Nonthermal Emission from Clusters of Galaxies

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Petrosian, V. 2001, ApJ, 557, 560
Fusco-Femiano, R., et al. 1999, ApJ, 534, L21
Rephaeli, Y., Gruber, D., & Blanco, P. 1999, ApJ, 511, L21

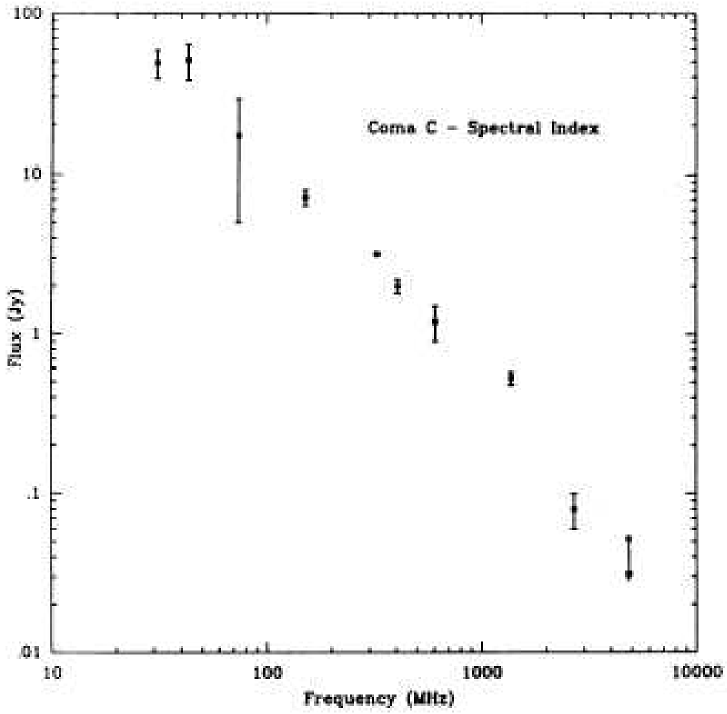
Galaxy Clusters: What are they good for?

- Largest known self-gravitating systems
- Dark Matter mass estimates
  - X-ray emission from thermal electrons
  - Gravitational lensing of background galaxies and AGNs
- SZ effect
  - Distance ladder
  - Kinematic SZ → peculiar velocities → probe of matter distribution of the Universe
  - Temperature evolution of CMB
- Dynamics of the intracluster medium (ICM)
  - Cooling flows (?)
  - Respository of AGN and galaxy output

Non-thermal Emission in Galaxy Clusters

- Radio halo observations show synchrotron spectra
  - B-field and relativistic population of electrons
  - Inverse Compton scattering of CMB photons
- Key question: Origin of non-thermal electron distribution
  - acceleration in shocks from mergers
  - injection by cosmic rays (SNR), AGNs, etc.
  - second order acceleration in turbulent plasma
- Contribution of B-field, non-thermal electrons to ICM pressure directly or by heating of thermal component.

Best Case Example: The Coma Cluster



Giovannini, et al. 1993, ApJ, 406, 399.

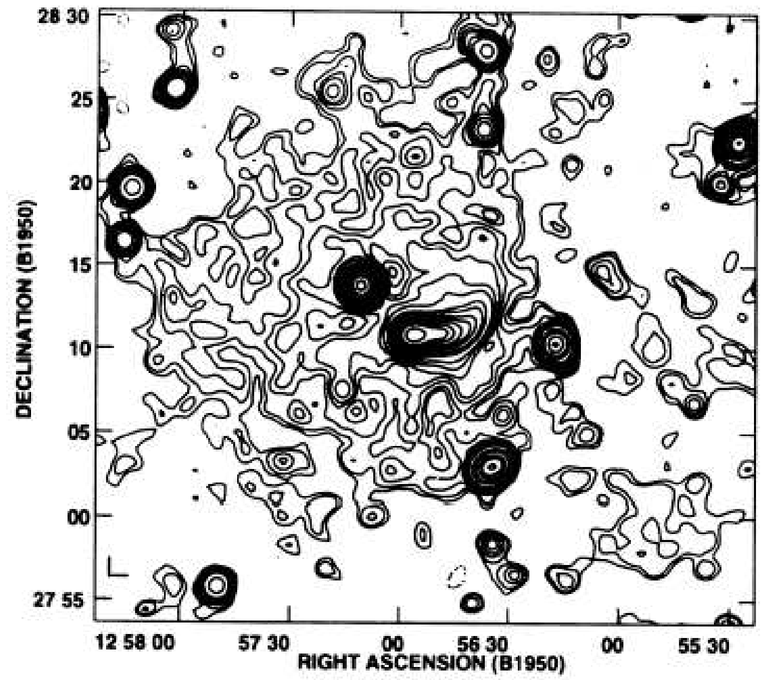


Fig. 1b

Map at 608.5 MHz; 17 contours, ∼ logrithimically spaced, covering 1–400 mJy.

