RESULTS FROM X-RAY SATELLITES

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ABSTRACT. One of the best studied results of the X-ray observations of
Active Galactic Nuclei is the statistical correlation which has been
observed between the X-ray and optical luminosities in these objects.
In this paper I will review the present situation of the analysis of
such correlation, focusing my attention on the large number of topics
which are more or less directly linked to it.

1. INTRODUCTION

It is not easy to give today a review talk on "Results from X-ray
Satellites" for quasars and Active Galactic Nuclei (AGNs). The main
reason for this is that the X-ray data for these objects (mainly from
the EINSTEIN Observatory) have been extensively discussed and already
presented in many Meetings in the past few years.   Extensive reviews,
which cover many different aspects of the X-ray properties of AGNs, such
as statistical analysis of the correlations observed in various samples
of quasars (radio quiet vs.   radio loud), X-ray spectra, X-ray
variability, X-ray evolution and luminosity functions, have been
recently published (see, for example, Zamorani 1984a, 1984b; Avni 1985a,
1985b; Mc Hardy 1985; Elvis and Lawrence 1985). As a consequence, at
least until EXOSAT data are more diffusely presented and discussed in
the literature, it is difficult to say something new on these subjects.
This does not mean that all the possible information has already been
extracted from the EINSTEIN data. On the contrary, very interesting new
results are becoming available only now, as, for example, the results on
the spectral data, presented at this Meeting (Elvis et al. 1986, Wilkes
and Elvis 1986).
    For this reason, and since other papers on a variety of various
topics connected to the X-ray properties of quasars and other AGNs are
presented in this Meeting, this paper will be organized as a sort of
monography. Rather than showing a long list of results, not immediately
related with each other, I will discuss, instead, a single observational
result, the correlation between X-ray and optical luminosities, trying
to show how an in depth analysis of this correlation is directly linked

to   many other both observational and interpretative data, some of which
will be addressed in more detail in other papers in these Proceedings.
As an example, some of the questions on which the study of the
correlation between X-ray and optical luminosities has some bearing are:
a) evolution, with cosmic time, of the X-ray and optical luminosities;
b) estimate of the X-ray counts and of the contribution of AGNs to the
soft X-ray background;
c) variability;
d) low energy absorption in low luminosity AGNs;
e) differences in the X-ray properties of radio quiet and radio loud
quasars;
f) comparison with other existing correlations as, for example, the
infrared – X-ray correlation.
In the next Sections it will be shown how our knowledge of each of these
topics is connected to the study of the correlation between X-ray and
optical luminosities.

2.   THE CORRELATION BETWEEN X-RAY AND OPTICAL LUMINOSITIES

2.1.   The Data

Since the first EINSTEIN observations of radio quiet quasars, the
existence of some kind of statistical correlation between X-ray and
optical luminosities became evident (Zamorani et al.   1981).   On the
basis of different samples, this relationship has been described by
various authors as a power law (log L_x = β log L_o + constant), with β in
the range 0.6-1.0.
      The most recent and complete analysis on this topic is by Avni and
Tananbaum (1986; AT) on a large sample (154 objects) of optically
selected quasars.   Their sample is mainly based on two complete
magnitude limit samples, the BQS and the BF quasars with blue magnitude
limits 16.16 and 19.8, respectively. The large number of objects, and
the wide dynamical range (both in luminosity and redshift) spanned by
these objects allowed them to apply a very detailed statistical
analysis. Figure 1 shows the X-ray versus optical monochromatic
luminosity for the objects analyzed by AT. They fit their data with a
simple linear dependence of α_{ox} on cosmological look-back time $\tau(z)$ and
on log L_o:

$$\alpha_{ox}(z,L_o) = A_z \ \tau(z) + A_o \ \log L_o + A + \text{(residual)} \qquad (1)$$

assuming, as initial guess, that the residuals are Gaussian distributed
around the best fit line. Determining, with a parametric version of the
Detections and Bounds (DB) method (Avni et al.   1980), the allowed
region of the parameters A_z and A_o, they find that α_{ox} depends
predominantly on L_o, rather than on redshift. In particular, they find
that A_z = 0.0 is fully consistent with their data. The best fit value
of the parameter A_o corresponds to L_x proportional to $L_o^{0.8}$.   The
dispersion around the best fit line (one sigma) is at least a factor of
3.0. Similar results, from a partially independent sample, have been
obtained by Kriss and Canizares (1985).

