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BEAMED AND UNBEAMED X-RAY EMISSION IN FR1 RADIO GALAXIES

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NASA Grant NAG5-1882

Performance Report No. 8

For the Period 16 December 1996 through 15 December 1997

Principal Investigator
Dr. Diana M. Worrall

December 1997

Prepared for:

National Aeronautics and Space Administration
Goddard Space Flight Center
Greenbelt, Maryland 20771

Smithsonian Institution
Astrophysical Observatory
Cambridge, Massachusetts 02138

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Mark Birkinshaw's recent re-write of our radial-fitting software, known as *radial*, has allowed a wider variety of models of the central X-ray structures in radio galaxies to be fitted. Furthermore, the superposition of several models can now be fitted simultaneously, whereas this was previously possible only for the limited combination of one β model, appropriate for gas in hydrostatic equilibrium, and a point source. In particular, the new ability to model a central cooling flow will allow us to determine better the likelihood that such cooling gas is a significant contributor to emission which is essentially unresolved with the PSPC. A paper reporting detailed results for all those sample radio galaxies which were observed by us with the PSPC is currently being drafted.

For sample radio galaxies observed only with the HRI, our main difficulty has been that image blurring, caused by ROSAT aspect problems, has made it difficult for us to determine whether or not small extensions seen in some sources are real. We have looked into this issue in some depth, via consultation with Guenther Hasinger from the ROSAT project in Germany and Dan Harris from the US-RSDC at SAO. Assisted by preliminary versions of IRAF scripts being written by John Silverman and Dan Harris for distribution by the US-RSDC, we have investigated this problem in the context of a somewhat brighter source, a BL Lac-like radio source earlier identified as interesting by Tananbaum et al. (1997, ApJ, 476, 83), and our results appear in a paper by Worrall et al. in the final stages of preparation. An empirical treatment of the image blurring caused by the ROSAT aspect problems has also now been incorporated into *radial*, so that we are getting improved reliability for separating point-source AGN components from extended components.

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Procs. Conference 'Relativistic Jets in AGNs', Cracow, May 1997

X-ray Emission from Jets in Centrally Obscured AGN

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Abstract: There is good evidence for X-ray emission associated with AGN jets which are relativistically boosted towards the observer. But to what jet radius does such X-ray emission persist? To attempt to answer this question one can look at radio galaxies; their cores are sufficiently X-ray faint that any unbeamed X-ray emission in the vicinity of the central engine must be obscured. The jets of such sources are at unfavourable angles for relativistic boosting, and so their relatively weak X-ray emission must be carefully separated from the plateau of resolved X-ray emission from a hot interstellar, intragroup, or intracluster medium on which they are expected to sit. This paper presents results arguing that jet X-ray emission is generally detected in radio galaxies, even those of low intrinsic power without hot spots. The levels of emission suggest an extrapolated radio to soft X-ray spectral index, α_{rx}, of about 0.85 at parsec to perhaps kiloparsec distances from the cores.

1 High-Power Jets

Other papers in this volume amply illustrate an association of the X-ray emission of γ-ray emitting quasars and BL Lac objects with synchrotron emission or Compton scattering in a relativistic jet strongly boosted in the line of sight towards the observer. However, the correlation of X-ray emission with core-radio emission which is so striking in core-dominated quasars (see e.g. Fig. 1) does not extend to lobe-dominated quasars, suggesting that in addition to highly anisotropic jet-related emission there is an X-ray component which is considerably more isotropic (Zamorani 1984; Worrall et al. 1987). X-ray spectral measurements lend support to the idea that this second component (1) is associated with emission from the vicinity of the central engine and (2) may be similar to the dominant X-ray component in radio-quiet quasars (Wilkes and Elvis 1987).

The X-ray central component is either absent or obscured in radio galaxies, since as a class they are considerably fainter than radio-quiet quasars. Obscuration is in line with Unification models, and implies that any AGN-related X-ray

