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EUV excess in the inner Virgo cluster

F. De Paolis, G. Ingrosso, A. A. Nucita, and D. Orlando

Dipartimento di Fisica, Università di Lecce and INFN, Sezione di Lecce, Via Arnesano CP 193, 73100 Lecce, Italy

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Abstract. Observations with the Extreme UltraViolet Explorer (EUVE) satellite have shown that the inner region of the Virgo cluster (centered in M 87 galaxy) has a strong Extreme UltraViolet (EUV) emission (up to 13′) in excess to the low-energy tail expected from the hot, diffuse IntraCluster Medium (ICM). Detailed observations of large scale radio emission and upper limits for hard, non-thermal X-ray emission in the 2−10 keV energy band have been also reported. Here we show that all available observations can be accounted for by the existence of two electron Populations (indicated as I and II) in the M 87 Galaxy. The mildly relativistic Population I is responsible for the EUV excess emission via IC scattering of CBR and starlight photons. Population II electrons (with higher energy) are instead responsible for the radio emission through synchrotron mechanism. The same electrons also give rise to hard non-thermal X-ray emission (via IC scattering of CBR photons), but the resulting power is always below the upper bounds placed by present observations. The non-negligible energy budget of the two electron populations with respect to that associated with thermal electrons indicates that the M 87 galaxy is not today in a quiescent (relaxed) phase. Nuclear activity and merging processes could have made available this energy budget that today is released in the form of relativistic electrons.

Key words. galaxies: clusters: individual: Virgo – radio continuum: galaxies – ultraviolet: galaxies

1. Introduction

Observations with the EUVE satellite (Bowyer & Malina 1991) have provided evidence that a number of clusters of galaxies produce intense EUV emission, substantially in excess of the low-energy tail expected from the X-ray emission by the hot, diffuse ICM at temperature of a few keV. EUV excesses have been reported for Virgo (Lieu et al. 1996a), Coma (Lieu et al. 1996b), A1795 (Mittaz et al. 1998), A2199 galaxy clusters (Lieu et al. 1999), A4038 (Bowyer et al. 1998) and A4059 (Durret et al. 2002). However, although there is no doubt about the detection of the EUV excess emission for Virgo and Coma clusters, considerable controversy still exists for the other clusters since EUVE results are affected by the variation of the telescope sensitivity over the field of view and depend also on subtraction of background signals that do not come from the cluster (see Berghöfer & Bowyer 2002; Durret et al. 2002).

The initial explanation for the EUV excess emission was that it is produced by a warm ($T \sim 10^6$ K) gas component of the ICM (Lieu et al. 1996b). For Virgo and Coma clusters, Bonamente et al. (2001) have proposed that HI cold clouds might have, at least in part, been released in the intergalactic space by ram pressure stripping. In this framework, warm gas can be generated at the interface between the cold phase (HI clouds) and the hot ICM, e.g. by the *mixing layer* mechanism (Fabian 1997). The resulting scenario is then a three phase gas model, where the hot and warm gas components are responsible for the bulk of X-ray emission and the soft excess emission, respectively, while the cold component accounts for X-ray absorption (Buote 2001).

Models invoking the presence in galaxy clusters of the warm gas component have problems since they refer to unrelaxed or turbulent gas conditions: the longevity of such multiphase gas would then require the presence of a heat source to carefully balance the radiative cooling, but no obvious heating mechanisms have been found (Fabian 1996). Indeed, it is difficult for a warm intracluster gas to remain for a long time at $\sim 10^6$ K since at this temperature the cooling function for a gas with solar chemical composition has a value $\Lambda \simeq 2 \times 10^{-22}$ erg cm^3 s^{-1} (Saito & Shigeyama 1999) implying for the M 87 galaxy warm gas component with metallicity $Z \simeq 0.2$–$0.3\ Z_\odot$ (Gastaldello & Molendi 2002) and mean number density $n \simeq 10^{-3}$ cm^{-3} (Bonamente et al. 2001) a cooling time of about 150 Myr.

