X–ray emission from FRII’s radio lobes and the relativistic particle content

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Abstract. It is pointed out that copious X-rays from the lobes of FRII radio galaxies are expected as a natural consequence of the unification linking FRIIs and radio-loud quasars. The detection of extended X-ray emission from 3C 219, likely due to Inverse Compton scattering of the IR photons from a hidden quasar with the relativistic electrons in the lobes, provides the first observational evidence supporting this conjecture. The X-ray fluxes detected in the directions of other five powerful FRIIs with large redshifts may be similarly accounted for (an alternative to a thermal origin from hot intracluster gas). Much less energetic electrons than those producing the synchrotron radio emission are involved in the process. Then the equipartition conditions imply stronger fields, and significantly stronger internal pressures of the relativic plasmas, than those derived with conventional equipartition equations. The importance of this effect in the pressure balance with the confining intergalactic gas is pointed out.

1. Introduction

At first glance it may appear that the title of this contribution is somewhat unrelated to the main subject of this workshop. There are, however, several aspects concerning the physics of strong radio galaxies (FRII) that may be relevant to the subject being discussed.

First, one can mention the general question of the magnetic field strengths and of the energy deposited in relativistic particles in the lobes of radio galaxies. This has a direct bearing on the pressure balance with the ambient gas and, by inference, on the estimates of these quantities in the radio halos of galaxy clusters. A related aspect is the prediction of large fluxes of X-rays from the Inverse Compton (IC) process in the lobes of extended FRII radio galaxies; this may account for a sizeable fraction or all of the extended soft X-rays emission detected in the direction of FRII’s at large redshifts and generally attributed to the presence of surrounding hot intracluster gas. As a third point it is worth mentioning the possibility of obtaining important information on the intracluster gas properties from the interaction with the relativistic plasma in the lobes. We adopt the unification scheme linking FRII radio galaxies and radio-loud quasars (Barthel, 1989). Then the radio lobes are flooded by the radiation from the hidden quasar, leading to very significant X-ray emission from the IC of the quasar’s far/near IR photons with relativistic electrons having Lorentz factors in the range 100–300 (Brunetti, Setti & Comastri, 1997; hereafter Paper I). The energies of these electrons are much lower than those typically sampled by the synchrotron radio emission and, therefore, their presence must be assumed. However, evidence that this might indeed be the case has been recently gathered by high angular resolution X-ray observations of 3C 219 with ROSAT-HRI (Brunetti et al., 1999; hereafter Paper II).

2. Equipartition Fields

In general magnetic field intensities in the radio lobes have been evaluated assuming the minimum energy condition (equipartition). By convention this is based on the observed, and extrapolated as required, synchrotron spectrum in the 10 MHZ-100 GHz radio band (source frame), involving electrons with $\gamma > 10^3$ in typical fields to be found in the lobes. Only recently the detection of diffuse X-rays from the extended radio lobes of Fornax A and Cen B, interpreted as IC scattering of the cosmic microwave background photons (CMB), has permitted an independent estimate of the ultra-relativistic electron ($\gamma > 10^5$) densities with the conclusion that the energy in the relativistic particles, the energy densities of positive and negative charges being equal, exceeds that in the magnetic fields (Kaneda et al.1995; Tashiro et al.1998). The departure from the equipartition would be further enhanced with increasing ratio of the energy density in positive charges (protons) to that in the electron component. Of course, there is no basic reason why the equipartition argument should strictly apply, except that it minimizes the energy requirements.

Since the IC production of (soft) X-rays from the scattering of the hidden quasar IR photons requires relativistic electrons of much lower energies, it is convenient (and in any case more correct) to work out the minimum energy
condition based on a low energy cut-off ($\gamma_{\text{min}}$) in the electron energy distribution (Paper I). Ionization losses may provide a natural mechanism to obtaining a low energy break in the particle spectra. Under the assumption that the particle energy distribution follows a power law with exponent $-\delta$ and that particles and fields are uniformly and isotropically distributed, one finds that the equipartition field is

$$B_{eq} \simeq 1.3 \cdot B_{eq}' \frac{2(\gamma - 0)}{\gamma_{\text{min}}}$$  \hspace{1cm} (1)$$

