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Search for Inverse Compton X-rays from the Lobes of Fornax A
X-rays from Radio Galaxies Straddling the Fanaroff-Riley Transition

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Search for Inverse Compton X-rays from the Lobes of Fornax A

First, an important and novel astrophysical result has been obtained in the search for X-rays from the lobes of the nearby radio galaxies Fornax A. While the nuclei (presumed to be accreting massive black holes) of radio galaxies and radio-loud quasars are well-known emitters of X-rays, there was no clear case of detection of X-rays from the diffuse radio-emitting lobes ejected by these nuclei. Considerable effort was devoted to this search by the SAS-3 and Einstein X-ray Observatory without clear success. The only plausible case was an Einstein HRI report of X-rays from the radio halo of M87 (Feigelson et al. 1987), but this could also be interpreted as bremstrahhlung radiation from the gas surrounding the lobe.

The issue is of great astrophysical importance for the following reason. The physics of synchrotron radio lobes is only partially defined by radio observations, which gives a function of the magnetic field and the electron particle density. Radio astronomers usually assume 'equipartition' between the field and particle energies to derive the basic energetics of radio lobes. But there has been no direct proof that equipartition actually holds; it could be incorrect by orders of magnitude. The solution to this problem is to observe inverse Compton scattering of the energetic electrons off the cosmic microwave background radiation. Since the background radiation density is well-established, this unambiguously measures the number of energetic electrons and thus resolved the debate over equipartition. The problem has been that the inverse Compton X-ray emission is weak, often much less than other sources of X-rays (the active galactic nucleus, an intracluster medium) in the vicinity of the lobes. We carefully selected Fornax A as the best target for this observation, because its predicted inverse Compton emission was high and the extraneous sources of X-rays were low.

A rather complex data analysis methodology was used to extract the faint diffuse inverse Compton emission from the various sources of noise and background in the detector. Standard *ROSAT* point source analysis techniques cannot be applied to extended sources primarily because the background can vary significantly both spatially and as a function of energy, making accurate background subtraction exceedingly difficult. Snowden *et al.* (1994) identified five different components of noncosmic background in *ROSAT* PSPC observations: particle-induced background (PB), afterpulsing (AP), scattered solar X-rays (SSX), short term enhancements (STEs) and long term enhancements (LTEs). We have chosen to implement the techniques discussed in Snowden *al.* to characterize and eliminate the effects of the particle background, afterpulsing and scatter solar X-rays. We did not attempt to characterize the effects of short or long term enhancements.

We used new Interactive Data Language (*IDL* (v3.0.0)) routines to perform all of the background modeling and corrections. The procedure we utilized was: (1) we eliminated all data where the Master Veto Rate exceeded 170 cts/s and created a "good times file"; (2) we then eliminated AP events; (3) and determined the PB as a function of time; (4) we

created light curves for different energy bands (C M and J); (5) we subtracted the PB rates from the light curves; (6) we modeled the SSX background; (7) we filtered the data based on the SSX model and the light curves produced above, creating a "good times" file; (8) we created images in the different energy bands based on the final good times file; (9) we created PB images and subtracted them from the image files; (10) we created and applied energy dependent exposure maps to the images created in step (9); (11) we removed point sources from the flat fielded, background corrected, images. Point source removal was performed by subtracting all counts in a particular circular region. To avoid artificial "gaps" in the data, these areas were filled in with background based upon an extrapolation of the counts in an annulus surrounding the location of the point source.

The ratio of synchrotron emission to IC emission is a function of the magnetic field strength. The "inverse Compton" magnetic field, B_{ic}, is given by Harris & Grindlay (1979):

$$B_{ic} = [\frac{(4790)^{\alpha}C(\alpha)G(\alpha)(1+z)^{3-\alpha}S_r E_x{}^{\alpha}}{10^{70}S_x \nu_r^{\alpha}\sin\phi}]^{\frac{1}{1-\alpha}} \tag{1}$$

where α is the radio spectral index ($S_{\nu} \propto \nu^{+\alpha}$), z is the redshift, S_r is the radio flux density in Janskys at ν_r (GHz), S_x is the X-ray flux density (in ergs/s/cm^2/Hz) at energy E_x (in keV), $G(\alpha)$ is a correction factor given in Table 1 of Harris & Grindlay (1979), and $C(\alpha)$ is a slowly varying function of α given by:

$$C(\alpha) = \frac{C_1^{\frac{1}{2}}2^{\alpha}}{4\pi C_5(\mathrm{p})} \tag{2}$$

where $C_1 = 6.27 \times 10^{18}$ (in cgs units) and $C_5(\mathrm{p})$ is given in Table 7 of Pacholczyk (1970) and p is the (negative of the) powerlaw index of the electron distribution (p $= 1 - 2\alpha$).

