Radio Astronomy Bremsstrahlung Radiation

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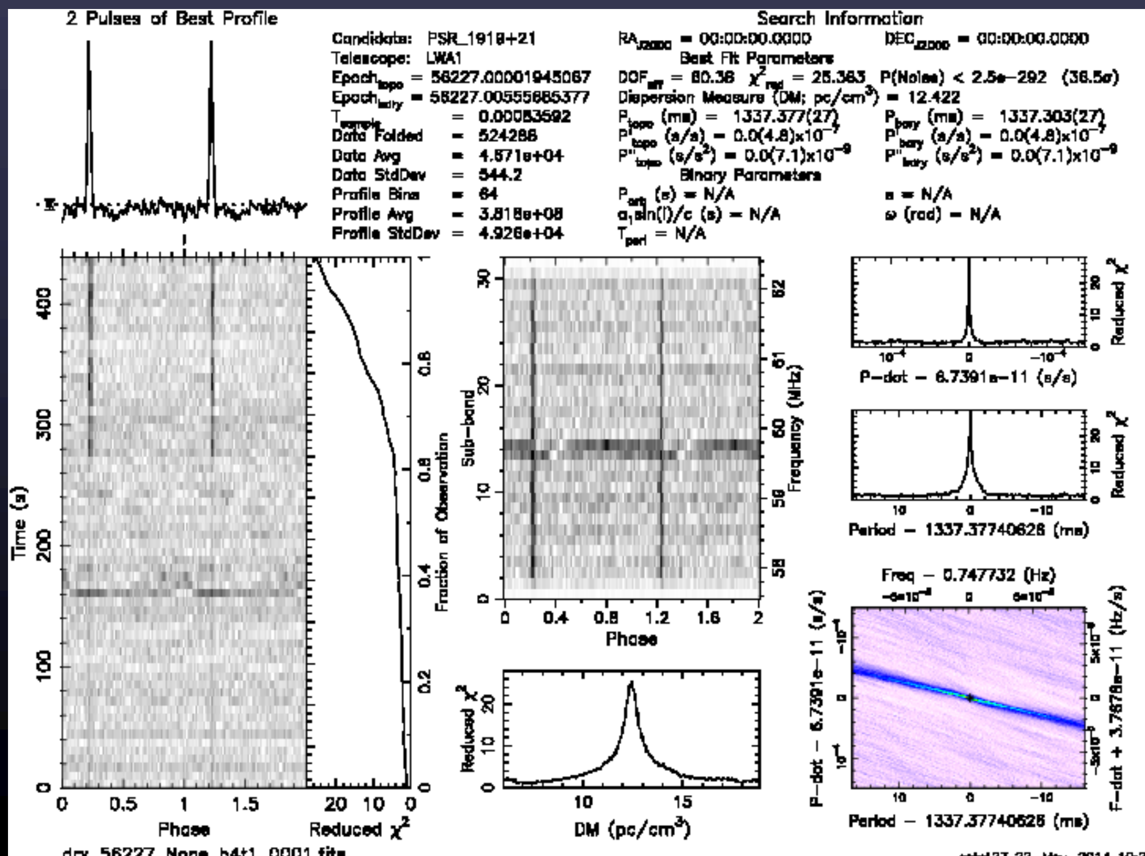
Astronomy 423 at UNM

Radio Astronomy

Announcements

- Show pulsar observing on OPS page
- For HW#9 problem 4 you need to analyze the results of your LWA1 observations and submit the PDF file created by prepfold. See example:



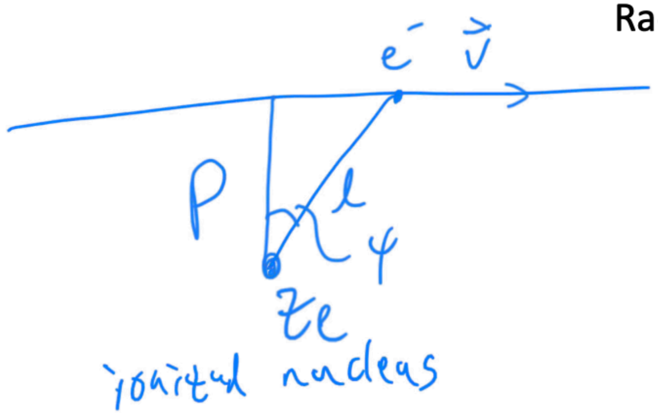
Announcements

- Where’s my data?
- Connect to Hercules with x2go, then
  - ssh –X lwaucf2 (password is the same)
  - cd /data/local/astr423/axxx   (xxx is group/session ID)
  - Data is in /data/network/recent_data/astr423

```
astr423@lwaucf2:/data/local/astr423$ ls /data/network/recent_data/astr423
059274_000047893  059278_000020808  059282_000059084  059316_000138250
059274_000240409  059278_000023487  059282_000067478  COMGT_0422.tgz
059276_000001376  059280_000040138  059316_000133529  COMGT_0423.tgz
059276_000001675  059280_000045300  059316_000134997  COMGT_0424.tgz
```

  - Except for session ID 421 which observes soon

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

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

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

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

Dipole

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

would prefer as integral of ψ

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

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

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

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

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

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

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

total energy radiated by a single e^-

What does spectrum look like?

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

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

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

$$\omega_g = 0.463 \frac{v}{\rho}$$

radiation from a cloud of e^-s

Maxwellian velocity distribution

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

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

N_e in a volume^{-3} with collisions between p and $p+dp$

emissivity $2\pi p\, dp\, v N_e\, f(v)\, dv$

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

$$4\pi \epsilon_\nu = \int_{p_1}^{p_2}\int_0^\infty \frac{8}{3}\frac{Z^2 e^6}{c^3 m^2}\frac{1}{p^2 v^2} N_i N_e f(v)\, 2\pi p v\, dp\, dv$$

$$\boxed{\epsilon_\nu = \frac{8}{3}\frac{Z^2 e^6}{c^3}\frac{N_i N_e}{m^2}\sqrt{\frac{2m}{\pi k T}}\ln\left(\frac{p_2}{p_1}\right)}$$

Gaunt factor

or

$$\epsilon_\nu = 5.44\times10^{-39}\, g_{ff}\,\frac{Z^2 n_e n_i}{T^{1/2}}\, e^{-h\nu/kT}$$ erg cm^{-3} s^{-1} sr^{-1} Hz^{-1}

