Radio Astronomy Bremsstrahlung Radiation

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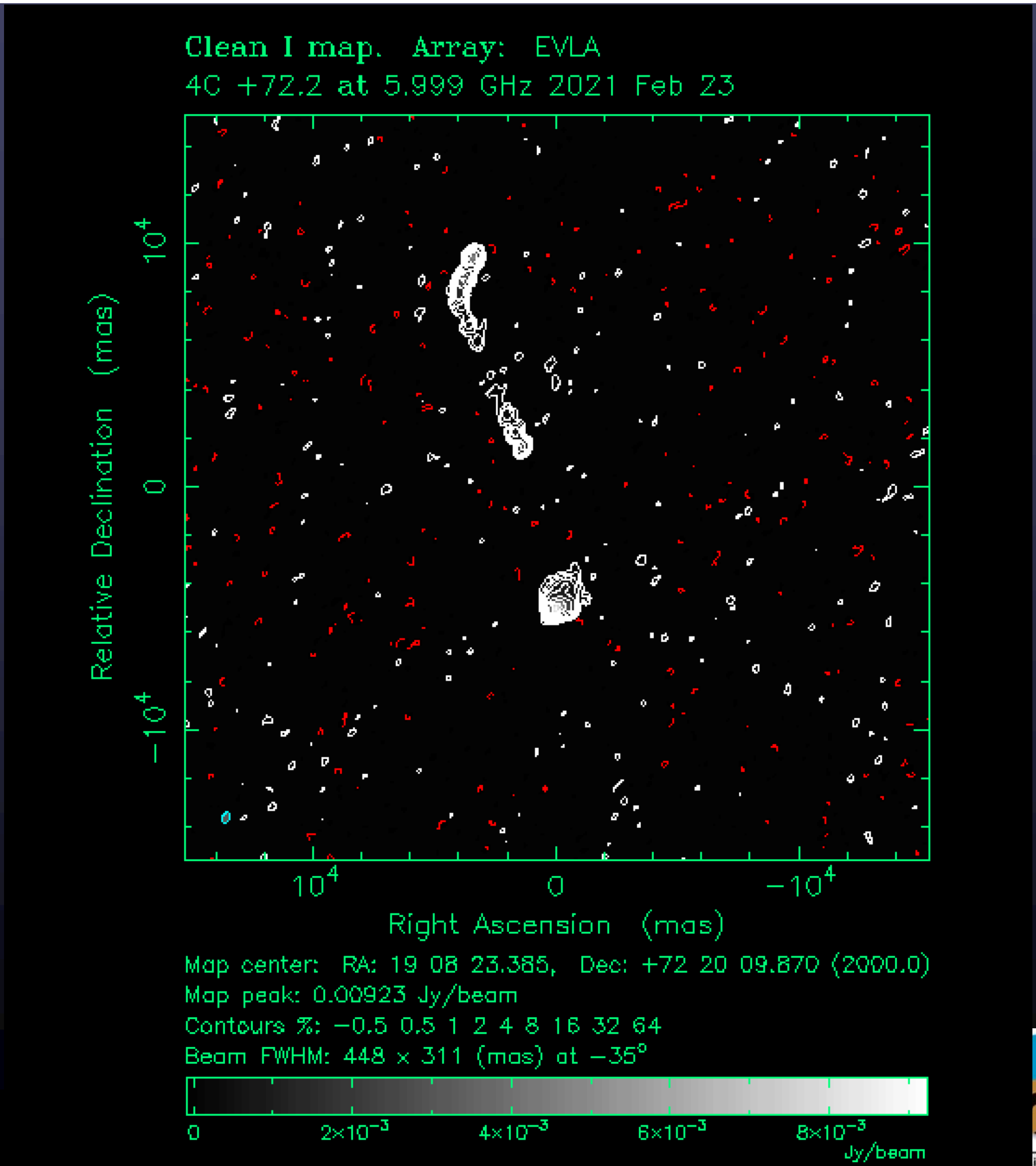
Astronomy 423 at UNM

Radio Astronomy

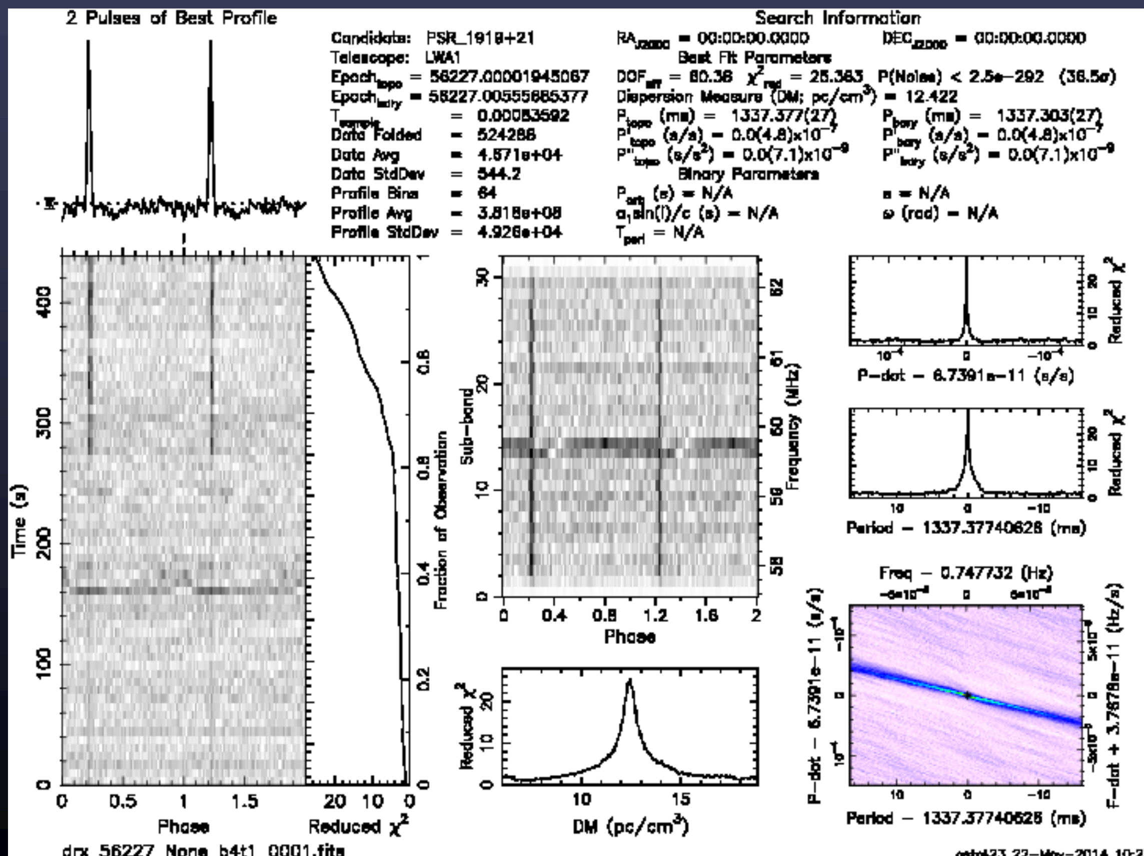
Announcements

- HW#8 solution



Announcements

- For HW#9 problem 4 you need to analyze the results of your LWA1 observations and submit the figure created by prepfold. See example:



Announcements

- Project Outlines due today
- Where's my data?
- Connect to Hercules with x2go, then
  - ssh –X lwaucf3 (password is the same)
  - cd /data/local/astr423/xxx (xxx is group ID)
  - Data is in /data/network/recent_data/astr423

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astr423@lwaucf3: /data/network/recent_data/astr423/060773_013648070
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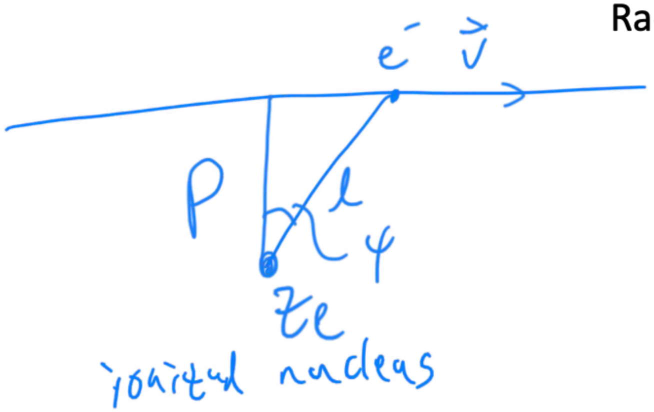
  - Project data converted to circular polarization is on lwaucf3 in /data/local/astr423

Bremsstrahlung (free-free) radiation



assume motion of e^- is in a straight line (deflection is small)

$$l = \frac{p}{\cos\psi}$$

accel of e^- is given by Coulomb's la

$$F = ma = m\dot{v} = \frac{-Ze^2}{l^2}$$

$$\dot{v} = |\dot{v}| \cos\psi$$

$$\dot{v} = \frac{-Ze^2}{m_e p^2} \cos^3\psi$$

would prefer as integral of ψ

Dipole
$$W = \frac{\frac{4}{3} Z^2 e^6}{c^3 m_e p^4} \int_0^t \cos^6\psi(t)\, dt$$

define $dF = \frac{1}{2} \ell^2 d\psi$

$$\frac{dF}{dt} = \frac{1}{2} \ell^2 \frac{d\psi}{dt} = \text{const}$$

now solve for $\frac{dF}{dt}$

at $t=0$ $\quad \frac{dF}{dt} = \frac{1}{2} p \cancel{x} \frac{v}{\cancel{p}} = \frac{1}{2} p v$

$$dt = \frac{\ell^2}{vp} d\psi = \frac{p}{v \cos^2 \psi} d\psi$$

$$W = \frac{4}{3} \frac{z^2 e^6}{c^3 m_e^2 p^4} \frac{p}{v} \int_0^{\frac{\pi}{2}} \cos^4 \psi \, d\psi \Rightarrow \frac{4\pi}{16}$$

$$W = \frac{\pi}{4} \frac{z^2 e^6}{c^3 m_e^2 p^3} \frac{1}{v}$$

total energy radiated by a single e^-

What does spectrum look like?

$$A(\omega) = \frac{1}{2\pi} \int_{-\infty}^{\infty} E(t)\, e^{i\omega t}\, dt \quad \text{by FT}$$

$$C(\omega) = \frac{1}{2\pi} \int_{-\infty}^{\infty} \dot{v}(t) \cos(\omega t)\, dt$$

$$= \frac{-z e^2}{m_e p^2} \frac{1}{2\pi} \int_0^{\infty} \cos(\omega t) \cos^3 \psi(t)\, dt$$

$$\omega_g = 0.463\,\frac{v}{p}$$

radiation from a cloud of e^-'s

Maxwellian velocity distribution

$$f(v) = \frac{4v^2}{\sqrt{\pi}}\left(\frac{m}{2kT}\right)^{3/2} e^{-\frac{mv^2}{2kT}}$$

$$P_\nu(p,v) = \frac{16}{3}\,\frac{Z^2e^6}{c^3m^2}\,\frac{1}{p^2v^2}$$ for $v < v_g$ and 0 for $v > v_g$

N_e in a volume^{-3} with collisions between ρ and $\rho + d\rho$

$$2\pi \rho \, d\rho \, v N_e f(v) \, dv$$

emissivity

$$4\pi \epsilon_\nu \, d\nu = P_\nu(v, \rho) \, dN(v, \rho) \, d\nu$$

$$4\pi \epsilon_\nu = \int_{\rho_1}^{\rho_2} \int_0^\infty \frac{8}{3} \frac{Z^2 e^6}{c^3 m^2} \frac{1}{\rho^2 v^2} N_i N_e f(v) \, 2\pi \rho v \, d\rho \, dv$$

$$\epsilon_\nu = \frac{8}{3} \frac{Z^2 e^6}{c^3} \frac{N_i N_e}{m^2} \sqrt{\frac{2m}{\pi k T}} \ln\left(\frac{\rho_2}{\rho_1}\right)$$

Gaunt factor

or

$$\epsilon_\nu = 5.44 \times 10^{-39} g_{ff} \frac{Z^2 n_e n_i}{T^{1/2}} e^{-h\nu/kT}$$

$\mathrm{erg\,cm^{-3}\,s^{-1}\,sr^{-1}\,Hz^{-1}}$

recall

$$\frac{\epsilon_\nu}{\kappa_\nu} = B_\nu(T)$$ ← Planck Function

for R.J. $B_\nu(T) = \frac{2kT}{\lambda^2}$

$$\kappa_\nu = \frac{\epsilon_\nu}{B_\nu(T)} = \frac{4 Z^2 e^6}{3c} \frac{n_i n_e}{\nu^2} \frac{1}{\sqrt{2\pi (mkT)^3}} \ln\left(\frac{p_2}{p_1}\right)$$

assume $n_i = n_e$ and uniform T

$$\tau_\nu = -\int_0^s \kappa_\nu \, ds$$

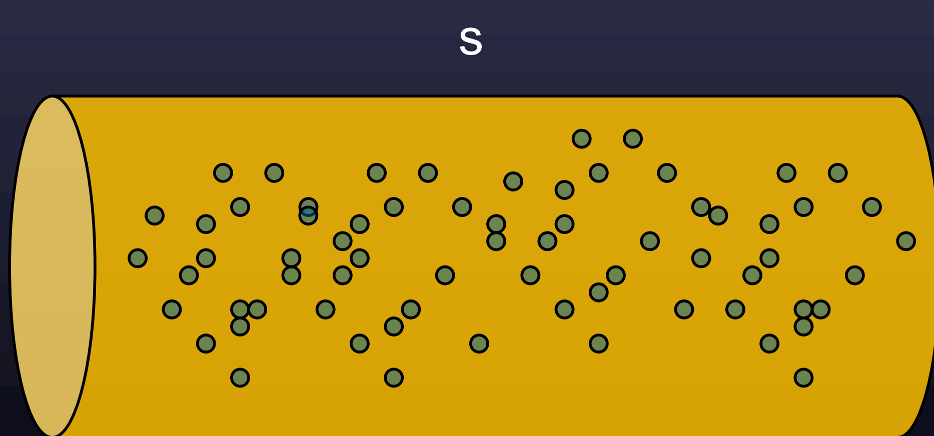
~4~

$$\tau_\nu = 3.014 \times 10^{-2} \left(\frac{T}{K}\right)^{-3/2} \left(\frac{\nu}{GHz}\right)^{-2} \left(\frac{EM}{pc\ cm^{-6}}\right) g_{ff}$$