Burbidge first showed (1956) that the minimum energy condition for radio lobes corresponds to roughly an equipartition between the magnetic field energy density and the particle energy density. The magnetic field corresponding to the minimum energy condition, B_{me}, can be shown to have the form (Miley, 1980):

$$B_{me} = 5.69 \times 10^{-5}[\frac{(1+k)}{\eta}(1+z)^{3-\alpha}\frac{1}{\theta_x\,\theta_y\,s\,\sin^{\frac{3}{2}}\phi}\frac{S_o}{\nu_o^{\alpha}}\frac{\nu_2^{\alpha+\frac{1}{2}}-\nu_1^{\alpha+\frac{1}{2}}}{\alpha+\frac{1}{2}}]^{\frac{2}{7}} \tag{3}$$

where k is the ratio of the energy in heavy particles to that in electrons, η is the filling factor for the synchrotron emitting region, z is the redshift, θ_x and θ_y corresponds to the lobe size in arcseconds, s is the path length through the source in kiloparsecs, ϕ is the angle between the uniform magnetic field and the line of sight, S_o is the flux density (in Janskys) of the radio emission at a frequency of ν_o, measured in GHz, ν_1 and ν_2 (GHz) are the upper and lower cutoff frequencies for the radio synchrotron spectrum, and α is the spectral index ($S_{\nu} \propto \nu^{\alpha}, \nu_1 \leq \nu \leq \nu_2$). The equipartition magnetic field has been frequently used, but with limited observational justification.

The result of our analysis is that, for reasonable assumptions regarding the lob geometry, magnetic field entanglement and proton particle energies, the field strength inferred from

the X-ray inverse Compton emission is 2.5μG for the east lobe and 1.8μG for the west lobe. These values are very close the the equipartition fields of 2.5μG and 2.9μG respectively. Our study thus vindicates the decades-old hypothesis that diffuse radio lobes are close to their equipartition, minimum energy configurations.

We have considered whether the lobe X-rays could arise instead from thermal bremsstrahlung rather than inverse Compton processes. The principal limitation on the bremsstrahlung origin is that such an entrained thermal gas would have to produce Faraday depolarization of the radio emission. Our examination of the (yet unpublished) radio polarization data provided by Dr. Ed Fomalont (NRAO) shows a constant rotation measure and slight depolarization. The depolarization was fit to the homogeneous spherical Faraday model of Cioffi & Jones (1980, eq. 6a). It appears that thermal bremsstrahlung is an unlikely explanation for the observed lobe X-rays, though this analysis is not quite completed.

This effort is emerging with two publications. Copies of the first paper are attached.

"X-rays from the Lobes of Fornax A", Laurent-Muehleisen, S. A., Feigelson, E. D., Kollgaard, R. I., and Fomalont, E. B., Proc. ROSAT Science Symposium, in press (1994).

"X-rays from the Lobes of Fornax A", Feigelson, E. D., Laurent-Muehleisen, S. A., Kollgaard, R. I., and Fomalont, E. B., to be submitted to *Astrophysical Journal.*

X-rays from Radio Galaxies Straddling the Fanaroff-Riley Transition

Radio galaxies (RGs) can be divided into two broad morphological groups based on whether the lobe radio power is greater or less than a critical value (Fanaroff and Riley 1974). Lower luminosity RGs (178 MHz power, $P_{178} < 10^{25.8}$ W Hz^{-1}, assuming $H_0 = 100$ km s^{-1} Mpc^{-1}, and $q_0 = 0.5$) exhibit diffuse, plume-like jets and lobes which are brightest near the core (Fanaroff-Riley class I), while higher luminosity RGs ($P_{178} > 10^{25.8}$ W Hz^{-1}) have jets which are brightest away from the core, usually near a compact hotspot (Fanaroff-Riley Class II). Many characteristics demonstrate that the FR transition represents a fundamental shift in the physical processes of AGN: jet magnetic field structures, jet prominence, jet symmetry, jet width, core brightness VLBI polarization structures, optical spectra, host galaxy morphology, host galaxy brightness, local galaxy density, and evidence from the *Einstein Observatory* that X-rays from FR I RGs are more likely from diffuse emission, while those from FR II RGs are dominated by a compact nuclear source (see review by Bridle 1988).