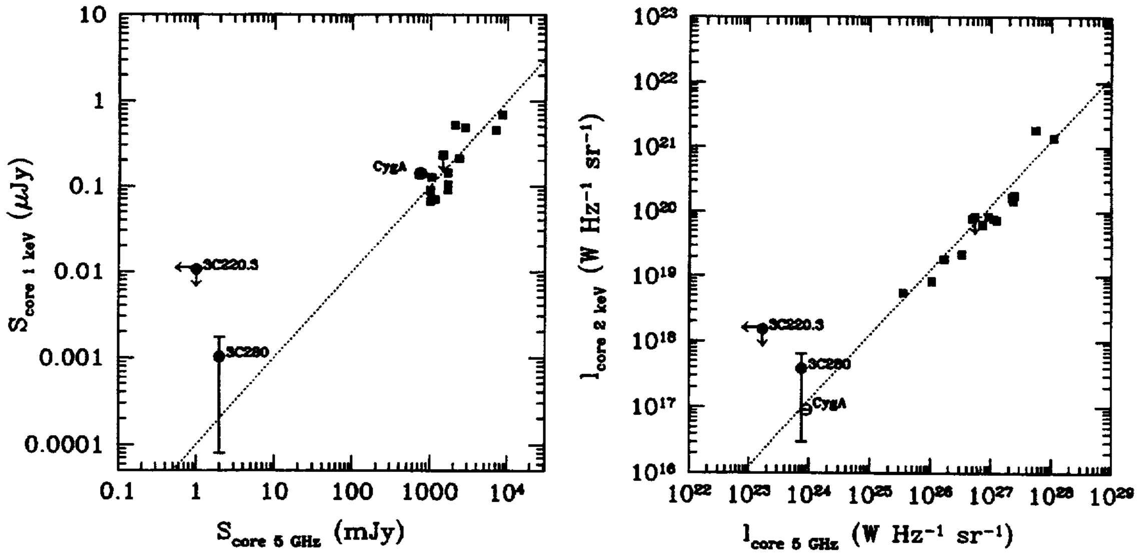

Fig. 1. 3C quasars and radio galaxies matched in isotropic radio power and redshift: Total (= core) X-ray *vs* core radio emission for core-dominated quasars (squares) and core X-ray *vs* core radio for radio galaxies 3C 280 and 3C 220.3 (circles) from Worrall et al. (1994). See text for discussion of Cygnus A. Flux-density plot on the left; Luminosity density on the right $[H_o = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}]$. Lines of slope unity are drawn for reference, and the correlation gives an extrapolated radio to X-ray spectral index $\alpha_{rx} \simeq 0.86$.

emission measured in radio galaxies is either seen through a large absorbing column of neutral gas or originates in the jet at a radius beyond the obscuration.

The 3C radio survey selects the sources brightest in low-frequency (and thus predominantly unbeamed) radio emission, but the distributions of total unbeamed radio power (a key parameter in the selection of sources believed to differ only though orientation) for its quasars and galaxies overlap only at the highest powers (Laing, Riley & Longair 1983). In a flux-limited survey like 3C, high power means a bias towards high redshift. So, to view a powerful radio-loud quasar oriented as a twin-jet radio source we are forced towards redshifts ≥ 0.4, where only very long exposures with ROSAT detect radio galaxies in the X-ray (e.g., Crawford & Fabian 1996). Where enough counts are present to measure source extent, it is generally found that the galaxies are resolved, and so much or all of the emission is thought to be associated with X-ray emitting gas of cluster dimension.

For the $z = 1$ radio galaxy 3C 280, Worrall et al. (1994) were so bold as to attempt a separation of resolved and unresolved X-ray emission. They found that the unresolved X-rays fitted on an extrapolation of the X-ray to core-radio proportionality found for core-dominated quasars (Fig. 1), and claimed this as evidence for a jet related component of X-ray emission in the host radio galaxies of quasars.

Cygnus A, with a 5 GHz $0.4''$-resolution core-radio flux density of 750 mJy (Carilli & Barthel 1996) is well matched to 3C 280 in core and total radio power and is unique for its proximity. X-ray spectra taken with EXOSAT and *Ginga* have found evidence for core emission absorbed by a column density of $\sim 4 \times 10^{23}$ cm^{-2} (Arnaud et al. 1987; Ueno et al. 1994). The high absorption implies this component should not have been detected in the 42 ks ROSAT HRI exposure because of the HRI's lower-frequency X-ray response, and yet an unresolved core X-ray component of 270 ± 60 net counts was seen (Harris et al. 1994). I suggest that the low-frequency HRI core component instead arises from the jet in regions where the only absorption along the line of sight is the Galactic value of 3.3×10^{21} cm^{-2}. For a power-law spectrum of energy index 1.0 the HRI counts correspond to a 1 keV flux density of 0.13 μJy. With this assumption, I have plotted Cygnus A on Fig. 1. The remarkable agreement with the correlation suggests that the correct interpretation for the low-energy X-ray core of Cygnus A is unobscured jet-related emission.

The search for jet-related X-ray emission from powerful radio galaxies must concentrate on soft X-ray energies, where the contribution from highly absorbed core X-ray emission is negligible, and galaxies devoid of the broad emission-lines which may indicate a partially unobscured view of the central engine. Results are encouraging and suggest that the X-ray emission from powerful radio galaxies should not be interpreted merely as a mixture of absorbed-core and hot-gas components.

2 Low-Power Jets

Strong cases have been made that BL Lac objects and quasars should be treated separately because of divergent properties and likely different host populations: low-power FRI radio galaxies for BL Lacs, and high-power, hotspot, FRII radio galaxies for quasars (e.g., Browne 1989). I've argued that for high-power sources the viewing-angle progression goes from radio galaxy (where X-rays from the central engine suffer obscuration) to lobe-dominated quasar (where X-rays from the central engine can be seen) to core-dominated quasar (where X-rays from the central engine become swamped by beamed jet emission). However, the equivalent of lobe-dominated BL Lac objects are not readily identified. This begs the question as to whether or not the central engine of a BL Lac object is X-ray bright. What is clear is that unresolved X-ray emission from low-power radio galaxies is sufficiently faint and well correlated with core radio strength (see later) that as in the case of quasar host galaxies, any substantial unbeamed X-ray emission in the vicinity of the central engine must be obscured.