A Simple(-minded) Synchrotron Calculation

The single electron energy loss rate (assuming an isotropic pitch angle distribution),

$$P_{\rm syn} \simeq \frac{4}{3} c\sigma_T \gamma^2 u_B, \qquad u_B = \frac{B^2}{8\pi}. \tag{1}$$

Characteristic photon frequency:

$$\nu_c = \frac{3}{4\pi}\gamma^3 \omega_B \sin\alpha, \qquad \omega_B = \frac{eB}{\gamma m_e c} \tag{2}$$

$$\approx \frac{3}{4\pi}\gamma^3 \omega_B <\sin\alpha> \tag{3}$$

$$\approx \frac{3}{16}\frac{eB}{m_e c}\gamma^2 \equiv \nu_B \gamma^2 \qquad \nu_B \equiv \tilde{\nu}_B B \tag{4}$$

Since the single electron synchrotron spectrum has a constant shape, $K_{5/3}(x)$ where $x = \nu/\nu_c$, we can approximate it by a δ-function,

$$\frac{dE}{d\nu dt} \approx P_{\rm syn}\delta(\nu - \nu_c) \tag{5}$$

$$\approx P_{\rm syn}\frac{\delta(\gamma - \gamma_c)}{2\nu_B\gamma_c} \tag{6}$$

when integrating over a power-law distribution of electrons,

$$\frac{dn_e}{d\gamma} = n_0 \gamma^{-p}, \tag{7}$$

in order to obtain the observed photon spectrum:

$$\begin{aligned}
L_{\nu,\mathrm{syn}} &= \int d\gamma \frac{dn_e}{d\gamma} \frac{dE}{d\nu dt} && (8) \\
&= \int d\gamma \;\; n_0 \gamma^{-p} \;\; \frac{4}{3} c\sigma_T \gamma^2 u_B \;\; \frac{\delta(\gamma - \gamma_c)}{2\nu_B \gamma_c} && (9) \\
&= \frac{c\sigma_T}{12\pi} \tilde{\nu}_B^{(p-3)/2} n_0 B^{(p+1)/2} \nu^{(1-p)/2}. && (10)
\end{aligned}$$

Typically, one defines an energy index α such that $L_\nu \sim \nu^{-\alpha}$, so that here $\alpha = (p-1)/2$. For Coma, $\alpha = 1.34$, so that $p = 3.68$.

Inferences about the B-field and Particle Distribution

- Coma: $p = 3.68$.
- Assume B-field is in equipartition with the non-thermal electron distribution:

$$\frac{u_e}{u_B} = 1 \qquad (11)$$

$$u_e \approx \frac{m_e c^2}{V} \frac{n_0 \gamma_{\rm min}^{1-p}}{p-1} \qquad (12)$$

$$\gamma = \left(\frac{\nu}{\nu_B}\right)^{1/2} \qquad (13)$$

$z = 0.0232 \Rightarrow d_l \sim 138\,\mathrm{Mpc}$, $R \sim 1\,\mathrm{Mpc}$,

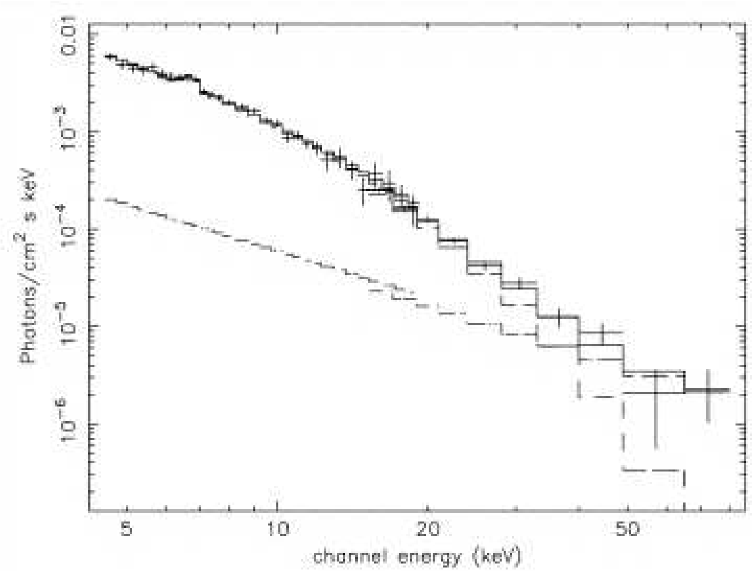
$$B_{\rm eq} \approx 10^{-8}\mathrm{G} \left(\frac{p-1}{2.68}\right)^{-1/3} \left(\frac{F_{\rm syn}}{50\,\mathrm{Jy}}\right)^{1/3} \left(\frac{d_l}{138\,\mathrm{Mpc}}\right)^{2/3} \left(\frac{R}{1\,\mathrm{Mpc}}\right)^{-1/3} \qquad (14)$$

(hmmm...seems sorta low. Giovaninni et al. report $B_{\rm eq} \sim 0.5\mu$G)

- Lorentz factors of electrons producing synchrotron emission:

$$27\,\mathrm{MHz} < \nu < 2.7\,\mathrm{GHz} \;\Rightarrow\; 3 \times 10^4 < \gamma < 3 \times 10^5. \qquad (15)$$