It is likely that the nature of the gaseous medium is important in determining the nature of the jet flow, i.e. the FR class. Bicknell *et al.* (1990) have successfully applied a subsonic high-density jet model to FR I jets. FR II jets, however, have been modeled as plasmas of low density and high Mach number (possibly relativistic) subject to confinement by their own magnetic field. They likely interact with the ambient medium though shock fronts, ambient density and pressure gradients and mass entrainment. However, differences

in radio core luminosity suggest that intrinsic AGN powers are crucial and VLBI polarization observations imply that jet magnetic field configurations are set within a few parsecs of the core.

We obtained ROSAT HRI observations of four bright radio galaxies around the FR transition to search for X-ray indications of either nuclear engine or ambient medium differences in the two classes: FR I galaxies 3C66B and 3C293, and FR II galaxies 3C192 and 3C382. They are drawn from the 3CR catalog of the brightest 100 hundred radio galaxies in the sky, and are relatively closeby with $0.2 < z < 0.6$. We have written a computer code to model the emission as the sum of a compact nuclear source and a diffuse medium. The figure below shows a result from this analysis: the radial profile of 3C282 can be accurately modeled as the sum of a point source and an isothermal sphere model with a core radius of $3''$.
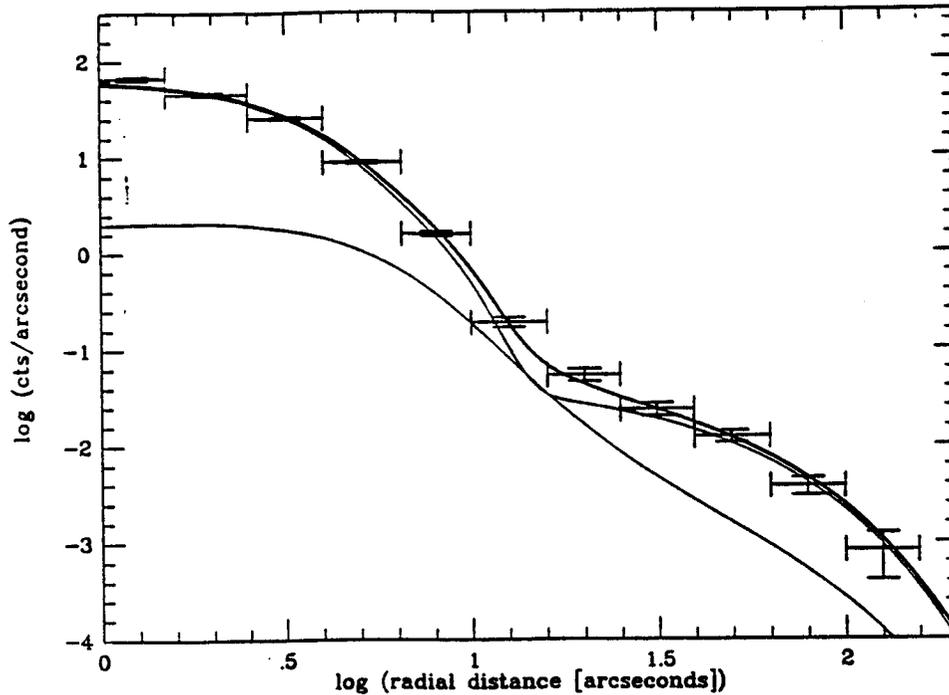
However, we have chosen to delay completing and publishing the effort, because the sample is quite small for a statistical study, and we have acquired HRI observations of other radio galaxies to supplement the four observed in this program. Three FR 1 radio galaxies – PKS 0548-317, B2 1144+35, and B2 1553+24 – were observed from AO-2 and AO-3 proposals entitled 'Do BL Lac Nuclei Lurk Inside of Radio Galaxies', and two FR II radio galaxies – 3C 388 and 3C 303 – are approved for observations from an AO-5 proposal entitled 'HRI Observations of Powerful Radio Galaxies'. The latter observations should take place in late-1994 or early-1995. We intend to combine the samples and complete the effort when the entire sample is in hand.

