Particle reacceleration in the Coma Cluster*

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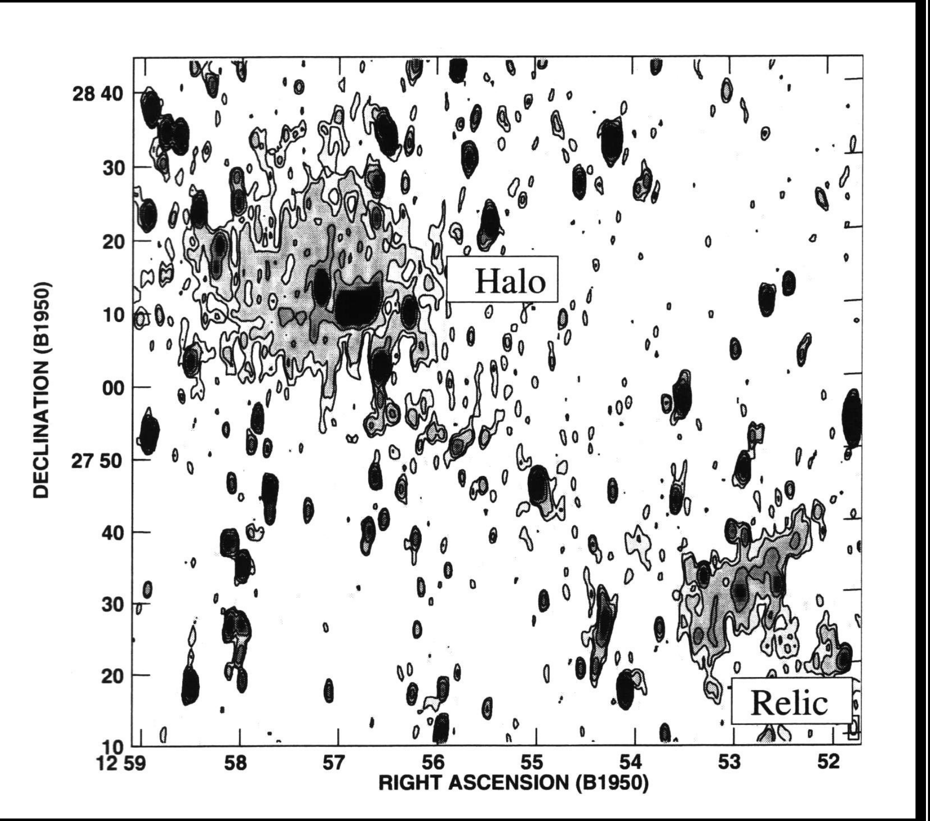
* Brunetti, Setti, Feretti, and Giovannini 2001

Radio Halo

- Radio Halo – existence of cluster magnetic fields and relativistic electrons.
- Relatively recent
  - Lifetime of relativistic electrons (due to Inverse Compton (IC) losses – 10^{7-8} years
- Either freshly injected or reaccelerated electrons



Radio Emission of Coma C

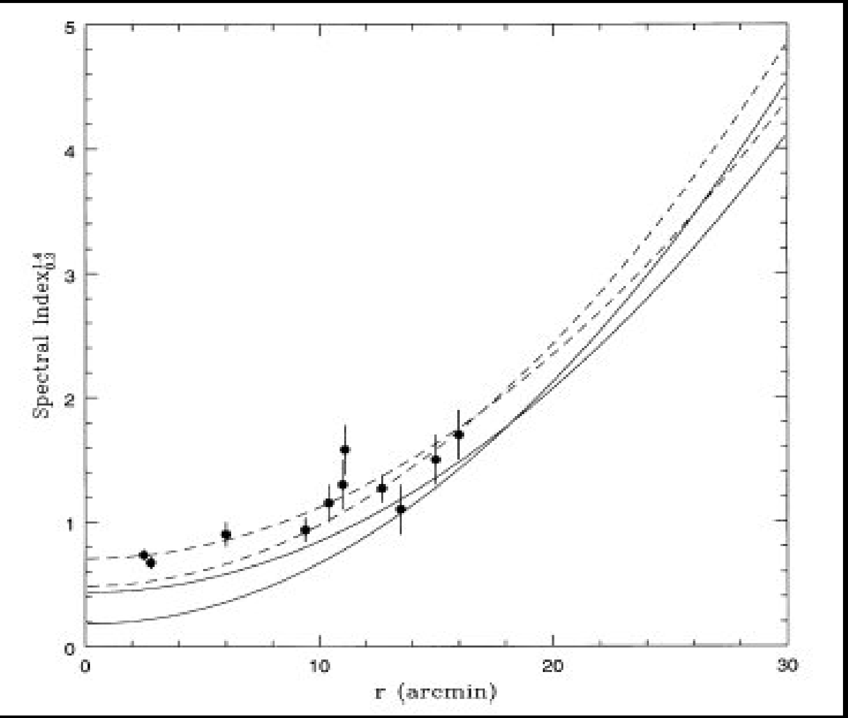
- Radio emission (at low frequencies) extends to ~30-40 arcmin from center
- Total radio spectrum is steep $\alpha \sim 1.2$ and it steepens rapidly from the center
  - Continuous injection of electrons may explain the total spectrum, but not the steepening with increasing radius.