where $EM = \int_0^s n_e^2\, ds$

n_e in cm^{-3}

s in pc



Emission Measre (EM) is a column density

−4−

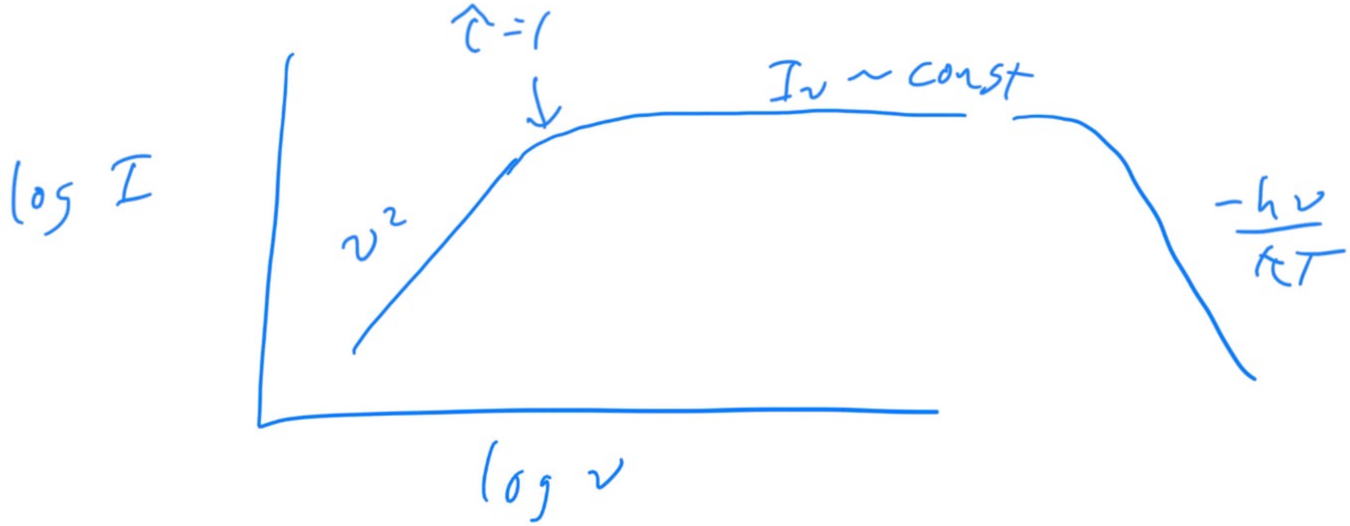
$$\tau_\nu = 3.014 \times 10^{-2} \left(\frac{T}{K}\right)^{-3/2} \left(\frac{\nu}{GHz}\right)^{-2} \left(\frac{EM}{pc\ cm^{-6}}\right) g_{ff}$$

where $EM = \int_0^s n_e^2\, ds$ n_e in cm^{-3}, s in pc

$$W = 1.435 \times 10^{-27}\, Z^2\, g_{ff}\, T^{1/2}\, n_e^2 \ \text{erg cm}^{-3}\,\text{s}^{-1}$$

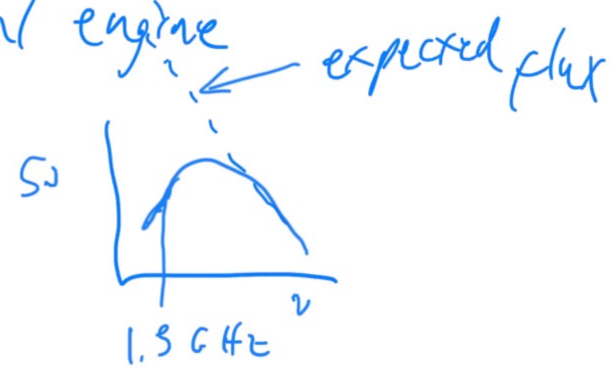
correcting for g_{ff} (slow function of T and ν)

$$\tau_\nu = 8.235 \times 10^{-2} \left(\frac{T_e}{K}\right)^{-1.35} \left(\frac{\nu}{GHz}\right)^{-2.1} \left(\frac{EM}{pc\ cm^{-6}}\right)$$



At high temperatures velocity distribution no longer maxwellian and e^-'s are relativistic in the tail.

