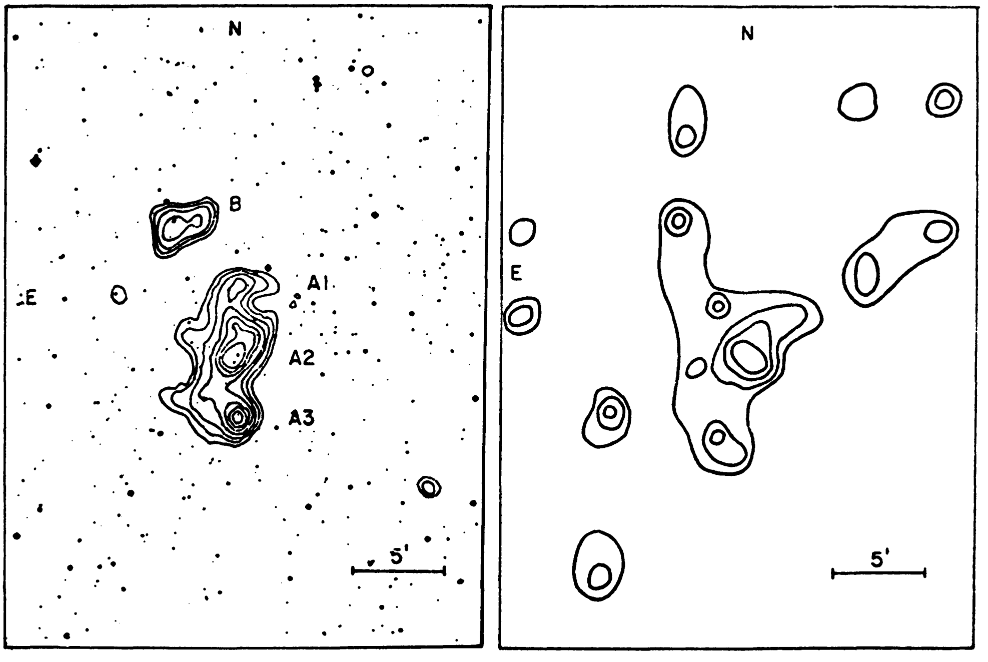

Figure 6. X-ray (left) and optical (right) contours for the cluster of galaxies A2069 (adapted from Gioia et al. 1982b).

In the case of A98 such analysis has recently been done by Beers et al. (1982). They conclude that at the 98% confidence level the two components are bound, and they estimate that in about 3 billion years the two subclusters will finally merge. A similar analysis for other clusters is already in progress (Beers et al. 1983).

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5. SUMMARY

We have seen that for optically selected QSOs Lx/Lo decreases with increasing Lo, that X-ray selected AGNs evolve cosmologically and that the rate of evolution required by the X-ray data is smaller than the rate determined from optically selected samples. We have shown that both the difference in the evolution rate between optically selected and X-ray selected AGNs and the anomalous redshift and absolute magnitude distribution of X-ray selected AGNs are possibly induced by the discussed relation between Lx/Lo and Lo.
We have also shown that BL Lacs, in the X-rays, do not evolve as AGNs do. These two classes of objects differs also in their X-ray spectrum. While AGNs are characterized by a very narrow distribution of spectral indexes, BL Lacs do not show any preference for a particular spectral index. Moreover BL Lacs have, on average, a steeper X-ray spectrum and in several cases variation of the shape of the spectrum have been reported.

X-ray images of clusters of galaxies are a powerful tool for the study of their morphological structure and have revealed that most clusters are not symmetric relaxed systems. Clusters of galaxies characterized by double or multiple structure have been found, which may represent an intermediate evolutionary stage in the process of the cluster formation. Dynamical studies have revealed, at least in some cases, that the sub-systems in these clusters are gravitationally bound and will eventually merge.