where $B_{eq}'$ is the equipartition field computed with standard formulae (Pacholczyk, 1970). (The ratio between particles and fields energy densities depends on the spectral slope, being 1 for $\delta = 3$ and the classical 4/3 for $\delta = 2$). For $\delta > 2$, $B_{eq} > B_{eq}'$, if $B_{eq}' < 1/\gamma_{\text{min}}^2$, a condition always satisfied in the radio lobes. With $\alpha$ in the range 0.8–1.0 it is found that $B_{eq}/B_{eq}'$ is typically comprised in the range 1.5 – 3.0, depending on $\gamma_{\text{min}}$ and on $B_{eq}'$. Correspondingly the normalization of the electron spectrum is decreased by at least a factor 2, or larger, an effect that should be taken into account in computing the IC emission expected on the basis of the equipartition value, whereas the ratios of the total energy densities and of the pressures (particles plus fields) is increased by a factor $\sim (B_{eq}/B_{eq}')^2$. The last point is of particular importance not only for the evaluation of the minimum energy stored in the radio volumes, but even more so in any discussion concerning the pressure balance with the surrounding intergalactic gas. For instance, by applying the conventional equipartition relations it has been found (Feretti, Piorolo & Fanti, 1992) that radio tails are underpressurized by factors 5–10 compared with the hot confining intracluster gas. By considering, as an example, the sources with the weakest equipartition fields ($B \sim 1\mu G$), and $\gamma_{\text{min}} = 20$, we find that the tail internal pressure should be increased by a factor $\sim 8$. This may not fully solve the problem of the pressure balance for the large sample of sources considered by these authors, but it certainly alleviates the need of strong departures from the equipartition and/or the assumption of large ratios between relativistic nuclei and electrons.

### 3. The case of 3C 219

3C 219 is a well known powerful double-lobed FRII radio galaxy, identified with a CD galaxy at a redshift $z = 0.174$ (Clarke et al. 1992 and ref. therein). The total projected size is $\sim 460$ Kpc (180 arcsec): it has a strong jet protruding in the direction of the south-western lobe with a projected size $\sim 50$ Kpc; its radio spectrum, largely dominated by the extended structures, is a typical power law with spectral index $\alpha_r = 0.81$ in the 178–750 MHz interval. From the combined analysis of ROSAT-PSPC and ASCA archival data we have concluded (Paper II) that the 0.1-10 keV emission spectrum of 3C 219 can be best represented by a partially ($\sim 74\%$) absorbed power law (photon index $\Gamma \simeq 0.75$, absorption column density $N_H = 2 - 3 \times 10^{21}$ cm$^{-2}$). This could be interpreted as indicating a two component model: an absorbed nuclear source, with a spectrum typical of steep spectrum radio- loud quasars, and a scattered component contributing $\sim 38\%$ of the total flux in the 0.1-2.4 keV energy interval and with a spectral index $\alpha \simeq 0.8$, close to the spectral slope measured in the radio band. In addition, from the spectral analysis we were able to exclude any thermal component contributing more than 10% to the total flux in the ROSAT band.

The above scenario has been largely confirmed by a subsequent deep ROSAT HRI (0.1-2.4 keV) observation as described in Paper II. The X-ray image of 3C 219 is dominated by a point-like source coincident, within the positional errors, with the radio core (nucleus) of the galaxy, but a diffuse component extending up to the hundred kpc scale is also present. Taking into account the results of the spectral analysis we find that the point-like source accounts for $\sim 60\%$ of the total net counts, while its de-absorbed isotropic luminosity in the 0.1-2.4 keV band is $\sim 3.6 \times 10^{44}$ erg s$^{-1}$, thus strengthening the suggestion that we are dealing with the emission of a quasar hidden in the nucleus of the galaxy in agreement with the unification scheme.

The distribution of the extended emission after subtraction of the point-like source is shown in Fig.1 superposed on the VLA radio image at 1.4 GHz. The striking result is the very close coupling between the X-ray and the radio images. One can distinguish three main components: the central component (C), which accounts for $>50\%$ of the extended flux and appears more elongated in the northern direction along the bottom part of the northern radio lobe, the south component (S), located mid way between the nucleus and the southern hot-spot, and the northern component (N). It is also striking that the X-ray isophotes appear to carefully avoid the regions of the hot-spots.

Since we know from the spectral analysis that the X-ray spectrum up to 10 keV has a slope very close to that measured in the radio band, it is tempting to associate the X-ray emission to the IC process involving the relativistic electrons in the radio lobes. If so, the emission of component C, whose brightness distribution falls off roughly as the inverse distance from the nucleus, must be dominated by the IC scattering of the IR photons from the hidden quasar with relatively low energy electrons ($\gamma \sim 100 – 300$). By considering various observational upper limits and the correlations linking IR, optical, radio and X-ray radiation properties of quasars and radio galaxies, we have estimated that the isotropic $6$-$100 \mu m$ luminosity of the hidden quasar could be $5.5 \times 10^{45}$ erg s$^{-1}$, about an order of magnitude less than that of a typical radio-loud quasar (see the next section). We have also included in the photon bath of the electrons the CMB radiation. We have then constructed an IC model of the
source taking into account the following constraints and assumptions:

