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On the thermal origin of the hard X-ray emission from the Coma cluster

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Abstract. We analyze the origin of the hard X-ray flux from the Coma cluster observed by the Beppo-SAX satellite. This flux is typically assumed to be produced by nonthermal particles accelerated in the Coma medium. We show, however, that in the case of in-situ acceleration of particles from the thermal pool, the hard X-rays in the range of Beppo-SAX observations ($30-80$ keV) are generated by bremsstrahlung radiation of thermal particles with the Maxwellian spectrum distorted by the acceleration. This mimics the effect of a two-temperature thermal spectrum. The power-law nonthermal spectrum of accelerated particles is formed at energies above 900 keV. The fraction of particles accelerated from the thermal pool is estimated in the range $(1-3)\cdot 10^{-6}$. For the acceleration parameters derived from the hard X-ray flux we conclude that the strength of the magnetic field in the Coma halo is about $0.2-7$ μG. In the framework of the model the maximum frequency of the radio emission from Coma is several GHz in agreement with observations. At higher frequencies there is a strong steepening in the radio spectrum. For some values of acceleration parameters and magnetic fields, clusters of galaxies emit only hard X-rays but no radio flux comes from them.

Key words: galaxies: clusters: individual: Coma cluster – X-rays: general – ISM: cosmic rays – radiation mechanisms: non-thermal

1. Introduction

The Coma cluster is one of the most widely investigated metagalactic objects. Its extended emission was found in X-rays and in the radio range of electromagnetic waves (see, e.g., Sarazin 1988). The radio halo has a size of ~ 1 Mpc, while the X-ray emission is more extended. The thermal X-ray emission was measured with several instruments. In our analysis we used the ROSAT data (Briel et al. 1992). The central gas density of the cluster was found to be $n \simeq 3\cdot 10^{-3}$ cm^{-3} and the average temperature to be $kT \simeq 8$ keV.

The origin of the radio emission is definitely nonthermal. This emission is produced by relativistic electrons radiating in the intracluster magnetic fields. The energy of these electrons is several GeV. The most interesting conclusion that follows from the synchrotron origin of the radio emission is that these electrons cannot be emitted by galaxies of the cluster. They must be in-situ accelerated in the cluster medium because the large number of relativistic electrons necessary to fill the halo cannot be produced by diffusion from active radio galaxies of the cluster (see, e.g., Jaffe 1977; Roland 1981; Roland et al. 1990; Giovannini et al. 1993; Feretti et al. 1995; Sarazin 1999). The main difficulty of this scenario is the short path length (~ 10 kpc) of the electrons.

The large scale and the tangled components of the intracluster magnetic field were estimated from the measurements of Faraday rotation of the polarized radiation (Kim et al. 1990; Feretti et al. 1995) that gave $0.1-0.3$ μG and $3-8$ μG, respectively.

Recently, Lieu et al. (1996) (see also Bowyer et al. 1999) found an extended, extreme ultraviolet (EUV) emission from the cluster in excess of the thermal one. One of the possibility is that the EUV emission is due to the inverse Compton (IC) scattering of several hundred MeV electrons on relic or starlight photons (Lieu 1996; Enßlin et al. 1999).

A similar explanation was suggested for the origin of hard X-rays ($E_x > 10$ keV) observed with the Beppo-SAX X-ray satellite (see Fusco-Femiano et al. 1999). Its intensity is also above the thermal distribution. In the case of the IC origin, the energy of fast electrons must be nearly several GeV. However, Enßlin et al. (1999) showed that the IC models for hard X-rays require implausible conditions. They assumed this emission to be due to the bremsstrahlung loss of suprathermal electrons accelerated by turbulence within the medium. This means that electrons of energies slightly above kT (above several tens keV) are under the action of acceleration mechanisms. Thus, Sarazin and Kempner (2000) assumed the nonthermal population to consist of electrons with kinetic energies $E > 3kT$ and the total number of nonthermal particles to be 1% of the thermal population of electrons.

We define the electron acceleration efficiency as $\eta_e = n_{acc}/n_{th}$ where n_{acc} is the accelerated electron density and n_{th} is the background (thermal) electron density. Therefore the value of η_e assumed by Sarazin and Kempner (2000) is $\eta_e = 10^{-2}$. This acceleration efficiency in the whole extended cluster halo is extremely high. Indeed, the maximum efficiency

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of electron acceleration from the thermal pool by supersonic turbulence (by an ensemble of shock waves), estimated by Bykov & Uvarov (1993), equals only $\eta_e \sim 10^{-5}$, which is three orders of magnitude less than the value obtained by Sarazin and Kempner (2000). We notice here that the shock waves generated by the galaxies of the cluster are supposed to be responsible for the electron acceleration in the Coma halo.

The other explanation was analyzed by Fusco-Femiano et al. (1999). They attempted to fit their results with two temperatures, but ruled out this interpretation because one temperature was 8 keV, but the other was unbelievably high (> 40 keV). On the other hand, this model does not need an effective acceleration which is necessary for the nonthermal models.

