RADIO INDUCED X-RAY EMISSION IN RADIO QUASARS

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ABSTRACT. The relationship between low energy X-ray emission and radio emission in radio quasars is considered. A survey of early results is presented and the current status summarized. Some remarks are made on the simultaneous correlation of X-ray emission with optical and radio emission.

1. INTRODUCTION

Low energy X-ray emission from a few hundred radio, optical and X-ray selected quasars has so far been observed, thanks to the EINSTEIN X-ray observatory. The information is however of a rather limited nature : some data regarding the temporal variability (Zamorani et. al. (1984)) and the low energy X-ray spectrum (see Wilkes and Elvis, these proceedings) is available, but in most cases we have only the X-ray flux, or a 3σ upper limit to it, in the (nominal) 0.5 - 4.5 keV band. In this circumstance it is difficult to understand the nature of the mechanism(s) which leads to the X-ray emission. Some tentative steps towards this may however be taken by considering the statistical correlation of the X-ray luminosity with luminosities in other bands. The pattern of correlations will hopefully lead to the elimination of some mechanisms of X-ray production and a better understanding of the allowed set. We will consider in the following the relationship between the X-ray and radio luminosities of radio quasars.

2. RELATIONSHIP BETWEEN X-RAY AND RADIO EMISSION - EARLY RESULTS

It was established by Ku et. al. (1980) and Zamorani et. al. (1981) that the presence of strong radio emission leads to increased X-ray emission in quasars. This followed from the fact that both optical and radio quasars were found to be powerful ($\sim 10^{44}$ - $\sim 10^{47.5}$ erg/sec) X-ray emitters, with $\langle L_x/L_{op}\rangle$ for radio quasars upto $\sim$ 3 times as high as $\langle L_x/L_{op}\rangle$ for optical quasars. A weak correlation between the optical to X-ray spectral index α_{ox}, and the radio to optical spectral index α_{ro}

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was also found, which substantiated this conclusion. However there was no direct correlation evident between the radio and X-ray luminosities or fluxes, in contrast to the strong correlation observed between X-ray and optical luminosity, with $L_x \sim L_{op}^{0.7}$.

A very good correlation between the X-ray flux and 90 GHz radio flux was found in a sample of strong millimetre sources by Owen, Helfand and Spangler (1981). These authors argued that such a millimetre source should be a strong X-ray emitter because of the inverse Compton scattering of radio photons to X-ray energies by high energy electrons (Lorentz factor $\gamma \sim 10^3$) in the nuclear region. They observed a set of 25 flat spectrum sources with S (90 GHz) > 1 Jy, of which 12 were quasars, with the IPC detector on the EINSTEIN observatory. Twentyfour of these sources produced a positive X-ray detection, and the 90 GHz to X-ray spectral index α_{mx} was found to be tightly clustered around a mean value $<\alpha_{mx}> = 1.02$ with standard deviation 0.05, which corresponds to a factor of only 2.2 in the ratio of the 90 GHz flux to the X-ray flux. The value $\alpha_{mx} \sim 1$ is consistent with the value expected for the synchrotron self-Compton mechanism. A single synchrotron spectrum from the millimetre to X-ray wavelengths with slope unity could also explain the observations, but in this case an additional component for the optical and uv continuum would be required, since the flux in these bands lies substantially above the millimetre to X-ray extrapolation.

A sample of optical and radio quasars with known X-ray luminosity was observed by Owen and Puschell (1982) for possible 90 GHz emission. Only 21 of the 51 sources observed were detected at 90 GHz, and α_{mx} was found to have a much wider range than for the strong millimetre sources. Most optical quasars observed were not detected. It is clear from these observations that the X-ray emission from quasars cannot in general be attributed to the inverse Compton scattering of millimetre photons.