- Assume a uniform distribution of the relativistic electrons throughout the source and the power law energy spectrum of the radio electrons \((2\alpha_r + 1)\) extrapolated downward to a \(\gamma_{\text{min}} = 50\);
- Consider the radiation from the hidden quasar, as seen by the electrons, made of two components: a direct radiation within two opposite cones of half-opening angle 45 deg and that re-radiated by the surrounding dusty torus;
- Assume, according to Bridle et al. (1986), that the radio jet makes an angle of 30 deg with respect to the plane of the sky;
- Let the orientation of the torus axis be a free parameter subject to the constraint that the inner part of component C appears to be elongated in a direction making a large angle with the radio jet (Fig. 1) and that the line of sight to the quasar must intercept the torus. The results of our model computations are shown in Fig. 2 for the case in which the torus axis makes an angle of \(\sim 37\) deg with the radio jet and one of \(\sim 73\) deg with the line of sight. Clearly the model reproduces fairly well the main features of component C, including the extension of the brightness distribution toward the northern lobe due to the dominance of nearly front scatterings in the far lobe in the observer’s direction (as discussed in Paper I). The observed flux densities, however, can only be matched under the assumption that the electron density exceeds the equipartition value (the particle energy density being equally shared among the electrons and the nuclei) by about a factor 10, the corresponding magnetic field strength being \(\approx 3\mu G\). A similarly strong departure from the equipartition has been proposed by Tashiro et al. (1998) to explain the X-ray emission from Cen B.

We have considered the possibility, also in view of the cluster membership of 3C 219, that component C could be the result of a non-symmetric cooling flow. The main point here is that a cooling flow model implies a thermal contribution far in excess (at least an order of magnitude) of the upper limit set by the spectral analysis within 2 arcmin radius from the source and, in addition, a cluster emission exceeding the ROSAT HRI background. We conclude that at this stage our IC model represents the most solid interpretation of component C, providing at the same time strong supportive evidence in favour of the unification scheme linking FRII radio galaxies and radio-loud quasars.

It is worth mentioning that, if the IC interpretation holds, then the observed coincidence of the X-ray and radio spectral slopes implies a sufficiently uniform distribution of particles (with the same spectrum) and fields throughout the source.

Our model is unable to explain the S and N components without introducing significant changes in the basic assumptions. For instance, both components can be accounted for by the IC mechanism (mainly from up-
scattering of CMB photons) if one is prepared to admit
an increase of a factor 2-2.5 in the density of the relativistic
electrons at the location of the two components. An
inspection of the radio maps, including the spectral index
distribution and polarization, reveals that both compo-
nents are located in regions where there is an indication
of back-flows from the hot-spots. It is also possible that
there is a thermal contribution due to a hot ($kT \approx 1.5$
keV) and clumpy intracluster gas surrounding the radio
source in localized regions. This is particularly true for
the S component whose almost precise coincidence with a
region of moderate depolarization is striking. The nature
of the emission of these components may soon be clarified
by upcoming observations of 3C 219 with *Chandra*.

4. X-ray emission of FRIIs at large redshift

We briefly report here on a previous work on six strong
FRII’s (3C 277.2, 280, 294, 324, 356, 368) at large dis-
tances ($z \approx 0.7 – 1.8$) which had been detected by ROSAT
PSPC/HRI and discussed in published papers (Paper I
and ref. therein). These sources show direct or indirect
evidence of extended emission, but appear very weak typ-
ically contributing only several tens of net counts after
long exposure times, so that also their spectra are in gen-
eral poorly constrained. The main steps of our procedures
were as follows:

- derive a typical quasar IR-optical spectrum (100 $\mu$m -
350 nm) and the corresponding (isotropic) luminosity
$\approx 9.5 \times 10^{46}$ erg s$^{-1}$ ($M_V \approx -26.1$) typical of high redshift
radio-loud quasars;
- for each source assume a relativistic particle power
law spectrum from the synchrotron radio emission extrap-
olated downward to a Lorentz factor $\gamma_{min} = 20$ and derive
the equipartition field for equal energy density of relativistic
electrons and protons;
- compute the hidden quasar luminosity required to
match the observed X-ray flux of each source by the IC
scattering of the quasar photons emitted within two op-
opposite cones of half opening angle 45 deg coaxial with the
radio axis, including possible corrections due to enhanced
anisotropic IC emission toward the observer for the (un-
known) inclination of the radio axis on the plane of the sky
and taking into account the IC X-rays from the scatter-
ing of the CMB photons (non negligible at these large
redshifts). We have concluded that the soft X-ray fluxes of five strong FRIIs at large redshifts can also be accounted for as IC scattering of the hid-
den quasar IR photons with the relativistic electrons in the
radio lobes: under equipartition conditions the required
luminosities of the quasars are very reasonable and con-
sistent with spectral and polarization data analysis when
available. This also implies that for such distant objects
one should be careful in ascribing the observed X-ray emis-
sion to a different origin, such as a hot intracluster gas in
which these sources might be embedded.

The equipartition values referred to in our analysis have
been obtained by extrapolating the synchrotron electron
spectra downward to a minimum cut-off energy, im-
plying equipartition fields that are significantly stronger
than those derived by the conventional equipartition re-
lationships. It follows that the total energy and internal
pressure in the radio emitting regions could be much larger
than usually estimated. This should be taken into account
while discussing the pressure balance for the confinement
of the radio volumes.

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