Nevertheless, we shall show that the thermal interpretation of the Beppo-SAX results may be correct. The point is that the Coulomb collisions inject particles from the energy range of Maxwellian distribution (equilibrium (thermal) distribution with the temperature T) to the energy E_{inj} where they are picked by acceleration. We shall show that in the case of in-situ acceleration of background electrons, the effect of acceleration is not limited by generation of the nonthermal spectrum only. This process significantly changes the equilibrium distribution of thermal particles. These thermal electrons with a distorted Maxwellian spectrum may be responsible for the observed hard X-ray emission.

To show this, let us summarize the main results of observations.

- The cluster gas is hot and fully ionized. The average gas temperature is about 8 keV, and the density is $3\cdot10^{-3}$cm^{-3};
- There are nonthermal particles in the cluster, which generate emission in the radio, EUV, and perhaps, hard X-ray energy ranges;
- These particles are accelerated in the cluster medium, i.e., the processes of in-situ acceleration should be assumed in Coma.

2. Particle acceleration in astrophysical plasma

Let us first briefly summarize the parameters of cosmic ray (CR) acceleration that may be responsible for particle production in the cluster medium. The idea was first suggested by Fermi (1949), who showed that the scattering of particles on magnetic field fluctuations leads to their slow stochastic acceleration. The acceleration rate in this case is

$$\frac{dp}{dt} = \alpha_0 p \,, \tag{1}$$

where p is the particle momentum and α_0 is the coefficient proportional to the characteristic velocities U_0 of the fluctuations. For the regular motions, we have $\alpha_0 \propto U_0$ (Fermi I acceleration) and for the chaotic motions $\alpha_0 \propto U_0^2$ (Fermi II acceleration). We notice, however, that in the case of Fermi II acceleration this process is described as diffusion in the momentum space with a diffusion coefficient $\alpha(p)$. In many cases the coefficient $\alpha(p)$ has the form (see, e.g., Toptygin 1985)

$$\alpha(p) = \alpha_0 p^2 \,. \tag{2}$$

If the characteristic frequency of particle scattering by the fluctuations over their pitch angles is ν_H, then the coefficient α_0 is

$$\alpha_0 \sim \frac{\pi U_0^2}{3vL_{cor}} \,, \tag{3}$$

where the correlation length is $L_{cor} \sim v/\nu_H$, and v is the particle velocity, $U_0 \ll v$.

This value of α_0 can in principle be specified for different cases (models) of acceleration (see, e.g., Berezinsky et al. 1990). If the acceleration is due to scattering on resonant magnetohydrodynamic (MHD) fluctuations then

$$\alpha_0 \sim 2\pi^2 \mid \omega_H \mid \left(\frac{v_A}{v}\right)^2 \frac{\delta H^2}{H_0^2} \,, \tag{4}$$

where v_A is the Alfven velocity, δH is the magnetic field strength of resonant MHD fluctuations, H_0 is the strength of the large-scale magnetic field, and $\omega_H = eH_0c/\varepsilon$ is the gyrofrequency of electrons (ε is the total energy).

For the acceleration by an ensemble of shock waves we should use the velocity of shock waves U_{sh} in Eq. (3) as U_0 and the average distance between shocks as L_{cor}.

The production spectrum of accelerated particles (per unit time) is a power-law one:

$$q(p) \propto p^{-\left(3+\frac{1}{\tau\alpha_0}\right)} \,, \tag{5}$$

where τ is the characteristic particle lifetime. In general, the condition of effective Fermi acceleration is

$$\tau\alpha_0 \gg 1 \,. \tag{6}$$

However, there are exceptions, e.g., the stochastic acceleration by a single shock wave.

Here and below we determine the particle production with momentum larger than p (the normalization condition) as

$$Q(>p) = \int\limits_p^\infty q(p)p^2dp \,. \tag{7}$$

This Fermi acceleration can easily be realized in cosmic space. The point is that the astrophysical plasma is in a turbulent state owing to various instabilities. The presence of a large number of unstable modes (waves) makes an energy exchange possible between particles and waves. For the conditions of the Coma medium, these instabilities can be excited by motions of the galaxies in the cluster and/or accretion which generate both MHD and supersonic turbulences. The corresponding values of α_0 are presented by Eqs. (3) and (4).

The spectrum of particles accelerated by a single strong shock front is steeper than determined by Eq. (5) (see, e.g., Berezinsky et al. 1990)

$$q(p) \propto p^{-4} \,, \tag{8}$$

because $\tau\alpha_0 \simeq 1$ in this case (cf. Eq. (6)). The characteristic acceleration time equals

$$\alpha_0^{-1} \sim \frac{D}{U_{sh}^2} \,, \tag{9}$$

where D is the spatial diffusion coefficient near the shock front.

Below, we shall estimate how many background particles can be accelerated by "in-situ" mechanisms. The acceleration (as mentioned above) is described here as the momentum diffusion. The goal of our analysis is to estimate the main parameter of the electron acceleration in the cluster, namely, the characteristic acceleration time.

3. Equation for accelerated particles

The problem of particle acceleration from the background gas was analyzed by Gurevich (1960) for the spatially uniform case of Fermi acceleration and by Bulanov & Dogiel (1979) for acceleration by shock waves.