Example: Consider an AGN with absorption in a disk around the central engine



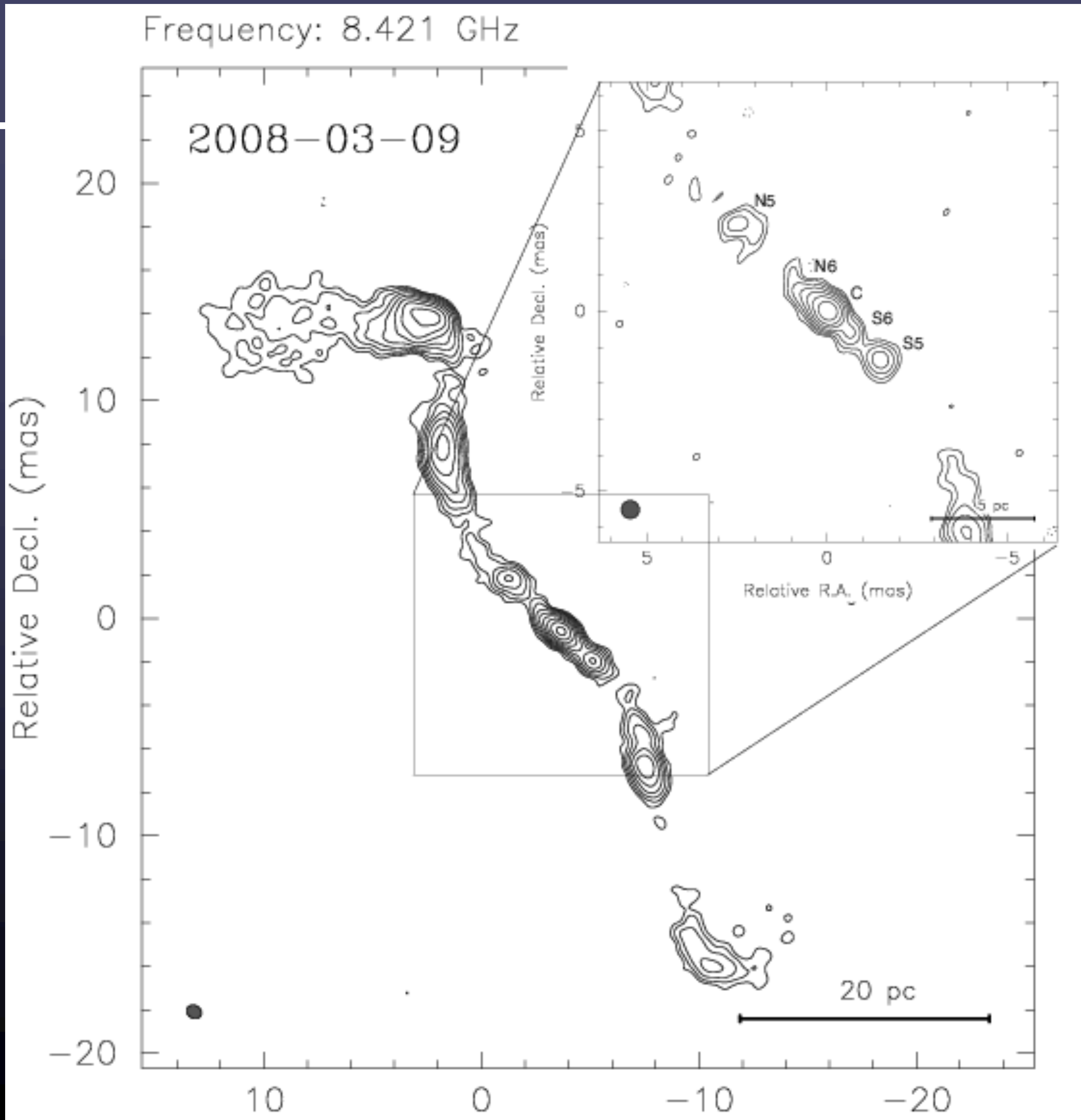
$T \sim 8000\,K$ path 50 pc

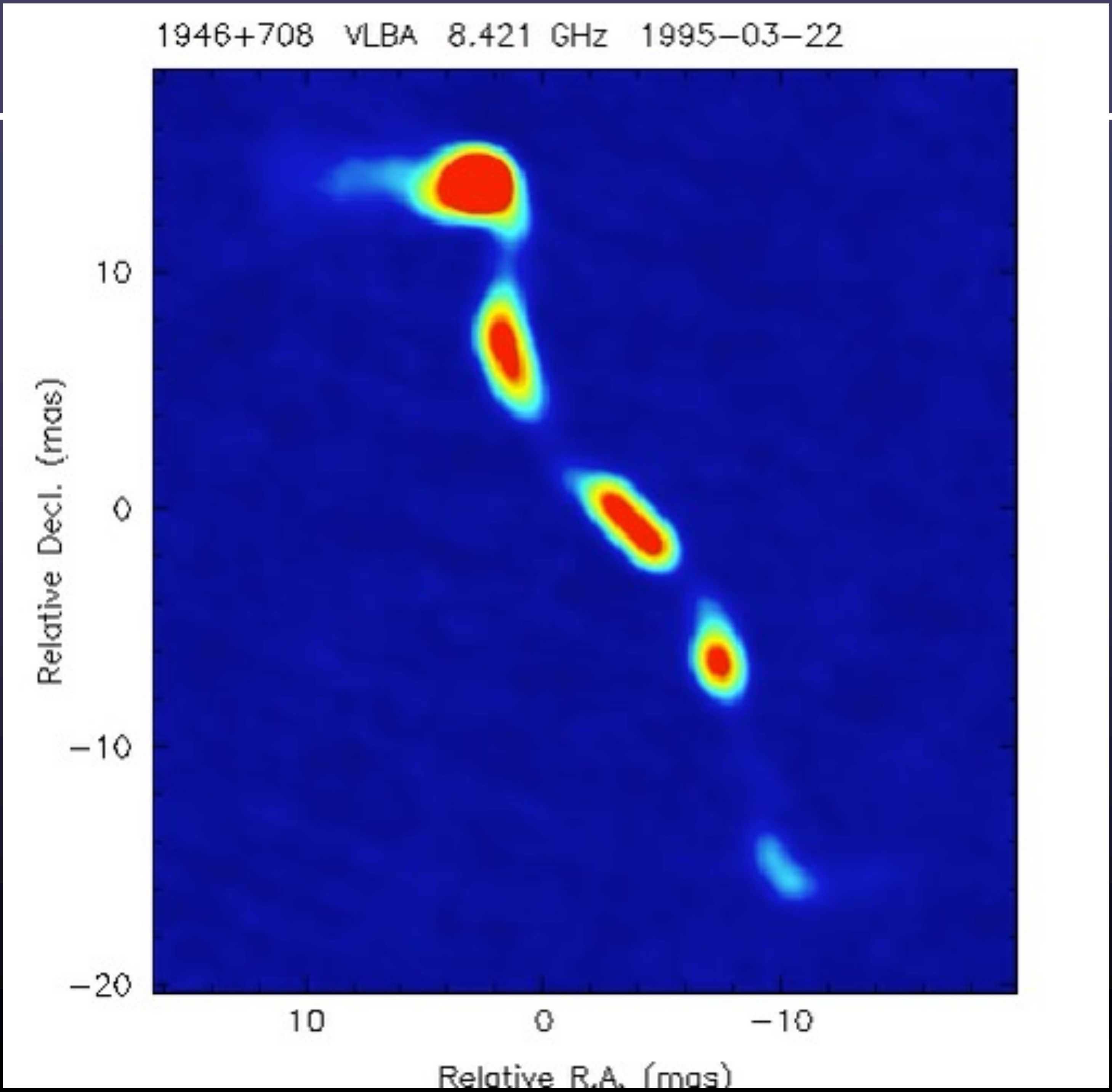
$S_{obs} = 10$ mJy at 1.5 GHz what is n_e?

$S_{exp} = 250$ mJy " "

