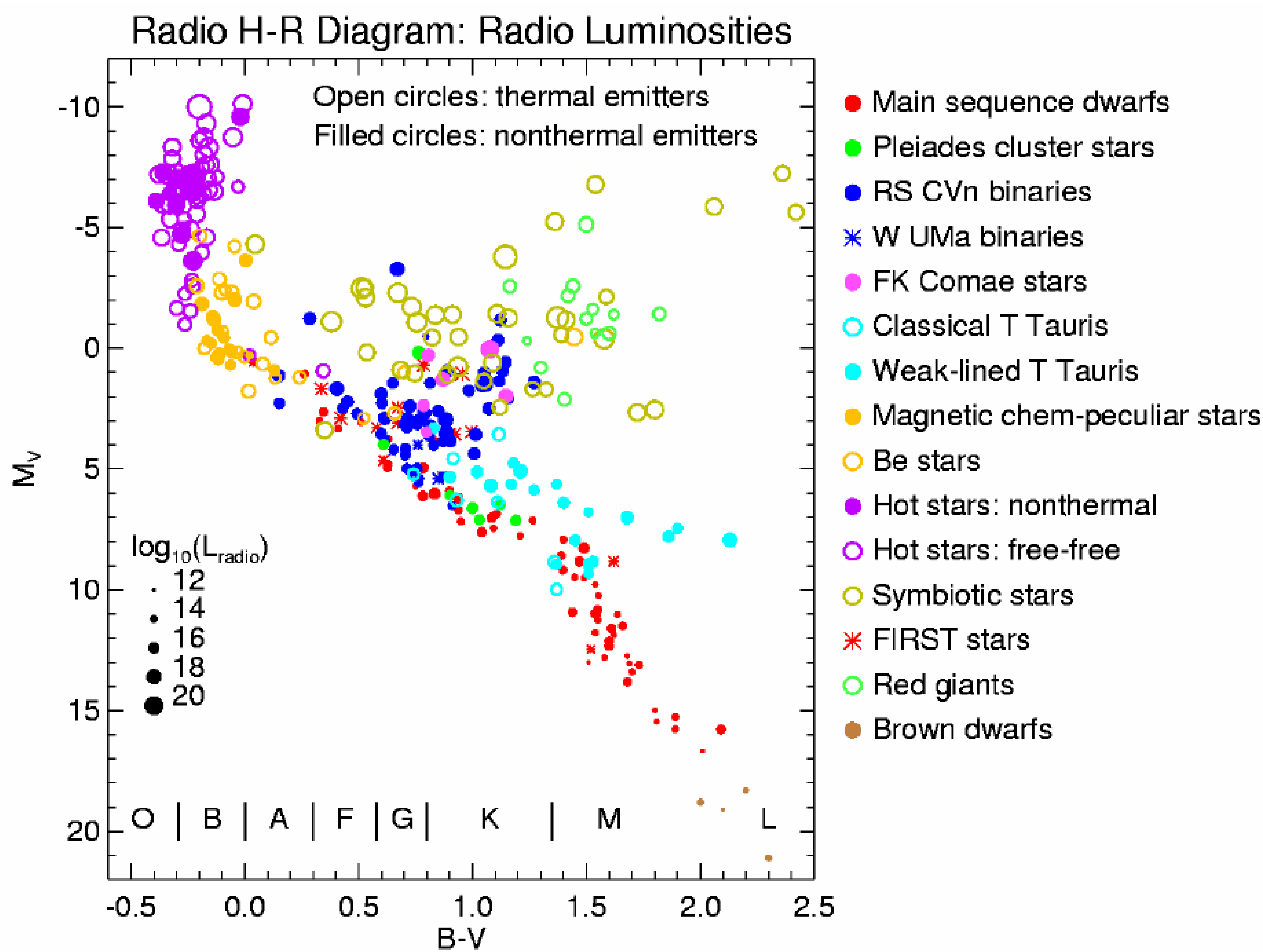