To estimate the number of accelerated particles, we have to solve an equation describing the background spectrum as well as the spectrum of accelerated particles.

In an ionized plasma, the equilibrium (Maxwellian) spectrum of background charged particles is formed by the Coulomb collisions whose frequency for energies above kT is

$$\nu(E) \simeq \nu_0 \left(\frac{kT}{E}\right)^{3/2}, \qquad (10)$$

where $E = mv^2/2$ is the kinetic energy of electrons,

$$\nu_0 = \frac{4\pi n_0 e^4}{(kT)^{3/2} m^{1/2}} \ln\left(\frac{kTd}{e^2}\right), \qquad (11)$$

and d is the Debye radius

$$d = \sqrt{\frac{kT}{8\pi n_0 e^2}}\,. \qquad (12)$$

For the cluster parameters we have

$$\nu_0 \simeq 1.7 \cdot 10^{-12}\ \mathrm{sec}^{-1}\,. \qquad (13)$$

The Coulomb collisions tend to establish the equilibrium Maxwellian distribution of background particles, which means that for each energy E the particle flux along the spectrum due to collisions equals zero.

For energies higher than kT, the particle spectrum is described by the equation

$$\frac{\partial f}{\partial t'} - \frac{1}{u^2}\frac{\partial}{\partial u}\left(\frac{1}{u}\frac{\partial f}{\partial u} + f\right) = 0\,, \qquad (14)$$

where t' is dimensionless time, $t' = t\cdot\nu_0$, and u is dimensionless particle velocity:

$$u = \frac{v}{\sqrt{kT/m}} = \sqrt{\frac{2E}{kT}}\,. \qquad (15)$$

In the stationary (equilibrium) case the spectrum is Maxwellian and has the form

$$f = \sqrt{\frac{2}{\pi}} n_0 \exp\left(-\frac{u^2}{2}\right)\,. \qquad (16)$$

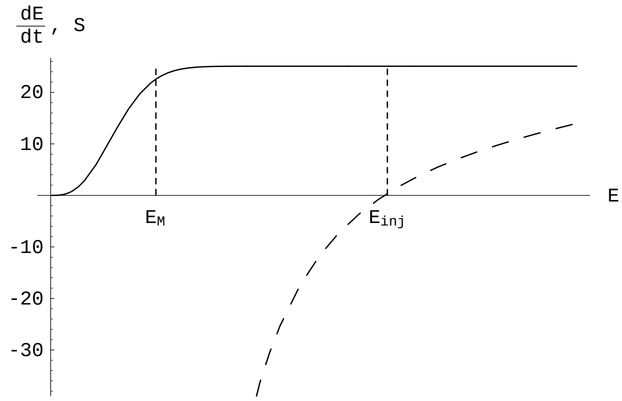

Fig. 1. The rate of energy variations (dE/dt) due to Coulomb collisions and Fermi acceleration (dashed line), and the particle flux $S(E)$ along the spectrum (solid line). The values are given in arbitrary units.

If there is acceleration everywhere in the volume and we can neglect spatial variations of the distribution function f, then the equation for background and accelerated particles is reduced to

$$\frac{\partial f}{\partial t'} - \frac{1}{u^2}\frac{\partial}{\partial u}\left(\left(\frac{1}{u} + u^2\alpha(u)\right)\frac{\partial f}{\partial u} + f\right) = 0\,, \qquad (17)$$

where $\alpha(u)$ describes the stochastic acceleration (momentum diffusion) of particles. Here we assume (which is rather natural) that only a small part of background particles is accelerated, i.e. $\alpha_0 \ll \nu_0$.

4. Injection energy of accelerated particles

Thus, the background particles in our case are under the influence of acceleration gains and of ionization loss (Coulomb collisions). Their energy variations for $E > kT$ are given by

$$\frac{dE}{dt} = \alpha_0 E - \nu_0 E \left(\frac{kT}{E}\right)^{3/2} \qquad (18)$$

The rate of energy variation is shown in Fig. 1 (dashed line) and it equals zero for the energy

$$E_{inj} \sim kT \left(\frac{\nu_0}{\alpha_0}\right)^{2/3} \qquad (19)$$

Only above this energy ($E > E_{inj}$), where $dE/dt > 0$, does the acceleration increase the particle energy continuously in time. As a result, a flux of run-away particles from the collisional region into the region of nonthermal particles is formed. Below this energy ($E < E_{inj}$) the particle spectrum is formed by the Coulomb collisions.

It may seem that the energy E_{inj} determines the boundary between the Maxwellian distribution (below this energy) and the power-law nonthermal spectrum (above E_{inj}). With this assumption, from Eq. (19) we can estimate the characteristic acceleration time. Thus, using the estimate of Sarazin and Kempner (2000): $E_{inj} \sim 3kT$, we find that the acceleration parameter is slightly less than the frequency of Coulomb collisions. Indeed,

$$\alpha_0 \simeq \left(\frac{kT}{E_{inj}}\right)^{3/2} \nu_0 \sim 3.5 \cdot 10^{-13}\ \mathrm{sec}^{-1}\,. \tag{20}$$

We notice, however, that this interpretation is incorrect because in the case of acceleration of background particles deviations from the equilibrium, Maxwellian distribution start at the energy E_M, which is much lower than E_{inj}, $E_M \ll E_{inj}$ (see Gurevich 1960). The density of particles in the range between E_M and E_{inj} exceeds the thermal (Maxwellian) distribution, but the spectrum is not nonthermal there because it is formed by Coulomb collisions. In this sense the estimate (20) may be wrong. The function can be described as Maxwellian only in the range $E \ll E_M$ (see Fig. 1). We determine the value E_M in Sect. 5.

