X-RAY MEASUREMENT OF PARTICLE AND FIELD ENERGY DISTRIBUTIONS IN LOBES OF RADIO GALAXIES

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Abstract

Measurements are reported of electron and magnetic field energies in lobes of numbers of radio galaxies, by means of the detection of inverse Compton X-ray emission using *ASCA*, *Chandra* and *XMM-Newton*. Following three important results have been revealed. The first is that the electron energy density dominates the magnetic field one by an order of magnitude in an average. The second is that the electron energy integrated over the lobe seems to be proportional to the intrinsic X-ray luminosity of the active nucleus, while the magnetic energy appears to be relatively independent. The third is that in several objects the electrons are uniformly distributed over the lobes while the magnetic field becomes stronger toward the lobe periphery. These three imply that the electrons play more important role than the magnetic fields in the evolution of the lobes, besides maybe in the jet formation.

1 IC X-ray emission from the lobes

Lobes of radio galaxies and quasars contain a large amount of electrons and magnetic fields, both of which are originally supplied by jets emanating from active galactic nuclei. Therefore, the measurement of the energy densities of these electrons and magnetic fields $u_{\rm e}$ and $u_{\rm m}$, respectively, should offer us a very important information closely related to the jet physics. Inverse-Compton (IC) X-ray emission from the electrons in the lobes which also radiate the synchrotron radio emission, is one of the most useful probe for this purpose, because the comparison of the IC X-ray and the synchrotron radio fluxes from the lobes allow us to precisely estimate $u_{\rm e}$ and $u_{\rm m}$ independently. In the lobes, the seed photons of IC scattering are usually dominantly provided by the cosmic microwave background (CMB) radiation (Harris & Grindlay, 1979), otherwise on a small scale the infra-red radiation from the active nucleus (Brunetti et al., 1999).

In 1995, we have made a pioneering discovery of this IC X-ray emission from the lobe-dominant bright radio galaxy Fornax A (Kaneda et al., 1995) with *ASCA*. Subsequently, we have detected the IC X-rays from the lobes of 3 radio galaxies (Tashiro et al., 1998; Isobe, 2002). After the advent of *Chandra* and *XMM-Newton* in 1999, we further extended our investigation and detected the lobe IC X-rays from 4 more objects. At present, $u_{\rm e}$ and $u_{\rm m}$ are precisely determined in the lobes of more than 10 radio galaxies, including the results published by authors, through the IC technique.

As an example of our results, Fig. 1 shows the *Chandra* ACIS image of the radio galaxy 3C452 (Isobe et al., 2002). The diffuse X-ray emission, which fills the radio lobes structure almost entirely, is significantly detected. Base on the spectral analysis, the diffuse X-ray emission is securely confirmed to be of IC origin.