Tananbaum et. al. (1983) have observed a complete sample of 33 3 CR radio quasars in such a way as to produce a positive X-ray detection in every case. Study of the Spearman rank and partial rank correlation coefficients for this sample showed that the X-ray luminosity L_x was tightly correlated with the optical luminosity L_{op}. But L_x showed no correlation either with the total radio luminosity L_t or the redshift z. Tananbaum et. al. argued that the lack of correlation with L_t could be because for the 3 CR sample, which was initially selected at 178 MHz, L_t is dominated by radio lobe emission, which might not be related to the X-ray emission. They therefore considered a restricted sample of 13 "triple" 3 CR quasars with radio core luminosity known from Cambridge 5 km - telescope maps. A rank correlation was found between Log $(L_x/L_{op}^{0.5})$ and α_{ro} at the 98.5 percent confidence level.

3. RELATIONSHIP BETWEEN X-RAY AND RADIO EMISSION - CURRENT STATUS

There are indications from the X-ray variability data on quasars and high spatial resolution X-ray observations of active galaxies that a significant fraction of the X-ray emission arises in a compact region. X-rays could also arise from the extended radio jets because of the 'in situ' acceleration of electrons in knots, for instance, or the inverse Compton scattering of the cosmic microwave background photons. It is therefore necessary to consider separately the correlation of X-ray emission with core and extended radio emission.

Radio maps at 6 cm with a resolution of a few seconds of arc are now available for a large number of radio quasars with EINSTEIN X-ray observations. In particular, such maps are now available for all the radio quasars from the samples of Ku et. al. (1980) and Zamorani et. al. (1981). The radio data includes VLA observations at 6 and 20 cm of a sample of 35 radio quasars by A. Kembhavi and E. Feigelson, made explicitly to extend the sample available for the study of X-ray/radio correlations.

An exhaustive correlation study of 44 radio quasars with observed extended radio emission and X-ray emission was made by Feigelson, Isobe and Kembhavi (1984). The only significant correlation observed was between the X-ray luminosity L_X and the 178 MHz radio lobe luminosity, with the Spearman rank correlation coefficient $\rho_S = 0.39$, for 39 sources including 4 upper limits for which worst ranks were assumed. This is significant at the 98.5 percent level. No significant correlation was observed between L_X and 5 GHz radio emission, or between L_X and any of the radio spectral or morphological properties like the linear diameter of the radio source, the asymmetry parameter denoting the ratio of distances between the core to the two lobes, or the bending angle between the vectors which connect the core to each lobe. Even the L_X/ L_{178} correlation could be partly due to the exclusion of quasars with high L_X but low L_{178}, which could have extended structure below the resolution or dynamic range of the radio maps.

In contrast to the situation with quasars, X-ray emission is tightly correlated with 178 MHz and 5 GHz emission in 3 CR radio galaxies (Feigelson and Berg 1983, Fabbiano et al. 1984). This difference could be due to different production mechanisms for the X-ray emission in the two cases. In the case of quasars the X-ray emission is predominantly of nuclear origin, whereas in the case of radio galaxies it could have a significant component arising in a hot, diffuse interstellar or intracluster medium. Since such a gas would affect the extended radio structure, correlations of the type observed are expected.

The relationship between X-ray emission and radio core emission in radio quasars has been explored in detail by Kembhavi, Feigelson and Singh (1985). The sample here consists of 116 sources, for each one of which either the core radio luminosity at 6 cm is known, or the radio source is unresolved at the scale of a few arcseconds, in which case the whole emission is attributed to the core (see Kembhavi et al. 1985 for the data and details of the analysis). The search for statistical association is based on linear regression analysis in the logarithmic luminosity plane :

$$\mathrm{Log}\ L_X = b\ \mathrm{Log}\ L_r + \mathrm{constant},$$

where L_X is now the 0.5-4.5 keV X-ray luminosity and L_r the 5 GHz radio core luminosity. Possible spurious correlation between the luminosities, due to the use of redshifts in evaluating them, is examined using the partial rank correlation coefficient, and a correlation accepted as genuine only when this is not significant. X-ray upper limits are ignored in the analysis because they constitute only ∿ 10 percent of the sample.