It is this distortion of the Maxwellian distribution function in the region $E_M \ll E \ll E_{inj}$, where collisions still play a significant role, that can in principle be interpreted either as emission of nonthermal particles (then we may falsely assume that the deviations from the equilibrium Maxwellian distribution start at the energy E_{inj}), or as an appearance of the "second" effective temperature which is higher than the gas temperature T.

5. Distortion of the Maxwellian spectrum in the collisional region and the number of accelerated particles

Following Gurevich (1960), we calculate the number of accelerated particles for the acceleration in the form (2). For details of the analysis we refer the reader to the original paper of Gurevich (1960). However, we present here the main results of this paper.

The above-mentioned distortions occur in the energy range $E < E_{inj}$ because collisions cause the energy of certain electrons to increase from the main equilibrium (thermal) region to the injection value. The particles then leave the main region and are accelerated. Thus, the flux of run-away electrons into the acceleration region is formed. The situation is therefore nonequilibrium and is described by variations of the spectrum parameters with time.

However, if the acceleration is weak ($\alpha_0 \ll \nu_0$), the situation is quasi-stationary and we can seek the solution of Eq. (17) assuming time variations to be small. In the energy range $E \ll E_M$ the spectrum f^I is close to the equilibrium Maxwellian one. The effect of acceleration can be neglected there and Eq. (17) is reduced to

$$\frac{\partial f^I}{\partial t'} - \frac{1}{u^2}\frac{\partial}{\partial u}\left(\left(\frac{1}{u}\right)\frac{\partial f^I}{\partial u} + f^I\right) = 0\,, \tag{21}$$

Since the time variations of the distribution function are very slow, we can decompose our distribution function

$$f^I = f^I_1 + f^I_2 + f^I_3 + \ldots\,, \tag{22}$$

neglecting in the first approximation the time variations of f^I. Therefore, we obtain the following system of equations for $f^I_1,\ f^I_2, \ldots$

$$\frac{1}{u^2}\frac{\partial}{\partial u}\left(\left(\frac{1}{u}\right)\frac{\partial f^I_1}{\partial u} + f^I_1\right) = 0\,, \tag{23}$$

$$\frac{1}{u^2}\frac{\partial}{\partial u}\left(\left(\frac{1}{u}\right)\frac{\partial f^I_2}{\partial u} + f^I_2\right) = \frac{\partial f^I_1}{\partial t'} \tag{24}$$

The first equation of this system describes the Maxwellian distribution with slow-time variations due to the acceleration

$$f = C_1(t')\exp\left(-\frac{mv^2}{2kT}\right)\,. \tag{25}$$

The second equation describes the run-away flux of electrons $S = u^{-1}\partial f^I_2/\partial u + f^I_2$

$$S(u) = S_0\sqrt{\frac{2}{\pi}}\int\limits_0^u x^2\exp\left(-\frac{x^2}{2}\right)dx\,, \tag{26}$$

where S_0 is constant. The flux variations are shown in Fig. 1 (solid line). The analysis of Eq. (26) shows that the flux value is almost zero at small u and increases to $S_0 = const$ for large u. The important point is that the flux reaches the value $S \simeq S_0$ for energies $E \simeq E_M \ll E_{inj}$, where

$$E_M \sim kT(\nu_0/\alpha_0)^{2/5}\,. \tag{27}$$

Above energy E_M we cannot neglect the acceleration processes. The distribution function f^{II} is described by Eq. (17) in the energy range $E > E_M$. It is important that a constant particle flux, $-S_0$, passes through this region. Therefore, for f^{II} we obtain

$$\left(\frac{1}{u} + u^2\alpha(u)\right)\frac{\partial f^{II}}{\partial u} + f^{II} = -S_0\,, \tag{28}$$

and the solution of this equation is

$$f^{II} = \sqrt{\frac{2}{\pi}}n(t')\exp\left(-\int\limits_0^u \frac{u\,du}{1+\alpha_0 u^5/\nu_0}\right) - S_0\,. \tag{29}$$

Here $n(t')$ is the density of background particles which changes slowly with time owing to the acceleration. The parameter S_0 for the functions f^I and f^{II} is determined from the boundary conditions at $E = E_M$,

$$S_0 = \sqrt{\frac{2}{\pi}}n(t')\exp\left(-\int\limits_0^\infty \frac{x dx}{1+\alpha_0 x^5/\nu_0}\right)\,. \tag{30}$$