Ulrich (1989) has shown that the B2 radio-galaxy sample (complete set of 50 sources from the B2 radio survey, $S_{408\mathrm{MHz}} \geq 0.25$ Jy in 6.7% of the sky, identified with elliptical galaxies brighter than $m_{\mathrm{ph}} = 15.7$) is well matched to radio-selected BL Lac objects in their extended radio properties and galaxy magnitudes. This sample, now mostly observed in ROSAT pointed observations with the PSPC or the HRI or both, is therefore an ideal testbed for Unification models and derivation of X-ray beaming factors using methods similar to those of Padovani & Urry (1990), but with the added advantage of X-ray component separation.

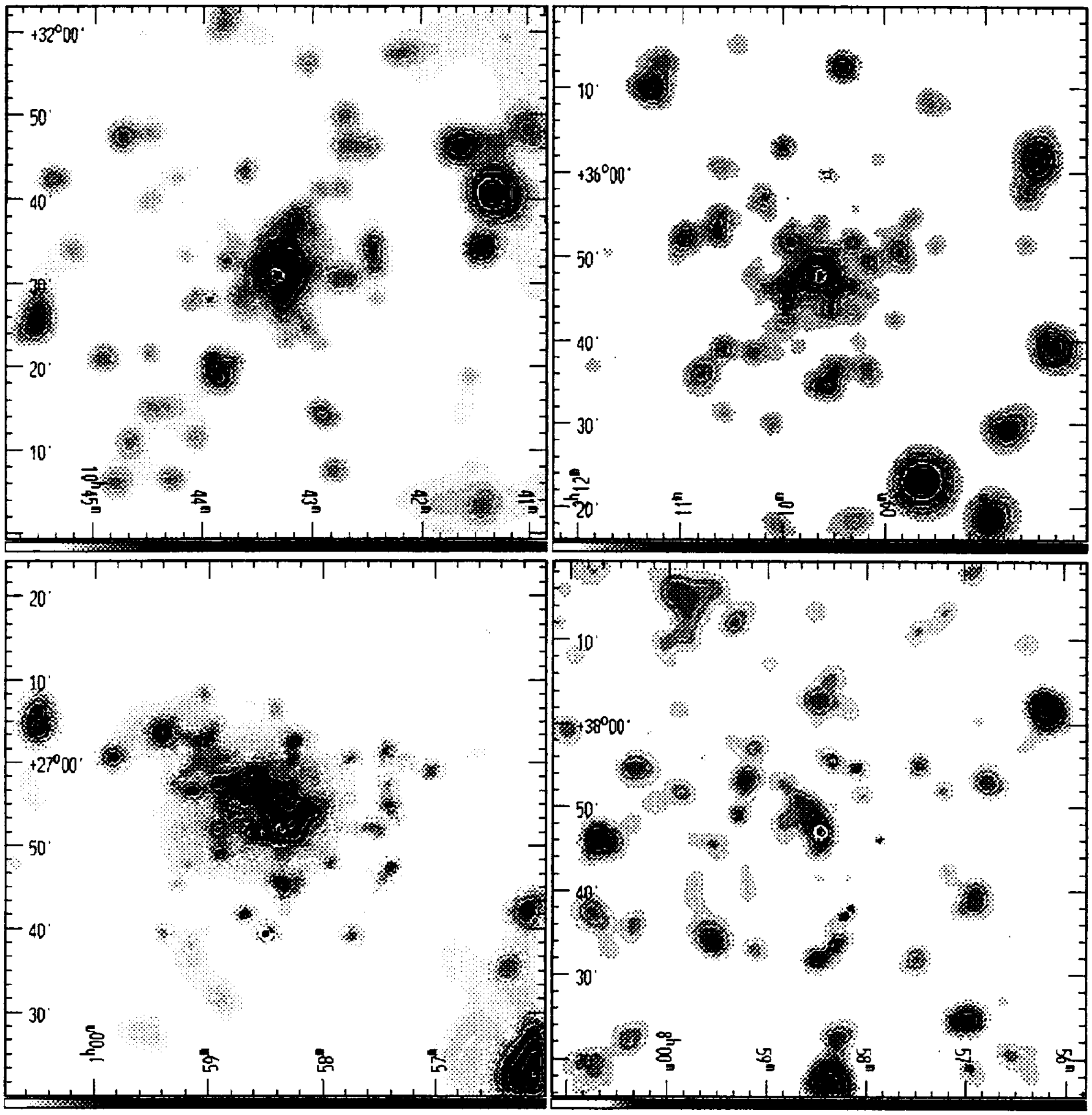

Fig. 2. ROSAT PSPC observations of 1.3 square degree fields centered on four B2 sample radio galaxies of similar redshift, illustrating diversity in the amount and extent of resolved (thermal) X-ray emission relative to the unresolved core. Clockwise from top left: (a) B2 1040+30, $z = 0.036$ (b) 4C 35.03, $z = 0.0375$ (c) NGC 2484, $z = 0.0413$ (d) NGC 326, $z = 0.047$. 10 arcmin corresponds to between 600 & 770 kpc, depending on z, for $H_o = 50$ km s^{-1} Mpc^{-1}. [From Worrall et al. 1997, in preparation.]