2.2 Evolution with Cosmic Time of X-ray and Optical Luminosities

As seen in Eq. 1, A_z = 0.0 means that two objects with the same optical luminosity and different redshift statistically have the same X-ray luminosity. In other words, this implies that there is no explicit evolution with cosmic time of the ratio of X-ray to optical luminosity. On the other hand, within the framework of pure luminosity evolution models (which have become quite popular in the recent years) one can interpret the observed correlation between X-ray and optical luminosities as the path along which single objects move, while dimming with cosmic time. In this case, a value in the slope different from 1.0 introduces an implicit dependence on redshift: while an object dims, its ratio of X-ray to optical luminosity is changing. This is an interesting case in which the same observed correlation has two different physical interpretations as a function of the assumed evolutionary model. Theoreticians may tell us which interpretation they like more.

Moreover, as shown by Avni and Tananbaum (1982), a slope smaller than one in the correlation implies that, within pure luminosity evolution models, the cosmological evolution of the X-ray luminosity
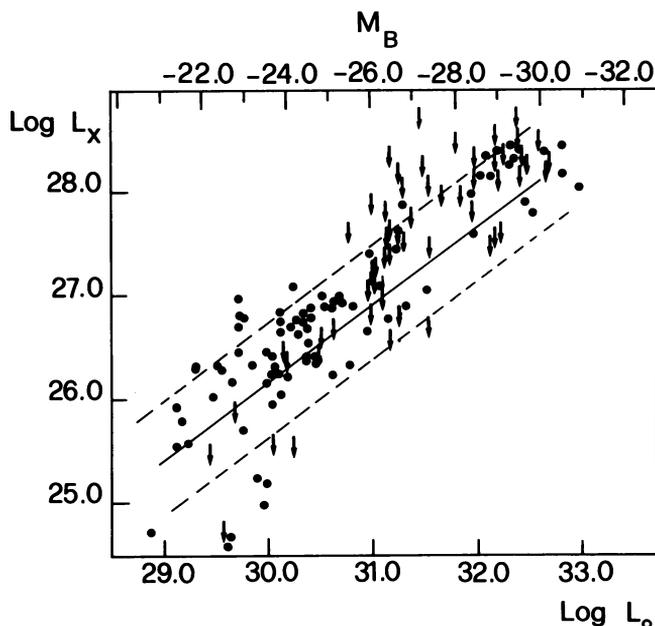

Figure 1. X-ray versus optical monochromatic luminosity for a sample of 154 optically selected quasars (see Avni and Tananbaum 1986). The solid line represents the best fit (slope 0.8). The two dashed lines represent the width (one sigma) of the Gaussian distribution of the residuals.

function should be weaker than the evolution of the optical luminosity function. The available data seem to be in agreement with this prediction (Maccacaro, Gioia and Stocke 1984).

2.3 Skewness of the α_{ox} Distribution

In their regression analysis (see Eq. 1), AT found that the distribution of the residuals around the best fit line is not well represented by a single gaussian, but requires a significant skewness, with a longer tail at high α_{ox} (low L_x) and a shorter tail at low α_{ox} (high L_x). This result is not a purely mathematical exercise, because the exact shape of this distribution has important numerical implications in computing, for example, the expected X-ray number counts. The correlation between L_x and L_o has been used by various authors to predict the X-ray counts starting from the optical luminosity and evolution functions (see, for example, Avni and Tananbaum 1986; Schmidt and Green 1986). All these computations are critically affected by the detailed shape of the assumed correlation, so that the best possible analysis of the "observed" data points is crucial for this purpose. Franceschini, Gioia and Maccacaro (1985) have shown that the use of the "observed" distribution of residuals around the best fit line in the L_x-L_o plane leads to significant inconsistencies between predictions and observations. Most of these discrepancies can be eliminated if one assumes a narrower "intrinsic" width, which has been artificially broadened into the observed one due to a variety of external effects. The most obvious of these effects are variability and absorption (at both optical and X-ray frequencies) and errors in the estimated optical and X-ray fluxes as well. A completely independent analysis led Zamorani (1985) to conclude that long term variability may, indeed, have produced a significant broadening in the observed distribution of the X-ray to optical fluxes in the optically selected sample. While there is no doubt that the net result is a broadening of any intrinsic correlation, a quantitative estimate of this effect can only be achieved by obtaining a better understanding of each of the causes which may determine such broadening. This is an excellent example of the necessity of linking the study of the L_x-L_o correlation with the knowledge of other intrinsic X-ray properties of quasars.

Looking at Fig. 1, we see that while the low luminosity part of the diagram is reasonably well determined (61 Detections and 19 Bounds for log L_o < 31.0), the high luminosity region is populated by a large number of limits (34 Detections and 40 Bounds for log L_o > 31.0). The situation is even worse in redshift space:

Redshift	Detections	Bounds
0.0–1.0	71	16
>1.0	24	43

This implies that the shape of the distribution of residuals around the best fit line which results from the DB analysis is largely determined by low luminosity, small redshift objects. In this respect, it would be

extremely interesting to check whether other high redshift samples (in
particular the grism selected sample described in Anderson (1985) and
presented at this Meeting by Margon and Anderson (1986)) are consistent
with this overall description or require some minor change.