The main results which emerge are the following : (i) There is a very highly significant (confidence level > 99.99 percent) correlation in the whole sample, with $L_x \sim L_r^{0.42\pm.04}$. (ii) The scatter at lower luminosities (see Fig. 1) is much reduced if the sample is split up into subsamples such as unresolved sources, cores of resolved sources, sources with the 6-20 cm core spectral index $\alpha_6^{20} > 0.3$ and those with $\alpha_6^{20} < 0.3$. The regression lines for two subsamples are shown in Fig. 1. (iii) There is a tendency for subsamples with steeper core spectra to have lower log L_x/log L_r slopes. The differences in slope are statistically significant. (iv) The steepest slope is obtained for unresolved sources with $\alpha_6^{20} < 0.3$, for which $L_x \sim L_r^{0.71\pm.07}$ (note that 0.3 is used as a dividing line only because a change of slope occurs around this value, one possible reason for which is discussed below. No particular significance is to be attached to the precise value used). (v) The flattest slope, $L_x \sim L_r^{0.35\pm.04}$, is obtained for the cores of resolved quasars.

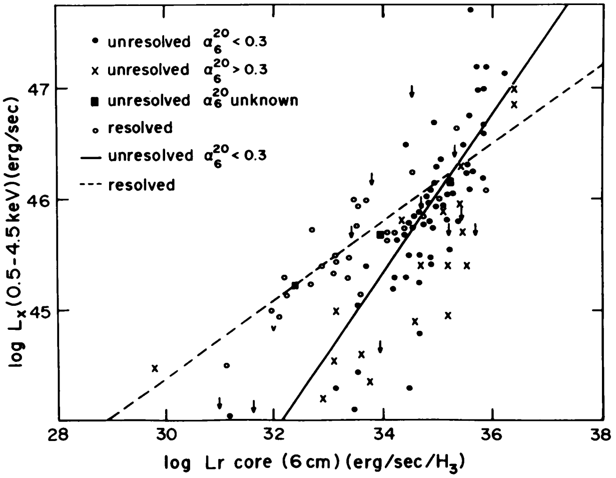

Fig. 1

The flattening of the radio/X-ray slope as one passes to quasars with steeper 6-20 cm radio spectra may be due to the presence, in the presently unresolved radio cores, of extended steep spectrum radio emission which is not related to the X-ray emission. High resolution X-ray observations of Centaurus A (see Feigelson 1982 for a review) show that the radio jet contributes only ∿ 1 percent of the X-ray flux. With this in mind we assume that the core radio luminosity L_r may be written as $L_r = L_c + L_e$, where L_c arises in a compact region on the VLBI scale, and is related to the X-ray emission, whereas L_e is steep spectrum extended emission which makes a negligible contribution to the X-ray emission. Since we are observationally limited to considering the correlation between L_x and L_r, the slope of the regression line obtained is

$$b' = \frac{d(\mathrm{Log}\ L_x)}{d(\mathrm{Log}\ L_r)} = b\,\frac{d(\mathrm{Log}\ L_c)}{d(\mathrm{Log}\ L_r)}\ , \qquad (1)$$

where $b = d(\mathrm{Log}\ L_x)/d(\mathrm{Log}\ L_c)$ is the slope of the true regression line. If we assume that $L_e = f(L_c)$, it can be shown quite generally (Kembhavi et. al. 1985) that b' may be written as

$$b' = b \times \frac{1 + L_e/L_c}{1 + \gamma L_e/L_c}\ , \qquad (2)$$

where γ is a constant which enters the functional form of $f : L_e \sim L_c^{\gamma}$. For $\gamma > 1$, $b' < b$, with the value of b' determined by b and the proportion of extended radio emission present in the now unresolved radio core.