We see that two (not one) energies characterize the problem and there are three energy ranges in the spectrum where the distribution functions differ from each other (see Fig. 2). For small kinetic energies, $E = kTu^2/2$ determined by

$$E < E_M\,, \tag{31}$$

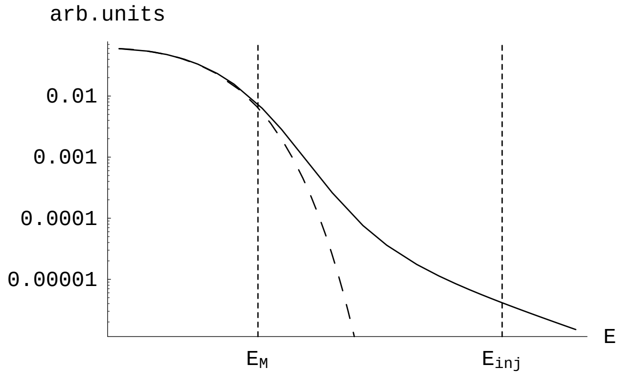

Fig. 2. Distribution of background and accelerated particles (solid line). Equilibrium Maxwellian distribution at the same temperature T (dashed line).

where the flux is small enough ($S < S_0$), the distribution function is almost in equilibrium and it can be presented by the thermal (Maxwellian) spectrum with the temperature T,

$$F_M \simeq n\frac{2}{\sqrt{\pi(kT)^3}}\sqrt{E}\exp\left(-\frac{E}{kT}\right) . \quad (32)$$

Here we use the normalization condition which determines the number of particles with energies higher than E

$$N(>E) = \int\limits_E^\infty F\,dE . \quad (33)$$

In the energy range

$$E_M \ll E \ll E_{inj} , \quad (34)$$

the spectrum is also formed by collisions, but (since the flux S in this region is not negligible) this collisional distribution function is strongly (exponentially) distorted and cannot be described as Maxewllian. There are substantial deviations from the Maxwellian distribution in this energy range because of the constant particle flux escaping from the collisional region. To reproduce this part of the spectrum as thermal, one should assume another "effective" temperature $T^* \gg T$ of these particles.

The collisions are ineffective only in the energy range $E \gg E_{inj}$, and a nonthermal power-law spectrum of accelerated particles is formed there

$$F_{ac} = C_2(t')E^{-1} . \quad (35)$$

The solution of Eq. (28) for the distribution function in the energy range $E_M \ll E$ can be written in the form

$$F = n\frac{2}{\sqrt{\pi(kT)^3}}\sqrt{E}\exp\left(-\int\limits_0^\infty \frac{xdx}{1+\alpha_0 x^5/\nu_0}\right) \cdot \left(\exp\left(\int\limits_{\sqrt{2E/kT}}^\infty \frac{xdx}{1+\alpha_0 x^5/\nu_0}\right) - 1\right) . \quad (36)$$

The resulting spectrum of background and accelerated particles is shown in Fig. 2. For comparison, we also show the equilibrium Maxwellian spectrum at the same temperature T (dashed line).

Acceleration of background particles by shocks was analyzed by Bulanov & Dogiel (1979). The problem was impeded by spatial nonuniformity. Therefore, the spatial propagation of particles cannot be neglected. Nevertheless, as in the case of Fermi II acceleration, the conclusion is that the spectrum of particles below the injection energy can be presented as a two-temperature distribution near shocks. One of these temperatures is the real temperature of the background gas and the other is due to the distortion of the equilibrium Maxwellian function.

6. Bremsstrahlung interpretation of the Beppo-SAX data

The bremsstrahlung cross section for a non-relativistic electron with kinetic energy E_k is (Hayakawa 1969)

$$\sigma_{br} = \frac{8}{3}\frac{e^2}{\hbar c}\left(\frac{e^2}{mc^2}\right)^2 \frac{mc^2}{E_k}\frac{1}{E_x} \cdot \ln\frac{\left(\sqrt{E_k}+\sqrt{E_k-E_x}\right)^2}{E_x} , \quad (37)$$

where E_x is the energy of the emitted photon. The Coma X-ray flux near Earth can be estimated as

$$\frac{dL_x(E_x)}{dE_x} = \frac{V}{4\pi R_C^2}\int\limits_{E_x}^{W_m} F(W)\sigma_{br} v n_0 dW , \quad (38)$$

where V is the volume of the emitting region, and R_C ($H_0 = 50$ km s^{-1}Mpc^{-1}) is the distance to the Coma cluster, $R_C = 140$ Mpc and W_m is the maximum energy of the accelerated electrons. Its value can be derived from analyses of acceleration processes (see, e.g., Sect. 8).

Using the distribution function given by (36), we calculate the hard X-ray spectrum of the Coma cluster shown in Fig. 3, together with the Beppo-SAX data. For comparison, we also present the thermal bremsstrahlung spectrum (dashed line) at the temperature of 8 keV.