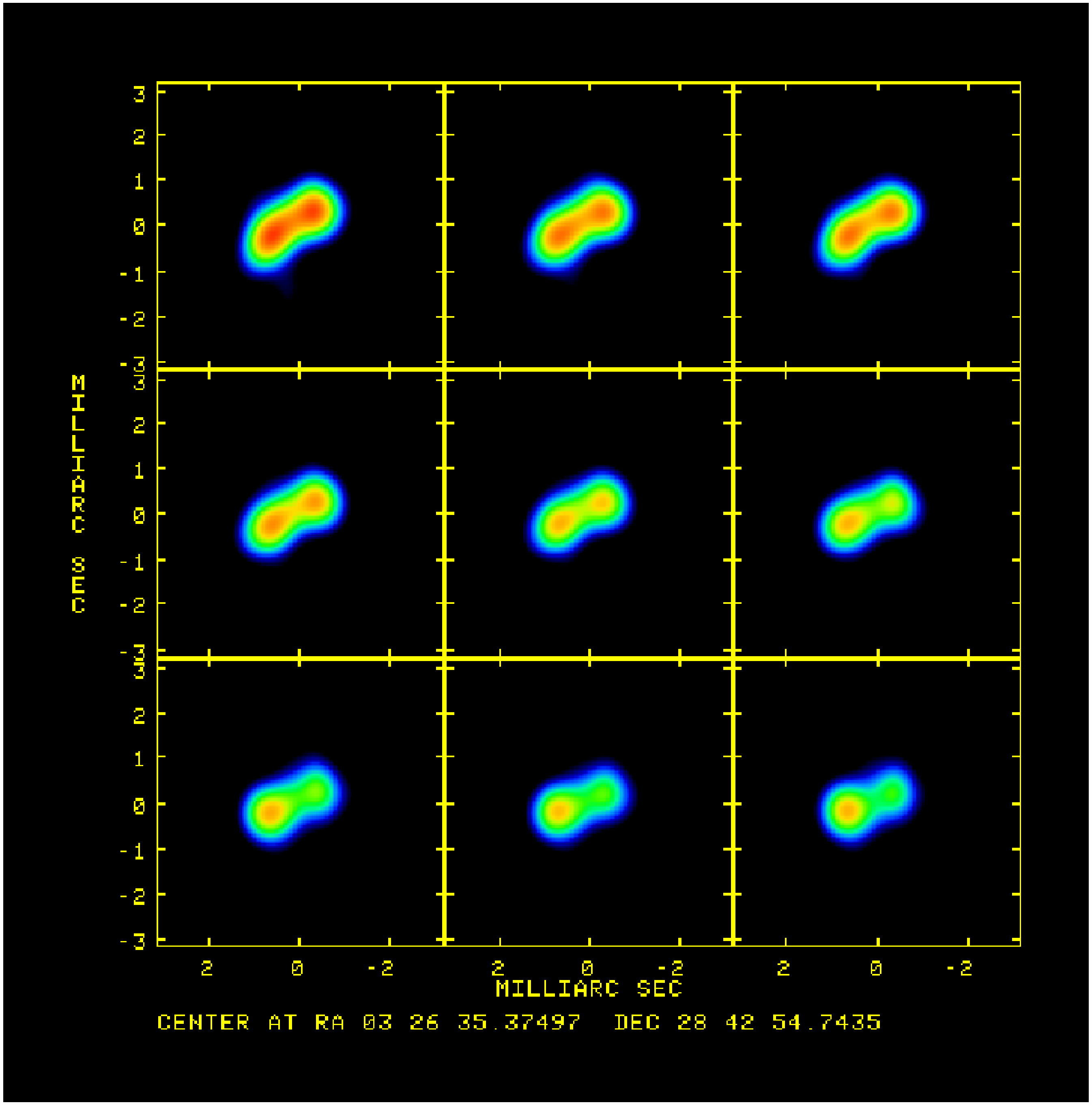
Solar Radio Emission