Paper Objective

- Look at a two phase model to investigate:
  - Explain steepening with increasing radius
  - Effects of energy losses and reacceleration gains on energy distribution of the relativistic electrons
  - Obtain radial trend of magnetic field strength
  - Compare the derived IC emission with hard X-ray flux measured by BeppoSAX

Radio Spectral Steepening

- Solid lines – intrinsic
- Dashed lines – predicted observed
  - From Deiss et al. 1997
- Dots are from Giovannini et al. 1993 spectral map
- Steepening occurs at a distance from the center



Phase 1: Injection

- Injection in the past could be do to:
  - Starburst activity and violent galactic winds
  - AGN activity
- Both would create and inject relativistic electrons
- Also the ICM’s high temperature could be do to a major merger, which could create shocks that heat the ICM and accelerate particles

Injection

- Start with kinetic equation to solve for particle energy distribution (N)

$$\frac{\partial N(\gamma, \theta, t)}{\partial t} = -\frac{\partial}{\partial \gamma}\left[\frac{d\gamma}{dt} N(\gamma, \theta, t)\right] + Q_{\text{inj}}(\gamma, \theta, t),$$

- Q is injection function
- Assume cooling is dominated by Coulomb(ξ) and radiation losses (ignoring relativistic bremsstrahlung.
- Cooling: $$\frac{d\gamma}{dt} = -\xi - \beta(\theta, z)\gamma^2.$$

Injection

- Coulomb losses (depend on ICM density)

$$\xi \simeq 1.2\times 10^{-12} n\left[1+\frac{\ln(\gamma/n)}{75}\right] \sim 1.4\times 10^{-12} n\,\mathrm{s}^{-1},$$

- Radiation losses Coefficient(β(θ,z))

$$\beta(\theta, z) = 1.9\times 10^{-9}[B^2 \sin^2\theta + B_{\mathrm{IC}}^2(z)]\,\mathrm{s}^{-1},$$

Injection

- Assuming a time independent injection function $Q_{\rm inj} = K_e \gamma^{-\delta}$,

$$N(\gamma, \theta) = \frac{K_e}{\beta(\theta)(\delta - 1)} \gamma^{-\delta+1} \left[\gamma^2 + \frac{\xi}{\beta(\theta)} \right]^{-1},$$

- Goes as $\gamma^{-\delta+1}$ when dominated by Coulomb losses (low energies) and $\gamma^{-\delta-1}$ when dominated by radiation losses (higher energies)

Second Phase: Reacceleration

- When the injection of fresh particles stops the energy distribution rapidly steepens, and there are less high energy radio-emitting electrons.
- They assume reacceleration starts shortly after injection stops
- Could have been reaccelerated by merger (there have been mergers in Coma C history)

Reacceleration

- They calculate a typical break energy of γ_b of $10^4(B_{\mu G})^{-1/2}$ and a radiative lifetime T of $5x10^{15}\,(B_{\mu G})^{1/2}$ for relatively weak magnetic fields.
- Reacceleration should balance radiation losses, giving a reacceleration efficiency:

$$\chi \sim 1/T \sim 2 \times 10^{-16}/\sqrt{B_{\mu G}}\,\mathrm{s}^{-1}$$

Evolution of Electrons and Synchrotron Spectra

- The time evolution of the electron energies:

$$\frac{d\gamma}{dt} = -\beta(\theta)\gamma^2 - \xi + \chi\gamma - \eta(\gamma)\gamma,$$

- They decide to ignore the bremsstrahlung losses since they are about 100 time less at typical cluster densities.

Ummm ok here it is

- The solution:

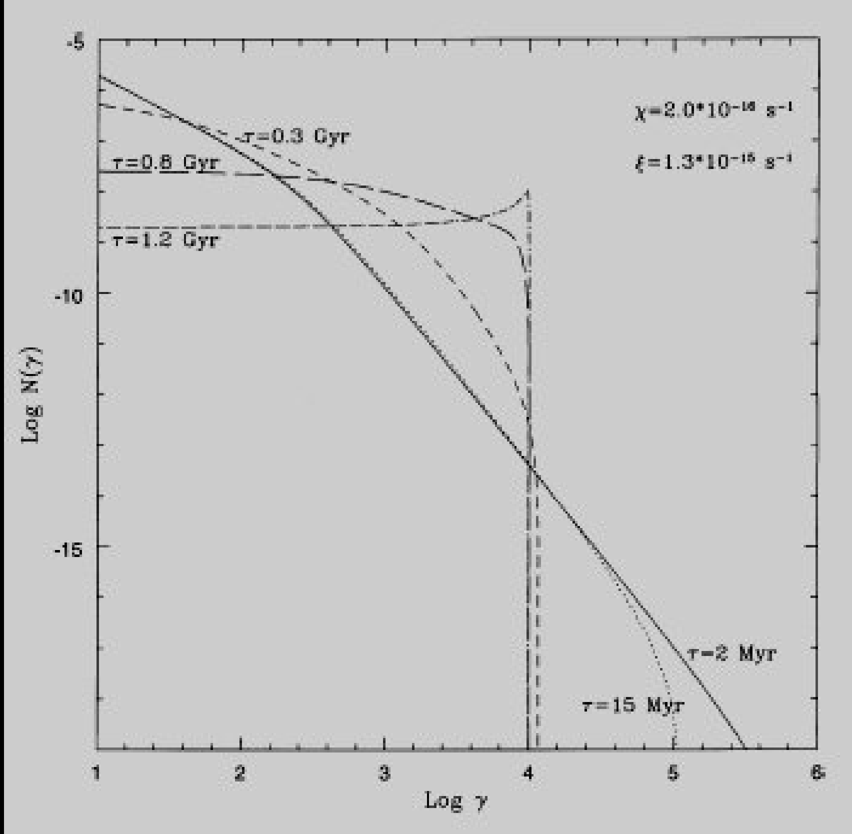
$$N(\gamma, \tau, \theta) = \frac{K_e q(\theta)}{\delta - 1} \frac{[1 - \tanh^2(\tau\sqrt{q}/2)]\gamma^{-\delta+1}}{[2\gamma_b(\tau, \theta)\tanh(\tau\sqrt{q}/2)]^2 \beta^3(\theta)}$$