The high energy range of the spectrum depends on the acceleration parameter α_0. Any variation of α_0 does not change the Maxwellian distribution of background particles at $E < E_M$. But, at $E > E_M$ the intensity of electrons and the flux of bremsstrahlung photons are sensible to this parameter. From the Beppo-SAX data we derive that

$$\alpha_0/\nu_0 \simeq 9 \cdot 10^{-4} . \quad (39)$$

Then we obtain that the acceleration parameter α_0 is (cf. Eq. (20))

$$\alpha_0 \sim 1.5 \cdot 10^{-15}\ \text{sec}^{-1} . \quad (40)$$

From Fig. 2 we see that deviations from the Maxwellian distribution start near E_M.

From Eq. (40) we can estimate the density of resonant MHD-waves (δH^2 in Eq. (4)) or the characteristic distance between shock fronts (Eq. (3)) needed for the acceleration.

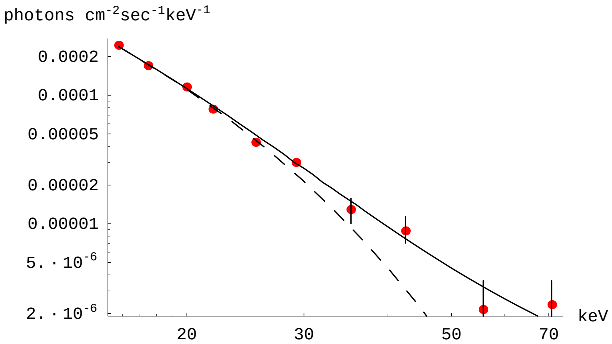

Fig. 3. Bremsstrahlung X-ray emission from the Coma cluster for the acceleration parameter $\alpha_0/\nu_0 = 9 \cdot 10^{-4}$ (solid line), thermal bremsstrahlung emission at $T = 8$ keV (dashed line) and the Beppo-SAX data (points).

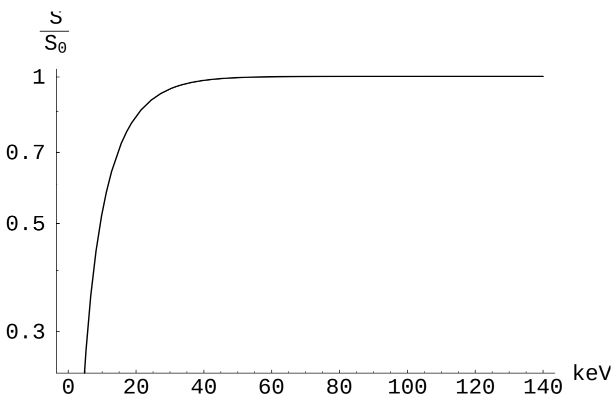

Fig. 4. The run-away flux $S(E)$ (in units S_0).

The PDS telescope of Beppo-SAX has the angular resolution of $\sim 1.3^o$ and so it was unable to resolve the region emitting hard X-rays whose angular size in the sky is less than 1^o. However, in the case of in-situ acceleration, this size can easily be estimated from the Beppo-SAX data. Indeed, from Eq. (38) we obtain that

$$V \simeq 4 \cdot 10^{72}\ \text{cm}^3\,, \tag{41}$$

for the density $n_0 = 3 \cdot 10^{-3}$ cm^{-3}, $kT = 8$ keV, or the size r of the emitting region is of the order of $0.5 - 1$ Mpc (if we take into account the density variations in the halo). Thus we conclude that the X-ray flux is emitted by the region which occupies a significant part of the Coma halo, which definitely points to the mechanism of in-situ acceleration.

7. Spatial diffusion of accelerated electrons in the Coma halo

In the case of in-situ acceleration, the spatial and momentum diffusions are related to each other. Therefore it is easy to check whether our assumption that processes of spatial propagation are insignificant in the Coma halo, is correct. To do this, we fix the medium parameters which are: $n_0 = 3 \cdot 10^{-3}$ cm^{-3}, $T = 8$ keV ($U_0 \sim 10^8$ cm s^{-1}, if we take as the characteristic velocity U_0 the sound speed of the intracluster gas), and the

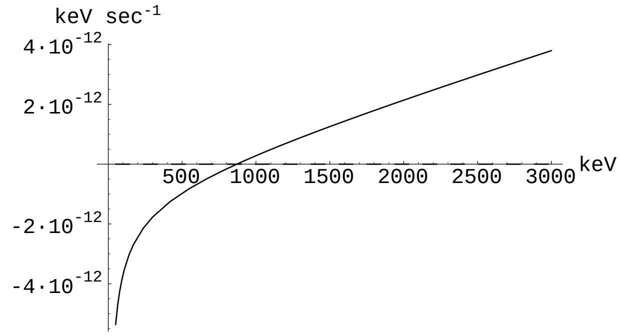

Fig. 5. The rate of energy variations in the Coma cluster at energies $E \sim E_{inj}$ for the parameter $\alpha_0 = 1.5 \cdot 10^{-15}$sec^{-1}.