Although strong evidence for cooling flows has been found in low-resolution X-ray imaging and spectra, high-resolution observations with the Reflection Grating Spectrometer on the XMM-Newton satellite show inconsistencies with the simple cooling flow models. The main problem is the lack of the

Send offprint requests to: F. De Paolis,
e-mail: depaolis@le.infn.it

emission lines expected from gas cooling below 1–2 keV[1]. Indeed, observations with both the Hopkins Ultraviolet Telescope (Dixon et al. 1996) and FUSE (Dixon et al. 2001a, 2001b) found no significant far-UV line emission from gas at 10^6 K[2]. Also the observation of a large number of clusters by the XMM-Newton satellite (Tamura et al. 2001, 2002) detected no warm gas component. All these pieces of evidence seem overwhelming in the sense that a thermal mechanism for the EUV excess can be ruled out.

Therefore, other mechanisms must be investigated as the source of the EUV excess emission in clusters of galaxies. Indeed, Inverse Compton (IC) scattering of Cosmic Background Radiation (CBR) photons by relativistic electrons present in the ICM was proposed to explain the EUV excess in the case of the Coma Cluster (Hwang 1997; Ensslin & Biermann 1998; Ensslin et al. 1999).

Here, we will examine in detail the case of Virgo cluster, referring in particular to the results of a re-analysis of archival EUVE data for the central region of the cluster performed by Berghöfer et al. (2000a).

In Fig. 2 of the above cited paper, the azimuthally averaged radial intensity profile of the background-subtracted EUV emission in the central region of the Virgo cluster (centered in the M 87 galaxy) is given, as well as the contribution of the low-energy tail of the X-ray emitting hot ICM. Comparison between the two curves shows the presence of a diffuse EUV excess which extends up to a radius of $\sim 13'$ (corresponding to ~ 65 kpc, for an assumed M 87 distance $D = 17$ Mpc), in the M 87 halo region[3].

The aim of the present paper is to show that IC scattering of CBR and starlight photons by a population (hereafter denoted as Population I) of mildly relativistic electrons with energy up to a few hundred MeV is able to account for the EUV excess emission observed from the central region of the Virgo cluster, centered in M 87 galaxy. As we will see in Sect. 2, Population I electrons have to be described by a power law energy spectrum with an energy cut-off at $E_{\rm c} \sim 250$ MeV (or slightly above) in order to avoid both a hard, non thermal, X-ray excess (due to IC scattering of CBR photons) with respect to the upper limit of $\simeq 4 \times 10^{-12}$ erg cm^{-2} s^{-1} in the 2–10 keV energy band, set by observations (Reynolds et al. 1999) and over-production of radio waves by synchrotron emission (Owen et al. 2000).

The existence in the M 87 galaxy of a highly relativistic electron population (which we refer to as Population II) is well demonstrated by the observations of large-scale radio emission in the 10 MHz–100 GHz band (Owen et al. 2000). This radio emission is generally interpreted as synchrotron radiation produced by relativistic electrons interacting with the halo magnetic field. To b exact, taking a value $B \simeq 2.5\ \mu$G as typical for the M 87 halo magnetic field, one gets an electron energy range $\sim 1-170$ GeV. Population II electrons have to be described with a power law energy spectrum with slope $\alpha_{\rm e} = 2.68$ in order to fit the observed radio power law spectrum $\alpha_{\rm R} = 0.84$. Electrons belonging to the same Population II, but with energy in the range 0.7–1.7 GeV, also could give rise to a hard, non thermal X-ray emission in the 2–10 keV region (through IC scattering of CBR photons), but the resulting power is always negligible with respect to the upper limit quoted by Reynolds et al. (1999).

