X-RAY PROPERTIES OF EXTRAGALACTIC COMPACT OBJECTS +

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1. INTRODUCTION

The compact objects which are the subject of this talk are essentially quasars and Seyfert galaxies; I will only briefly mention a couple of results about BL Lac objects. Before describing the X-ray properties of these objects, it is useful to introduce a "working" definition of radio-quiet and radio-loud quasars: I will call radio-loud quasars all the objects which have been detected at radio frequencies and have a spectral index between radio (5 GHz) and optical frequencies (2500 A) greater than 0.35 (Zamorani et al. 1981); all the other objects will be considered radio-quiet. Note that this definition is independent of distance and is a function only of the relative importance of radio and optical emission.

Before discussing in detail the X-ray properties of radio-loud quasars (Section 3), and their correlations with radio characteristics (i.e. spectral index, morphology and radio luminosity), it is necessary to know which are the X-ray properties of radio-quiet quasars (Section 2). The need of this approach is clearly shown by two very interesting sets of observations due to Owen and collaborators. In the first one (Owen, Helfand and Spangler 1981), they observed with the Einstein Observatory a sample of 25 extragalactic sources selected on the basis of a high millimeter flux (S > 1 Jy at 90 GHz). From the high rate of X-ray detections and the small dispersion in the ratio of the millimeter to X-ray flux density they concluded that there is some physical relationship between the emission in the millimeter and X-ray regimes, at least for sources selected for their strong millimeter emission. In order to check about the possible extension of this correlation to other classes of quasars, Owen and Puschell (1982) observed at 90 GHz a sample of about 50 quasars which were already known to be X-ray sources (Zamorani et al. 1981). About 60% of these

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objects were not detected at 90 GHz, showing a significantly wider distribution of the ratio of millimeter to X-ray fluxes. The problem is then to understand which mechanism can give rise to a one-way correlation such that, while the X-ray flux can be predicted within a factor of two for a sample of millimeter-loud QSOs, the knowledge of the X-ray flux does not allow any prediction about the millimeter flux.

A qualitative explanation for these effects can be given if one accepts the following working hypothesis: The X-ray emission is due to at least two different mechanisms. The first one, present in all classes of quasars, has a broad α_{ox} distribution, peaked at about 1.45, which is the typical value observed in radio-quiet quasars. The second one, which connects millimeter and X-ray frequencies, has a narrow α_{mx} distribution around a typical value of about one and is likely to be Inverse Compton emission on radio photons, as suggested by Owen, Helfand and Spangler (1981). The relative importance of the two mechanisms is visualized in Fig. 1 a) and b) where the data for the two samples (millimeter selected and X-ray detected respectively) are plotted in the plane $\alpha_{mo} - \alpha_{ox}$. In this plane the loci of constant α_{mx} are straight lines parallel to each other; in both figures the straight line corresponds to the average value of α_{mx} found by Owen, Helfand and Spangler (1981). Looking at Fig.1, it is clear that, as far as $\alpha_{mo} > 0.75$, the X-ray emission is dominated by the second mechanism (for $\alpha_{mo} > 0.75$ and α_{mx} about one, the expected α_{ox} is < 1.45), and the correlation between millimeter and X-ray emission becomes evident. When $\alpha_{mo} < 0.75$, the α_{ox} expected on the basis of the second mechanism is > 1.45, so that the correlation with millimeter emission disappears and we see the intrinsic dispersion in α_{ox} due to the first

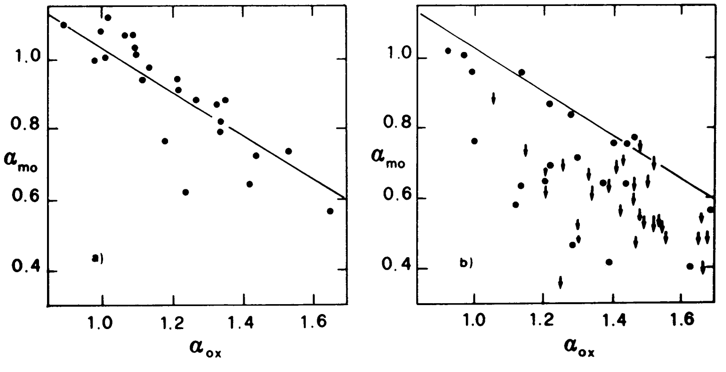

Fig. 1 Spectral index between millimeter and optical frequencies (α_{mo}) versus spectral index between optical and X-ray frequencies (α_{ox}) for: a) millimeter selected sources; b) X-ray detected quasars. The straight line corresponds to $\alpha_{mx} = 1.0$.