$$\times \left[1 - \frac{\gamma}{\gamma_b(\tau, \theta)}\right]^{\delta-3} \left[1 + \frac{\xi\gamma^{-1} - \chi}{\gamma_b(\tau, \theta)\beta(\theta)}\right]^{-\delta+1}$$

$$\times \left[\gamma^2 \left\{\frac{1 + (\xi\gamma^{-1} - \chi)[\gamma_b(\tau, \theta)\beta(\theta)]^{-1}}{1 - \gamma/\gamma_b(\tau, \theta)}\right\}^2 + \frac{\xi}{\beta(\theta)}\right]^{-1},$$

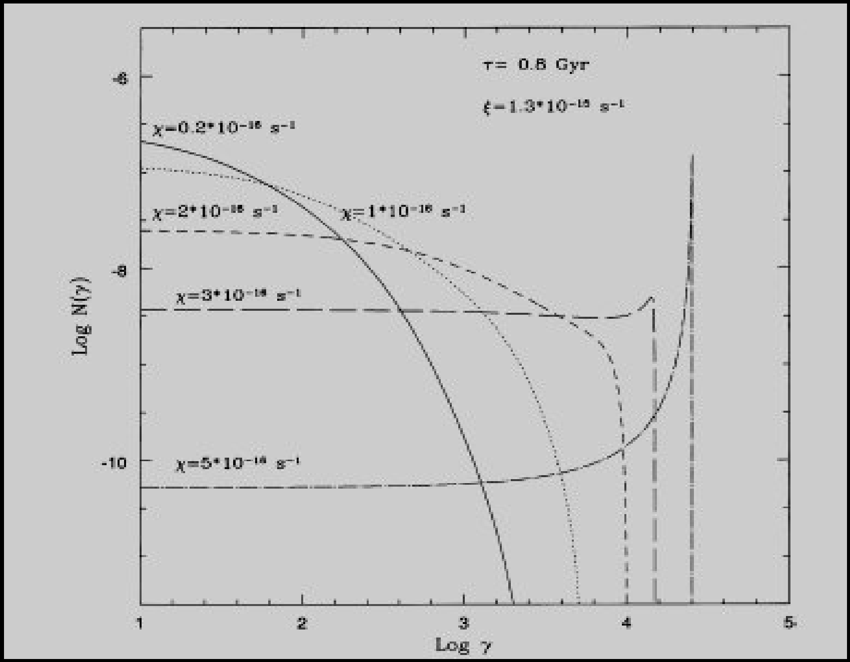
Energy Distribution evolution with time

- $\tau = t - t_i$
- Energy distribution vs. energy for 5 different times
- For a reacceleration efficiency 2.0×10^{-16} s^{-1} (reacceleration time of 1.6×10^{8} yrs)
- As time becomes larger than reacceleration time, the energy distribution flattens