The importance of component separation is illustrated in Fig. 2, which shows images from ROSAT PSPC $\simeq 20$ ks pointed exposures of four B2 radio galaxies. Analysis of these and other sample members finds some amount of unresolved X-ray emission in them all, but the fraction of the total emission that is unresolved varies from a few per cent to more than 70%. The resolved emission varies in scale size from galaxy to group to cluster dimension and is associated with hot gas. The

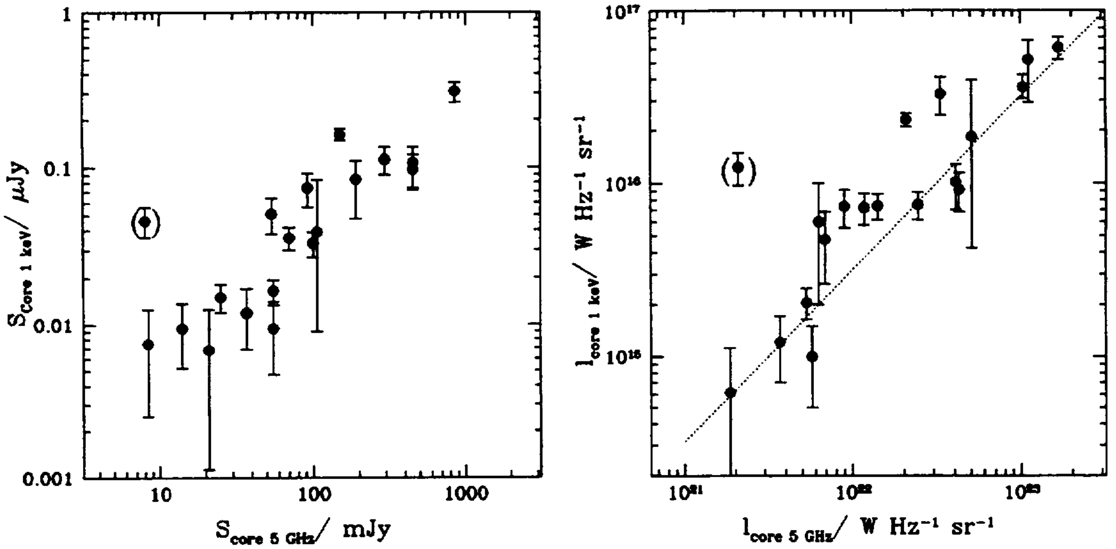

Fig. 3. Unresolved X-ray versus core radio emission for a subset of 17 B2 sources together with NGC 6251 and NGC 4261: Flux-density plot on the left; Luminosity density on the right $[H_o = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}]$ with line of slope unity drawn for reference and giving an extrapolated radio to X-ray spectral index $\alpha_{rx} \simeq 0.85$. The bracketed point represents a source which shows an atypical X-ray structure where only part of the apparent core X-ray flux is believed to be associated with the radio core.

unresolved X-ray emission is correlated with core radio emission; Fig. 3 extends the work of Worrall & Birkinshaw (1994). The earlier claim of an X-ray/core-radio correlation from *Einstein* data (Fabbiano et al. 1984) is now greatly strengthened by a larger sample of X-ray detected sources and careful component separation. The extrapolated radio to soft X-ray spectral index, α_{rx}, has the same value of $\simeq 0.85$ for high-power and low-power jets within errors.

The $\sim 5''$ angular resolution of ROSAT with the HRI is unfortunately not met due to smearing caused by errors in ROSAT's attitude determination. If the apparent resolution of some cores on scale sizes between about $5''$ and $8''$ is taken as real, and the X-ray emission is modelled as X-ray emitting gas in hydrostatic equilibrium, typical cooling times for the gas are $< 8 \times 10^8$ yrs. The fact that this is much less than a Hubble time ($\sim 2 \times 10^{10}$ yrs) does not favour a thermal explanation for the small-scale X-ray emission.