Coulomb frequency $\nu_0 \simeq 1.7 \cdot 10^{-12}$ s^{-1}. The coefficient of spatial diffusion D_x due to scattering on the fluctuations of the intracluster magnetic fields is (compare with Eq. (3))

$$D_x = \frac{vL_{cor}}{6} = \frac{\pi U_0^2}{18\alpha_0}\,. \tag{42}$$

Then from the ratio $\alpha_0/\nu_0 = 9 \cdot 10^{-4}$ ($\alpha_0 \simeq 1.5 \cdot 10^{-15}$s^{-1}) we obtain

$$D_x \simeq 10^{30}\ \text{cm}^2\text{s}^{-1}\,. \tag{43}$$

The escape time from the cluster can be estimated as

$$\tau \simeq \frac{r_C^2}{D_x}\,, \tag{44}$$

which for the halo size $r_C \simeq 1$ Mpc and $D_x \simeq 10^{30}$ cm^{2}s^{-1} is $\tau \simeq 10^{19}$s. This is much larger than the acceleration time $\tau_{ac} = \alpha_0^{-1} \simeq 7 \cdot 10^{14}$ s, i.e., the propagation of particles can indeed be neglected since $\alpha_0 \cdot \tau \gg 1$.

8. Characteristic energies of the electron spectrum in Coma

From Eq. (26) we can calculate the run-away flux S at different energies for the derived value of the acceleration parameter (40). The flux is shown in Fig. 4. We see that the flux reaches its maximum value S_0 at energies about 30 keV. So, we conclude that

$$E_M \simeq 30\ \text{keV}\,. \tag{45}$$

The energy E_{inj} can be obtained from the analysis of the rate of energy variations (18). This rate is shown in Fig. 5.

From this figure we find that the particle acceleration starts from the energy

$$E_{inj} \simeq 900\ \text{keV} \tag{46}$$

If we estimate from Eq. (36) the fraction of background particle which are accelerated, we obtain the value $\eta_e \sim (1-3) \cdot 10^{-6}$ that is three–four orders of magnitude less than estimated by Sarazin and Kempner (2000).

The maximum energy of the accelerated electrons can be determined from either the analysis of the acceleration efficiency or the ratio between the acceleration and energy losses at high energies.

The high-energy electrons lose their energy by synchrotron emission and inverse Compton scattering (see, e.g., Ginzburg & Syrovatskii 1964). The rate of the energy loss is equal to

$$\frac{dE}{dt} = -\beta E^2 = = -\frac{32\pi c}{9}\left(\frac{e^2}{mc^2}\right)^2\left(w_{ph}+\frac{H^2}{8\pi}\right)\left(\frac{E}{mc^2}\right)^2 , \quad (47)$$

where H is the total strength of magnetic fields and w_{ph} is the energy density of background photons (relic, optical, etc.). The electron lifetime in these magnetic fields equals

$$\tau_e \sim \frac{1}{2\beta E} , \quad (48)$$

and their path length is estimated by

$$r_e \sim \sqrt{D_x\tau_e} = \sqrt{\frac{D_x}{2\beta E}} . \quad (49)$$

From the value r_e we can estimate the efficiency of electron acceleration. It is clear that only electrons with path lengths $r_e > L_{cor}$ can be accelerated by Fermi acceleration, and the maximum energy is determined from the condition: $r_e(W_m) \sim L_{cor}$, since at higher energies the spectrum of electrons accelerated by, e.g., supersonic turbulence is extremely steep (see Bykov & Toptygin 1990). From Eqs. (3), (42) and (49) we obtain

$$W_m \sim \frac{\alpha_0 c^2}{4\pi\beta U_0^2} , \quad (50)$$

which gives a very high energy of W_m (higher than thousand GeV) for the Coma parameters. Here we take the density of the relic photons $w_{ph} \simeq 0.25$ eV cm^{-3} as the lower limit of the photon density in Coma, and the magnetic field strength equals $H \simeq 3\ \mu$G.

We shall show, however, that W_m hardly exceeds 30 GeV. The point is that the maximum energy W_m can also be determined from the rate of energy losses at high energies (47). The power-law spectrum of the nonthermal electrons with the spectral index γ has an exponential cut off at the energy determined by the losses (see Bulanov & Dogiel 1979)

$$F \propto E^{-\gamma} \exp\left(-\frac{E}{W_m}\right) , \quad (51)$$

where

$$W_m \simeq \frac{\alpha_0}{\beta} \quad (52)$$

for the synchrotron and IC energy losses (47). This effect is clearly seen from the total rate of energy variations at high energies if we combine Eqs. (18) and (47). The rate of energy variations at high energies for the magnetic field $H = 3\ \mu$G is shown in Fig. 6. We see that the electron spectrum has an exponential cut off at the energy determined by synchrotron losses

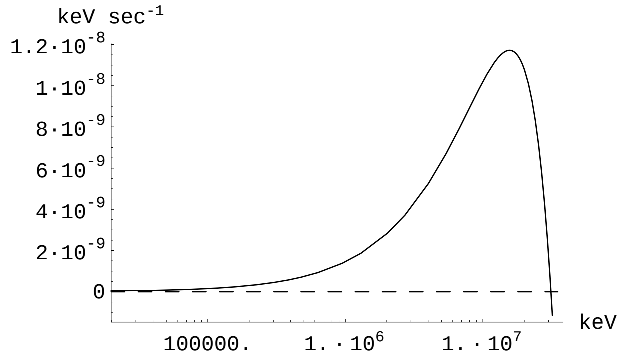

Fig. 6. The rate of energy variations in the Coma cluster at high energies for $\alpha_0 = 1.5\cdot 10^{-15}$sec^{-1} and the magnetic field strength $H = 3\ \mu$G.

where the rate dE/dt changes its sign again. For the acceleration parameter α_0 derived from the observed hard X-ray flux the maximum energy of the accelerated electrons is

$$W_m = 30 \text{ GeV} . \quad (53)$$

In this way we derived all characteristic energies of the electron spectrum in Coma for the acceleration parameter α_0 obtained from the Beppo-SAX data.