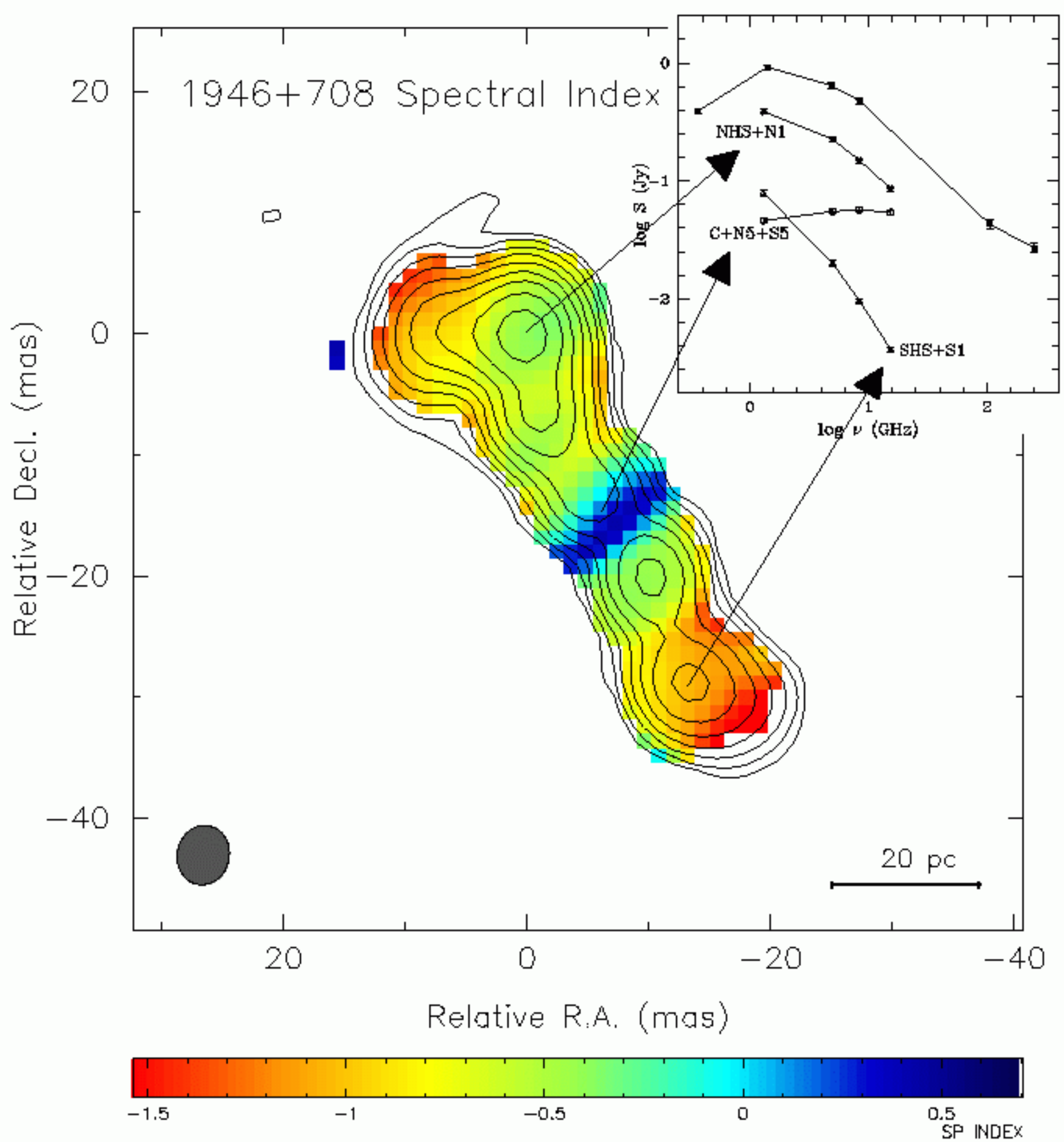
$S_{obs} = S_{exp}\, e^{-\tau}$ $\tau = 3.2$

$EM = 1.7 \times 10^8 \text{ pc cm}^{-6} = n_e^2 \cdot 50\text{ pc}$ $n_e = 1800 \text{ cm}^{-3}$


Frequency: 8.421 GHz
2008−03−09
Relative Decl. (mas)
20
10
0
−10
−20
10
0
−10
−20
20 pc
N5
N6
C
S6
S5
5 pc
Relative Decl. (mas)
Relative R.A. (mas)
5
0
−5


1946+708 VLBA 8.421 GHz 1995-03-22
Relative Decl. (mas)
10
0
−10
−20
10
0
−10
Relative R.A. (mas)

Free-free absorption in 1946+708



Peck & Taylor (2001)

Spectral index map from 1.3/5 GHz VLBI observations

free-free optical depth:

$\tau_{ff} \sim T^{-3/2}\, n_e^2 \nu^{-2}\, d$

$N_e \sim 8 \times 10^{22}$ cm^{-2}

ionization ~ 10%

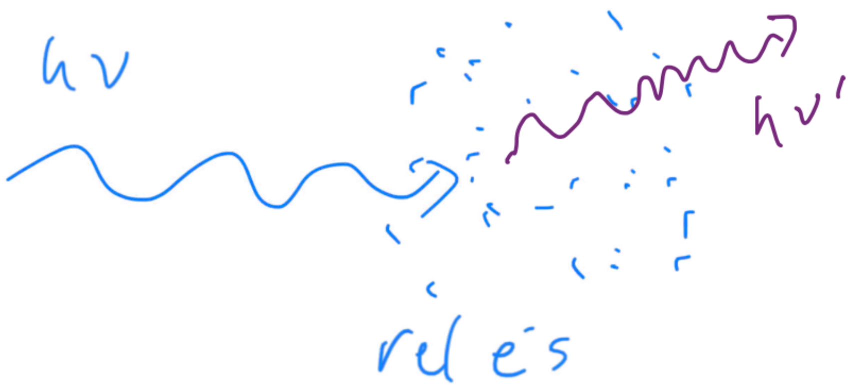
Free-Free Emission

Polarization: Intrinsically zero

Beaming: Intrinsically none

Radiation is isotropic

Bonus: Inverse Compton Emission



$$h\nu' = \gamma h\nu (1 + \beta\cos\theta)$$

$$-\frac{dE}{dt} = \sigma_T \, c \, u'_{rad}$$

$$u'_{rad} = \left[\gamma\left(1 + \frac{v}{c}\cos\theta\right)\right]^2 u_{rad}$$

$$-\frac{dE}{dt} = \frac{4}{3} \sigma_T c \, u_{rad} \, \gamma^2$$

looks a lot like synchrotron emission

$$-\frac{dE}{dt} = \frac{4}{3} \sigma_T c \, \gamma^2 \, u_{mag} \qquad u_{mag} = B^2/8\pi$$

$$\frac{\frac{dE}{dt}\text{ compton}}{\frac{dE}{dt}\text{ synch}} = \frac{u_{ph}}{u_B}$$

Inverse Compton Scattering as the Source of Diffuse Extreme-Ultraviolet Emission in the Coma Cluster of Galaxies

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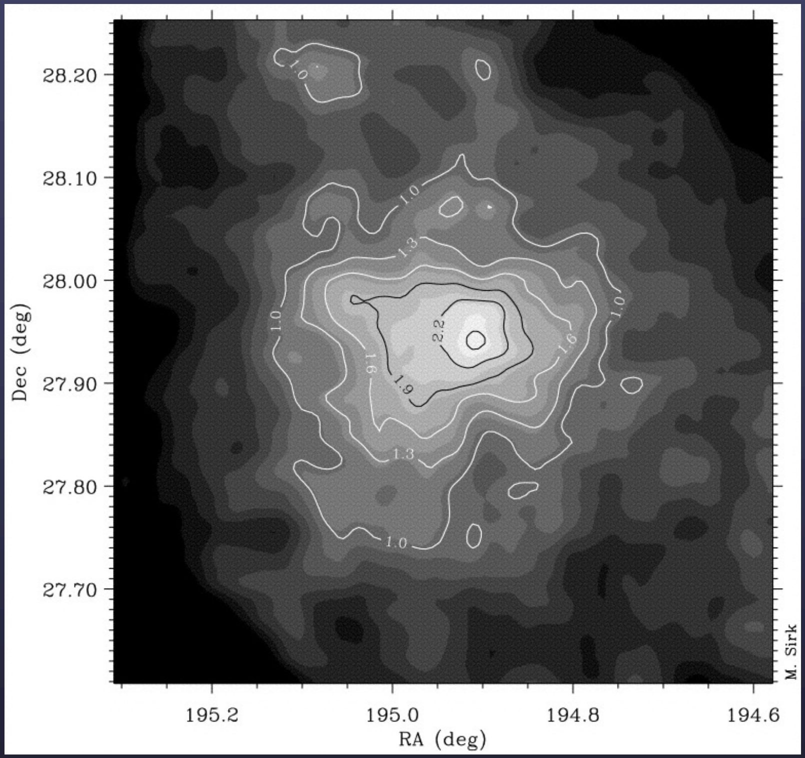
Received 1997 December 17; accepted 1998 May 29