Since $8''$ corresponds typically to about 8 kpc for the B2 sample, Fig. 3 can be interpreted as the observation of jet-related X-ray emission out to this jet radius. However, since in low-power sources it is not certain that the centre is obscured (see above) it could be argued that the X-rays might come from very central regions. To investigate this further it is interesting to consider the radio galaxy M87, 16 Mpc away, from which X-rays are detected in knot A at about 0.95 kpc from the nucleus. At a 5 GHz flux density of 1.7 Jy and a 1 keV flux density of 0.34 μJy (Biretta et al. 1991), knot A fits rather well on the correlation of Fig. 3. Similarly X-ray emission is associated with several radio features in the jet of Cen A, 3.5 Mpc away. Knot B at 1 kpc from the nucleus is perhaps the best separated from surrounding emission in both the X-ray and radio; Clarke et al. (1992) report a 5 GHz flux density of 314 mJy, and the X-ray luminosity reported by Döbereiner et al. (1996) corresponds to 0.12 μJy, again fitting the correlation. Were M87 and Cen A at the distances of the B2 galaxies, the knot emission would be within the region regarded as the radio and X-ray core. So, in at least two nearby cases jet-related X-ray emission is present at the expected level. Birkinshaw & Worrall (1993) point out that the X-ray non-detection of a radio feature at $\sim$ 10 kpc from the core of the more distant $z = 0.024$ radio galaxy NGC 6251 is at a jet radius where local electron acceleration is not required. This X-ray non-detection, which is inconsistent with Fig. 3, may then be indicative of the changing conditions at larger jet radii which result in the B2 sample displaying a poor correlation of *total* radio power and core X-ray emission.

Results show measurable levels of jet-related X-ray emission in low-power radio galaxies, with $\alpha_{rx} \simeq 0.85$. Radio-selected BL Lac objects from the 1 Jy sample have a similar $\bar{\alpha}_{rx}$ (Sambruna et al. 1996) and fit on an extrapolation of Fig. 3 but with a dispersion in S_x of a factor > 50 whose size, compared to the tight correlation for quasars (Fig. 1), needs accounting for when different emission models are applied to the data.

Acknowledgements. I thank Mark Birkinshaw, Tino Canosa, and Martin Hardcastle for discussions and for contributing to results reported in this paper. I thank the organizers for a stimulating workshop and am grateful for support from PPARC grant GR/K98582 & NASA grant NAG 5-1882.

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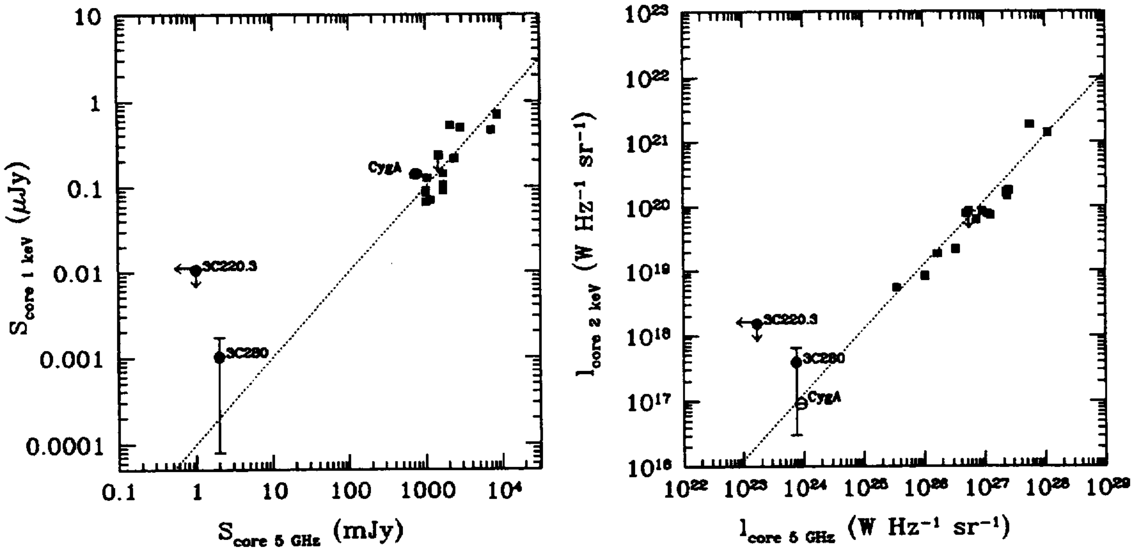

Fig. 1. 3C quasars and radio galaxies matched in isotropic radio power and redshift: Total (= core) X-ray *vs* core radio emission for core-dominated quasars (squares) and core X-ray *vs* core radio for radio galaxies 3C 280 and 3C 220.3 (circles) from Worrall et al. (1994). See text for discussion of Cygnus A. Flux-density plot on the left; Luminosity density on the right [$H_o = 50$ km s^{-1} Mpc^{-1}]. Lines of slope unity are drawn for reference, and the correlation gives an extrapolated radio to X-ray spectral index $\alpha_{rx} \simeq 0.86$.

emission measured in radio galaxies is either seen through a large absorbing column of neutral gas or originates in the jet at a radius beyond the obscuration.