recall $\dfrac{\epsilon_\nu}{\kappa_\nu} = B_\nu(T)$ Planck Function

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

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

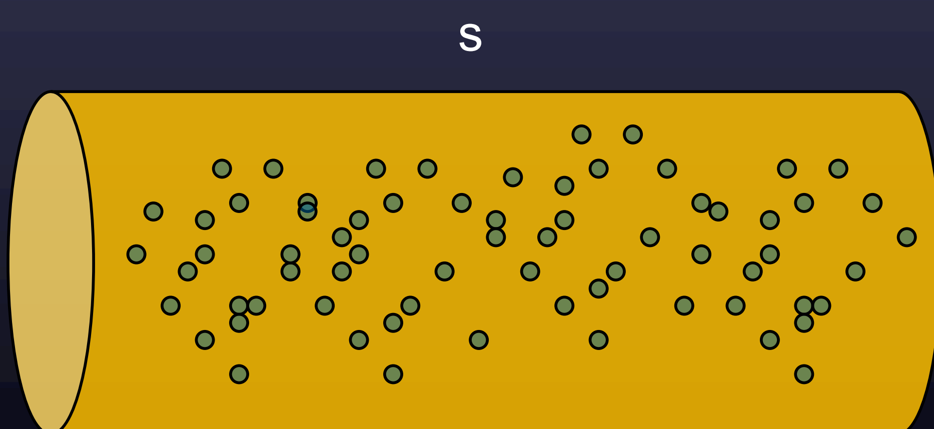
assume $n_i = n_e$ and uniform T

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

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



Emission Measre (EM) is a column density

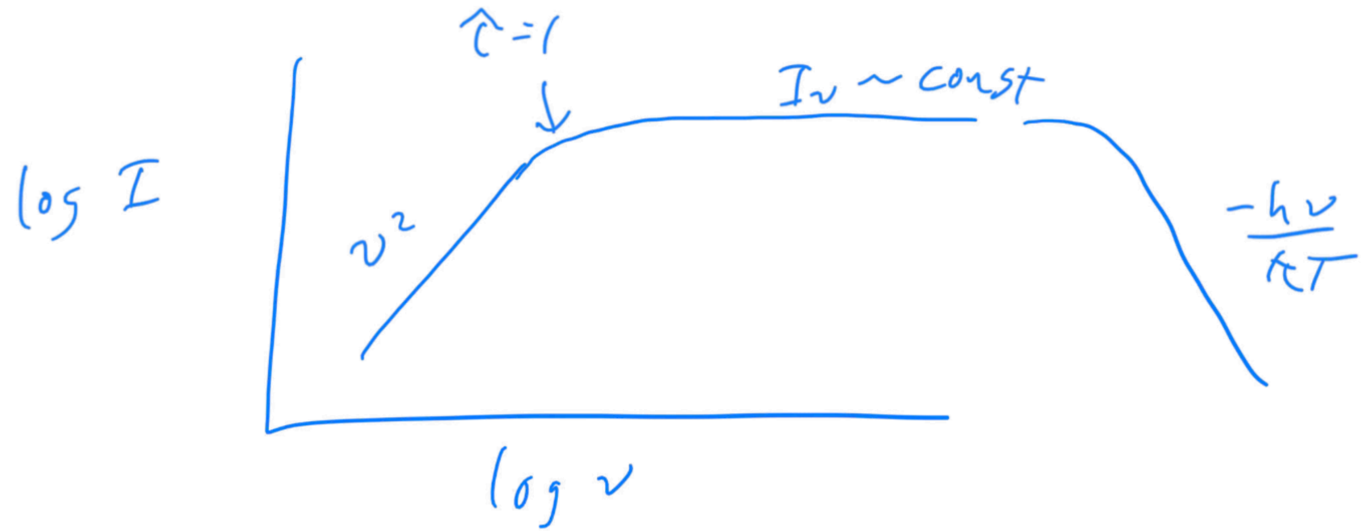
$$\tau_\nu = 3.014 \times 10^{-2} \left(\frac{T}{K}\right)^{-3/2} \left(\frac{\nu}{GHz}\right)^{-2} \left(\frac{EM}{pc\ cm^{-6}}\right) g_{ff}$$

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

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

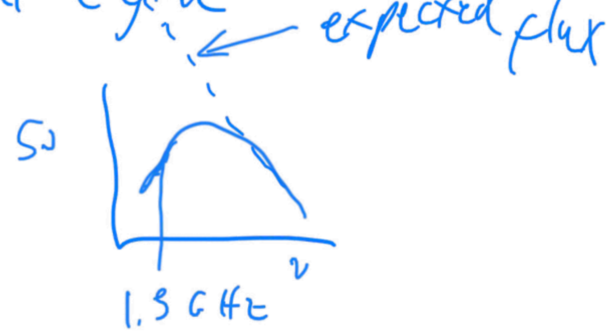
correcting for g_{ff} (slow function of T and ν)