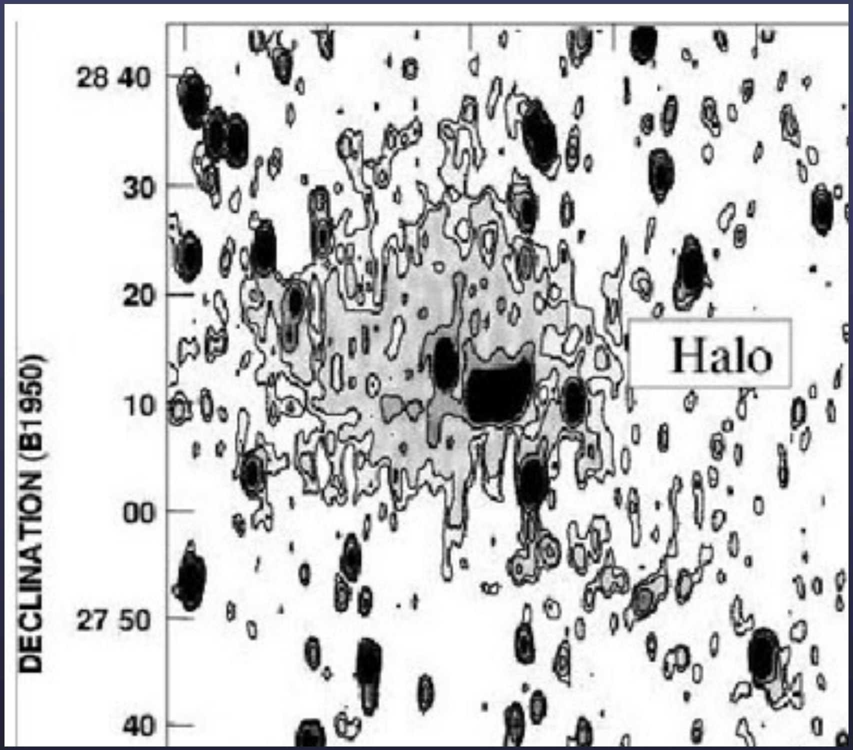
ABSTRACT

We have examined the hypothesis that the majority of the diffuse EUV flux in the Coma Cluster is due to inverse Compton scattering of w-energy cosmic-ray electrons ($0.16 < \epsilon < 0.31$ GeV) against the 3 K blackbody background. We present data on the two-dimensional atial distribution of the EUV flux and show that these data provide strong support for a nonthermal origin for the EUV flux. However, we ow that this emission cannot be produced by an extrapolation to lower energies of the observed synchrotron radio emitting electrons and at an additional component of low-energy cosmic-ray electrons is required.