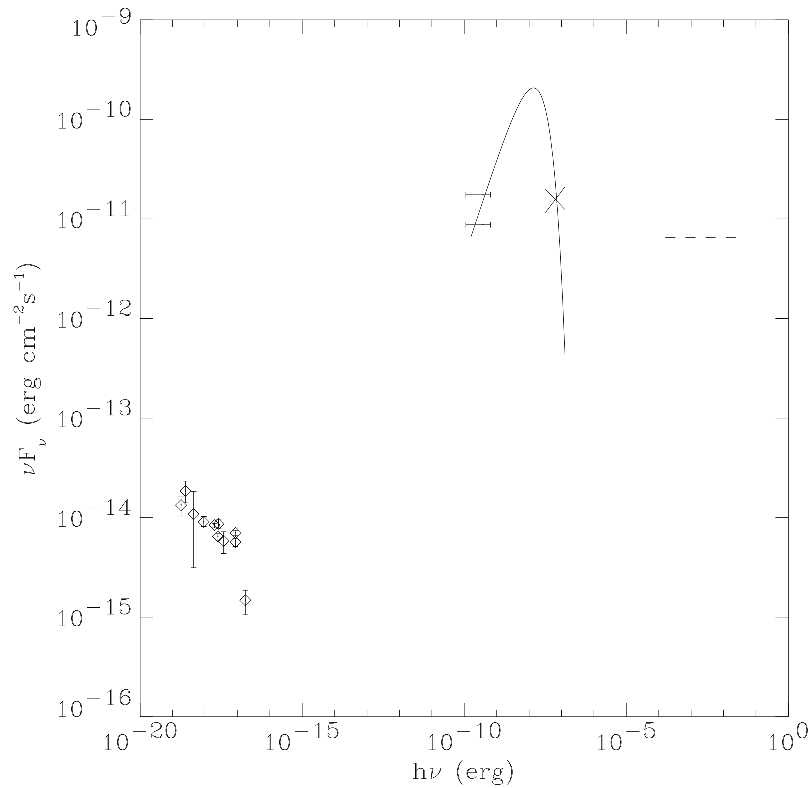
X-ray Observations (Fusco-Femiano et al., Rephaeli et al. 1999)



Fusco-Femiano et al. (1999)

- Thermal Bremsstrahlung ($kT_e \sim 8\,\mathrm{keV}$) dominates the X-ray spectrum.
- Non-thermal tail at $E > 20\,\mathrm{keV}$ seen in Beppo-SAX and RXTE data.
- $F_{20-80\mathrm{keV}} = 2.2 \times 10^{-11} \mathrm{erg\,cm^{-2}s^{-1}}$ from SAX measurements
- Spectral index highly uncertain:
  SAX: $0.7 < \Gamma < 2.5$ ($\Gamma = 1.57^{+0.36}_{-0.39}$ if kT fixed at 8.5 keV)
  RXTE: $\Gamma = 2.35 \pm 0.45$ with $kT = 7.5\,\mathrm{keV}$ (free)
- Need INTEGRAL and Astro-E2 observations!

Coma Cluster SED



Radio:	Giovaninni et al. 1993
EUV:	Lieu, et al. 1999, ApJ, 510, L25
SXR:	Hughes, et al. 1993, ApJ, 404, 611
HXR:	Fusco-Femiano, et al. 1999
	Rephaeli, et al. 1999
γ-ray:	Sreekumar et al. 1996, ApJ, 464, 628

Inverse Compton spectrum from scattering of CMB

Form of IC loss rate is identical to synchrotron's (in Thomson limit):

$$P_{IC} \approx \frac{4}{3} c\sigma_T \gamma^2 u_{ph} \tag{16}$$

where $u_{ph} = (4\sigma/c)T_{CMB}^4 = 4 \times 10^{-13}\,\mathrm{erg\,cm^{-3}}$. Make a similar approximation for the characteristic IC photon energy, for a single scattering:

$$\nu_{IC} \approx \nu_0 \gamma^2 \tag{17}$$

where $\nu_0 = (5.88 \times 10^{10}\mathrm{Hz\,deg^{-1}})(2.7\,\mathrm{K})$.

$$L_{\nu,IC} \approx \frac{2}{3} c\sigma_T n_0 u_{ph} \nu_0^{(p-3)/2} \nu^{(1-p)/2} \tag{18}$$

Try to recover eq. 2 of Rephaeli et al.: Plug in $F_{\mathrm{syn}} = 50$ Jy at $\nu_{\mathrm{min}} = 27\,\mathrm{MHz}$ into the synchrotron expression and solve for n_0:

$$f_x \approx 1.5 \times 10^{-18}\mathrm{cm^{-2}s^{-1}keV^{-1}} \left(\frac{B}{1\mathrm{G}}\right)^{-(p+1)/2} \left(\frac{\varepsilon_x}{1\mathrm{keV}}\right)^{-(p+1)/2} \tag{19}$$