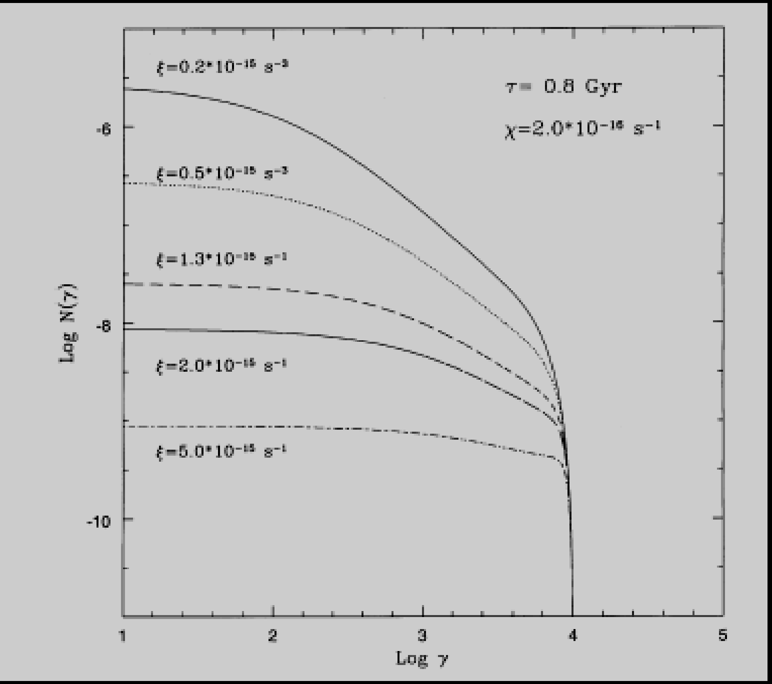
Reacceleration Efficiencies

- For τ=0.8Gyr 5 different reacceleration efficiencies
- Energy distribution flattens with increased reacceleration
- Also higher energy breaks



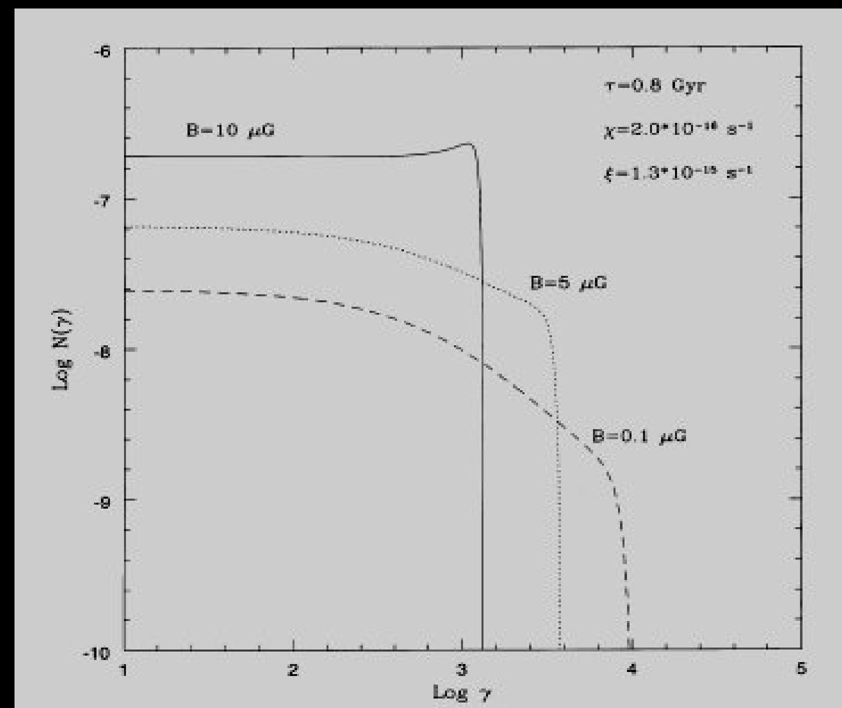
Coulomb Losses

- Increasing ξ is like increasing ICM density
- Increased ICM density/Coulomb losses causes greater flattening
- Since ICM density decreases with distance from center, the energy distribution is flatter near center



Magnetic Field

- Energy distribution flattens with increased B
- Lower energy breaks



More once again

- Emissivity:

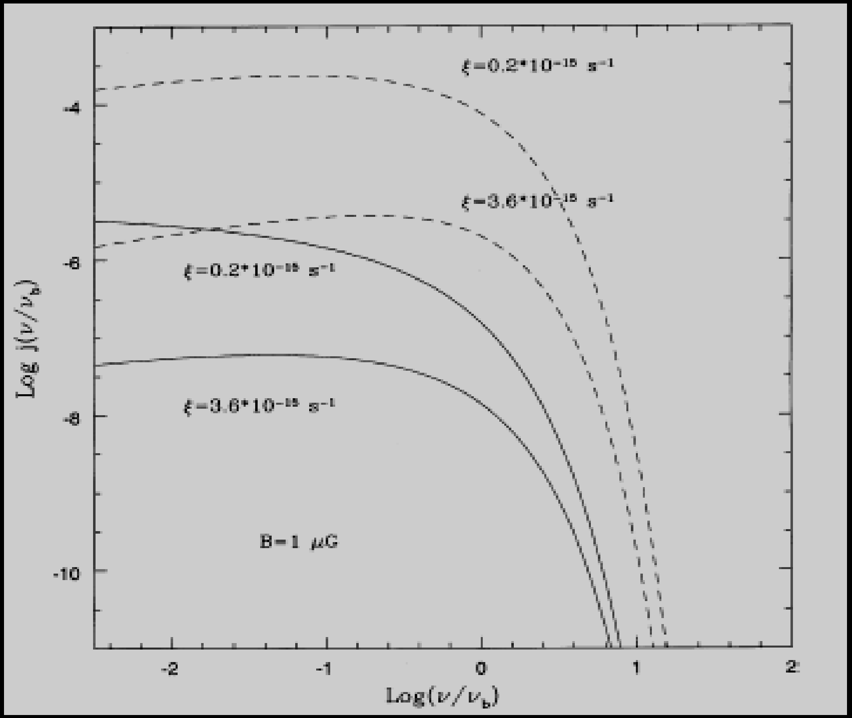
$$
\begin{aligned}
j\left(\frac{\nu}{\nu_{\mathrm{b}}}, \tau\right) = {} & \frac{K_{\mathrm{e}}}{\delta - 1}\frac{\sqrt{3}}{4}\frac{e^3}{mc^2}B\int_0^{\pi/2} \mathrm{d}\theta \sin^2\theta\,\phi(\theta) \\
& \times \int_0^1 \mathrm{d}u F\left(\frac{\nu/\nu_{\mathrm{b}}}{u^2\sin\theta}\right)(1-u)^{\delta-3}u^{-\delta+1} \\
& \times \left[1 + \frac{\xi u^{-1} - \chi\gamma_{\mathrm{b}}(\theta)}{\beta(\theta)\gamma_{\mathrm{b}}^2(\theta)}\right]^{-\delta+1} \\
& \times \left[u^2\left\{\frac{1 + [\xi u^{-1} - \chi\gamma_{\mathrm{b}}(\theta)]/[\gamma_{\mathrm{b}}^2(\theta)\beta(\theta)]}{1-u}\right\}^2\right. \\
& \left. + \frac{\xi}{\beta(\theta)\gamma_{\mathrm{b}}^2(\theta)}\right]^{-1}
\end{aligned}
$$