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X-RAYS FROM THE LOBES OF FORNAX A

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ABSTRACT

We present a deep *ROSAT* PSPC image of the radio lobes of the nearby galaxy Fornax A (= NGC 1316) and find, after image processing, X-ray emission closely mimicking the radio emission. We argue that this is the long-sought inverse Compton radiation produced when cosmic microwave background photons are upscattered off synchrotron emitting electrons in the radio lobes. The derived magnetic field in the lobes is compared with equipartition values and we also discuss the possibility of thermal Bremsstrahlung emission as a source of lobe X-rays. This observation constitutes the best case for detection of inverse Compton X-rays in radio lobes to date.

1. Introduction

When a low energy photon encounters a high energy particle with a Lorentz factor of γ, its energy is increased by $\sim\gamma^2$ via the inverse Compton (IC) process. The synchrotron emitting lobes of radio galaxies are a plentiful source of high energy electrons with $\gamma \approx 10^2 - 10^4$ and the cosmic microwave background is an ubiquitous source of low energy photons ($\nu\sim10^{11}$Hz). IC X-ray emission therefore must be associated with all radio-emitting lobes. The measurement provides a rare opportunity to test the oft-adopted hypothesis that lobe particles and magnetic fields are in energy equipartition.

However, no convincing case of IC emission associated with radio lobes has been observed, although it has been searched for in a number of sources including Centaurus A (Marshall & Clark 1981; Morini *et al.* 1989), M 87 (Feigelson *et al.* 1987), and Abell 1367 (Gavazzi & Trinchieri 1983). We chose Fornax A (NGC 1316) as the best target for IC X-ray emission as the radio lobes are strong, have a convenient angular size, and are not contaminated by cluster gas.

2. Observations of Fornax A (NGC 1316)

We present a deep image of the radio galaxy Fornax A obtained with the *ROSAT* Position Sensitive Proportional Counter (PSPC) consisting of 16 separate orbital intervals taken between January 13 and January 20, 1992 for a total of 25.48 ksec. The color figure shows a 1.5 GHz image of Fornax A

(Fomalont *et al.* 1989) with X-ray contours of the 0.9-2.0 keV flux smoothed to 5′. Scattered solar X-rays and the particle induced background have been modeled and subtracted from the data (Snowden *et al.* 1994). In addition, afterpulses and point sources have been removed from the X-ray image.

3. Are the X-rays Inverse Compton?

If a large fraction of the observed X-ray flux is produced via the thermal Bremsstrahlung mechanism, a significant Faraday depolarization ought to be present. We have used the homogeneous spherical model of Cioffi & Jones (1980) and the equipartition magnetic field to predict the thermal electron density. The resulting thermal flux is a factor of 10-200 below that observed, depending on exact values of the electron density and temperature. However, fits to a Raymond-Smith plasma are consistent with the hard portion of the X-ray lobe spectra, although with electron densities a factor of 5-10 larger than the depolarization observations suggest. We conclude the observed X-ray emission is probably **not** thermal in nature.

## 4. Is the Lobe Magnetic Field in Equipartition?

Burbidge (1956) first showed the minimum energy condition for radio lobes corresponds to roughly an equipartition between the magnetic field and particle energy densities. This equipartition magnetic field has often been assumed to be the value of the true field, although there is little observational evidence for this. Because the ratio of synchrotron emission to IC emission is a function of the magnetic field strength, the detection of IC X-ray lobe emission provides a direct measure of the true magnetic field. For the east lobe we find $B_{ic}=2.5\mu G$ and $B_{eq}=2.5\mu G$. For the west lobe we find $B_{ic}=1.8\mu G$ and $B_{eq}=2.9\mu G$. These calculations assume the radio spectral index is -0.8 ($S_\nu \propto \nu^\alpha$), the B-field is perpendicular to the line-of-sight, the ratio of the energy in electrons to protons is unity, the upper and lower cutoffs of the synchrotron spectrum are 0.01 and 100 GHz, respectively, and the filling factor is unity. Decreasing the filling factor by a factor of 10, as suggested by the observed radio filamentation, increases the equipartition field by only a factor of $\sim$2.