The 3C radio survey selects the sources brightest in low-frequency (and thus predominantly unbeamed) radio emission, but the distributions of total unbeamed radio power (a key parameter in the selection of sources believed to differ only though orientation) for its quasars and galaxies overlap only at the highest powers (Laing, Riley & Longair 1983). In a flux-limited survey like 3C, high power means a bias towards high redshift. So, to view a powerful radio-loud quasar oriented as a twin-jet radio source we are forced towards redshifts ≥ 0.4, where only very long exposures with ROSAT detect radio galaxies in the X-ray (e.g., Crawford & Fabian 1996). Where enough counts are present to measure source extent, it is generally found that the galaxies are resolved, and so much or all of the emission is thought to be associated with X-ray emitting gas of cluster dimension.

For the $z = 1$ radio galaxy 3C 280, Worrall et al. (1994) were so bold as to attempt a separation of resolved and unresolved X-ray emission. They found that the unresolved X-rays fitted on an extrapolation of the X-ray to core-radio proportionality found for core-dominated quasars (Fig. 1), and claimed this as evidence for a jet related component of X-ray emission in the host radio galaxies of quasars.

Cygnus A, with a 5 GHz 0.4″-resolution core-radio flux density of 750 mJy (Carilli & Barthel 1996) is well matched to 3C 280 in core and total radio power and is unique for its proximity. X-ray spectra taken with EXOSAT and *Ginga* have found evidence for core emission absorbed by a column density of $\sim 4 \times 10^{23}$ cm^{-2} (Arnaud et al. 1987; Ueno et al. 1994). The high absorption implies this component should not have been detected in the 42 ks ROSAT HRI exposure because of the HRI's lower-frequency X-ray response, and yet an unresolved core X-ray component of 270 ± 60 net counts was seen (Harris et al. 1994). I suggest that the low-frequency HRI core component instead arises from the jet in regions where the only absorption along the line of sight is the Galactic value of 3.3×10^{21} cm^{-2}. For a power-law spectrum of energy index 1.0 the HRI counts correspond to a 1 keV flux density of 0.13 μJy. With this assumption, I have plotted Cygnus A on Fig. 1. The remarkable agreement with the correlation suggests that the correct interpretation for the low-energy X-ray core of Cygnus A is unobscured jet-related emission.

The search for jet-related X-ray emission from powerful radio galaxies must concentrate on soft X-ray energies, where the contribution from highly absorbed core X-ray emission is negligible, and galaxies devoid of the broad emission-lines which may indicate a partially unobscured view of the central engine. Results are encouraging and suggest that the X-ray emission from powerful radio galaxies should not be interpreted merely as a mixture of absorbed-core and hot-gas components.

2 Low-Power Jets

Strong cases have been made that BL Lac objects and quasars should be treated separately because of divergent properties and likely different host populations: low-power FRI radio galaxies for BL Lacs, and high-power, hotspot, FRII radio galaxies for quasars (e.g., Browne 1989). I've argued that for high-power sources the viewing-angle progression goes from radio galaxy (where X-rays from the central engine suffer obscuration) to lobe-dominated quasar (where X-rays from the central engine can be seen) to core-dominated quasar (where X-rays from the central engine become swamped by beamed jet emission). However, the equivalent of lobe-dominated BL Lac objects are not readily identified. This begs the question as to whether or not the central engine of a BL Lac object is X-ray bright. What is clear is that unresolved X-ray emission from low-power radio galaxies is sufficiently faint and well correlated with core radio strength (see later) that as in the case of quasar host galaxies, any substantial unbeamed X-ray emission in the vicinity of the central engine must be obscured.

Ulrich (1989) has shown that the B2 radio-galaxy sample (complete set of 50 sources from the B2 radio survey, $S_{408\mathrm{MHz}} \geq 0.25$ Jy in 6.7% of the sky, identified with elliptical galaxies brighter than $m_{\mathrm{ph}} = 15.7$) is well matched to radio-selected BL Lac objects in their extended radio properties and galaxy magnitudes. This sample, now mostly observed in ROSAT pointed observations with the PSPC or the HRI or both, is therefore an ideal testbed for Unification models and derivation of X-ray beaming factors using methods similar to those of Padovani & Urry (1990), but with the added advantage of X-ray component separation.