Coma Cluster

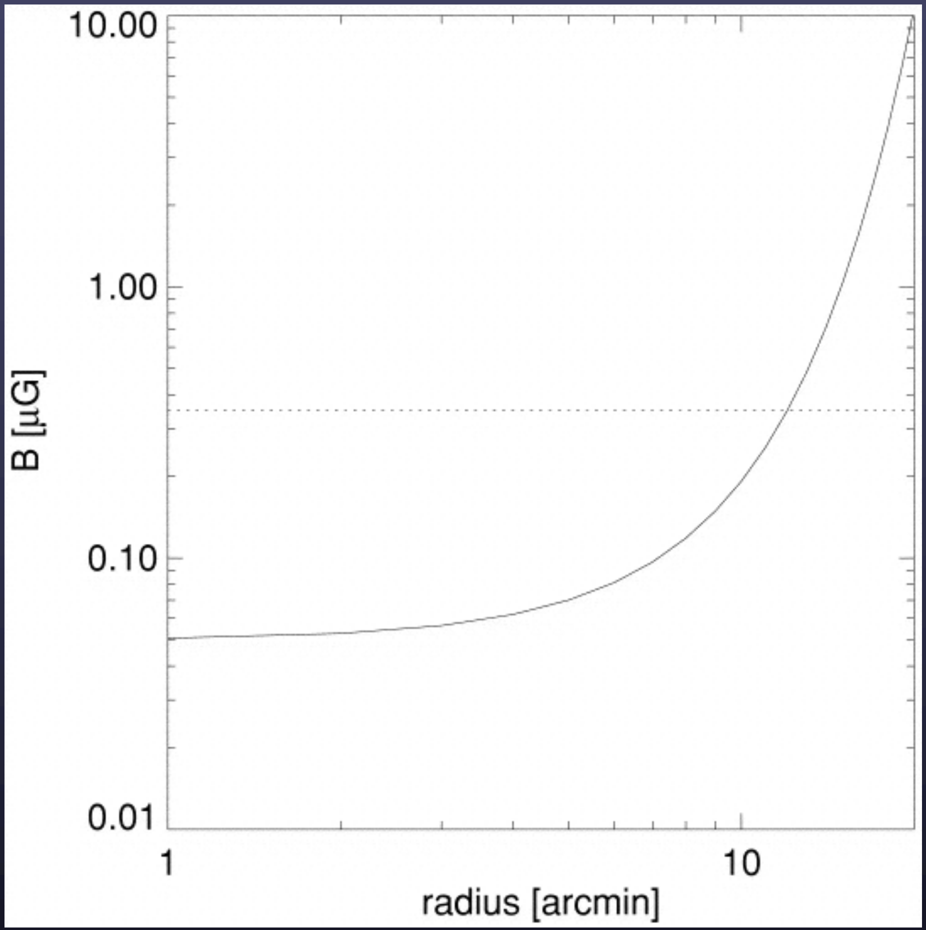


Coma Cluster in EUV Hatsukade, I. 1990,



Coma Cluster in radio – Giovannini et al. (1993) WSRT

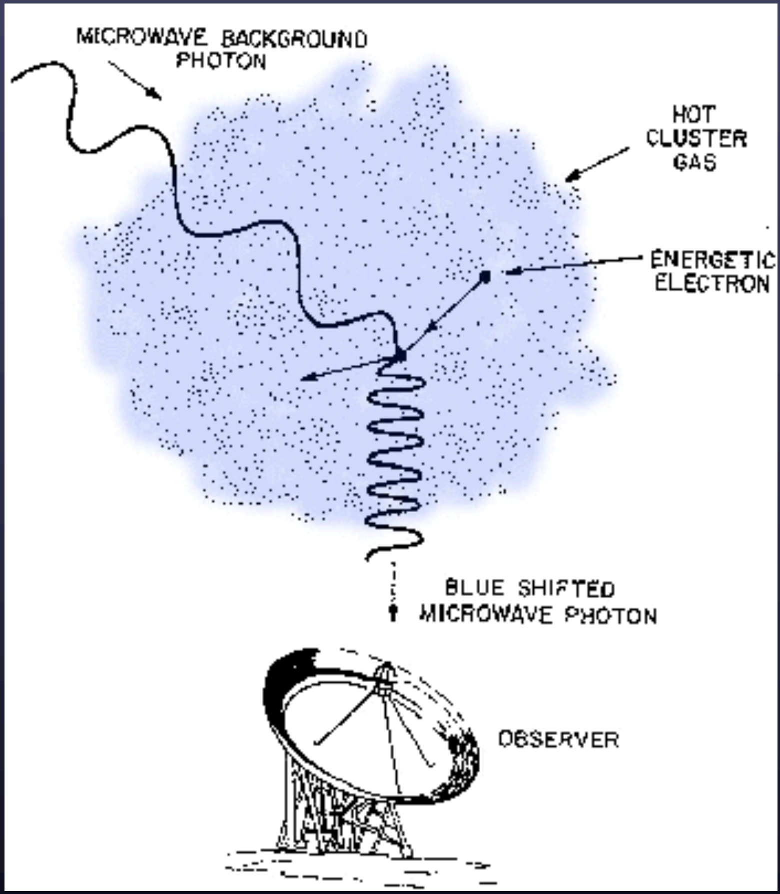
Coma Magnetic Fields



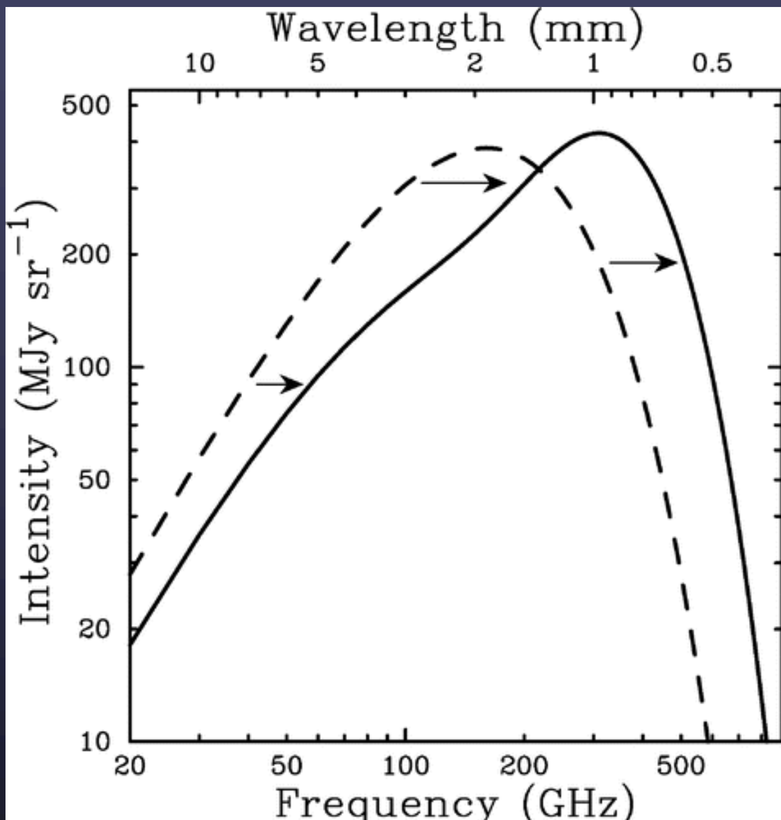
Magnetic field distribution in Coma cluster (Bowyer & Berghofer 1998)

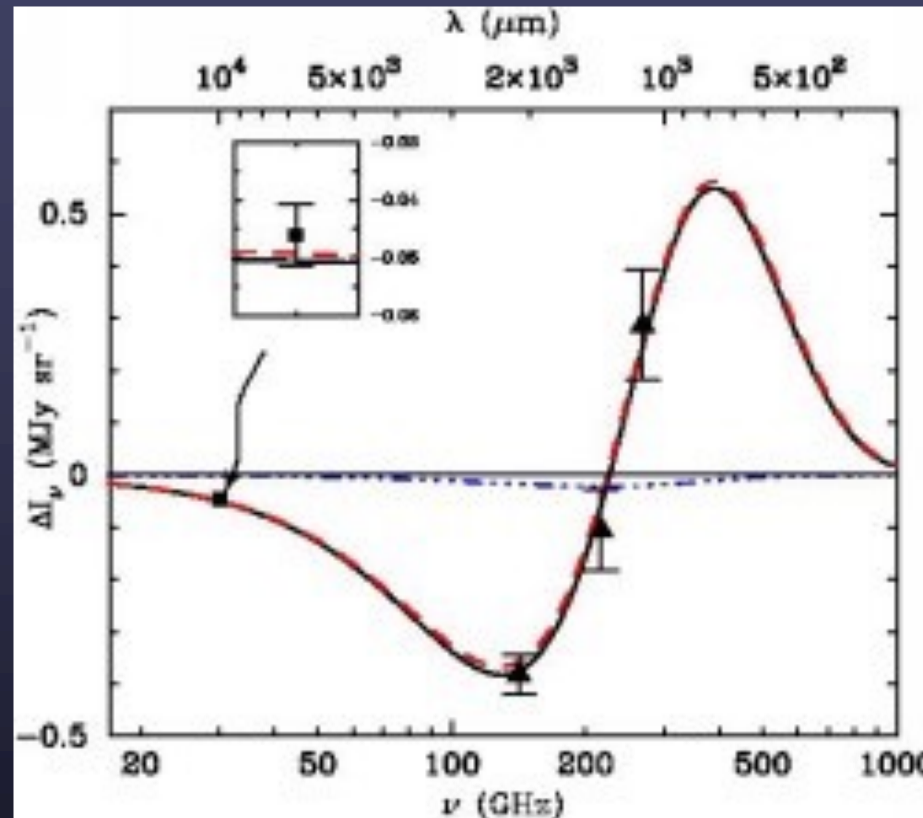
Sunyaev-Zeldovich effect

- The Sunyaev-Zeldovich effect
  - Photons of the CMB are scattered to higher frequencies by hot electrons in galaxy clusters, causing a negative brightness **decrement**.
  - Decrement is proportional to integral of electron pressure through the cluster, or electron density if cluster is isothermal.
  - Electron density and temperature can be estimated from X-ray observations, so the linear scale of the cluster is determined.
  - This can be used to measure the cluster distance and combined with z to get H_0.