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



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



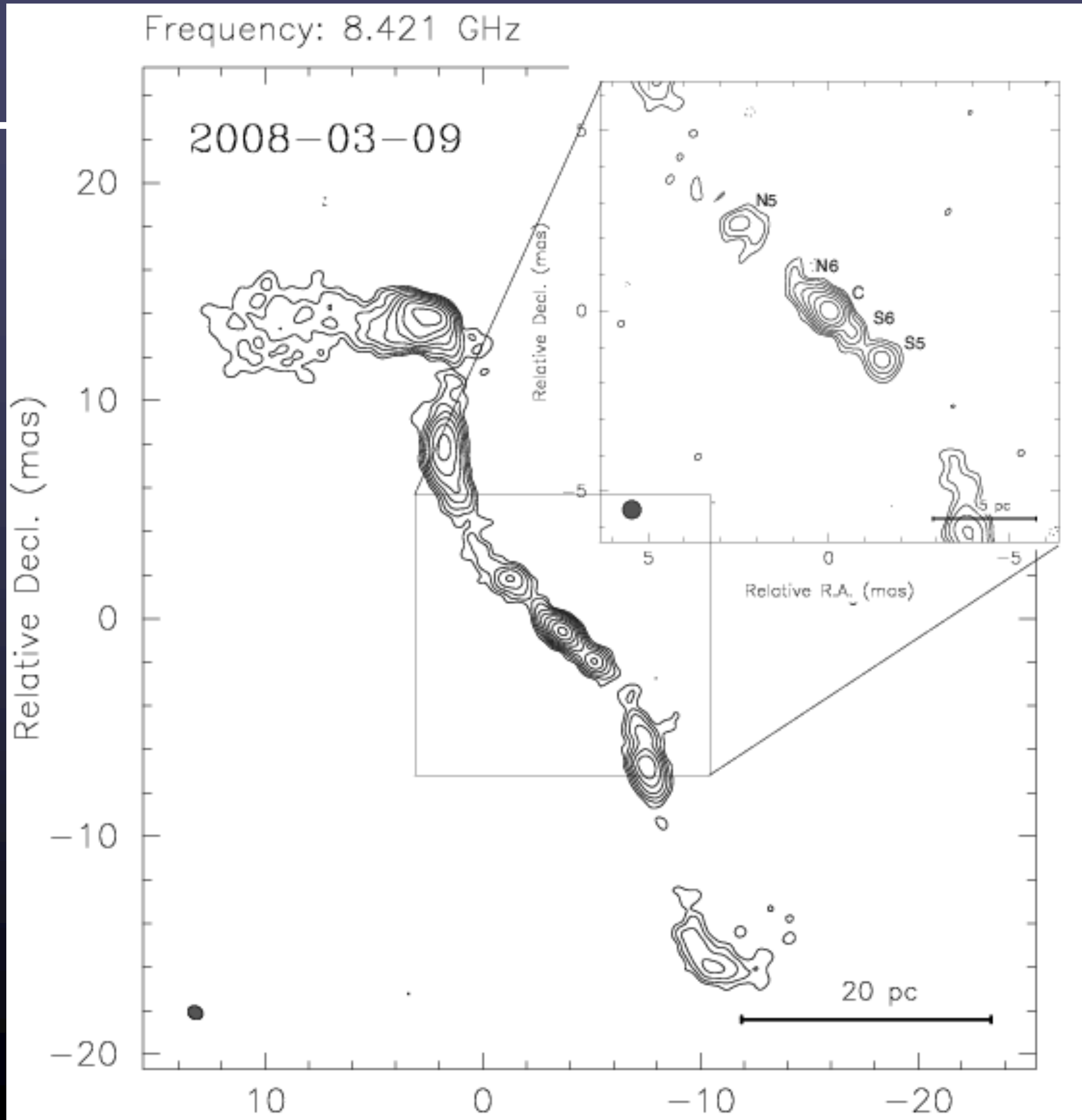