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mechanism. From this example, it follows the necessity of studying first the correlation between optical and X-ray luminosities in radio-quiet quasars if one wants to understand the different properties which are seen in radio-loud quasars.

2. THE RADIO-QUIET QUASARS

During the lifetime of the Einstein Observatory a few hundred quasars, both optically and radio selected, have been observed. In this Section, I will give a summary of the X-ray properties of optically selected quasars. The characteristics of the samples which will be used (range of optical magnitudes, number of X-ray detections and X-ray upper limits) are given in Table 1.

TABLE 1

X-ray Observations of Optically Selected Quasars.

Sample	m_b	Detections	Upper limits	X-ray References
Schmidt and Green	15-16	57	9	Tananbaum et al.(1983b)
Braccesi	18-20	16	19	Marshall et al.(1983)
Zamorani et al.	17-19	20	24	Zamorani et al.(1981)
Kriss et al.	14-16	11	0	Kriss et al.(1980)
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Total	14-20	104	52	

The first two samples consist of X-ray observations of either a complete (Braccesi sample; see Marshall et al. 1983) or an unbiased subset of a complete optically selected sample (Schmidt and Green 1983); the other two samples consist of X-ray observations of "miscellaneous" optically selected quasars (Zamorani et al. 1981) and Seyfert 1 galaxies (Kriss, Canizares and Ricker 1980).

Figure 2 a) and b) show the monochromatic X-ray luminosity at 2 KeV versus the monochromatic optical luminosity at 2500 A for the X-ray detections and upper limits, respectively. The best fit regression of X-ray versus optical luminosity (drawn in both panels of Fig. 2) gives:

$$\log L_x = 4.95 + 0.71 (\pm 0.04) \log L_o \quad (1)$$

This fit has been obtained using the Maximum Likelihood Method of Avni et al.(1980) (see also Avni and Tananbaum 1982) which makes full use of all the available data, including the upper limits. The fundamental

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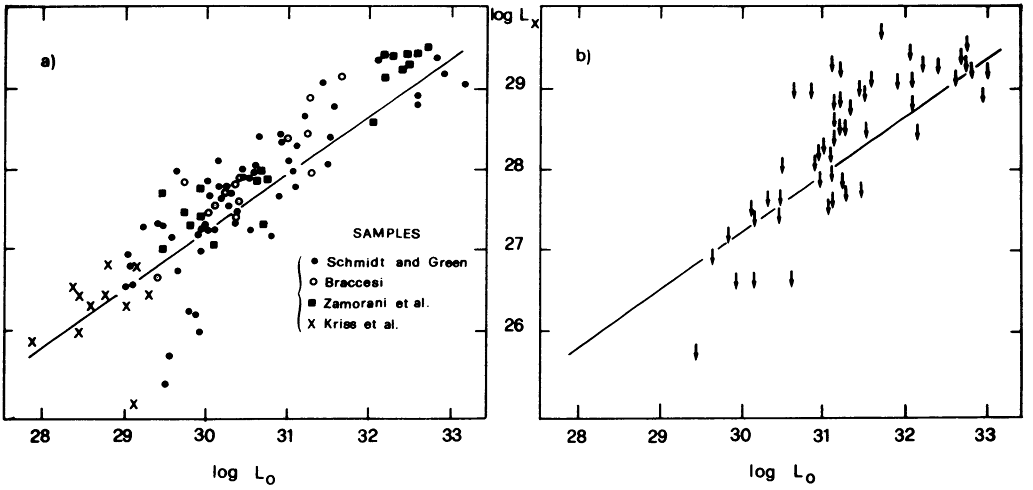