T. S. Bastian

NRAO



Radio H-R Diagram: Radio Luminosities
Open circles: thermal emitters
Filled circles: nonthermal emitters
Main sequence dwarfs
Pleiades cluster stars
RS CVn binaries
W UMa binaries
FK Comae stars
Classical T Tauris
Weak-lined T Tauris
Magnetic chem-peculiar stars
Be stars
Hot stars: nonthermal
Hot stars: free-free
Symbiotic stars
FIRST stars
Red giants
Brown dwarfs
log10(Lradio)
12
14
16
18
20
O B A F G K M L
-10
-5
0
5
10
15
20
Mv
-0.5 0.0 0.5 1.0 1.5 2.0 2.5
B-V



UX Ari

18 Nov 1995

$10^{35} – 10^{36}$ erg

VLBA

8.4 GHz

Plan

- Preliminaries
- Emission mechanisms
  - Gyro-emission
    - thermal gyroresonance
    - nonthermal gyrosynchrotron
  - Thermal free-free emission
  - Plasma emission
- Solar radio phenomenology

Preliminaries

Not surprisingly, the emission and absorption of EM waves is closely related to the natural frequencies of the material with which they interact.

In the case of a plasma, we encountered three frequencies:

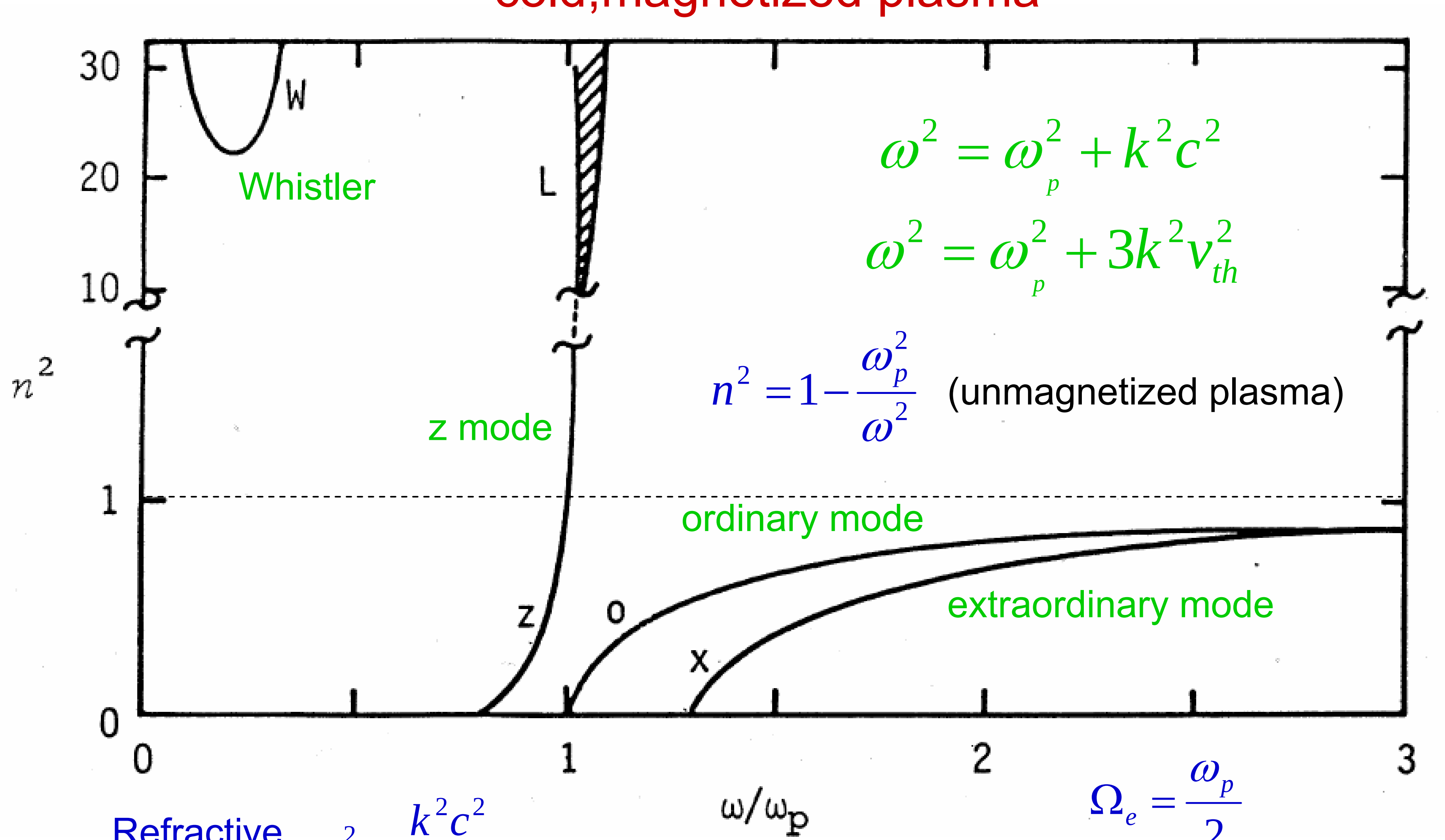
Electron plasma frequency $\nu_{\mathrm{pe}} \approx 9\ n_e^{1/2}$ kHz

Electron gyrofrequency $\nu_{\mathrm{Be}} \approx 2.8\ B$ MHz

Electron collision frequency $\nu_{\mathrm{c}} \ll \nu_{\mathrm{pe}}, \nu_{\mathrm{Be}}$

These correspond to plasma radiation, gyroemission, and "free-free" or bremsstrahlung radiation.