To determine b, we note that the mean value of L_e/L_c, at 6 cm, for a given subsample may be expressed as

$$\frac{L_e}{L_c}\,(6\ \mathrm{cm}) \simeq -\,\frac{(y^{\alpha_c} - y^{\alpha_r})}{(y^{\alpha_e} - y^{\alpha_r})}\ , \qquad (3)$$

where $y = 20/6$, α_c is the core spectral index, α_e is the extended emission spectral index, and α_r is the mean observed spectral index α_6^{20} of the presently unresolved radio emission. α_c and α_e have the same values for all subsamples. Using eqn. (3), it may be seen that the right hand side of equation (1) contains the 4 unknowns b, γ, α_c and α_e. Comparing the slopes of 2 subsamples at 6 and 20 cms, 4 equations of the type of equation (1) containing the four unknowns may be obtained. It is possible to solve these equations to obtain values for the 4 unknown parameters. Using the subsamples of unresolved quasars with $\alpha_6^{20} > 0.3$ and $\alpha_6^{20} < 0.3$ gives $b = 0.75$, $\gamma = 1.8$, $\alpha_c = -\ 0.24$ and $\alpha_e = 0.65$. If instead the subsamples $\alpha_6^{20} > 0.3$ and unresolved $\alpha_6^{20} < 0.3$ are used, the values obtained are $b = 0.76$, $\gamma = 1.41$, $\alpha_c = -0.42$ and $\alpha_e = 0.62$. The value of b obtained here may be considered to be the "ultimate" slope of the X-ray/radio regression line for our radio quasar sample.

If the first set of values for the unknown parameters are applied to the subsample of the cores of resolved quasars, it is found that $\langle L_e/L_c \rangle = 3$, $\langle \alpha_r \rangle = 0.5$. The spectral index α_6^{20} is unknown for many of the cores of the resolved quasars. If future observations show that the unknown α_6^{20} are considerably smaller than 0.5, then some additional mechanism must operate in these objects to lower the X-ray/radio regression line slope relative to the slope of the unresolved flat spectrum objects. It can be noticed from Fig. (1) that the cores of resolved quasars have considerably stronger X-ray emission, for a given radio core luminosity, than an unresolved object with the same radio luminosity.

This effect will be further enhanced if the X-ray/radio regression line slope for these objects is increased by some mechanism of the type described above. This "excess" emission may be traced to the relatively lower values of α_{ro} compared to other subsamples. Lower α_{ro} values imply a higher optical luminosity for a given radio luminosity. The optical contribution to the X-ray emission in these objects is therefore higher, increasing their total X-ray luminosity to values higher than those for other subsamples.

The X-ray/radio slope for the flat spectrum quasars, 0.71±0.07, is identical to the X-ray/optical and optical/radio slopes of the corresponding regression lines, 0.71±0.07 and 0.70±0.09 respectively, for the same subsample. The identity persists even if the "ultimate" X-ray/radio slope mentioned above is considered. The reason for this equality of slopes is not clear. Since a proportionality between the various luminosities is expected on simple physical grounds, it is possible that the observed slopes are obtained due to some unknown selection effect.

4. SIMULTANEOUS CORRELATION OF X-RAY LUMINOSITY WITH RADIO AND OPTICAL LUMINOSITY

Many lines of evidence suggest that the X-ray emission from a quasar contains independent contributions from mechanisms associated with the production of optical and radio continuum radiation. Some of these are: (1) Optically selected quasars which are relatively radio quiet can be strong X-ray sources. (2) The presence of strong radio emission enhances the X-ray emission. (3) "Optically quiet" radio sources are relatively weaker in their X-ray emission compared to quasars with the same level of radio emission (Ledden and O'Dell 1983). (4) The X-ray luminosity shows strong independent statistical correlation with radio and optical luminosity. It is therefore necessary to consider the simultaneous fit of L_x to L_{op} and L_r. The condition to be imposed on any such a fit is that it should reproduce the 2-dimensional correlations already known.