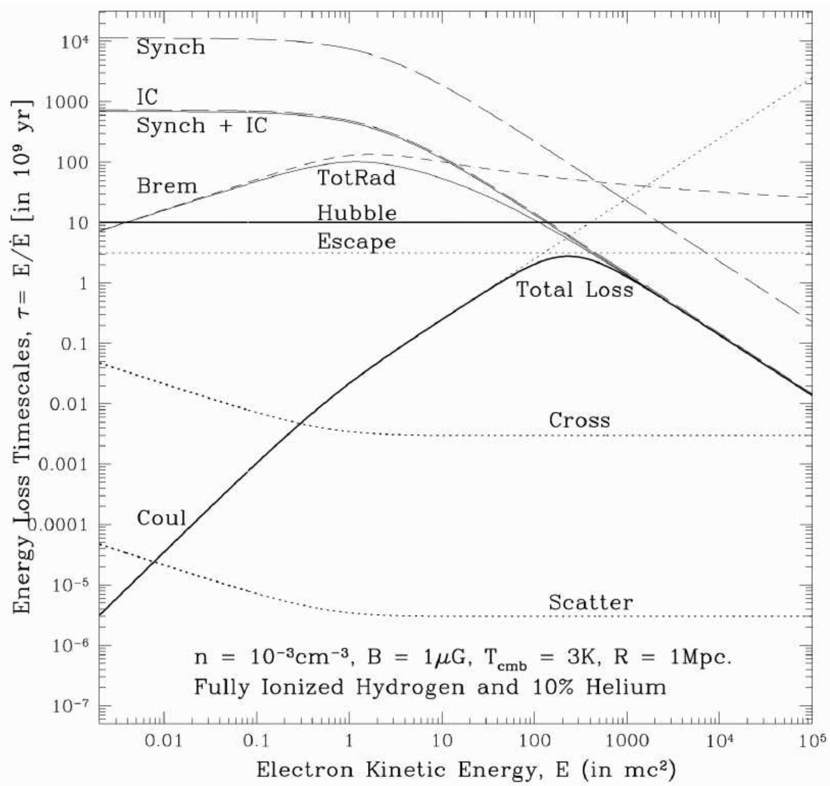
Integrating f_x over 20–80 keV, we find $B \approx 0.1\mu$G. NB: This is independent of d_l and R.

Vahé's Paper (finally)

The set-up:

- Faraday rotation measures (RM) imply $B \sim \text{few}\,\mu\text{G}$, $\mathcal{O}(10)$ larger than value inferred from X-ray flux.
- $F_{\rm IC} \propto B^{-(p+1)/2} \Rightarrow$ makes a neglible contribution to observed HXR emission.
- Non-thermal bremsstrahlung (NTB) as an alternative source of EUV/HXR emission.
- Outline of paper:
  - NTB cannot work (?)
  - IC is still viable
  - Particle spectrum derived
  - Various particle acceleration scenarios considered

Escape and Energy Loss Time Scales



- $T_{\rm loss} > T_{\rm cross}$+ no scattering ⇒ "thin target" case, particles exit the ICM retaining the bulk of their energy. As a result IC emission should surround the cluster, but this is not observed.
- Electrons must be trapped by scattering.

$$
\begin{aligned}
T_{\rm esc} &= T^2_{\rm cross}/T_{\rm scat} \qquad \text{(random walk)} \\
&> T_{\rm loss,max} \\
\Rightarrow T_{\rm scat} &= T_{\rm cross}/10^3 \\
\lambda_{\rm eff} &\sim (\lambda_{\rm scat}\lambda_{\rm loss})^{1/2} \ll R
\end{aligned}
$$

Smooth diffuse radio emission requires in situ acceleration throughout the ICM.

The Trouble with Non-Thermal Bremsstrahlung

- Faraday rotation measures for Coma:

$$\begin{aligned} B &\sim 0.3\mu\mathrm{G} && \text{if ordered} && (20) \\ &\sim 2\mu\mathrm{G} && \text{if chaotic on} \sim 10\,\mathrm{kpc}\ \text{scale} && (21) \end{aligned}$$

  Expected IC emission is reduced by factor $\sim 10^2$, therefore propose NTB as an alternative.

- $T_{\rm Coul} < 10^{-3}\, T_{\rm brem}$ for $E_e < 1\,\mathrm{MeV}$, so that most of the non-thermal power goes into heating the gas.

- $Y_{\rm brem} < 3 \times 10^{-6}$ in the 20–80 keV range, largely independent of acceleration details.

- An unacceptably large amount of power is fed into the ICM:

$$\begin{aligned} T_{\rm ICM} &> 10^8\mathrm{K} && \text{in } 3 \times 10^7\mathrm{y} && (22) \\ &> 10^{10}\mathrm{K} && \text{in a Hubble time} && (23) \end{aligned}$$

- If it is responsible for the observed hard X-ray tail, the epoch of NTB must be very short-lived.

Arguments for the Viability of IC as the Source of the HXR

- Selection effect: low B clusters are more likely to be seen with IC emission (recall $L_{\rm IC} \propto B^{-(p+1)/2}$).