Wave modes supported by a cold,magnetized plasma

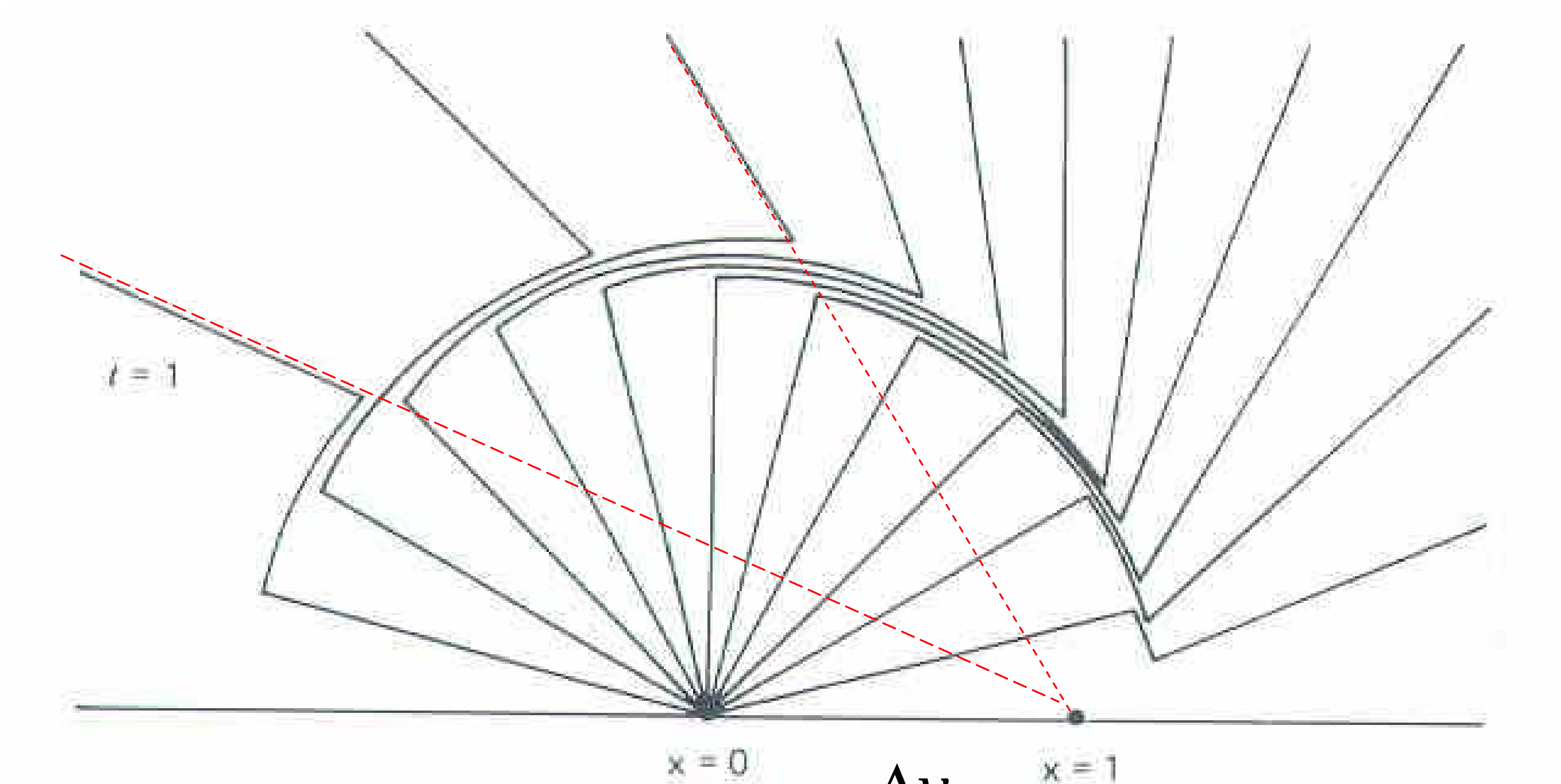


Refractive index $n^2 = \frac{k^2c^2}{\omega^2}$

$\Omega_e = \frac{\omega_p}{2}$

$\theta = 30^o$

Charge with constant speed suddenly brought to a stop in time Δt.