$T \sim 8000$ K path 50 pc

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

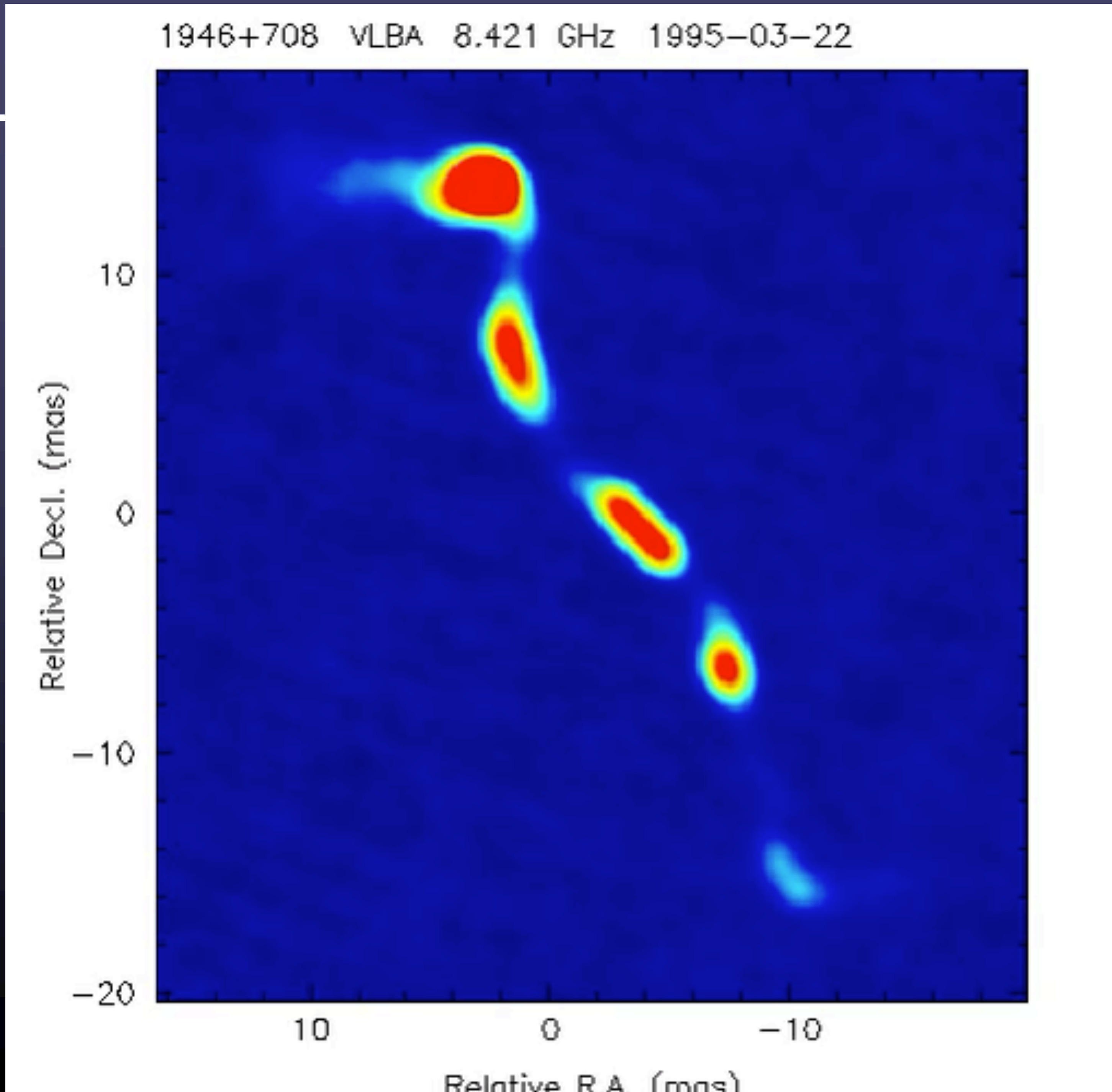
$S_{exp} = 250$ mJy " "