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DISCUSSION

Peacock: Kembhavi and Fabian have concluded that Lx/Lo for quasars <u>increases</u> with Lo. Why does your result differ from theirs? Might it be that by including Seyferts in your Lx-Lo plot you are obtaining a spuriously low slope for your regression line?

Maccacaro: The available data do not allow Lx/Lo to <u>increase</u> with increasing optical luminosity. There is no doubt about it. Data on Seyfert galaxies are in excellent agreement with data on low-luminosity quasars. I believe you have misinterpreted Kembhavi and Fabian's paper.

Zamorani: Kembhavi and Fabian's results were based on an analysis of X-ray and optical properties of QSOs as a function of "observed" optical magnitude, instead of intrinsic optical luminosity. Their conclusion was that the ratio of X-ray to optical luminosity is a decreasing function of "observed" optical magnitude.

Rowan-Robinson: The study by Janet Cheney and me (Monthly Notices 1981) of the optical evolution of quasars gave an evolution factor, C_{opt}, of 5 or 6, with pure exponential luminosity evolution.

Maccacaro: Other works (e.g., Marshall et al. 1982) give a higher value. It will be interesting to compare the samples used in the two studies.

Segal: Published studies (circa 1980-1981) have shown that the non-parametric chronometric cosmology fits very well the QSO X-ray luminosity redshift relation, with optimal statistical treatment of the cut-off bias, without evolution. Later V/V_{max} studies have indicated agreement with spatial homogeneity, i.e., lack of number evolution.

Therefore, is not your finding of strong evolution for X-ray sources:

a) Entirely an artifact of the use of a Friedmann model as the theoretical basis of your analysis;

b) Scientifically dubious in view of the total lack of predictive power of the Friedmann model as regards quasars and other large-redshift objects?

Maccacaro: Not being familiar with the chronometric cosmology, I cannot comment on your question.

Windhorst: Would not you have missed the BL Lacs at high redshifts in the Medium Sensitivity Survey, compared to the BL Lacs in the Bright Survey? (I presume the latter are at low-to-moderate redshifts.) You said that most BL Lacs have very steep X-ray spectra ($1 \lesssim \alpha_X \lesssim 4$). So BL Lacs at higher redshift must have an enormous dimming due to the redshift and will drop below the unit of the Medium Survey.

Maccacaro: The lack of BL Lacs in The Einstein Observatory Medium Survey cannot be easily accounted for even by the K correction. Besides, why are the low redshift BL Lacs unaffected?

Wampler: Complete samples of radio quasars show that the ratio of radio quasars to radio BL Lacs is 10:1. Your statement that there are too few BL Lacs discovered by Einstein is based on a much lower ratio from a small sample of X-ray quasars. Isn't it possible that the true ratio is closer to 10:1 than to 1:1?

Maccacaro: We have shown that the ratio of detection of QSOs and BL Lacs is a function of the X-ray flux. Moreover, the radio behaviour may differ from the X-ray behaviour.

Ekers: What is your definition of AGN?

Maccacaro: With the generic term of AGN (active galactic nuclei) we refer to quasars and Seyfert galaxies.

P. Veron: A few years ago, Setti and Woltjer showed that, optically, BL Lac objects are evolving less strongly than quasars (if they evolve at all); therefore, it is not surprising to see that you find the same to be true in the X-ray domain.

Maccacaro: Setti and Woltjer indeed suggested that BL Lacs are evolving less strongly than quasars. Our results give further support to this picture.

M. Burbidge: In the viewgraph you showed of the L_{opt}, L_x ratio against L_{opt}, to the eye it seemed that the points for QSOs and for Seyferts would be fitted better by two parallel lines, of steeper slope than the single line which you showed. Have you tried making such a fit?

Maccacaro: The eye can be misled by the presence of many upper limits. Points for quasars and for Seyfert galaxies lie, however, on the same correlation; the proof is that the same correlation is found if only QSOs are considered.

(The figure Prof. Burbidge asked about, which was displayed by Dr. Maccacaro, is from Zamorani 1982, and is not reproduced here. Ed.)

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