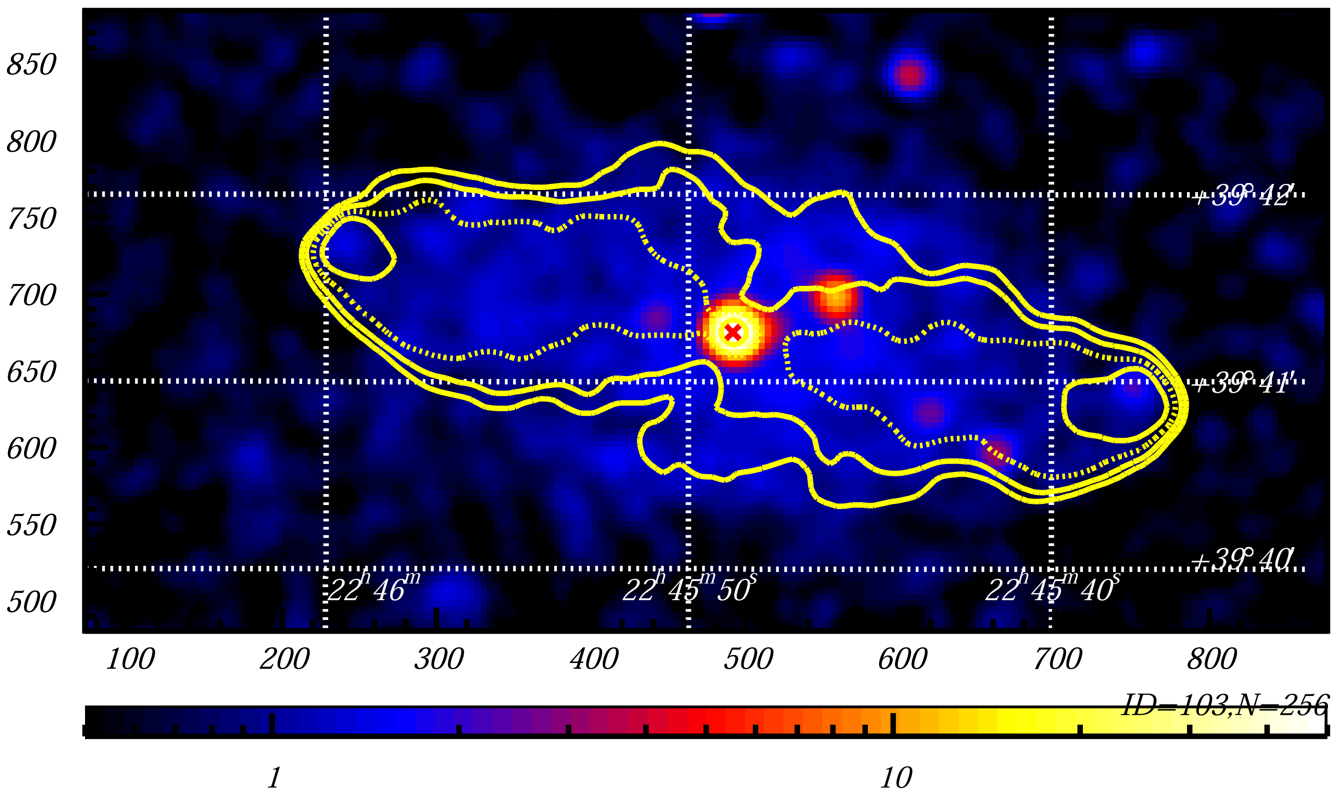

Figure 1: The 0.3–7 keV *Chandra* ACIS color image of 3C452 (Isobe et al., 2002). The 1.4 GHz VLA image (Laing; unpublished but downloaded through the web.) is overlaid with yellow contours. The cross indicated the position of the host galaxy.

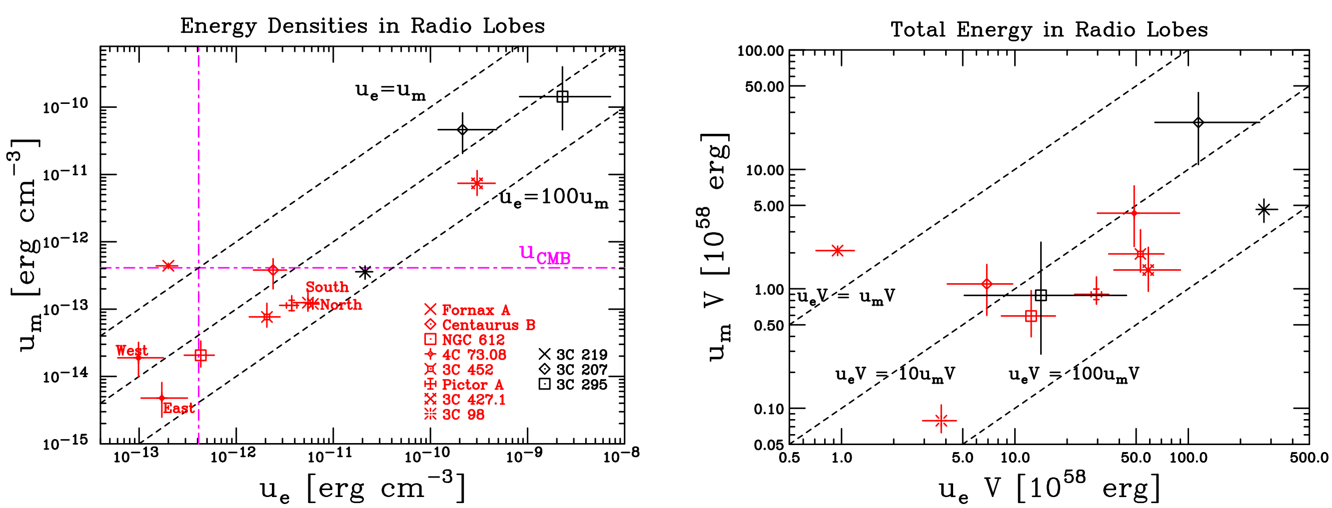

Figure 2: (left) u_e and u_m in lobes of radio galaxies, determined through the detection of the IC X-ray emission. The red data points are base on our results, and the black ones are estimated from others (Brunetti et al. 1999, Brunetti et al. 2001, and Brunetti et al. 2002). The symbol notation for each target is displayed within the figure. The three diagonal dashed lines correspond to the conditions of $u_\mathrm{e} = u_\mathrm{m}$ (i.e., equipartition between the electrons and the magnetic fields), u_e = 10 u_m and u_e = 100 u_m, from upper-left to lower-right. For comparison, the energy density of the CMB photons is also shown with dashed-dotted lines (u_CMB in the figure) neglecting the dependence on the redshift of the objects. (right) The total electron and magnetic field energies $u_\mathrm{e}V$ and $u_\mathrm{m}V$ respectively, in the lobes. The symbol notation and the color are both same as the left panel.