Moreover, the skewness of the α_{ox} distribution, as determined by AT
(1986), is largely required by the existence of a few detections and
upper limits with a large value of α_{ox}. All these objects are in the
low luminosity region of Figure 1, having log L_o < 31.0. Lawrence and
Elvis (1982), by comparing hard and soft X-ray luminosities, suggested
that a significant fraction of low luminosity AGNs might have their soft
X-ray fluxes decreased because of intrinsic absorption. No evidence for
a similar effect in high luminosity objects has been found up to now.
It is then possible that these high α_{ox} objects are simply those in
which low energy absorption is becoming dominant. If this is the case,
skewness might not be an intrinsic property of the α_{ox} distribution.   A
possible way to test this would be to sample, with X-ray detections, the
region of low X-ray, high optical luminosity. This can be achieved by
obtaining deep X-ray observations of relatively bright (in optical) and
high luminosity objects. It is possible that some of these observations
are already available in the EINSTEIN data bank; if not, this is
something that ROSAT might easily do.

3.   COMPARISON WITH OTHER STATISTICAL CORRELATIONS

3.1 Radio Quiet Versus Radio Loud Quasars

It is well known (Ku, Helfand and Lucy 1980; Zamorani et al. 1981; see
also Tananbaum et al.   1983) that the X-ray emission of radio loud
quasars is, on average, stronger than that of radio quiet quasars.
Recently, statistical associations between X-ray luminosity and extended
radio luminosity (Feigelson, Isobe and Kembhavi 1984) and between X-ray
luminosity and radio core emission (Kembhavi, Feigelson and Singh 1985)
have been studied. A review of these results is presented by Kembhavi
(1986).

The results of an extensive statistical analysis of the
correlations between radio, optical and X-ray luminosities for various
subsamples of radio loud quasars are presented by Worrall et al.
(1986). They find a significant difference in the L_x-L_o correlation
between radio loud with flat spectrum quasars, radio loud with steep
spectrum and radio quiet quasars. This difference is such that, for a
given optical luminosity, radio loud quasars with a flat radio spectrum
are the strongest X-ray emitters, while radio quiet quasars are the
faintest ones. Moreover, within each class of radio loud quasars the
X-ray luminosity (for a given optical luminosity) tends to increase with
increasing radio luminosity. They also find that the fits for the
steep, extended radio loud quasars improve somewhat if the radio
luminosity from the core alone is used.   Their conclusion is that a
radio loud quasar can be thought of as a radio quiet quasar with an
additional physical component producing the core radio luminosity and an
"extra" X-ray emission.   This extra X-ray emission would dominate the

observed X-ray flux in about 80% of flat radio spectrum objects. If
this is true, one might expect to see different X-ray spectral shapes
between radio quiet and core dominated radio loud quasars (see Wilkes
and Elvis 1986).

3.2 The Correlation Between Infrared and X-ray Luminosities

The existence of a possible correlation between the 3.5 micron nuclear
flux and the X-ray emission from Seyfert 1 galaxies was first pointed
out by Elvis et al. (1978), and later confirmed by Kriss, Canizares and
Ricker (1980). Recently, Malkan (1984) has found that a sample of more
than 50 Seyfert 1 galaxies and quasars (both radio quiet and radio loud)
shows a very tight correlation between infrared and X-ray luminosities.
The best fit between the two luminosities has a slope 1.0, the
dispersion around the best fit (one sigma) is only a factor of 2.0 and
apparently there is no obvious distinction in this correlation between
radio quiet and radio loud objects. Each of these findings is at
variance with the results of the analysis of the correlation between
optical and X-ray luminosities (see above). The best fit corresponds to
an average slope of 1.18 between infrared and X-ray frequencies. This
is a confirmation of what Malkan and Sargent (1982) suggested: an
extrapolation of the red/infrared power law gives an excellent
prediction of the 2 Kev flux, regardless of the ultraviolet or even the
radio properties of the AGNs. (See Elvis et al. (1986) and Fabbiano et
al. (1986) for more data on this subject).
       These results have been taken as an indication that infrared and
X-ray emissions are produced, in all these objects, by two related (or
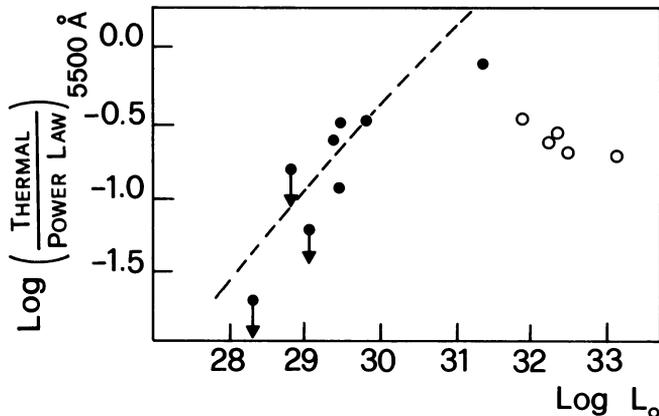even the same) mechanisms, probably non-thermal; at optical and UV

