Anisotropic inverse Compton scattering in radio galaxies and particle energy distribution

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Abstract. In this talk we briefly review the inverse Compton (IC) scattering of nuclear photons in the lobes of radio galaxies and quasars. We concentrate on the possibility to test this model with the Chandra observatory and to constrain the electron energy distribution by measuring the X-ray fluxes produced by this effect. We also discuss the evidence for IC scattering of nuclear photons in powerful radio galaxies.

1. Introduction

A full understanding of the energetics and of the energy distribution of the relativistic particles in the radio jets and lobes of radio galaxies and quasars is of basic importance to a complete description of the physics and time evolution of these sources. Synchrotron emission properties result from a complicated convolution of magnetic fields and relativistic electron distributions, so that they cannot be unambiguously derived by radio observations alone (see Rudnick, this meeting). In the lobes of radio galaxies and quasars this degeneracy could be broken by measurements of the X-rays produced by the inverse Compton (IC) scattering of CMB photons (e.g. Harris & Grindlay 1979), and/or nuclear photons (Brunetti et al. 1997).

While the X-rays produced by the IC scattering of the CMB photons typically involve the less energetic part of the radio emitting electrons (Lorentz factor $\gamma \sim 1000$), those from the IC scattering of the far IR – optic nuclear photons are mainly powered by $\gamma = 100 - 300$ electrons which are not detected, since their synchrotron emission falls in the hundred kHz to MHz frequency range. By combining measurements of the 0.1–10 keV extended fluxes it is then possible to obtain broad band information on the energy distribution of the relativistic electrons ($\gamma \sim 50 - 3000$) in the lobes of radio galaxies and quasars.

The knowledge of the low energy part of the electron spectrum is particularly important. Indeed, while at higher energies radiative losses are dominant, at lower energies the electron spectrum is particularly sensitive to the initial injection conditions and to the acceleration mechanisms (Eilek & Hughes 1990). Furthermore, the detection of X-ray fluxes produced by IC scattering of nuclear photons, implying the lack of a prominent low energy cut off ($\gamma < 300$) in the electron energy distribution, may significantly increase the energy budget in the radio lobes compared with present estimates based on standard equipartition formulae (Brunetti et al. 1997).
2. Anisotropic IC scattering and relativistic electron spectrum

In the framework of the unification between powerful radio galaxies and radio loud quasars, the IC scattering of far IR to optic/UV nuclear photons by the relativistic electrons in the radio lobes could give detectable X-ray fluxes (Brunetti et al. 1997). Due to the geometrical configuration, the IC scattering is anisotropic so that if a symmetric double lobed radio galaxy is inclined with respect to the plane of the sky, the far lobe should appear more luminous than the near one. The slope of the X-ray spectrum produced by this scattering are reasonably close to the radio synchrotron one, but, if a low energy flattening of the electron energy distribution (or a cut–off) is present at energies $\gamma < 100$ the spectrum should flatten in the low energy part of the X-ray band (Fig.1a) and, furthermore, since the photons from the far lobe are back scattered, the X-ray spectrum of the far lobe should appear slightly harder that that of the near one (Fig.1b).

For a given energy distribution of the scattering electrons, the anisotropic IC spectrum can be obtained by making use of Brunetti (2000) equations. A positive detection of X-rays generated by this process can be used to constrain the electron energy distribution and the possible presence of a low energy cut–off ($\gamma_{\text{low}}$). In addition to the brightness asymmetry caused by the orientation of the radio axis, the X-rays from IC scattering of nuclear photons are expected to be more concentrated in the innermost parts of the radio lobes due to the dilution.
Figure 2. a) The X–rays (color) after the cluster subtraction are shown superimposed on the radio image (contours; kindly provided by Taylor & Perley). b) The energy density of the nuclear photons along the radio axis of the northern lobe of 3C 295 is compared with those of the synchrotron and CMB photons ($L_{\text{qso}} = 10^{46}$ erg s$^{-1}$ is assumed).

of the nuclear photon flux with distance. Moreover, if the lobes of a radio galaxy are significantly different in shape, the radio lobe closer to the nuclear source is expected to be the most luminous. All these properties of the X–ray brightness distribution allow to recognise the X–rays from IC scattering of nuclear photons.