9. Radioemission of accelerated electrons

The synchrotron emission of a single electron with the energy E occurs near the frequency (see, e.g., Ginzburg & Syrovatskii 1964)

$$\nu \simeq 0.3\frac{3eH}{4\pi mc}\left(\frac{E}{mc^2}\right)^2 . \quad (54)$$

Combining Eqs. (47), (52), and (54) we find that electrons with the energy W_m radiate at the frequency ν_m

$$\nu_m \simeq 0.3\frac{3eH}{4\pi mc}\left(\frac{\alpha_0}{\beta mc^2}\right)^2 , \quad (55)$$

which is the maximum frequency in the emission spectrum of the accelerated electrons. This frequency increases as

$$\nu_m \propto H \quad (56)$$

at relatively small magnetic fields H and decreases as

$$\nu_m \propto 1/H^3 \quad (57)$$

for large magnetic fields. In Fig. 7 we show the variations of ν_m calculated for the parameter $\alpha_0 = 1.5\cdot 10^{-15}$ sec^{-1} and the magnetic fields ranging between 0.1 and $10\ \mu$G.

The Coma radio flux is observed up to the frequency ~ 2.7 GHz (see Schlickeiser et al. 1987). The measured flux at 2.7 GHz is at least a factor of three smaller than the power-law extrapolation from lower frequencies. At the frequency 4.85 GHz an upper limit of the radio flux from the Coma halo was found (Hanisch 1980). These data indicate a strong steepening of the Coma radio spectrum at high frequencies ($\nu > 1$ GHz) that is in agreement with our model. From the position of the

Fig. 7. The maximum frequency of the radioemission from Coma for different values of magnetic fields in the halo.

steepening we conclude that the strength of magnetic field in the Coma halo is in the range $0.2 - 7\ \mu$G.

We see also from Fig. 7 that clusters of galaxies do not generate a radio flux at high frequencies if the magnetic field is either very large or very small. On the other hand these clusters of galaxies emit hard X-rays, which are produced by low energy electrons in the case of their bremsstrahlung origin. This may explain that the cluster Abell 2199 emits hard X-rays (Kaastra et al. 1999), but no radio emission comes from it (Kempner and Sarazin 2000), if the hard X-ray emission of this cluster will be confirmed.

10. Conclusions

The bulk information obtained for the Coma cluster definitely points to particle in-situ acceleration, which proceeds in an extended halo. These accelerated particles are definitely responsible for the Coma emission in the radio range and probably the EUV energy range. The Beppo-SAX telescope discovered a "tail" of hard X-ray emission with intensity significantly higher than expected for the thermal bremsstrahlung radiation of the hot cluster gas. This emission can in principle be due to the nonthermal bremsstrahlung radiation of accelerated electrons, i.e., the acceleration mechanisms in the Coma cluster are supposed to be so effective that the injection energy is about several tens of keV. However, our analysis of the Beppo-SAX data shows that this assumption may strongly overestimate the efficiency of acceleration there. We found that the characteristic energies of the accelerated electrons are higher than 900 keV. Hence, the nonthermal electrons are responsible for the radio and EUV emission (which we hope to analyze in papers to follow), but not for hard X-rays. The Maxwellian distribution of the background electrons is in this case expected only in the energy range below 30 keV. At higher energies this Maxwellian distribution is distorted by the acceleration mechanism owing to the runaway flux of thermal particles into the region of acceleration. It is these "quasi-thermal" particles that produce the observed Beppo-SAX flux.

The ratio between thermal and nonthermal particles, estimated from the Beppo-SAX data, is $\sim 3 \cdot 10^{-6}$, i.e. a very small part of background electrons is accelerated in the Coma halo.

Our analysis shows that the Beppo-SAX data can only be explained if a significant part of the Coma halo is involved in particle acceleration and a consequent X-ray emission. The estimated radius of the emitting region is about $0.5 - 1$ Mpc. We also conclude that spatial propagation is insignificant in the Coma cluster. Both facts definitely point to in-situ acceleration there.

The maximum energy of accelerated electrons is determined from the balance between the acceleration rate and the synchrotron losses. The maximum energy of accelerated electrons derived for the parameters of the Coma cluster is of the order of 30 GeV. For the Coma magnetic fields we expect a noticeable radio flux up to frequencies of the order of several GHz. However, it is possible that some clusters do not emit a noticeable radio flux, because of an unfavorable ratio between particle acceleration and strength of magnetic fields there. On the other hand, a flux of hard X-rays is produced in these clusters by electrons with relatively small energies. This may be the case of the cluster Abell 2199.

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