Figure 2. Ratio of thermal to power law components (at 5500 A) versus
total optical luminosity. The data are taken from Malkan and Sargent
1982 (filled circles) and Malkan 1983 (open circles). The dashed line
represents the trend in this diagram which would be necessary to
reconcile with each other the two different slopes observed in the
optical – X-ray and the infrared – X-ray correlations.

frequencies, instead, other emission mechanisms (as, for example, Balmer continuum recombination taking place in the broad emission line regions (Richstone and Schmidt 1980; Malkan and Sargent 1982), and thermal emission from an optically thick accretion disk (Malkan 1983)) are dominant, producing the so-called blue bump and hiding the underlying, "universal" power law with a slope of the order of 1.0-1.2. Within this framework, then, the decrease of the ratio of X-ray to optical luminosities with increasing optical luminosity (L_x proportional to $L_o^{0.8}$) can be understood if the ratio of the thermal to the power law component increases with increasing luminosity. This trend was, infact, suggested by the data in Malkan and Sargent (1982) (see Figure 2). Unfortunately, when five higher luminosity quasars were added to the sample (Malkan 1983), the correlation almost completely disappeared. This implies that at least one very elegant and appealing explanation for the observed difference in the L_x-L_o and L_x-L_{ir} correlations is not so clear any more.

At this point, to clarify a little bit the situation, I think that a few obervations would be extremely important:

a) One should try to obtain the spectral decomposition (power law + thermal component) for a larger number of objects. These objects should span a range as wide as possible in luminosity.   In view of the difference in the X-ray – optical correlation for radio quiet, radio loud with flat spectrum and radio loud with steep spectrum quasars, all these classes of objects should be well represented in the sample. In costructing such a sample, objects which already have an X-ray measurement should have higher priority.

b) The infrared – X-ray correlation shown and discussed by Malkan (1984) was only for objects up to z = 0.3. It would be extremely important to extend it to higher redshift, by obtaining more infrared observations of high redshift objects. In order not to bias the sample, not only objects which have an X-ray detection, but also objects which have only an X-ray upper limit should be included in the sample. In this respect, it would be particularly interesting to check whether objects that appear to have an exceedingly low X-ray luminosity with respect to the optical are also amomalously infrared faint.

Before these data are available, I think we should be very careful in accepting the conclusion that infrared and X-ray emission mechanisms are strictly related to each other.

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DISCUSSION

Malkan : To update what you said about the correlation of the thermal/
nonthermal ratio with luminosity presented in Malkan & Sargent : though
it is poor for quasars, our new analyses of Seyfert 1's strengthen the
correlation at low luminosities. That is, high and low-luminosity qua-
sars appear to have blackbody/power-law ratios (at 5450 A) of 0.5 to 1,
whereas many Seyfert 1's have ratios of 0.1. So I think it's still pos-
sible this correlation may explain the α_{ox}/L trend, and the Baldwin
effect.

Wampler : There are a few (2) broad absorption line (BAL) quasars known
that have M II $\lambda 2800$ in absorption. The M II $\lambda 2800$ absorption line
has a central depth of only about 50% and seems to separate the emission
of a small central source from that of a larger source. At least in the
case of PG 1700+518 the underlying radiation from the small source is a
power law ($f_\nu \propto \nu^{-\alpha}$) with $\alpha = 1.2$. Other BAL quasars may be useful in
separating the various components that contribute to the optical conti-
nuum and aid in understanding of the general connection between the
IR-opt-X ray portions of the continuum.

Segal : An apparently high correlation between the luminosities in two
different frequency bands can easily be the spurious consequence of a
not necessarily valid cosmology in which flux varies rapidly with red-
shift since the derived luminosities will then have this flux-redshift
function as a common factor. Can you exclude this possibility in the
cases you report.

Zamorani : Yes, I think I can - infact, for the data that I have shown
there is a highly significant correlation also between the observed flu-
xes, which are obviously independent of any assumption on cosmology.