3. Observational evidence

3.1. The case of 3C 219

Possible evidence for this emission has been found in the case of the powerful radio galaxy 3C 219 ($z=0.1744$) by a relatively deep ROSAT HRI observation corroborated by a combined ROSAT PSPC and ASCA spectral analysis (Brunetti et al. 1999). In this case the observed X–ray flux can be matched by assuming that the magnetic field in the inner radio lobes is a factor of $\sim 3$ lower than the equipartition value (calculated with $\gamma_{\text{low}} = 50$), similarly to that found in the case of Cen B (Tashiro et al.1998). 3C 219 will be observed by Chandra and we eagerly expect confirmation of the IC scenario.

3.2. The case of 3C 295

We report here on a study (Brunetti et al., to be submitted) of the powerful and compact FR II radio source 3C 295, which extends for $\sim 5$ arcsec on the plane of the sky, and is identified with a giant elliptical (cD) galaxy at the center of a rich cluster, at redshift $z=0.461$. This source was observed by Chandra (calibration time) for an elapsed time of $\sim 20$ ks; the 0.5–7 keV image is dominated by the two hot spot regions and by a powerful nuclear source (Harris et al.2000) making the study of extended X–rays associated with the radio lobes very difficult. We have performed a 0.1–10 keV spectral analysis of the nucleus finding that it is
well fitted by a powerful X-ray source (\( \sim 10^{45}\text{erg s}^{-1} \)) absorbed below \( \sim 2\text{ keV} \) \((N_H \sim 10^{23}\text{cm}^{-2})\). Thus the 0.1-2 keV image is nucleus free allowing to study the extended X-ray emission after subtraction of the diffuse cluster component. The result is shown in Fig.2a: extended and asymmetric X-ray emission is clearly detected. In Fig.2b we report the energy densities due to synchrotron emission, CMB photons and hidden quasar photons by assuming a far IR to optic luminosity of \(10^{46}\text{erg s}^{-1}\). It can be noticed that in the region where extended X-ray emission is clearly detected the energy density due to the nuclear photons is more than one order of magnitude larger than that due to other processes. By assuming for simplicity that the radio volume is axisymmetric, an inclination angle with respect to the sky plane of \(\sim 5^\circ\) (with the northern being the far lobe) is sufficient to reproduce the X-ray brightness asymmetry when the different morphologies of the two radio lobes are taken into account; such an asymmetry cannot be explained with other X-ray mechanisms proposed so far. Furthermore, a faint radio jet has been recently discovered in the southern lobe by a deep MERLIN observation (Leahy, private comm) possibly confirming that the northern lobe is the farthermost. Spectral analysis in the 0.1-2 keV band of the extended emission with a power law model limits the photon index in the range 1.23–1.65 (90% confidence level) requiring \(\gamma_{\text{low}} < 100\) if a spectral energy injection index \(\delta = 2.3\) (as constrained by radio spectral fits, see Brunetti, this meeting) is assumed for the electron energy distribution. By comparing the synchrotron flux from the lobes with the extended X-ray flux we obtain a magnetic field \(B \sim 40 - 90\mu\text{G}\) (close to the equipartition value, but lower) if a reasonable far IR to optical luminosity of the hidden quasar of \(1 - 2 \cdot 10^{46}\text{erg s}^{-1}\) is assumed.

Acknowledgments. We would like to thank A.Comastri and L.Feretti who are actively involved in the IC scattering research, and M.Cappi and D.E. Harris who are coinvestigators for 3C 295. It is also a great pleasure to acknowledge Robert Laing and Katherine Blundell for organizing such an interesting meeting. This work was partly supported by the Italian Ministry for University and Research (MURST) under grant Cofin98-02-32, and by the Italian Space Agency (ASI).

References

Brunetti, G. 2000, APh, 13, 107–125
Brunetti, G., Setti, G., Comastri, A. 1997, A&A, 325, 898–910
Brunetti, G., Setti, G., Comastri, A., Feretti, L. 1999, A&A, 342, 57–68
Eilek, J.A., Hughes, P., 1990, in 'Astrophysical Jets', ed. Hughes, P., Cambridge Univ. Press, p.428
Harris, D.E., Grindlay, J.E., 1979, MNRAS, 188, 25
Harris, D.E., Nulsen, P.E.J., Ponman, T.J., et al., 2000, ApJ, 530, L81
Sanders D.B., Phinney E.S., Neugebauer G., Soifer B.T., Matthews K., 1989, ApJ347, 29
Tashiro M., Kaneda H., Makishima N., et al., 1998, ApJ, 499, 713