Regarding the origin of Population I and II electrons, it is well known that the main source of non-thermal energy in the M 87 galaxy is the active nucleus and jet. The current bolometric luminosity of the inner active region is $\sim 10^{42}$ erg s^{-1} – mainly emitted in the radio band (Owen et al. 2000) – although the kinetic power in the jet (which matches with the nuclear power for accretion at the Bondi rate) is $\sim 10^{44}$ erg s^{-1} (Di Matteo et al. 2002). This is believed to be a lower limit for the total power available for particle acceleration, since the central engine would have had a cyclic activity with time scale of the order of 100–200 Myr and today be in a quiescent phase (Owen et al. 2000; Corbin et al. 2002). Therefore, simple lifetime considerations indicate that the available current energy content is at least $\sim 10^{60}$ erg. On the other hand, in the past, the M 87 galaxy could have undergone a merging which would have made available a further energy budget (as suggested for the Coma cluster by Blasi 2000). This energy budget could be stored by accelerated protons that, being long-lived in the intergalactic medium (with lifetimes of the order of a Hubble time) could be confined in the galaxy and then released part of their energy to electrons by Coulomb and/or hadronic interactions (see e.g. Ensslin 2002) or by shock waves in plasma turbulence.

The observed radio luminosity requires that the power emitted by Population II electrons is $\sim 10^{42}$ erg s^{-1}. Since the cooling time of these electrons is dominated by synchrotron losses with a time scale of $\sim 10^{15}$ s, one gets a Population II energy budget of $\sim 10^{57}$ erg, much less than the current available energy content. This implies that most of the total energy made available by the M 87 nucleus could be stored in Population I electrons. If these electrons are responsible for the EUV excess emission by IC scattering of CBR and starlight photons, their power is about 10^{44} erg s^{-1}, which multiplied by the IC cooling time $\sim 10^{17}$ s, gives a Population I energy content close to that available.

As far as the electron acceleration mechanism is concerned, it is expected that Population II electrons have been directly accelerated in the active nucleus and jet with high Lorentz factors. Indeed, the two lobes in the observed radio map trace on a large-scale the jet injection, keeping initially the direction of collimated outflows from the core. Further diffusion

[1] Several solutions to this problem have been investigated, such as heating, mixing, differential absorption and inhomogeneous metallicity (Fabianet al. 2001), but each of these hypotheses still remain under debate (Molendi & Pizzolato 2001). In particular, in the case of the Virgo cluster, a multiphase gas model gives a better description of the available data than a single temperature model only if it is not characterized by a broad temperature distribution, but by a narrow one (Molendi & Pizzolato 2001). In the Virgo core (up to a radius $\sim 10'$), the gas temperature ranges between 1 keV and 2 keV, so that the gas is not cold enough to justify the observed EUV emission.

[2] For the M 87 galaxy Dixon et al. (1996) found upper limits to far-UV dereddened line emission of 4.84×10^{-6} erg cm^{-2} s^{-1} sr^{-1} for the $O_{\rm VI}$ line and 3.64×10^{-6} erg cm^{-2} s^{-1} sr^{-1} for the $C_{\rm IV}$ line. The absence of a significant far-UV line emission, which is expected from a warm gas component, is also confirmed by FUSE observations not only for Virgo but also for the Coma cluster (Dixon et al. 2001b).

[3] The initial analysis of the same data claimed to have detected EUV excess emission up to a distance of $20'$ (Lieu et al. 1996a).

by magnetic field inhomogeneities may give rise to a diffuse Population II component responsible for the overall radio emission. It is also known that the active nucleus and jet in the M 87 inner region are responsible for inflating bubbles of accelerated cosmic rays which rise through the cooling gas at roughly half the sound speed (Churazov et al. 2001). Shock acceleration at the bubble boundaries could give rise to Population I electrons.

Finally we note that the existence for Population I electrons of an energy cutoff at $E_c \simeq 250$ MeV may be justified by considering that a time evolution for power-law spectrum injected electrons is expected as a consequence of transport, diffusion and cooling effects (see Petrosian 2001 for a detailed analysis for the Coma cluster).