Importance of Radius from Center

- IC losses are constant throughout cluster
- Magnetic Field lessens with r
- Coulomb losses also depend on r
- This means the energy distribution also varies with r

Syncrotron Spectrum

- Used B = 1μG and τ =0.8 Gyr, which are typical for Coma Cluster center
- Solid lines are for χ $=2.5 \times 10^{-16}\ s^{-1}$
- Dashed lines are χ $=4.2 \times 10^{-16}\ s^{-1}$



More Equations

- β-model for Coulomb losses:

$$\xi(r) = 4.2\times 10^{-15}\left[1+\left(\frac{r}{R_C}\right)^2\right]^{-3\beta/2},$$

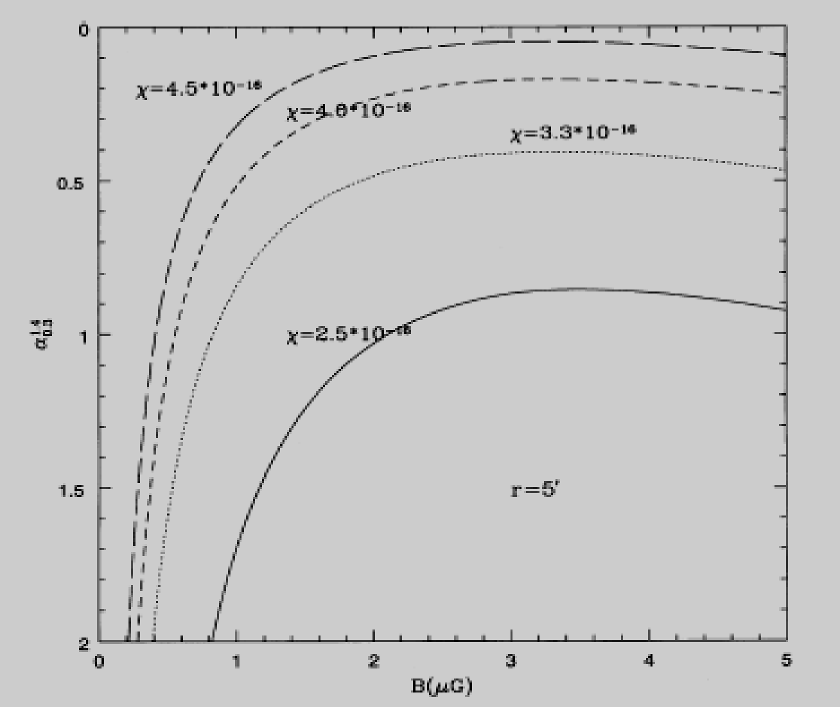
- For Coma R_C=10.5 arcmin and β=0.75
- Reacceleration efficiency is sum of large scale and small scale components:

$$\chi(r) = \chi_{LS} + \chi_{G0}\left[1+\left(\frac{r}{R_G}\right)^2\right]^{-\alpha_G/3},$$

- R_G=5.5 arcmin and α_G=0.8

Spectral Index

- Calculated intrinsic spectral index as a function of magnetic field for different reacceleration efficiences
- Small magnetic fields have steep spectral index
- Near center magnetic field depends on both χ_{LS} and χ_G, but further away from center it only depends on χ_{LS}

