The Origin of X-Ray Emission in Low-Redshift Radio-Galaxy Nuclei

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Abstract

We present spectral results from *Chandra* and *XMM-Newton* observations of a sample of 22 low-redshift (z < 0.1) radio galaxies, and consider whether the core emission originates from the base of a relativistic jet, an accretion flow, or contains contributions from both. We find correlations between the unabsorbed X-ray, radio, and optical fluxes and luminosities of FRI-type radio-galaxy cores, implying a common origin in the form of a jet. On the other hand, we find that the X-ray spectra of FRII-type radio-galaxy cores is dominated by absorbed emission, with $N_H > 10^{23}$ atoms cm^{-2}, that is likely to originate in an accretion flow. We discuss several models that may account for the different nuclear properties of FRI- and FRII-type cores, and also demonstrate that both heavily obscured, accretion-related, and unobscured, jet-related components may be present at varying levels in all radio-galaxy nuclei.

Analysis

As the orientation-dependent effects of relativistic beaming and the putative obscuring torus are expected to play a large part in determining the observed properties of a radio-galaxy nucleus, it is important to select sources based on their low-frequency (and hence isotropic) emission characteristics, such as in the 3C and 3CRR samples. We used X-ray data of the nuclei of 22 radio galaxies at z < 0.1, 19 of which are from the 3CRR catalogue, with the remaining sources, 3C 403, 3C 405 (Cygnus A), and Centaurus A, included due to their high-quality spectra. The high spatial resolution of *Chandra* means that it is possible to disentangle confusing kpc-scale jet emission from that of the core, while the large collecting area of *XMM-Newton* allows strong constraints to be placed on spectral parameters.

Spectral analysis was performed using an energy range of 0.5-7 keV for the *Chandra* data and 0.5-10 keV for the *XMM-Newton* data. We used local background subtraction from small regions immediately next to the unresolved nucleus and corrected for the resulting missing PSF in each case. In all cases, a power law was included in our spectral model. In some, a residual thermal component was also required; its normalization was verified using a radial-profile analysis.

Distribution of intrinsic absorption

In Figure 1, we plot the distribution of intrinsic absorption for the dominant component of X-ray emission in each of our sources. It is clear that X-ray emission components in FRI-type radio galaxies tend to have much lower intrinsic absorption than FRII-type radio galaxies. Any absorption detected in FRI-type galaxies can be associated with gas in the host galaxy. The high absorption seen in FRII-type galaxies is more plausibly associated with denser gas and dust close to the nuclei, such as a torus. This may suggest an intrinsic difference in the nuclear characteristics of FRI- and FRII-type sources. We also highlight the BLRG (and hence unobscured in unified AGN models) FRII source 3C 390.3.

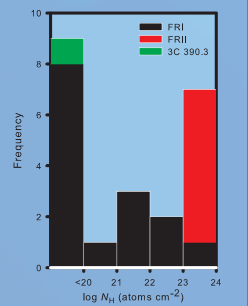

Fig. 1: Histogram of the intrinsic absorption associated with the dominant component of X-ray emission for FRI-type sources (black); FRII-type sources (red); and the FRII-type BLRG 3C 390.3 (green).

The radio core - X-ray core correlation

In Figure 2, we plot the luminosity and flux densities of the observed X-ray and radio emission for our sample. We separate components into those with intrinsic absorption less than 5×10^{22} atoms cm^{-2} (red) and those with intrinsic absorption greater than this value (black).

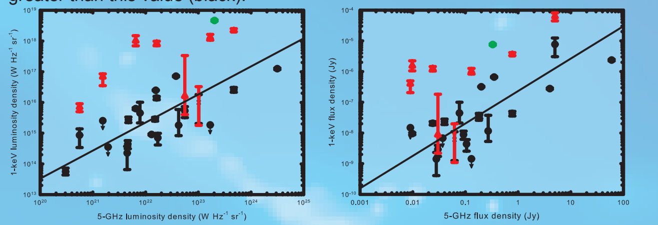

Fig. 2: 1-keV unabsorbed X-ray against 5-GHz radio core luminosity (left) and flux (right) density for each component of X-ray emission. Black circles and the line of best fit are the unabsorbed jet-related components that are seen in both FRI and FRII radio-galaxy nuclei. Red triangles are the heavily obscured ($N_H > 10^{23}$ atoms cm^{-2}) accretion-related emission that is detected in the FRII-type sources. The BLRG 3C 390.3 is indicated in green, and the crosses represent the LERG 3C 388.

It is evident that the X-ray emission separates into two distinct "bands": in other words, the X-ray emission of components with high intrinsic absorption (greater than 5×10^{22} atoms cm^{-2}) tends to lie significantly above those components with low intrinsic absorption (less than 5×10^{22} atoms cm^{-2}). It is then interesting that the FRII-type sources, whose X-ray emission is dominated by heavily absorbed emission, should have significantly stronger X-ray emission for a given radio luminosity than FRI-type sources.