In Sect. 2 we calculate the EUV source function for the IC scattering by relativistic electrons on CBR and starlight photons and the expected EUV excess radial profile towards the M 87 galaxy. In Sect. 3 we present our model results and address some conclusions.

2. Inverse Compton scattering

As stated in the Introduction, we assume that Population I electrons account for the large-scale EUV excess in M 87 galaxy through IC scattering of CBR and starlight photons. As far as the electron spatial distribution is concerned, despite evidence of granularity in the EUV excess map of M 87 (Fig. 5 in Berghöfer et al. 2000a), here we adopt for simplicity a continuous radial profile as representative of an azimuthally averaged radial distribution of the observed structures. Therefore, the electron density distribution $n_e(E_e, r)$ as a function of the electron energy E_e and the radial coordinate r, in units of $\mathrm{cm^{-3}\,eV^{-1}}$, is

$$n_e(E_e, r) = \frac{K_I}{\left[1 + \left(\frac{r}{r_e}\right)^2\right]^{3\beta/2}}\, g(E_e), \qquad (1)$$

where

$$g(E_e) = \begin{cases} \left(\frac{E_e}{\mathrm{eV}}\right)^{-\alpha_e} & \text{for } E_e < E_c \\ \left(\frac{E_e}{\mathrm{eV}}\right)^{-\alpha_e} \mathrm{e}^{-(E_e - E_c)/E_s} & \text{for } E_e > E_c, \end{cases} \qquad (2)$$

so that the integral number density in the energy band $E_1 - E_2$ can be calculated as

$$N_e(r) = \int_{E_1}^{E_2} n_e(E_e, r)\,\mathrm{d}E_e. \qquad (3)$$

Free parameters in Eqs. (1) and (2) are the constant K_I, the core radius r_e, the exponent β of the radial dependence, the electron spectral index α_e, the energy cutoff (E_c) and scale (E_s) parameters which, in order to avoid over production of hard X-rays and radio waves, turn out to be $E_c \simeq 250$ MeV and $E_s \simeq 125$ MeV, respectively. The remaining parameters have to be determined in order to fit the observed EUV excess radial profile in the energy band 50–200 eV. To this end we make use of the well-known relation giving the IC scattered photon energy (see e.g. Lang 1974)

$$E_\gamma = \frac{4}{3}\left(\frac{E_e}{mc^2}\right)^2 < E_{ph} > \qquad (4)$$

in terms of the average energy $< E_{ph} > \simeq 8/3\ KT_{ph}$ of target photons when a black body spectral distribution (at temperature T_{ph}) is assumed.

In our model the target photons are supplied by the CBR and Starlight (S) photons, with temperature $T_{CBR} \simeq 2.7$ K and $T_S \simeq 4400$ K[4], respectively. According to Eq. (4), Population I electrons in the energy bands 125–250 MeV and 3–10 MeV are involved in order to scatter the CBR and starlight photons, respectively, into the EUV energy range 50–200 eV.

The source function for EUV photon production through IC scattering is given by (Lang 1974), in units of $\mathrm{cm^{-3}\,s^{-1}\,eV^{-1}}$, as

$$Q_{IC}(E_\gamma, r) = \frac{c\sigma_T}{2}\left(\frac{mc^2}{\mathrm{eV}}\right)^{1-\alpha_e}\left(\frac{4}{3}\frac{< E_{ph} >}{\mathrm{eV}}\right)^{\frac{\alpha_e - 1}{2}} \times N_{ph}(r)\frac{K_I}{\left[1 + \left(\frac{r}{r_e}\right)^2\right]^{3\beta/2}} \times \left(\frac{E_\gamma}{\mathrm{eV}}\right)^{-\frac{\alpha_e + 1}{2}}, \qquad (6)$$

where $N_{ph}(r)$ is the target photon number density profile, indicated as N_{CBR} and $N_S(r)$ for CBR and starlight photons, respectively. Note that for $E_\gamma < 200$ eV (corresponding to $E_e < E_c$) the source function $Q_{IC}(E_\gamma, r)$ shows a power law spectrum with slope $\alpha_{EUV} = (\alpha_e + 1)/2$.