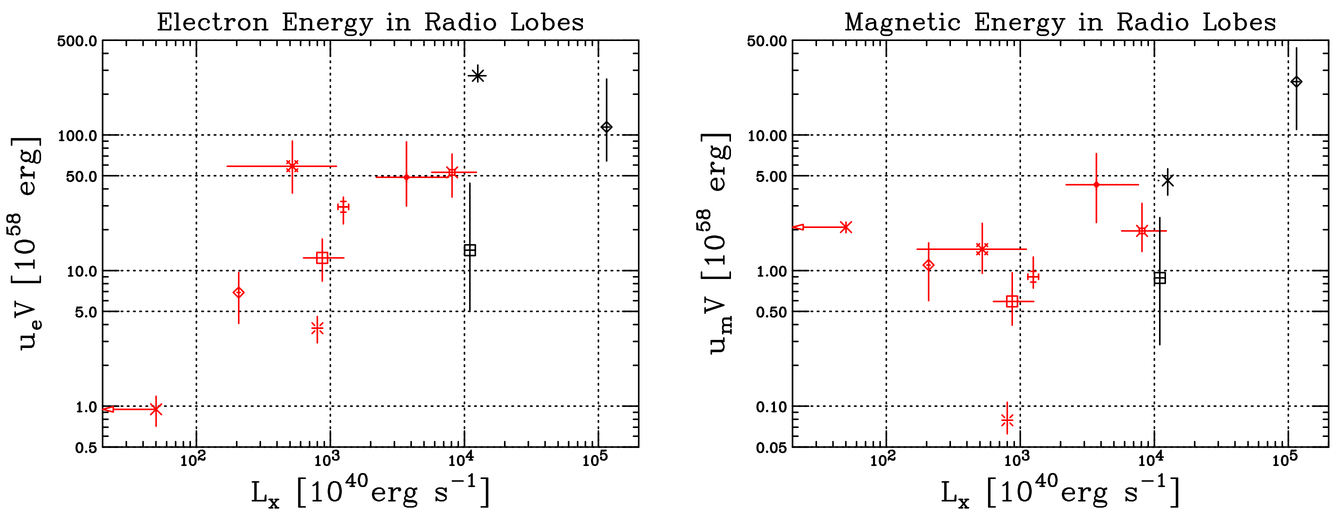

Figure 3: The total electron (left) and magnetic (right) energies in the lobes, plotted against the intrinsic 2–10 keV X-ray luminosity of the nucleus of the radio galaxies. The symbol notation and the color for the data points are same as for Fig. 2.

In the following sections, we review the physical parameters in the lobes, determined through our IC X-ray detections.

2 Physical parameters averaged/integrated over the lobes

The left panel of Fig. 2 shows the relation between u_e and u_m spatially averaged over the lobes (Isobe, 2002). Here, we integrated to obtain u_e the electron energy spectrum over the Lorentz factor from 10^3 to 10^5, because this range correspond the electrons which we directly observe as the synchrotron radio or the IC X-ray emission. This figure suggests at least one important fact that the *electron dominance* of typically $u_e/u_m \gtrsim 10$ is achieved in the lobes, with only one exception, Fornax A (Tashiro et al., 2001). If we take the lower limit of the electron Lorentz factor, considering a natural energy distribution expected in a shock acceleration, the electron dominance becomes more significant. The u_e/u_m ratio in Fig. 2 corresponds to the magnetic field of factor of 2 to 4 smaller than the value estimated under the classical minimum energy condition. Similar results are also reported, e.g., by Hardcastle et al. (2003) and Croston (2005), although their results are not shown in the figure.

u_e and u_m are distributed in a quite wide range of about six orders of magnitude. Especially, the lobes, located on the top-right in the left panel of Fig. 2, have a size of typically smaller than $\sim$ 50 kpc. In these smaller (and hence maybe younger) lobes, both u_e and u_m are significantly higher than the energy density of the CMB ($u_{\rm CMB} \gtrsim 4\times10^{-13}$ erg cm^{-3}), and the electrons are cooled by the synchrotron radiation. On the other hand, the others on the bottom-left are larger than $\sim$ 100 kpc, in which the electrons are mainly cooled by the IC losses.

We then converted u_e and u_m into the spatially-integrated electron and magnetic field energies, u_eV and u_mV, respectively, where V is the volume of the lobe, and shown them in the right panel of Fig. 2. Needless to say, the electron dominance is again confirmed. Both u_eV and u_mV is scattered over a range of about three orders of magnitude, relatively narrower compared with the distribution of u_e and u_m.