Fig. 2 Monochromatic X-ray luminosity at 2 Kev versus monochromatic optical luminosity at 2500 A for optically selected quasars and Seyfert galaxies. Panel a) shows the data for 104 detections; panel b) shows the data for 52 upper limits. In both panels the straight line represents the best fit regression of X-ray versus optical luminosity.

assumption which assures the applicability of this method is that all the objects in the sample (both the detections and the upper limits) are drawn from the same parent population with respect to the property which is being analyzed. Even if this assumption is not warranted by the existing data, the distribution of the upper limits (much more numerous at high optical luminosity) is such that the slope obtained with a fit which uses only the detections (0.77 ± 0.04) can be considered an overestimate of the real slope. This result confirms that in a sample of optically selected quasars the average ratio of X-ray to optical luminosity decreases with increasing optical luminosity (Zamorani et al. 1981, Avni and Tananbaum 1982).

From Fig. 2 three rather firm conclusions can be derived:

a) There is a definite correlation between X-ray and optical luminosities over a range of at least four orders of magnitude; the dispersion around the best fit line corresponds to a factor of about 3.2;

b) There is a continuity in the X-ray properties of Seyfert 1 galaxies and optically selected quasars;

c) There is no difference in the X-ray properties of quasars as a function of apparent magnitude in the range m_b = 16 - 20.

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3. THE RADIO-LOUD QUASARS

It was shown by Zamorani et al. (1981) that radio-loud quasars are stronger X-ray emitters than radio-quiet quasars. Now, the increased amount of available data allows a more detailed study of the X-ray properties of radio-loud quasars dividing them into different classes. An obvious classification is in terms of the radio spectral index. We will call flat (steep) spectrum quasars the quasars with a high frequency radio spectrum flatter (steeper) than 0.5. This classification corresponds largely to a morphological separation between compact and extended radio sources. Using all the data in Zamorani et al. (1981), Ku, Helfand and Lucy (1980) and Giommi et al. (1983) we have 57 flat spectrum quasars (54 detections and 3 upper limits in X-ray) and 48 steep spectrum quasars (43 detections and 5 upper limits).

Fig. 3 shows the X-ray luminosity versus the optical and radio luminosities for both samples. In both cases there is a definite correlation between the X-ray and optical luminosities, but well above the correlation which was found for the sample of radio-quiet quasars (dashed straight line). For a given optical luminosity, the X-ray luminosity of a radio flat (steep) spectrum quasar is about four (two) times higher than that of a radio-quiet quasar. This difference

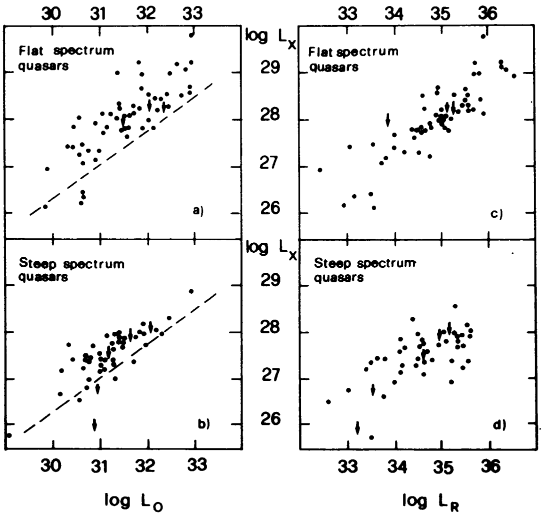

Fig. 3 X-ray luminosity versus optical and radio luminosity for radio loud quasars (flat and steep spectrum objects, respectively). The dashed line in panels a) and b) represents the best fit obtained for optically selected quasars (see Fig. 2).

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suggests that the presence of radio emission is somehow connected with an enhanced X-ray emission. However, while for radio flat quasars the correlation between radio and X-ray luminosity appears to be significantly better and with smaller dispersion than the correlation between optical and X-ray luminosity, the opposite is true for radio steep quasars.