  Coma: not applicable

  A2256: ok, but no RM

  A2199: ok...no radio halo!

- Anisotropic pitch angle distribution:

$$j_{\rm syn} \propto B_\perp^{(p+1)/2} \tag{24}$$

$$B_\perp \propto B \sin\alpha \tag{25}$$

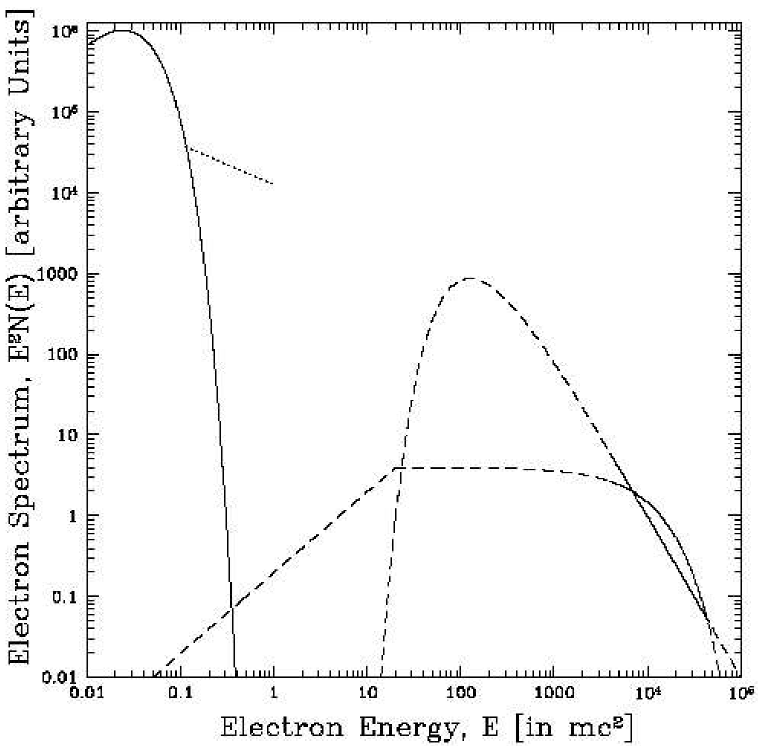
  but an unlikely explanation if scattering is important.

- A more complex electron spectrum:
  - For the inferred field strength, the electrons that produce the the radio are not quite the same as those responsible for the EUV or HXR.

    radio: $\gamma \sim 10^4$–10^5

    HRX: $\gamma \lesssim 10^4$
  - Note also the large uncertainty in the HXR photon index, $0.7 < \Gamma < 2.5$ and the extrapolation to EUV band.

Inferred Spectrum of Radiating Electrons



- Vahé's proposed spectrum:

$$\frac{dn}{dE} = n_0 \left(\frac{E}{E_p}\right)^{-p_l} \left(\frac{E_p}{E_{\rm cr}}\right), \qquad E < E_p$$

$$= n_0 \left(\frac{E}{E_{\rm cr}}\right)^{-p} e^{-(E-E_p)/E_{\rm cr}}, \quad E > E_p$$

  Here $E_p \sim 10\,\mathrm{MeV}$, $p_l \lesssim 0.5$, $E_{\rm cr} \simeq 10^4$, $p \sim 2$.

- Low energy break driven by energy constraints imposed by efficiency of Coulomb loss mechanism.
- Uncertainty in hard X-ray index allows great latitude in choice of p.

This spectrum is the lynch pin for the remainder of the paper. (This plot from Petrosian 2002, astro-ph/0207481.)

General Features of Particle Acceleration in the ICM

Isotropy and homogeneity allow one to average over particle directions and lead to a simplified form for the Fokker-Planck equation:

$$\frac{\partial f}{\partial t} = \frac{\partial^2}{\partial E^2}[D(E)f] - \frac{\partial}{\partial E}\{[A(E) - \dot{E}_{\rm loss}]f\} - \frac{f}{T_{\rm esc}(E)} + Q(E,t) \quad (26)$$

Acceleration time scale, $T_{\rm acc} \sim E/A$:

$$\frac{\Delta E}{E} \sim \beta_{\rm blob}^2 \qquad \text{from Gary's talk} \quad (27)$$

$$T_{\rm acc} \sim \frac{E}{\Delta E} T_{\rm scat} \sim \beta_A^{-2} T_{\rm scat} \quad (28)$$

$$\beta_A \sim \frac{1}{c}\left(\frac{B^2}{4\pi}\frac{1}{\rho_H}\right)^{1/2} \quad (29)$$

$$\sim 3 \times 10^{-4}\left(\frac{B}{1\mu{\rm G}}\right)\left(\frac{n_H}{10^{-3}{\rm cm}^{-3}}\right)^{1/2} \quad (30)$$

$$\Rightarrow \quad T_{\rm acc} \sim 10^7 T_{\rm scat} \quad (31)$$

The energy scale, $E_{\rm cr} \sim 10^4$MeV, for the exponential roll-over implies $T_{\rm acc} \sim T_{\rm loss} \sim 10^8$ y at these energies. Hence, we have $T_{\rm scat} \sim 10$ y (!), and a scattering mfp of $\lambda_{\rm scat} \lesssim 1$ pc.