As far as the average background photon density $N_{ph}(r)$ in Eq. (6) is concerned, in the case of CBR photons it is clearly constant ($N_{CBR} \simeq 400\ \mathrm{cm^{-3}}$) within the M 87 galaxy, whereas for starlight photons it is obtained by the relation

$$N_S(r) = \frac{J_S(r)}{< E_S > c}, \qquad (7)$$

in which the starlight energy flux $J_S(r)$, in units of $\mathrm{eV\,s^{-1}\,cm^{-2}}$, is obtained from the integration of the local emissivity $\mathcal{L}_S(r')$ on the M 87 volume

$$J_S(r) = \int_V \mathrm{d}V \frac{\mathcal{L}_S(r')}{4\pi|r - r'|^2}. \qquad (8)$$

We describe the local emissivity by the law (Binney & Tremaine 1987)

$$\mathcal{L}_S(r) = \frac{\mathcal{L}_S(0)}{[1 + (r/r_S)^2]^{3/2}}, \qquad (9)$$

[4] The temperature T_S associated with the starlight black body component can be directly obtained from the photometry observations (see e.g. Marcum et al. 2001) towards the M 87 galaxy. From these observations we derive that the absolute magnitudes in the B and V bands are $M_B = -21.15 \pm 0.07$ and $M_V = -22.08 \pm 0.05$, respectively. Consequently, the starlight black body temperature turns out to be

$$T_S = \frac{7200\ \mathrm{K}}{C_{B-V} + 0.68} \qquad (5)$$

where $C_{B-V} = M_B - M_V = 0.94 \pm 0.09$ is the M 87 color index.

which implies that the M 87 starlight luminosity profile at impact parameter b is given by the modified Hubble profile

$$I_S(b) = \frac{I_S(0)}{[1 + (b/r_S)^2]}. \quad (10)$$

In the previous two equations the relation $\mathcal{L}_S(0) = I_S(0)/(2r_S)$ holds; moreover $I_S(0)$ is connected to the total luminosity through the relation

$$I_S(0) = \frac{L_S}{\pi r_S^2 \log[1 + (R_{M\,87}/r_S)^2]}. \quad (11)$$

Therefore, the whole photon density profile $N_S(r)$ due to starlight is specified once the total luminosity L_S and the optical core radius r_S are given. According to Tenjes et al. (1991) and Zeilinger et al. (1993), we take $L_S = 1.07 \times 10^{11}\ L_\odot$ and $r_S \simeq 566$ pc, respectively. For definiteness we have taken the M 87 galaxy size to be $R_{M\,87} \simeq 100$ kpc, although our model results depend weakly on the chosen value.

At this point we are ready to estimate the expected EUV excess radial profile in the M 87 galaxy. By integrating the source function given in Eq. (6) along the line of sight at impact parameter b (neglecting internal absorption in M 87), we get the surface brightness profile (in units of cm^{-2} s^{-1} eV^{-1})

$$\Phi_{IC}(E_\gamma, b) = 2\int_0^{\sqrt{R_{M\,87}^2 - b^2}} \frac{Q_{IC}(E_\gamma, r)\, r}{\sqrt{r^2 - b^2}}\, dr. \quad (12)$$

Correspondingly, the total power emitted in the energy band $E_1 - E_2$ reads

$$L_{IC} = 2\pi \int_0^{R_{M\,87}} db\, b \int_{E_1}^{E_2} dE_\gamma\, \Phi_{IC}(E_\gamma, b)\, E_\gamma. \quad (13)$$