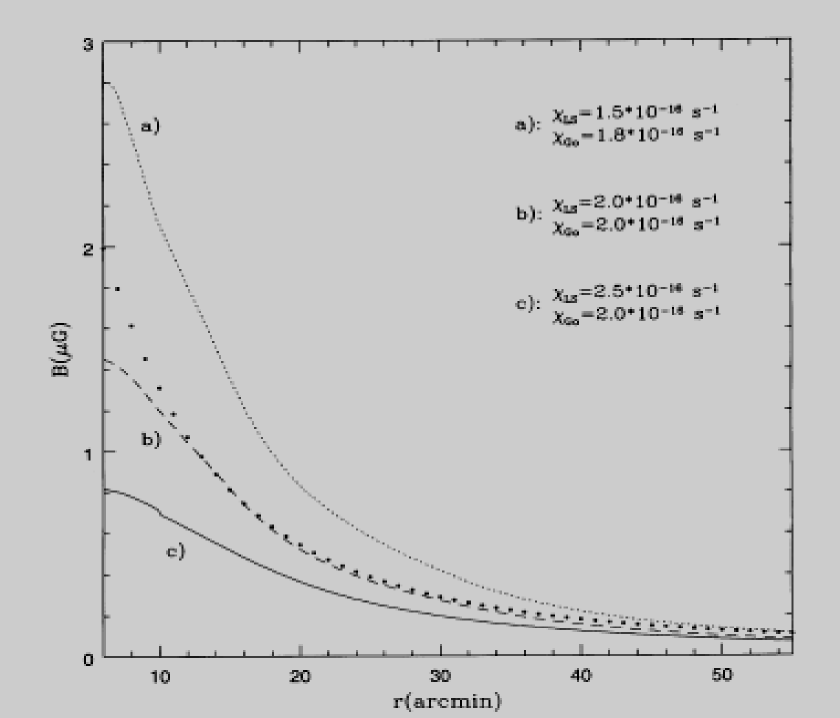


Some Bounds

- For a spectral index of 0.5:
  - Lower bound of reacceleration efficiency:
    - $\chi(0) = 3.3 \times 10^{-16}\ s^{-1}$
  - Upper magnetic field:
    - $B(0) \sim 3\ \mu G$
    - Some other measurements:
      - Kim et al. 1990 : B = (1.7 +- 0.9) μG in center
      - Feretti et al. 1995 B ~ 6 μG near NGC 4869

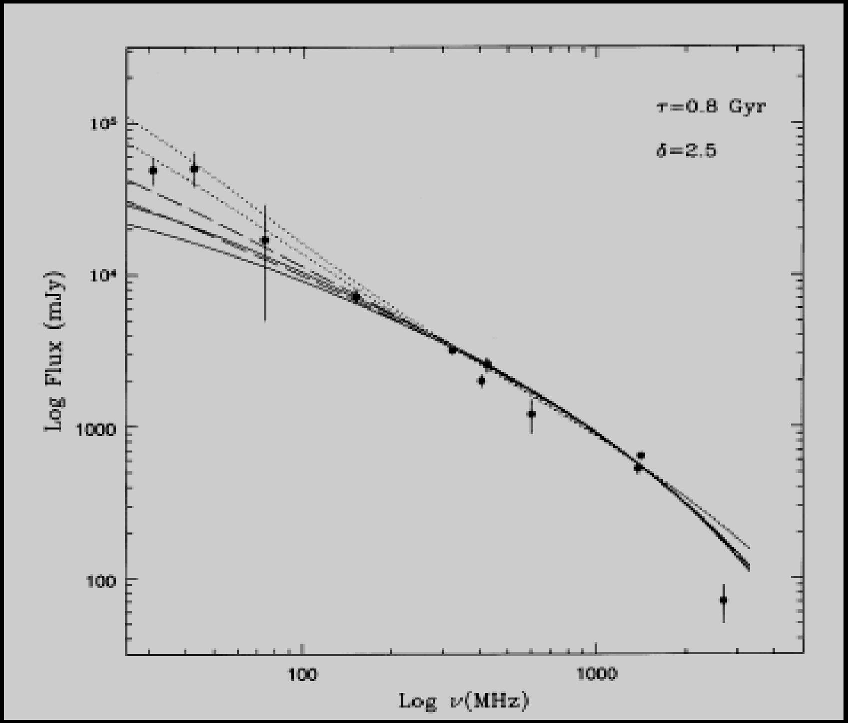
Magnetic Fields

- B distribution required to match spectral observations in model
- Dots are predictions by Jaffe 1980.
- At large distance only χ_{LS} matters