The 2-dimensional Log/Log correlations described above suggest the natural extension to 3 dimensions:

$$\text{Log } L_x = b_{op} \text{ Log } L_{op} + b_r \text{ Log } L_r + \text{constant}. \qquad (4)$$

For radio quiet sources this will produce the observed X-ray/optical correlation. For a sample of radio quasars, a series of parallel lines with slope b_{op} will be observed in the X-ray/radio plane, producing the kind of 2-dimensional fits we have considered above. The slope of the 2-dimensional fit can be somewhat steeper than b_r in equation (2) because low L_{op} values will dominate for lower L_r and high L_{op} values at the high radio luminosity end. Tananbaum et. al. (1983) have found, for the sample of 33 3 CR quasars mentioned in Section 1 that $b_{op} = 0.47 \pm 0.15$ and $b_r = 0.14 \pm 0.12$. The weak radio dependence here is of course due to the dominant radio lobe emission. For the subsample of unresolved quasars with $\alpha_6^{20} < 0.3$, we find $b_{op} = 0.44$ and $b_r = 0.39$, with 1σ errors of $\sim$ 10 percent. Accepting a fit of the type described by equation (4) would require one to find a physical basis for the relationship

$$L_x \sim (L_{op})^{b_{op}} \, (L_r)^{b_r} \, .$$

Another 3-dimensional fit has been suggested by Zamorani (1983). Here one simply adds together the optical and radio related contributions to the X-ray emission:

$$L_x = A_{op} \, (L_{op})^{b_{op}} \; + \; A_r \, (L_r)^{b_r} \, , \qquad (5)$$

where A_{op} and A_r are constants. Zamorani (1983) reports the best fit values $b_{op} = 0.75 \pm 0.90$ and $b_r = 0.95 \pm 0.15$ for flat spectrum quasars. It has not been possible to find a least squares minimum for the above fitting function for the subsample of unresolved quasars with $\alpha_6^{20} < 0.3$. However, we will provisionally accept Zamorani's values to see the behaviour of the function in 2 dimensions. Then equation (5) may be written as

$$\text{Log}\, L_x \;=\; \text{Log}(\, L_{op}^{0.75} \; + \; 5 \times 10^{-10} \, L_r^{0.95}\,) + 21.9 \, . \qquad (6)$$

The lines described by this function for various values of L_{op} are shown in Fig.2. It is clear that in the region populated by the unresolved, flat spectrum quasars, a behaviour of the form $L_x \sim (L_r)^{b_r}$ may be simulated. The horizontal portions of the L_{op} = constant lines are however an embarassment, but the situation might improve if the cores of resolved quasars which have a flatter Log / Log slope are included. Much work remains to be done on the 3 dimensional models.

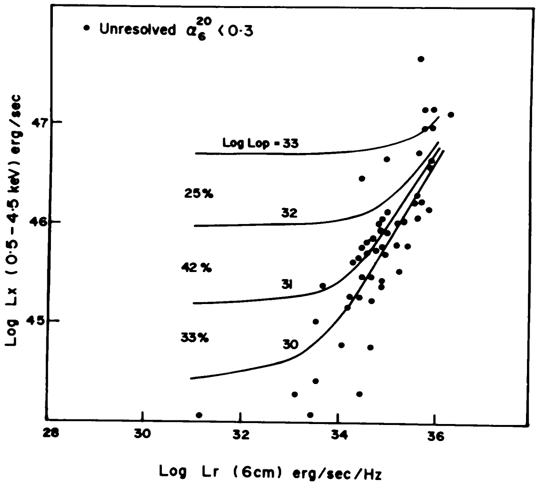

Fig. 2: Lines of constant L_{op} are shown. The percentage of sources in each luminosity interval is indicated.

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