In order to study in more detail the correlations between X-ray, optical and radio luminosities we have performed a multi-variate, non-linear fit of the type:

$$L_x = a*L_o^{\alpha} + b*L_r^{\beta} \quad (2)$$

Physically, this representation is equivalent to assuming that the total X-ray emission from these objects is the sum of two mechanisms, related to the optical and radio emission, respectively. Note that this fit is different from that used by Tananbaum et al. (1983a) in studying the X-ray properties of the complete sample of 3CR quasars ($\log L_x = a*\log L_o + b*\log L_r + c$). Table 2 gives the values of the slopes (and relative errors) obtained for the various samples.

TABLE 2
Slopes of various samples

Sample	α	β
Radio-Quiet	0.70 ± 0.05	
Radio-Loud Flat	0.75 ± 0.10	0.95 ± 0.15
Radio-Loud Steep	0.63 ± 0.10	0.75 ± 2.18

A few interesting points resulting from this analysis are:

a) The slope α in the correlation between X-ray and optical luminosities is consistent with being the same for all the three samples;

b) For both samples of radio-loud quasars the X-ray luminosity produced by the "optical mechanism" (i.e. the first term of Eq. 2) is about a factor of two higher than for radio-quiet quasars;

c) There is a strong correlation between X-ray and radio luminosities for radio flat quasars, with a slope of the order of one;

d) The correlation between X-ray and radio luminosities in radio steep quasars is, at best, weak: the slope β is consistent with zero. This implies that on the average the magnetic field in the extended lobes (which are the main contributors to the radio flux for these objects) is larger than about 0.05 times the equipartition field. Otherwise, a significant and detectable Inverse Compton X-ray emission would be expected from these regions.

As for flat spectrum radio-loud quasars, the direct proportionality between radio and X-ray luminosities (see Table 2) suggests a non-thermal origin for the X-ray emission. Moreover, the fact that the spectral index between the radio and X-ray frequencies is of the order of unity (Owen et al. 1981, Biermann et al. 1981 and this paper) is typical of a self-regulated Synchro-Compton mechanism (Pacini and Salvati 1978), in which approximately the same amount of energy is emitted at radio (Synchrotron) and X-ray (Compton) frequencies. Using the formulae given in Burbidge et al. (1974), the ratio of Compton to Synchrotron emission can be written as:

$$L_c/L_s = 1/(1-\alpha)i_\alpha^4 (\nu_b/10^{11})(\nu_n/\nu_b)^\alpha (T_n/10^{12})^5 \qquad (3)$$

where i_α is a function (of the order of unity) of the radio spectral index α, ν_n is the frequency at which the optical depth to synchrotron self-absorption is unity and ν_b is the high frequency cutoff. With typical values of α of the order of zero (flat spectrum sources) and ν_b of the order of 10^{11} Hz, our data imply the existence of an upper limit for the maximum brightness temperature (T_n) at about 10^{12} K. This is consistent with the fact that so far no measured brightness temperature exceeds this limit (Preuss 1981). Moreover, the observed dispersion in the ratio between the radio and X-ray fluxes would imply, if taken at the face value, an implausibly small dispersion in the value of the brightness temperatures (±30%). This is in contrast with existing VLBI observations. For example, Preston et al. (1983) report a wide distribution of brightness temperatures between 3×10^{10} and 1×10^{12} for a sample of about 100 sources observed at 2.3 GHz. This discrepancy can easily be explained if the contributions to the X-ray emission from the two parts of Eq. 2 (optical and radio luminosities) are of the same order of magnitude for an average object of our sample of radio flat quasars. As a consequence, it is difficult to separate the two mechanisms and almost impossible to sample low values of X-ray to radio fluxes. The best available sample of objects in which this separation can be done, at least in principle, is the sample of optically quiet, compact radio sources recently published by Ledden and O'Dell(1983). In fact, for these objects very little X-ray emission is expected as a contribution of the "optical mechanism". By comparing a sample of ten such sources with a sample of ten "control" sources, Ledden and O'Dell find that in these objects the X-ray luminosity is significantly weaker, relative to the radio, than in optically identified objects with comparable radio properties; at least four objects are still undetected in X-ray at values of X-ray to radio fluxes five times smaller than the average value observed in our sample. This result suggests that the real dispersion in the X-ray to radio luminosities is higher than what observed in our sample of radio flat quasars.