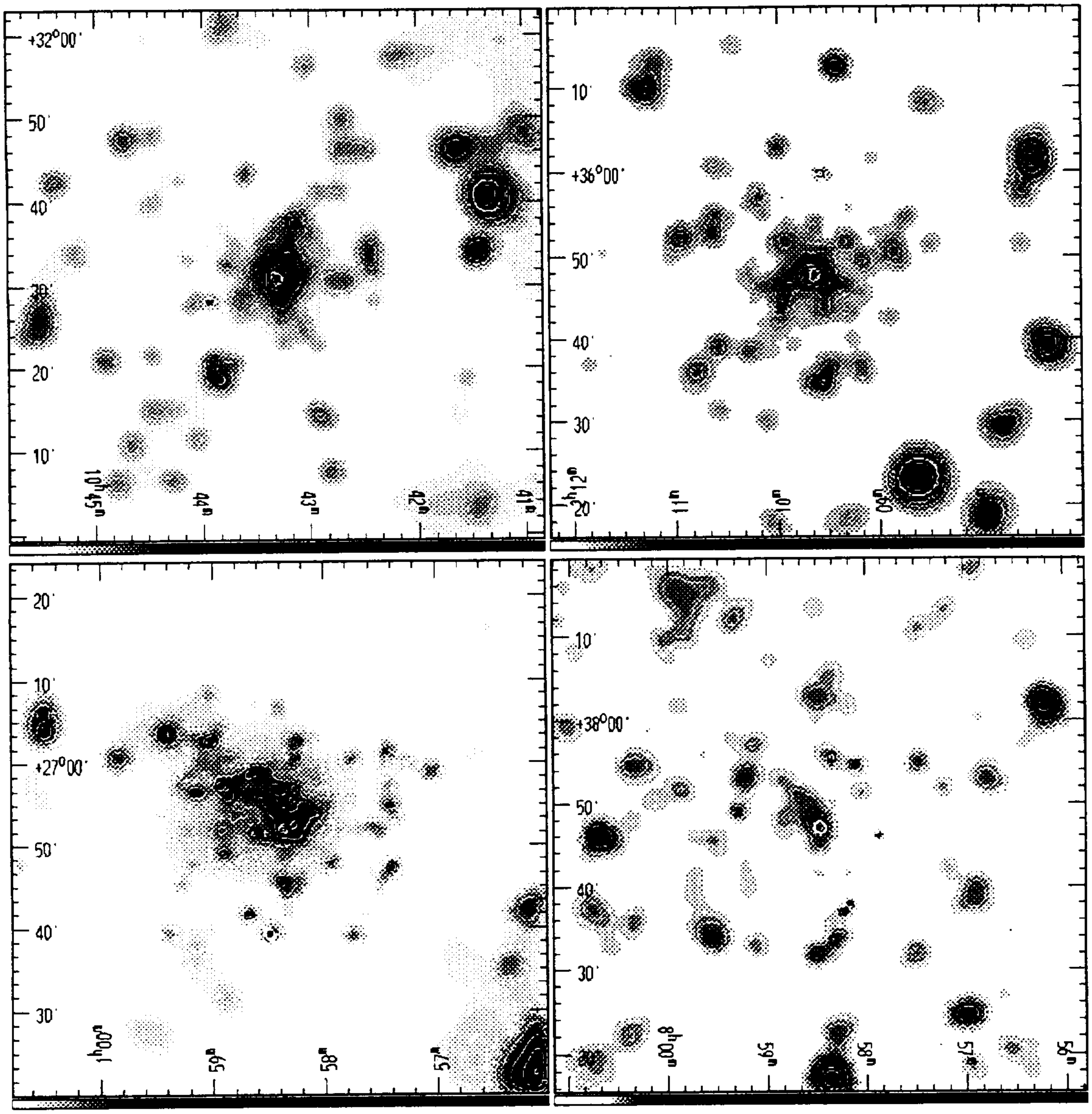

Fig. 2. ROSAT PSPC observations of 1.3 square degree fields centered on four B2 sample radio galaxies of similar redshift, illustrating diversity in the amount and extent of resolved (thermal) X-ray emission relative to the unresolved core. Clockwise from top left: (a) B2 1040+30, $z = 0.036$ (b) 4C 35.03, $z = 0.0375$ (c) NGC 2484, $z = 0.0413$ (d) NGC 326, $z = 0.047$. 10 arcmin corresponds to between 600 & 770 kpc, depending on z, for $H_o = 50$ km s^{-1} Mpc^{-1}. [From Worrall et al. 1997, in preparation.]

The importance of component separation is illustrated in Fig. 2, which shows images from ROSAT PSPC $\simeq 20$ ks pointed exposures of four B2 radio galaxies. Analysis of these and other sample members finds some amount of unresolved X-ray emission in them all, but the fraction of the total emission that is unresolved varies from a few per cent to more than 70%. The resolved emission varies in scale size from galaxy to group to cluster dimension and is associated with hot gas. The