$$\frac{\Delta v}{\Delta t}$$

The radiation power is given by the Poynting Flux (power per unit area: ergs cm^{-2} s^{-1} or watts m^{-2})

$$\mathbf{S} = \frac{c}{4\pi}\mathbf{E}\times\mathbf{H} = \frac{c}{4\pi}E^2$$

Intuitive derivation will be posted with online version of notes.

$$|\mathbf{S}| = \frac{c}{4\pi}\left(\frac{q\dot{v}\sin\theta}{rc^2}\right)^2 = \frac{q^2\dot{v}^2\sin^2\theta}{4\pi c^3 r^2}$$

$$P = \frac{2}{3}\frac{q^2\dot{v}^2}{c^3}$$

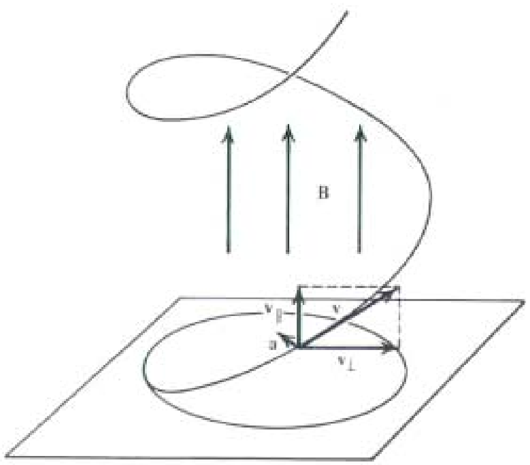
Power emitted into 4π steradians

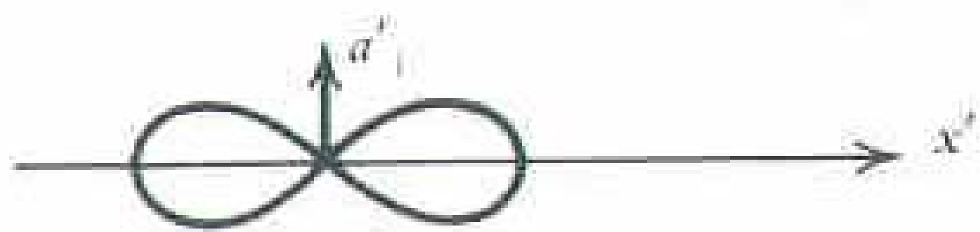
- Proportional to charge squared
- Proportional to acceleration squared
- Dipole radiation pattern along acceleration vector

Gyroemission

Gyroemission is due to the acceleration experienced by an electron as it gyrates in a magnetic field due to the Lorentz force. The acceleration is perpendicular to the instantaneous velocity of the electron.

When the electron velocity is nonrelativisitic (*$v<<c$* or *γ-1<<1*) the radiation pattern is just the dipole pattern.





Since the electron motion perpendicular to the magnetic field is circular, it experiences a constant acceleration perpendicular to its instantaneous velocity:

$$a_\perp = \nu_{Be} V_\perp$$

This can be substituted in to Larmor's Eqn to obtain

$$P = \frac{2e^2}{3c^3} \nu_{Be}^2 V_{perp}^2$$

In fact, this expression must be modified in when the electron speed is relativistic (i.e., near c):

$$P = \frac{2e^2}{3c^3} \gamma^4 \nu_{Be}^2 V_{perp}^2$$

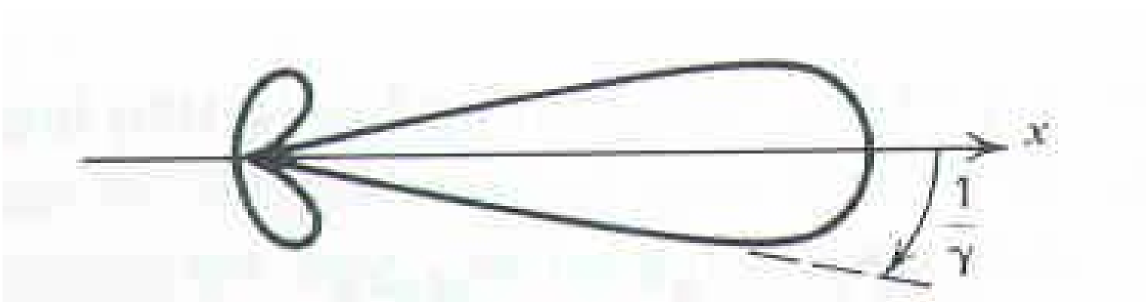
$$\nu_{Be} = \frac{eB}{\gamma\, mc}$$

When the electron is relativistic ($v \sim c$ or $\gamma >> 1$) we have, in the rest frame of the electron