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

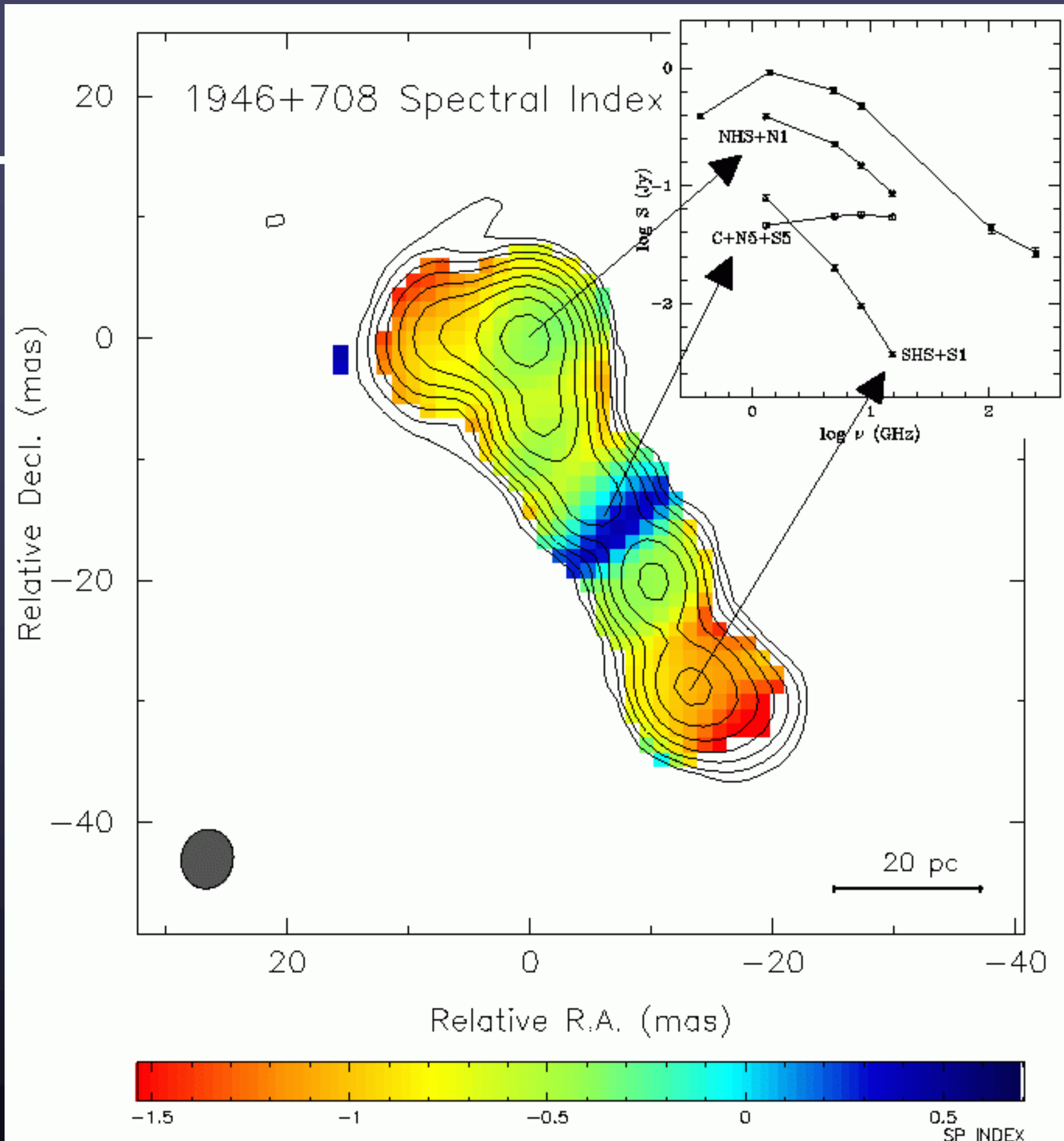
$EM = 1.7 \times 10^8 \text{ pc cm}^{-6} = n_e^2 \cdot 50\text{pc}$ $n_e = 1800 \text{ cm}^{-3}$



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 R.A. (mas)
5
0
−5


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

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

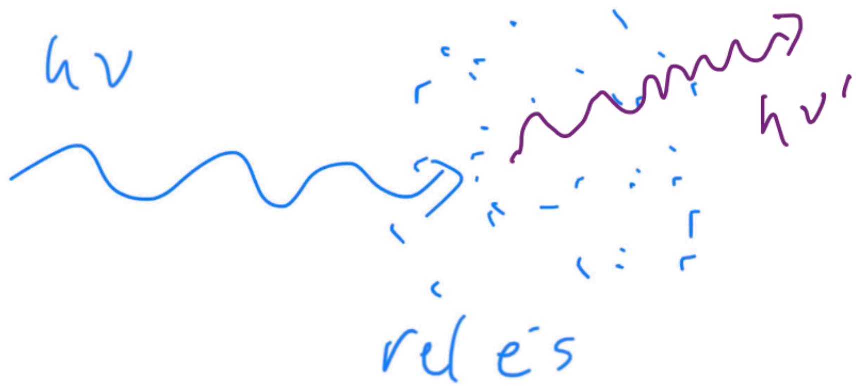
$N_e \sim 8 \times 10^{22}$ cm^{-2}

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

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

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