The photon number count, in units of arcmin^{-2} s^{-1}, expected to be measured by the Deep Survey telescope aboard the EUVE satellite as a function of the angular radius $\theta \simeq b/D$ results to be

$$\mathcal{N}_{EUV}(\theta) = \int_{E_1}^{E_2} \Phi_{IC}(E_\gamma, \theta D) e^{-\tau(E_\gamma)}\, A_e(E_\gamma) dE_\gamma, \quad (14)$$

where $[E_1 - E_2] \simeq [50\text{–}200]$ eV is the sensibility energy range of the DS instrument and $A_e(E_\gamma)$ its effective area given in Bowyer et al. (1994). In Eq. (14) we also take into account the galactic absorption through the optical depth $\tau(E_\gamma) = N_H\sigma(E_\gamma)$, $N_H = 1.7 \times 10^{20}$ cm^{-2} being the Milky Way column density towards M 87 (Hartman & Burton 1997) and $\sigma(E_\gamma) = [11\ \sigma_{\gamma H}(E_\gamma) + \sigma_{\gamma He}(E_\gamma)]/12$ is accounting for both the cross section of γH and γHe interaction, as parameterized by Morrison & McCammon (1983) and Yan et al. (1998), respectively.

3. Results and conclusions

Following the formalism discussed in Sect. 2, we fit the available EUV excess data towards the M 87 galaxy. For this purpose, experimental points (given with the respective error bars in Fig. 1) are derived from those given in Fig. 2 in Berghöfer et al. (2000a), by subtracting the contribution of the low-energy tail due to the X-ray emitting ICM.

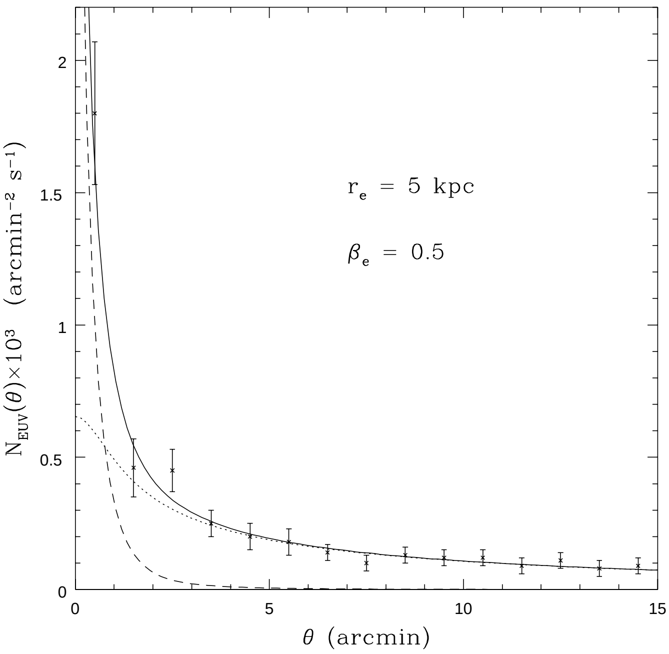

Fig. 1. The expected photon number count $\mathcal{N}_{EUV}$ is shown as a function of the angular radius θ, for the model giving the best-fit (solid line) to the observational data. Dotted and dashed lines represent the contribution from IC scattering of CBR and starlight photons, respectively.

Preliminarily, we have fitted the M 87 observed EUV excess by considering only the IC scattering of Population I electrons on CBR photons (Model I, with 11 d.o.f.). In this way, we obtain a poor fit with $\chi^2 = 2.3$ by considering all the 15 observed points (see the dotted line in Fig. 1)[5].

Consideration of the IC scattering by the same electron population also on starlight photons, distributed accordingly to Eqs. (7)–(11), (Model II, with 9 d.o.f.), allows us to substantially increase the expected photon number counts from the innermost part of the galaxy, therefore obtaining a much better confidence level $\chi^2 \simeq 0.5$, considering all the 15 points (see solid line in Fig. 1). This represents a significant improvement of the fit to all the observed points since the outcome of the F-test implies that Model II has to be preferred over Model I within a 3% confidence level (the F-test value is 3.9).