$$\frac{dP'}{d\Omega'} = \frac{q^2 \dot{v}^2}{4\pi c^3} \sin^2 \Theta'$$

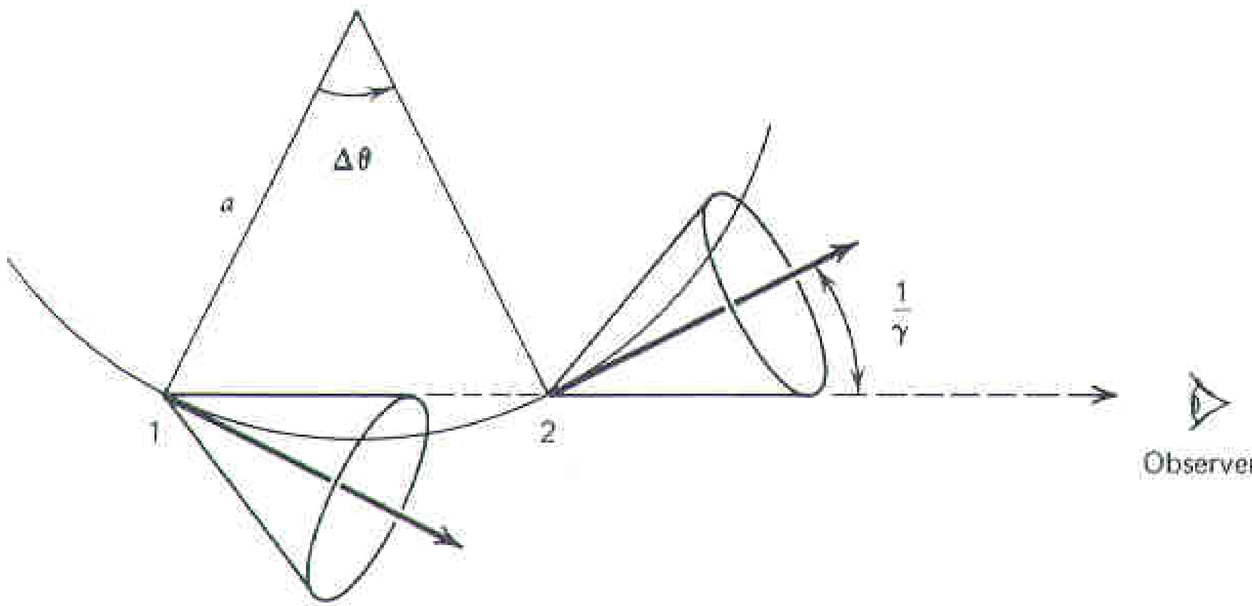
which, when transformed into the frame of the observer

$$\frac{dP}{d\Omega} = \frac{q^2 \dot{v}^2}{4\pi c^3} \frac{1}{(1-\beta\mu)^4} \left[1 - \frac{\sin^2\theta \cos^2\phi}{\gamma^2 (1-\beta\mu)^2} \right]$$