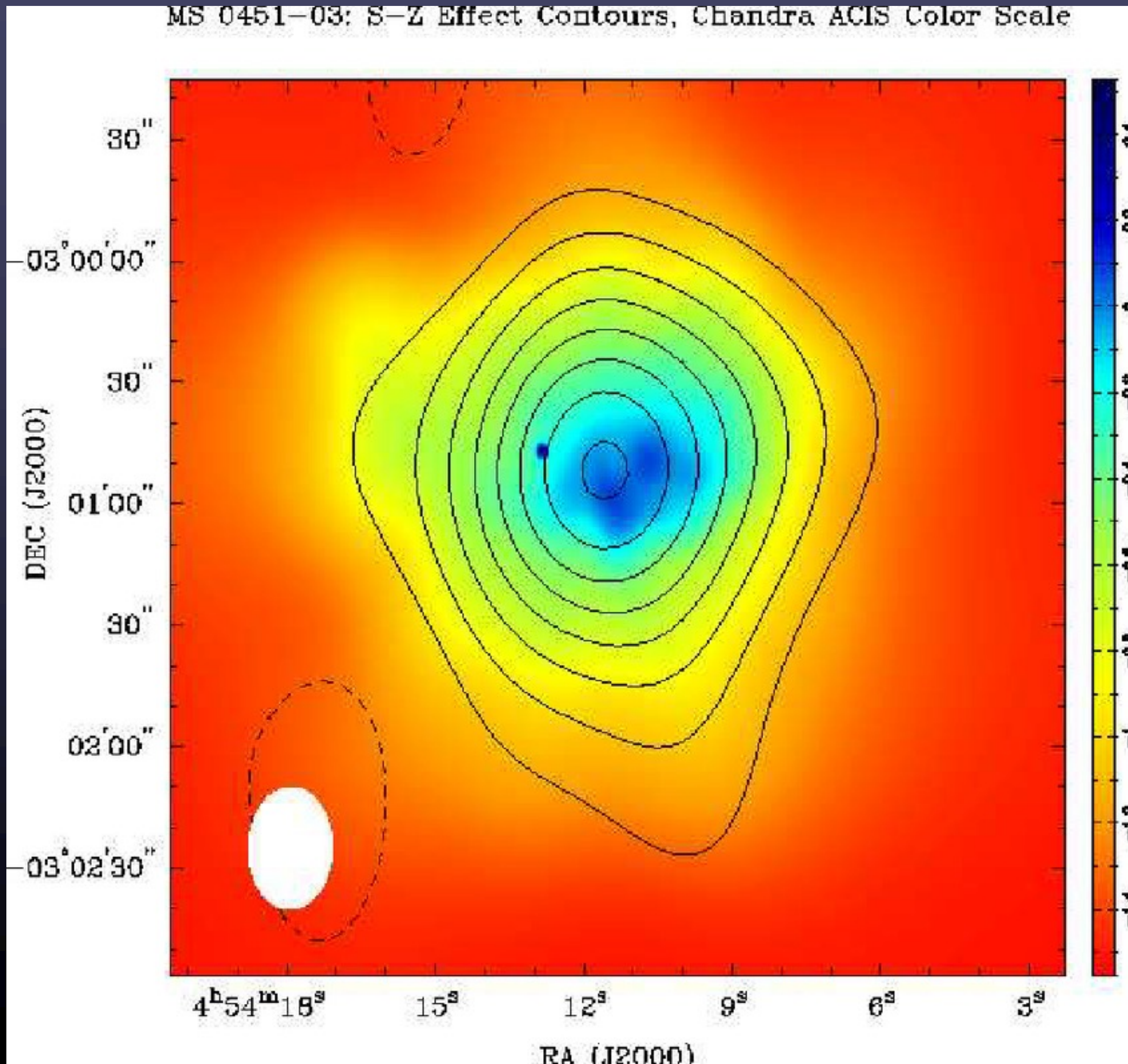


Sunyaev-Zeldovich effect





Sunyaev-Zeldovich Effect



SZ images

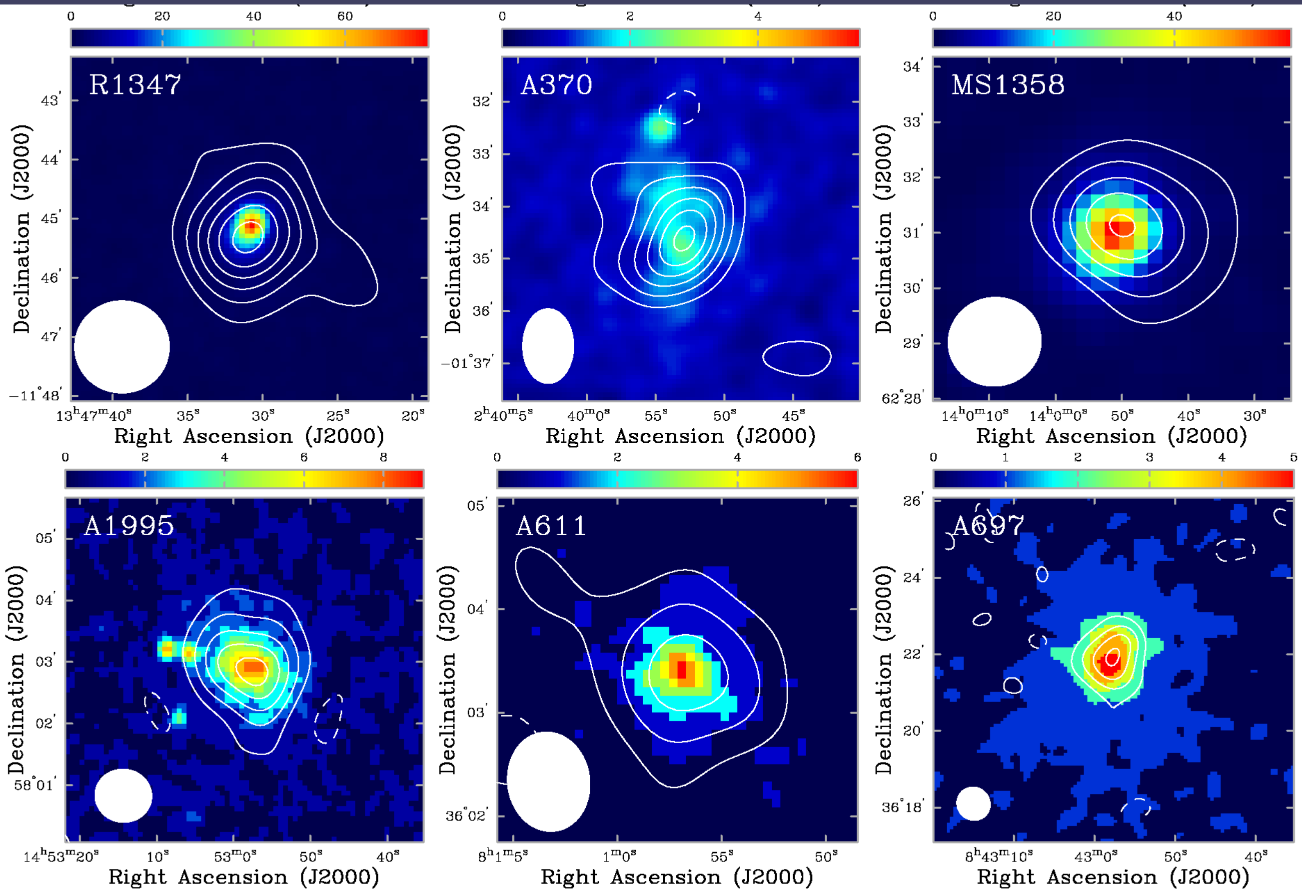


FIG. 2.—SZE (contours) and X-ray (color scale) images of each cluster in our sample. Negative contours are shown as solid lines. The contours are multiples of 2 σ and the FWHM of the synthesized beams are shown in the bottom left corner. The X-ray color scale images are raw counts images smoothed with Gaussians with $\sigma = 15''$ for PSPC data and $\sigma = 5''$ for HRI data. There is a color scale mapping for the counts above each image. The 30 GHz image statistics are summarized in Table 4.

Reese et al. astro-ph/0205350