Selected models with $\chi^2 < 1$ give a range of values for r_e and β given by $r_e = 5 \pm 1$ kpc and $\beta = 0.5 \pm 0.1$. As far as the remaining two parameters α_e and K_I – which are actually related by Eq. (3) – our acceptable $\chi^2 < 1$ fits give $2 < \alpha_e < 3$ and, correspondingly, $10^4 \lesssim K_I \lesssim 10^8$ eV^{-1} cm^{-3}. The obtained relative ratio between the EUV luminosity from IC scattering on starlight and CBR photons is in the range of 2%−6%. The parameter α_e cannot be further constrained by EUV excess data due to the absence of spectral measurements.

Recent experimental results (Reynolds et al. 1999) set an upper limit of 4×10^{-12} erg s^{-1} cm^{-2} for the hard, non-thermal X-ray flux in the 2−10 keV energy band from the M 87 galaxy.

[5] The χ^2 value gets reduced to $\chi^2 \simeq 0.7$ if we do not include the first observed point at 1′. Indeed, a substantial fraction of the observed number count at 1′ may be the result of the core and jet activity (Berghöfer et al. 2000a).

Moreover, radio observations in the 10 MHz–100 GHz band give a total luminosity $L_R \simeq 5 \times 10^{41}$ erg s^{-1} (Herbig & Readhead 1992; Owen et al. 2000). If we do not introduce an energy cutoff for Population I electrons (see Eq. (2)), we would find both a hard, non-thermal X-ray excess emission (in the 2−10 keV energy band, due to IC scattering of CBR photons) and radio wave excess by synchrotron mechanism, above the upper bound allowed by observations.

In the following, as stated in the Introduction, we assume that the radio emission is accounted for by Population II electrons described by the same distribution law as in Eq. (1) for Population I electrons, but with different parameter values for $K_{\rm II}$, $r_{\rm e}$, β, $\alpha_{\rm e}$ and without energy cutoff[6]. Here we recall that the characteristic frequency and the differential luminosity of the ultrarelativistic synchrotron radiation are given by (see e.g. Lang 1974)

$$\nu = \frac{3}{4\pi}\frac{eB}{mc}\left(\frac{E_{\rm e}}{mc^2}\right)^2 \tag{15}$$

and

$$L_R(\nu) = \frac{\sqrt{3}e^3 C_R F_{\rm e}}{8\pi mc^2}\left(\frac{3e}{4\pi m^3 c^5}\right)^{\frac{\alpha_{\rm e}-1}{2}} B^{\frac{\alpha_{\rm e}+1}{2}}\, \nu^{-\frac{\alpha_{\rm e}-1}{2}}, \tag{16}$$

where $C_R \simeq (1.602 \times 10^{-12}\ {\rm erg})^{\alpha_{\rm e}}$ and

$$F_{\rm e} = \int_0^{R_{\rm M\ 87}} \frac{K_{\rm II}}{\left[1+\left(\frac{r}{r_{\rm e}}\right)^2\right]^{3\beta/2}}\, 4\pi r^2\, {\rm d}r. \tag{17}$$

If we take $\alpha_{\rm e} \simeq 2.68$, so that the predicted radio power law spectrum $\alpha_R = (\alpha_{\rm e} - 1)/2 \simeq 0.84$ is in agreement with the observed value, and a value $B \simeq 2.5\ \mu$G for the magnetic field strength in the M 87 halo (Dennison 1980), there exists a set of acceptable values for the free parameters in Eq. (17) for which the obtained diffuse radio emission from the M 87 galaxy in the band 10 MHz–100 GHz is $L_R \simeq 5 \times 10^{41}$ erg s^{-1}, consistent with the observed value (Herbig & Readhead 1992; Owen et al. 2000).