3 Relation between the lobes and the nucleus

As briefly mentioned in Sect. 1, the electrons and the magnetic fields are both carried from the active nucleus by the jets. Then, we compare the physical parameters in the lobes with the 2–10 keV intrinsic X-ray luminosity L_X of the nucleus.

Figure 3 plots u_eV and u_mV against L_X. Apparently, u_eV seems to increase nearly proportional to L_X, in a relatively wide rage of L_X from 10^{42} to 10^{45} erg s^{-1}. On the other hand, u_mV appears to be almost independent of L_X, or even relatively constant excluding a few objects. The sum of u_eV and u_mV is thought to reflect the time-integration of the past jet activity, while L_X can be regarded as the good indicator of the current activity of the nucleus, i.e., of the current accretion rate

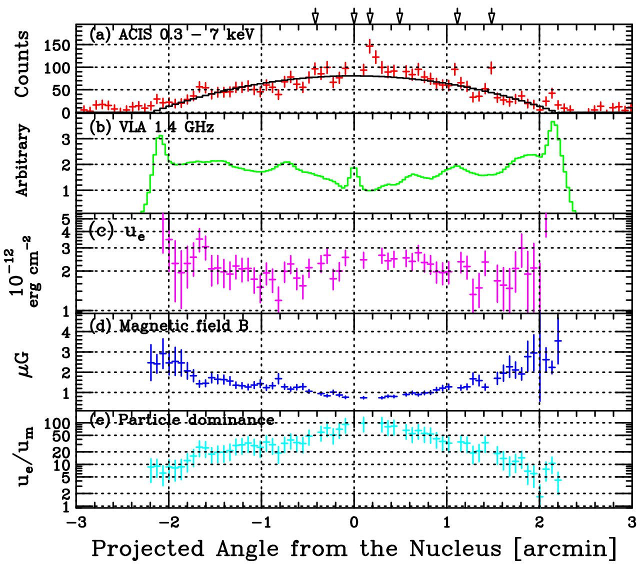

Figure 4: The distribution of (a) the IC X-rays, (b) the synchrotron radio, (c) $u_{\rm e}$, (d) the magnetic field B, and the ratio $u_{\rm e}/u_{\rm m}$ along the major axis of the lobes of 3C452. Arrows on the top of the figure indicate the position of the possible X-ray point source. The X-ray data corresponding to the nucleus is truncated. The histogram in the panel (a) shows the IC X-ray profile predicted when $u_{\rm e}$ is uniformly distributed within the ellipsoid.

onto the central supermassive black hole, because the jet axis of the sources in the sample dose not point to the line of sight and the contribution of the beamed radiation from the jet is thought to be negligible. Then, this proportionality may be a direct observational confirmation to the natural belief that the jets are launched by the energy released in the mass accretion onto the central black holes. And as shown in Fig. 2, the energy carried by the jets are stored in the lobes not in the form of the magnetic energy, but of the electron (and hence particle) energy.

4 Spatial distribution

Comparing the spatial distribution of IC X-ray emission and that of synchrotron radio emission, we can obtain the spatial distribution of $u_{\rm e}$ and $u_{\rm m}$. In Fig. 4, we show the profile of $u_{\rm e}$, the magnetic field strength B and the ratio $u_{\rm e}/u_{\rm m}$, together with the X-ray and radio brightness distribution, along the major axis of the lobes of 3C452 (Isobe et al., 2002). In the determination of the distribution of $u_{\rm e}$, the shape of the lobes is assumed to be an ellipsoid and the size of the major and the minor axes are estimated from the Very Large Array (VLA) radio image. We have found that $u_{\rm e}$ is relatively uniformly distributed over the lobe, although the magnetic field become stronger toward the edge of the lobe. As a result, in the center of the lobe, $u_{\rm e}$ highly dominates $u_{\rm m}$ nearly an order of magnitude, while nearly an equipartition is realized between $u_{\rm e}$ and $u_{\rm m}$ at the lobe periphery. We have found the same tendency also in the lobes of Fornax A (Tashiro et al., 2001) and Centaurus B (Tashiro et al., 1998).

5 Summary

In our X-ray investigation of the energetics in the lobes of radio galaxies, the following three important results are obtained.

- In the lobes the electron energy dominate the magnetic energy typically an order of magnitude.
- The total electron energy in the lobes seems to be proportional to the X-ray luminosity of the nucleus, while the magnetic energy appears to be independent.
- The electrons are found to have a relatively uniform spatial distribution over the lobes, although the magnetic fields seems to have a rim-strengthened feature.

All of these results may imply that the electrons (and hence particles) play more important role than magnetic fields in the energetics and the evolution of the lobe/jet system. But the larger sample is still required for the confirmation.

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