A Rundown of Possible Acceleration Scenarios: Continuous accleration and steady-state models

- ICM Acceleration of Thermal Electrons.
  - Plasma acceleration proceeds via resonant interactions, and for non-relativistic electrons this requires $\omega_p/\omega_B \lesssim 1$ or $\beta_A > (m_e/m_p)^{1/2} \sim 10^{-2}$.
  - Efficiency of Coulomb losses below $E \sim 1\,\mathrm{MeV}$ implies unacceptable heating of ICM.
- ICM Acceleration of Injected Non-thermal Electrons.
  Electrons may be injected with $E \gtrsim 50\,\mathrm{MeV}$ injected from galaxies and/or AGNs. However, in order to explain the exponential roll-over for $E > E_{\rm cr} = 10^4\,\mathrm{MeV}$, one must have either
  - $T_{\rm esc} < T_{\rm acc} \sim 10^8\,\mathrm{y}$. This is ruled out by observations, i.e., the lack of IC emission outside of radio halos.
  - $T_{\rm loss} < T_{\rm acc}$. However, the cooling of particles confined within the ICM produces a particle distribution below $E_{\rm cr}$ with $p \sim 1$, too flat to produce the observed EUV/HXR emission.
- Injected Electrons that only Cool and Diffuse in the ICM.
  Possible, in principle, but requires a contrived injection spectrum

$$Q(E) \propto E^{2-p} e^{-E/E_{\rm cr}} [(2-p)/E - 1] \tag{32}$$

in order reproduce the desired electron spectrum.

Time-dependent Models

Assume instantaneous power-law injection,

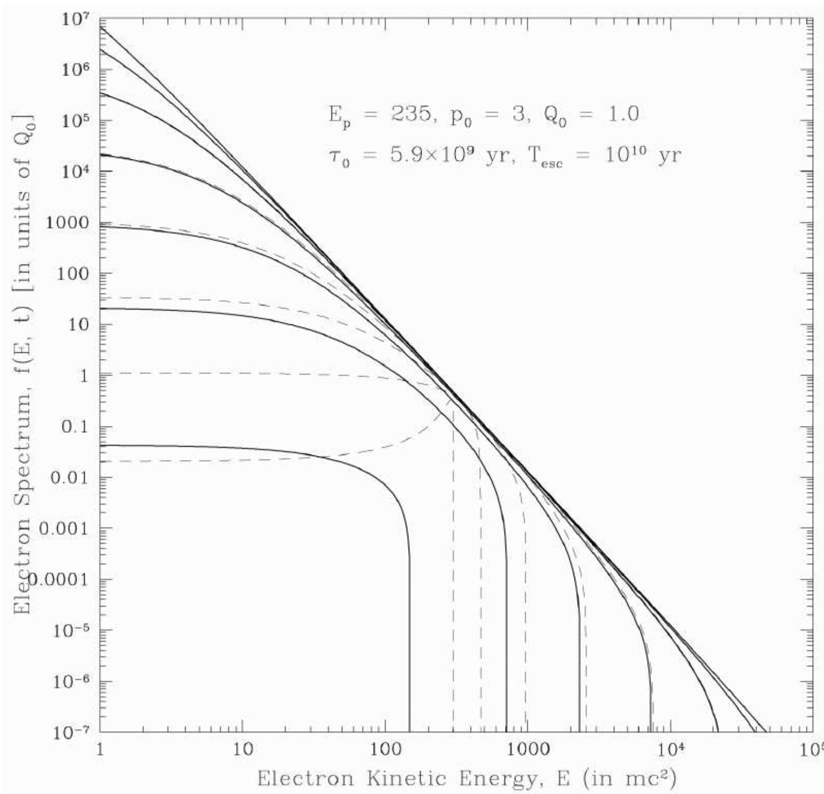
$$Q(E,t) = Q_0 (E/E_p)^{-p_0} \delta(t - t_0), \tag{33}$$