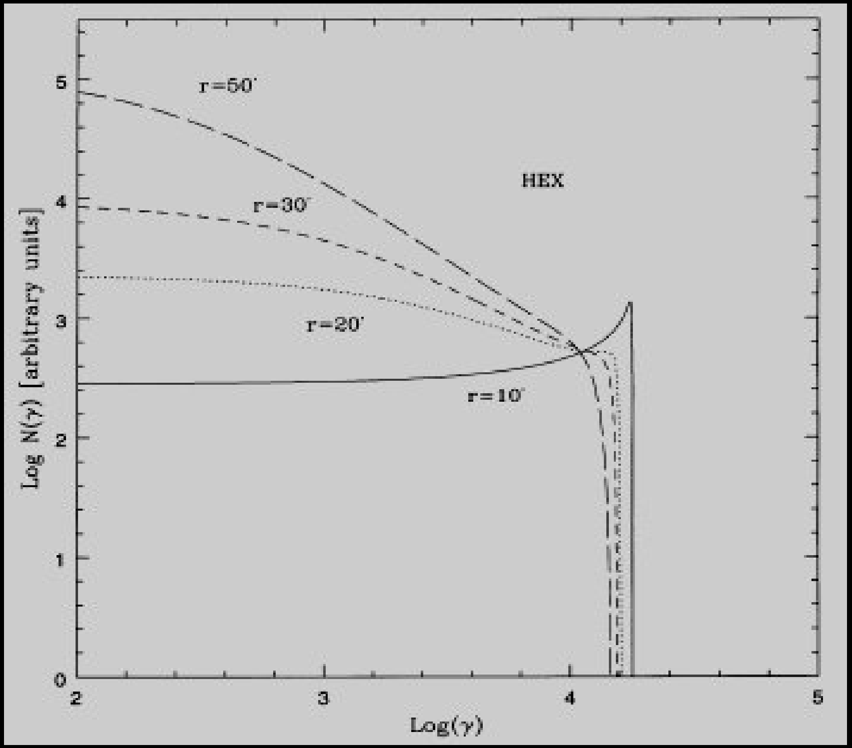
Syncrotron spectrum

- They integrated the syncrotron emissivity, considering those parameters that vary with r
- For different models from previous figure, compared to the data for total synchrotron emission



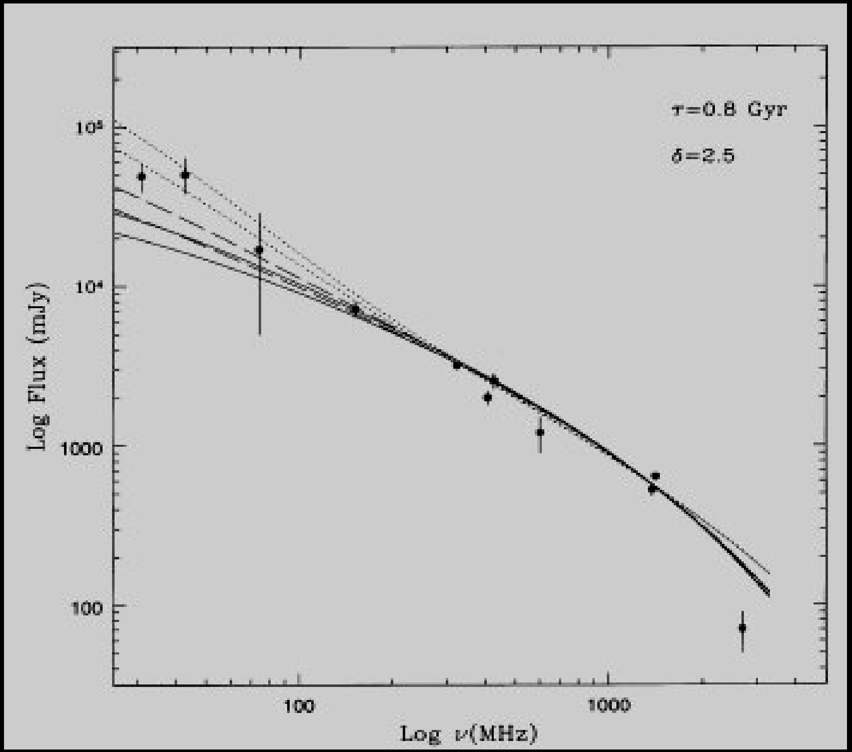
Effect of Radius

- Energy distribution at different radii from the cluster center
- More flattened and higher break energy closer to the center



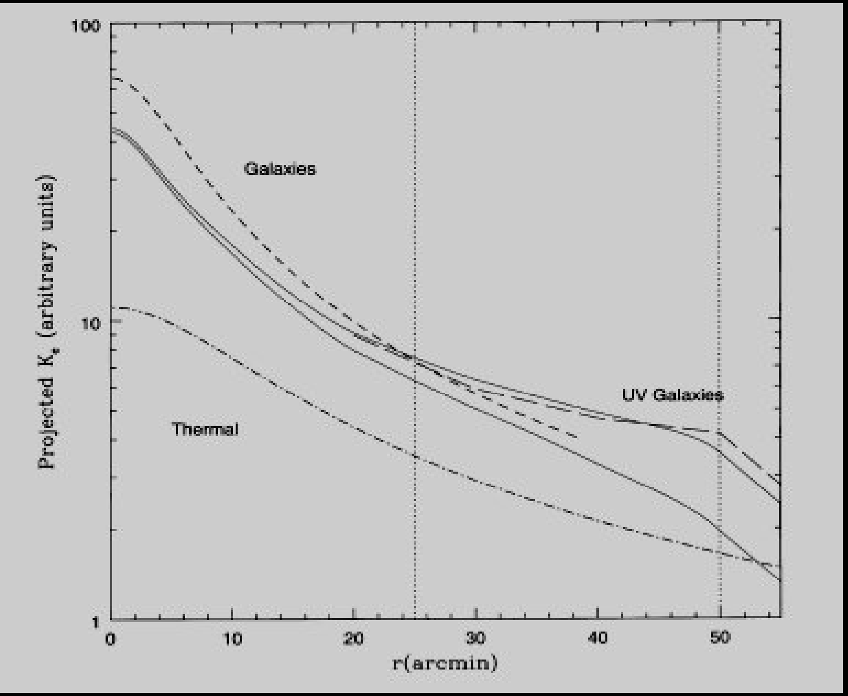
Bounding Reacceleration Efficiency

- For the dotted lines (model a) they overpredict observations and model c, solid lines, underpredict.
- So a good range for the large scale reacceleration efficiency is :
- $1.5\times10^{-16} < \chi < 3.0\times10^{-16}$