5. Conclusions

We present the first clear case for inverse Compton X-ray emission from radio lobes. The derived magnetic field is shown to be very close to the equipartition value. The possibility that the X-ray emission is thermal is discussed and found to be unlikely.

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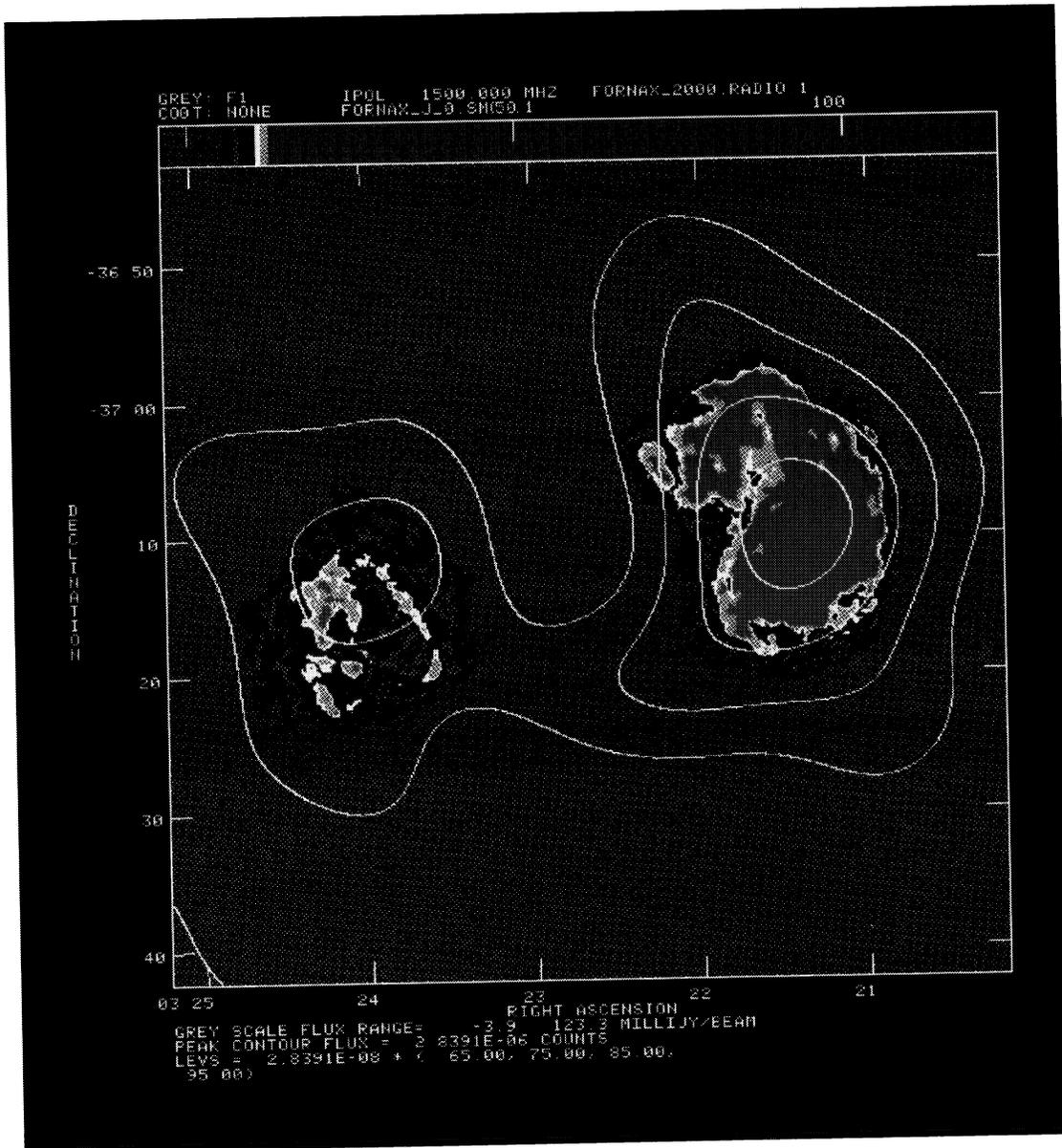
1.5 GHz image of Fornax A with X-ray contours of the 0.9-2.0 keV flux smoothed to 5 arcmin. X-ray contours are drawn at 65, 75, 85 and 95% of the peak flux.