and model ICM acceleration as a negative loss term,

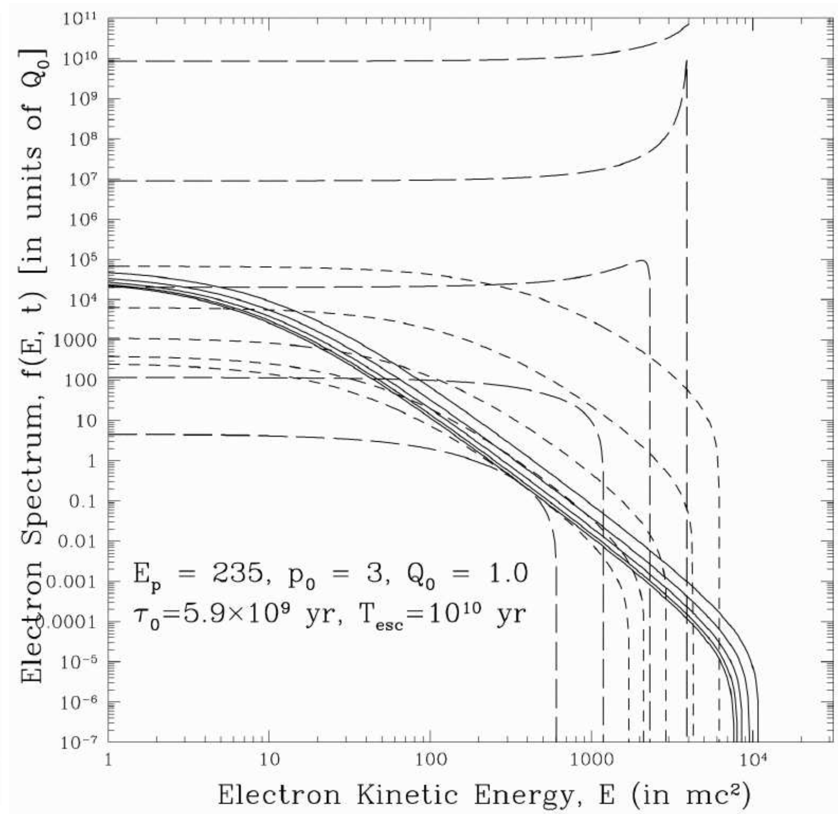
$$\frac{\dot{E}_{\rm loss}}{E_p} = \frac{1 + (E/E_p)^2 - b(E/E_p)^{q-1}}{\tau_0}. \tag{34}$$

Here $E_p \simeq 200\,{\rm MeV}$, $\tau_0 = 6 \times 10^9\,{\rm y}$, $q = 2$, $b \sim 1$–10^2 (2nd order $\rightarrow$ shocks)

From integrations of FP eq., one finds particle distributions of the desired shapes, but injection must be episodic on time scales of 10^8 years in order to produce the observed radio emission.