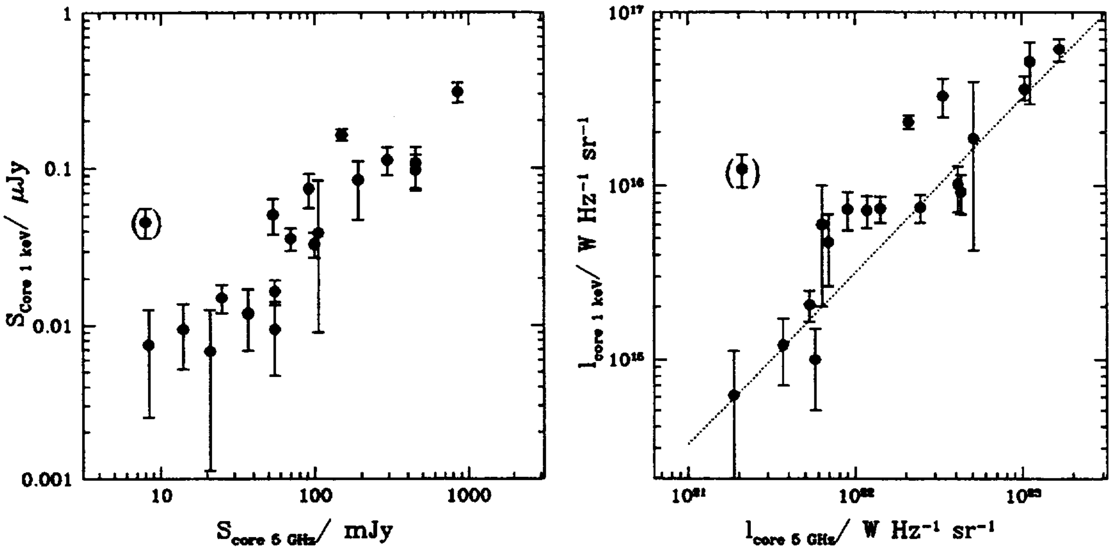

Fig. 3. Unresolved X-ray versus core radio emission for a subset of 17 B2 sources together with NGC 6251 and NGC 4261: Flux-density plot on the left; Luminosity density on the right [$H_o = 50$ km s^{-1} Mpc^{-1}] with line of slope unity drawn for reference and giving an extrapolated radio to X-ray spectral index $\alpha_{rx} \simeq 0.85$. The bracketed point represents a source which shows an atypical X-ray structure where only part of the apparent core X-ray flux is believed to be associated with the radio core.

unresolved X-ray emission is correlated with core radio emission; Fig. 3 extends the work of Worrall & Birkinshaw (1994). The earlier claim of an X-ray/core-radio correlation from *Einstein* data (Fabbiano et al. 1984) is now greatly strengthened by a larger sample of X-ray detected sources and careful component separation. The extrapolated radio to soft X-ray spectral index, α_{rx}, has the same value of $\simeq 0.85$ for high-power and low-power jets within errors.

The $\sim 5''$ angular resolution of ROSAT with the HRI is unfortunately not met due to smearing caused by errors in ROSAT's attitude determination. If the apparent resolution of some cores on scale sizes between about $5''$ and $8''$ is taken as real, and the X-ray emission is modelled as X-ray emitting gas in hydrostatic equilibrium, typical cooling times for the gas are $< 8 \times 10^8$ yrs. The fact that this is much less than a Hubble time ($\sim 2 \times 10^{10}$ yrs) does not favour a thermal explanation for the small-scale X-ray emission.

Since $8''$ corresponds typically to about 8 kpc for the B2 sample, Fig. 3 can be interpreted as the observation of jet-related X-ray emission out to this jet radius. However, since in low-power sources it is not certain that the centre is obscured (see above) it could be argued that the X-rays might come from very central regions. To investigate this further it is interesting to consider the radio galaxy M87, 16 Mpc away, from which X-rays are detected in knot A at about 0.95 kpc from the nucleus. At a 5 GHz flux density of 1.7 Jy and a 1 keV flux density of 0.34 μJy (Biretta et al. 1991), knot A fits rather well on the correlation of Fig. 3. Similarly X-ray emission is associated with several radio features in the jet of Cen A, 3.5 Mpc away. Knot B at 1 kpc from the nucleus is perhaps the best separated from surrounding emission in both the X-ray and radio; Clarke et al. (1992) report a 5 GHz flux density of 314 mJy, and the X-ray luminosity reported by Döbereiner et al. (1996) corresponds to 0.12 μJy, again fitting the correlation. Were M87 and Cen A at the distances of the B2 galaxies, the knot emission would be within the region regarded as the radio and X-ray core. So, in at least two nearby cases jet-related X-ray emission is present at the expected level. Birkinshaw & Worrall (1993) point out that the X-ray non-detection of a radio feature at $\sim$ 10 kpc from the core of the more distant $z = 0.024$ radio galaxy NGC 6251 is at a jet radius where local electron acceleration is not required. This X-ray non-detection, which is inconsistent with Fig. 3, may then be indicative of the changing conditions at larger jet radii which result in the B2 sample displaying a poor correlation of *total* radio power and core X-ray emission.

Results show measurable levels of jet-related X-ray emission in low-power radio galaxies, with $\alpha_{rx} \simeq 0.85$. Radio-selected BL Lac objects from the 1 Jy sample have a similar $\bar{\alpha}_{rx}$ (Sambruna et al. 1996) and fit on an extrapolation of Fig. 3 but with a dispersion in S_x of a factor > 50 whose size, compared to the tight correlation for quasars (Fig. 1), needs accounting for when different emission models are applied to the data.

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