With this caveat in mind, we can still derive order of magnitude estimates of the physical parameters for the typical objects in our sample. Assuming a simple Synchro-Compton mechanism in a homogeneous and uniform spherical source, we obtain typical sizes of the order of (10^{19} - 10^{20}) cm, corresponding to angular sizes of (0.3 - 3.0) milliarcsec at z = 1, and magnetic fields of the order of (10^{-3} - 10^{-2}) gauss. These values are in reasonable agreement with existing VLBI measurements (Kellermann and Pauliny-Toth 1981); similar values for the magnetic field and the size of the radio and X-ray emitting region have been recently derived by Bregman et al.(1983) from an analysis of multifrequency observations of the BL Lac object 0735+178.

Despite these apparently promising results, there are a few problems far from being understood within this extremely simple model:

1.) With the sizes and magnetic fields derived here and the typical overall spectrum of these objects (the optical emission lying well above the straight line connecting radio and X-ray frequencies), the energy density in the inner 10^{19} - 10^{20} cm would be dominated by the optical photons coming from the nucleus. If this is the case, the relativistic electrons would tend to lose their energy through Inverse Compton emission on the optical photons, instead of through Synchrotron-Self Compton mechanism, and no obvious correlation between X-ray and radio emission should be expected. A possible way out is to assume that the relativistic electrons are accelerated far away from the nucleus, at distances of 10^{19} cm at least (see, for example, Protheroe and Kazanas 1983);

2.) Some radio-loud, flat spectrum sources show X-ray variability on timescale of a few days (Zamorani et al. 1983) or a few months (Schwartz, Madejski and Ku 1983, Zamorani et al. 1983) implying sizes of the emitting region smaller than those derived here. A possibility is that in these cases the observed variability is not due to the Synchro-Compton mechanism, but to the X-ray emission mechanism which is present also in radio-quiet quasars and is likely to originate in the inner regions of the accretion disk around the central black hole (Tucker 1983);

3.) After subtracting the contribution of the "radio mechanism", the normalization in the correlation between X-ray and optical luminosities for radio-loud quasars (both flat and steep spectrum) is still about a factor of two higher than in radio-quiet quasars. No obvious explanation for this difference is apparent. A possibility would be Inverse Compton emission of low energy relativistic electrons ($\gamma \sim 30$)

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on optical photons. Also in this case sizes of the order of a few times 10^{19} cm are required in order not to give too high an X-ray emission. This effect would appear as a correlation of X-ray luminosity with optical luminosity (rather than radio), because these electrons would emit at very low frequencies (1-10 MHz) through synchrotron emission in the typical magnetic field.

4. CONCLUSION

From the analysis of a large sample of radio-quiet quasars we have shown that there is a well defined correlation between X-ray and optical luminosities over a range of at least four orders of magnitude, with a continuity in the X-ray properties from low luminosity Seyfert galaxies to the most luminous quasars. The dispersion around the best fit line corresponds to about a factor of three. This value has been obtained assuming that the upper limits (about one third of the total number of data points for radio-quiet quasars) have been drawn from the same parent population as the detections. In order to test this assumption, deeper X-ray observations of some of the objects which have not been detected with the EINSTEIN Observatory are clearly called for. The future German X-ray Observatory ROSAT (Trümper 1983) has all the required capabilities to make such observations.

As for radio-loud quasars, there appears to be a difference in the X-ray properties of objects with steep and flat radio spectrum. While quasars of both classes are stronger X-ray emitters than radio-quiet quasars with the same optical luminosity, only in flat spectrum quasars there is a clear correlation between X-ray and radio luminosities. This suggests that in these objects the observed "excess" X-ray luminosity is somehow related to the presence of compact radio emission. A simple Synchrotron-Self Compton model requires magnetic fields and sizes of the radio and X-ray emitting regions consistent with the existing data. Multifrequency (radio through X-ray) and VLBI simultaneous observations of a selected sample of "representative" objects would be of great value to clarify the physical processes in these sources.

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