Solid lines: $b = 0$, $t_n = 10^{n/2}\tau_0, n = -6 \ldots 1$;
Dashed: $b = 2$

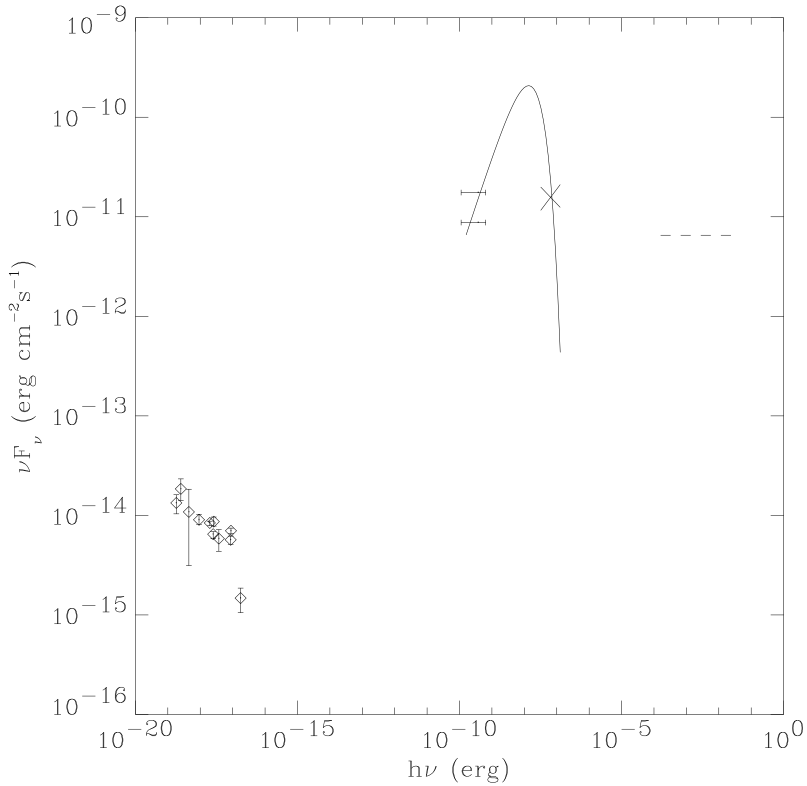


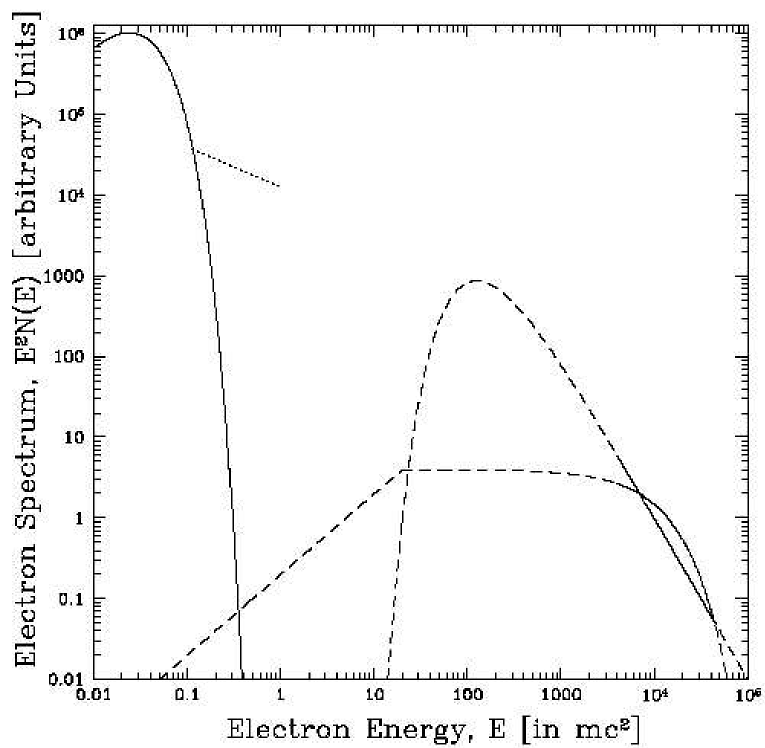
b =2, 5, 9, 17, 26 (lower to upper); $t/\tau_0 = 10^{-1.5}, 10^{-0.8}, 10^{-0.2}$ (solid, dotted, dashed)

Conclusions

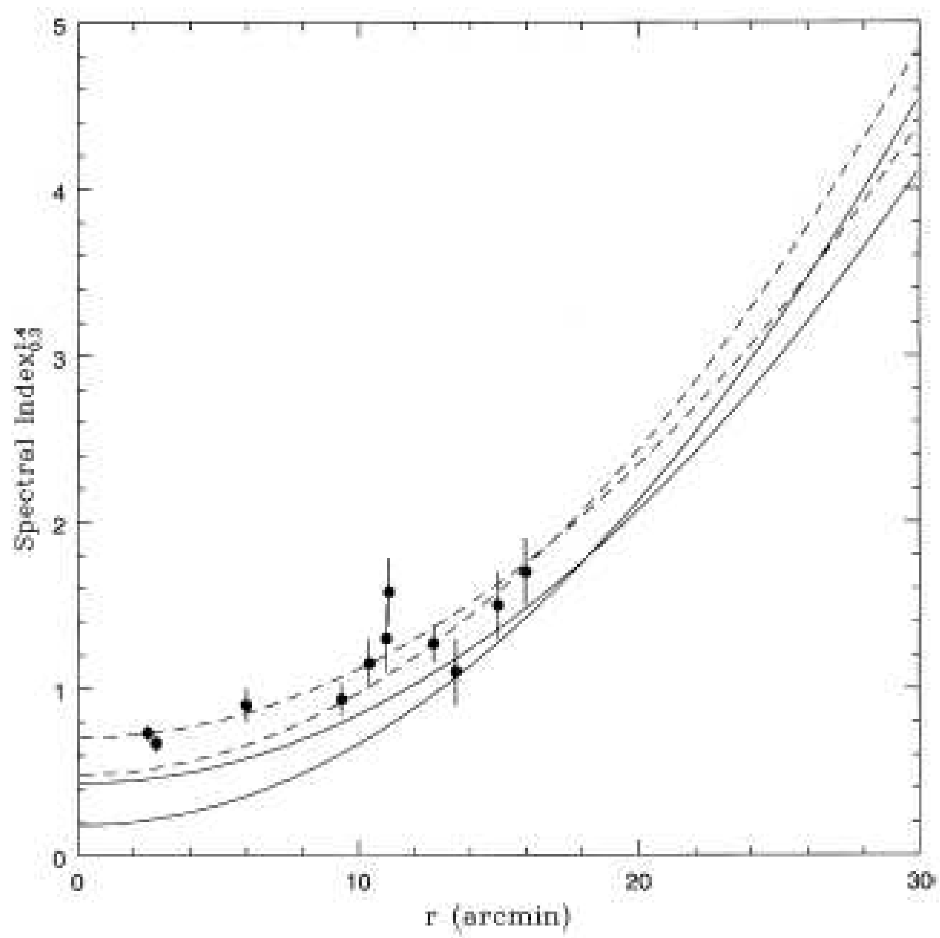
- The absence of IC emission outside of cluster radio halos requires that non-thermal electrons are confined to the ICM, most likely by scattering off plasma turbulence.
- The small effective mean free paths and smoothness of the diffuse emission means that acceleration sites must be distributed throughout the ICM.
- The same non-thermal electron distribution can produce both the radio and X-ray emission via synchrotron and IC processes, respectively, but it must have a specific shape to be consistent with Faraday rotation measures and overall energetics. Non-thermal bremsstrahlung is not a likely explanation of the HXR emission.
- The inferred electron distribution appears to rule out steady-state acceleration in the ICM plasma itself, but ICM acceleration of episodic ($T_{\rm recur} \sim 10^8$ y), injected non-thermal distributions seems feasible.

Finally, a couple words about γ-ray emission: Nonthermal bremsstrahlung





Radio Spectral Index Variation for Coma



Giovannini et al. 1993 cited in Brunetti et al. 2001, MNRAS, 320, 365