It is remarkable that the same set of values for Population II electron parameters that fit radio observations give a hard, non-thermal X-ray flux by IC scattering of CBR photons (by electrons in the energy range 0.7–1.7 GeV) in accordance with the upper bounds given by Reynolds et al. (1999) for the M 87 galaxy[7]. More recently, the XMM-Newton observatory has been pointed towards M 87 galaxy with the aim of investigating if non-thermal IC emission is present in the arms regions and if it is linked to the power emitted by the radio jet. The upper limit to the non-thermal X-ray emission has been found to be $\leq 4 \times 10^{-14}$ erg cm^{-2} s^{-1} in the 0.5−8 keV band, representing less than 1% of the flux from the thermal components (Belsole et al. 2001). Our model results give a hard non-thermal X-ray flux from the inner $\simeq 5'$ region of M 87 galaxy close to the above upper bound. Clearly, our model results depend on the chosen parameters for population II electrons which are not, at present, tightly determined by radio observations. For example, by increasing the Population II electron core radius (or decreasing the value of β) we can dilute the X-ray excess (and also the radio emission) within a wider region, leaving the same total power.

A few comments about the energy budget involved for the two electron Populations are in order. Observations show that the current bolometric luminosity of the M 87 inner active region is $\sim 10^{42}$ erg s^{-1} – mainly emitted in the radio band (Owen et al. 2000) – although the kinetic power in the jet is $\sim 10^{44}$ erg s^{-1} (Di Matteo et al. 2002). Simple lifetime considerations then indicate that the available electron energy content is at least $\sim 10^{60}$ erg. However, the total power available for particle acceleration may be larger since the central engine could have had a cyclic activity with a time scale of the order of 100−200 Myr and today be in a quiescent phase (Owen et al. 2000; Corbin et al. 2002). Moreover, in the past the M 87 galaxy could have undergone a merging phenomenon which would have made available a further energy budget, initially stored by relativistic protons and later released (partially) to electrons by Coulomb and/or hadronic interactions or by shock waves in plasma turbulence (Ensslin 2002).

Coming back again to our model results, we find that the energy budget associated with the two electron Populations is about 10^{60} erg (mostly in Population I electrons), which is always less or approximately equal to the total energy associated with thermal electrons[8]. This result represents an indication that the M 87 galaxy is not today in a quiescent (relaxed) phase.

However, further more accurate spectroscopic observations in both the EUV and X-ray bands (especially towards the external region of the M 87 galaxy) are necessary in order to confirm the presence of the two electron Populations invoked in the present paper. Moreover, observations towards the other galaxy clusters for which the EUV emission is still uncertain may establish whether the existence of these two electron Populations is a common feature in galaxy clusters or if it is particular to the central, massive, cD galaxies like M 87.

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[6] Indeed, Population I and II electrons are expected to have different spatial distributions although the radio map of the M 87 halo shows some similar features with respect to the observed distribution of the outer EUV excess (see Berghöfer et al. 2000a; Andernach et al. 1979 and Churazov et al. 2001).

[7] Of course, this estimate is obtained by using the same formalism described in Sect. 2 for the EUV excess by Population I electrons, but using in Eq. (6) the appropriate Population II electron parameter values.

[8] The energy associated with thermal electrons is estimated by assuming that the hot, virialized, X-ray emitting gas has a solar metallicity composition and is distributed following a β-model with $\beta \simeq 0.5$, core radius $\simeq$1.6 kpc and temperature $T_{\rm g} \simeq 2.5$ keV (Fabricant & Gorenstein 1983). Moreover, the gas central number density is taken to be $\sim 3 \times 10^{-1}$ cm^{-3} so that the total X-ray luminosity in the energy bands 0.2−4 keV and 2−10 keV turns out to be $\simeq 2.7 \times 10^{43}$ erg s^{-1} and $\simeq 3 \times 10^{43}$ erg s^{-1}, in accordance with the observed values (Forman & Jones 1982).

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