Injection Rate

- The shape of the injection rate of the relic electron population ($K_e(r)$)
- For the first phase = solid lines (for model c)
- Vertical dotted lines bound region where 80-90% of IC Xray flux from second phase occurs
- Dashed lines are predicts from Girardi et al. 1995



Total Energy

- For $\chi = 3.0 \times 10^{-16}\ s^{-1}$ the total energy of relativistic electrons is 10^{59} erg.
- This is smaller (by about 10) than other models
- The flat electron energy spectrum is more efficient in emitting sychrotron radiation at radio wavelengths.

Hard X-Ray Tail

- BeppoSAX found a hard X-ray tail, in the range of 20-80 keV, which was confirmed by RXTE.
- Origin is not well established
  - Could be IC scattering of radio-emitting electrons with CMB photons
  - Also could be relativistic bremsstrahlung
  - Or thermal emission of a modified Maxwellian distribution of hot ICM induced by acceleration
- IC origin could allow a measurement of magnetic field strengths, but their model doesn't allow for this (cant use for whole volume because of reliance on r)

IC Scattering

- Since IC scattering is only sensitive to number of electrons, the majority of the scattering will be at r>30 arcmin
- Models with a relatively high reacceleration efficiency can account for most or all of the X-ray flux.

Review

- Two-phase model can explain the observed radio properties of Coma C
  - Injection of electrons continuously at first
  - Reaccelerated for a typical duration of ~1 Gyr
- Reacceleration efficiency should be about $2 \times 10^{-16}\ s^{-1}$ for a reacceleration time of about 0.6 Gyr

Assumptions

- Assumptions used in the model:
  - The brightness distributions at 327 and 1400 MHz are describe as the sum of two Gaussians
  - The Coulomb losses are fixed by a βmodel
  - Reacceleration efficiency is sum of a large scale and small scale part
  - The relic electron population is allowed to evolve, subject to radiation and Coulomb losses for 0.8 Gyr

Results

- The electron energy distribution depends on r
  - Higher energy break and flatter near center
  - Higher B and χ near center as well
- Using spectral index of 0.5
  - B~ 3 μG
  - Lower bound χ=3.3x10^{-16} s^{-1}

Results

- At center, if B is at least 1μG upper limit to reacceleration efficiency at 5×10^{-16} s^{-1}
- Magnetic field goes from 1-3μG at cent to 0.05 – 0.1 μG at r~50 arcmin from center
- X-rays produced by IC scattering can account for hard X-ray Tail

Want more equations?

- Check out the appendix

$$N(\gamma,\tau,\theta) = \frac{q(\theta)K_e}{4}\frac{1-\tanh^{-2}(x)}{\beta^3(\theta)\gamma_b^2(\theta)}\frac{1+\tan^2[\sqrt{\beta(\theta)\xi}\Delta t]}{\delta-1}$$
$$\times\left[1-\frac{\gamma\mathcal{L}(\theta)}{\gamma_{b,1}}\right]^{\delta-1}$$
$$\times\left\{1+\left[\frac{1-\gamma\mathcal{L}(\theta)/\gamma_{b,1}}{\gamma\mathcal{L}(\theta)+\frac{\xi}{\beta(\theta)\gamma_{b,1}}}\right]^2\frac{\xi}{\beta(\theta)}\right\}^{-1}$$
$$\times\left[\gamma\mathcal{L}(\theta)+\frac{\xi}{\beta(\theta)\gamma_{b,1}}\right]^{-(\delta+1)}[1-\gamma/\gamma_b(\theta)]^{-2},$$

$$\tau = \begin{cases} q<0 \Rightarrow \\ \frac{2}{\sqrt{-q}}\left[\tan^{-1}\frac{\chi-2\xi\gamma(\tau)}{\sqrt{-q}}-\tan^{-1}\frac{\chi-2\xi\gamma(\Delta t)}{\sqrt{-q}}\right] \\ q>0 \Rightarrow \\ \frac{-2}{\sqrt{q}}\left[\tanh^{-1}\frac{\chi-2\xi\gamma(\tau)}{\sqrt{q}}-\tanh^{-1}\frac{\chi-2\xi\gamma(\Delta t)}{\sqrt{q}}\right], \end{cases}$$

$$\gamma_b(\tau,\theta) = \begin{cases} q<0 \Rightarrow \\ \sqrt{-q}\,[2\xi\tan(x)]^{-1}+\chi/2\xi \\ q>0 \Rightarrow \\ [\chi+\sqrt{q}/\tanh(x)][2\beta(\theta)]^{-1}. \end{cases}$$