FRI-type sources: Dominated by a jet

In short, for FRI-type radio-galaxy nuclei, we find:

1) Their nuclear X-ray spectra is dominated by unabsorbed, or at most lightly absorbed, emission

2) The strong (>99.9% significant) correlations between the radio and X-ray fluxes and luminosities can only exist if the X-ray emission is affected by beaming in the same manner as we know the radio emission to be, i.e., takes the form of a jet.

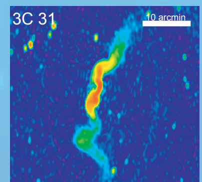

Fig. 3: 608-MHz radio image of the FRI-type radio galaxy 3C31 (Leahy et al., Atlas of DRAGNs)

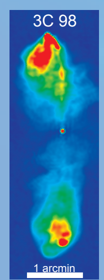

Fig. 3: 5-GHz image 3C 98 (FRII) (Leahy et al., Atlas of DRAGNs)

FRII-type sources: Dominated by accretion

Conversely, for FRII-type radio-galaxy nuclei, we find:

1) Their nuclear X-ray spectra is dominated by heavily absorbed ($N_H > 10^{23}$ atoms cm^{-2}) emission

2) Their unabsorbed X-ray flux and luminosity densities lie above those that are likely to have an origin in the form of a jet

3) All have Fe Kα lines

4) These continuum components are likely to have an origin in an accretion flow and be surrounded by a dusty structure, such as a torus

5) Each FRII-type source also has a component of soft X-ray emission, which follows the same correlations as the FRI-type sources, and is consistent with having a jet-related origin.

Do FRI-type galaxies harbor obscuring tori?

Our X-ray observations suggest that the X-ray emission of FRI-type sources is dominated by a jet. If this is the case, and if the X-ray jet emission originates on scales larger than that of the torus, the lack of strong X-ray absorption is not direct evidence against the existence of a torus. However, we can constrain the properties of any heavily obscured accretion flow. For our FRI-type sources, we estimate the 0.5-10 keV X-ray luminosity of a `hidden', accretion-related component of emission that could be obscured by an adopted column of 10^{23} atoms cm^{-2} to be in the range 10^{39}-10^{41} ergs s^{-1}. However, in FRII-type sources, we measure the accretion-flow luminosity to be several orders of magnitude higher, with a mean value of 10^{43} ergs s^{-1}. Accretion flows in FRI-type sources are likely to be sub-Eddington in nature: the ratio of their X-ray to Eddington luminosities, $\eta_{X,\ Edd}$ is 10^{-7}-10^{-5}. This contrasts with the FRII sources, whose $\eta_{X,\ Edd}$ is 10^{-3}-10^{-2}.

A Nuclear Fanaroff-Riley Dichotomy?

Why should there be a dichotomy in the observed properties of the X-ray nuclei of FRI- and FRII-type galaxies? We consider two models:

1) The relative contribution of accretion-related and jet-related emission varies smoothly as a function of total AGN power:

In this model, there is a smooth transition between the relative contribution of accretion-related and jet-related emission, such that the nuclei of FRI sources are dominated by emission from a jet, but the nuclei of FRII sources are instead dominated by emission from an accretion flow. The large-scale radio Fanaroff-Riley dichotomy is then governed by the *external* impact of the hot-gas environment on the jet propagating through it (e.g., Bicknell 1994, ApJ, 422, 542).

2) An intrinsic dichotomy exists in the accretion-flow structures of FRIs and FRIIs:

The most widely discussed model in this context (e.g., Reynolds et al. 1996, MNRAS, 283, L111) is one in which the accretion flows of FRI sources are in the form of a radiatively inefficient optically thin ADAF, whereas in FRII sources the flows take on a new *mode*, such as a thin disk. It is predicted (e.g., Esin et al. 1997, ApJ, 489, 865) that as the mass accretion rate increases, an accretion flow makes the transition from being ADAF-like to being dominated by a thin disk. In turn, there should be a step increase in the total accretion-flow luminosity, as may be suggested by the plot of 1-keV and 178-MHz luminosity densities (Figure 5).

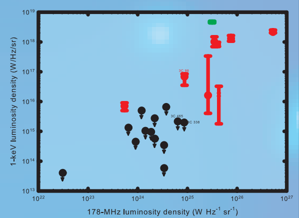

Fig. 5: 1-keV unabsorbed luminosity density of the accretion-related components of the sources against 178-MHz luminosity density. Red corresponds to FRII-type sources and Cen A; black corresponds to upper limits on `hidden', accretion-related emission in the FRI-type sources, under the assumption that the accretion flow is obscured by a column of 10^{23} atoms cm^{-2}.

Summary

1) The X-ray nuclei of FRI sources are dominated by unabsorbed emission from the base of a relativistic jet that may exist on scales larger than that of any torus.

2) The X-ray emission of FRII nuclei is dominated by heavily absorbed emission that we attribute to an accretion flow.

3) Our work may suggest that there exists an intrinsic nuclear Fanaroff-Riley dichotomy, which future observations will be able to test directly.