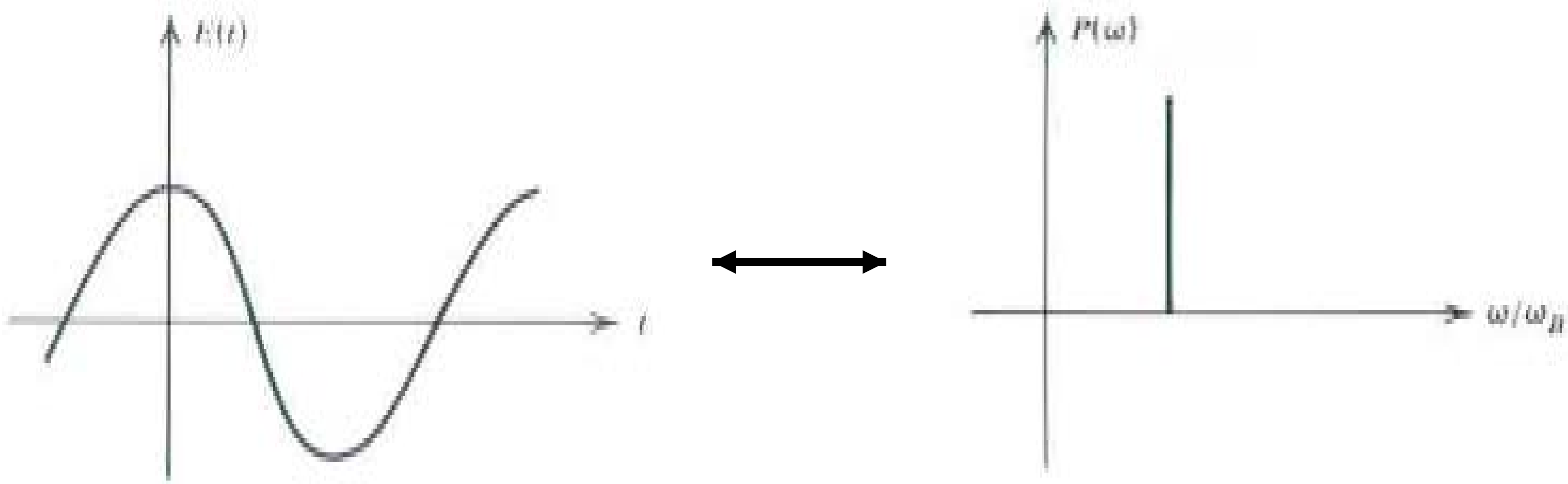


Strongly forward peaked!

What this means is that an observer sees a signal which becomes more and more sharply pulsed as the electron increases its speed (and therefore its energy).

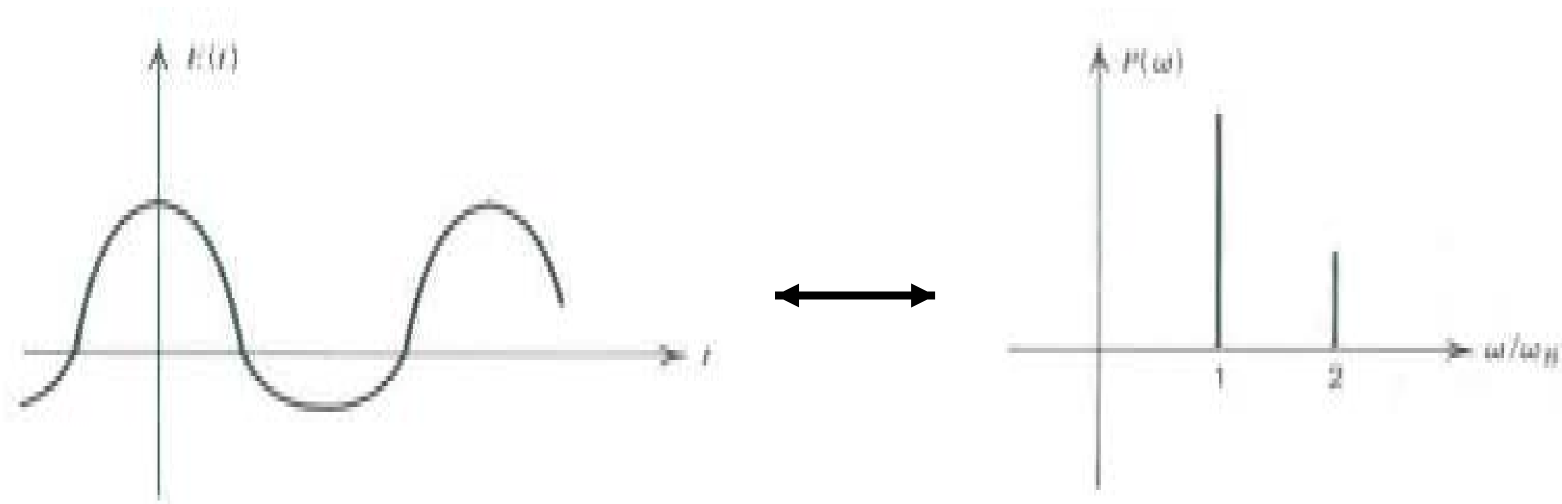


For a nonrelativistic electron, a sinusoidally varying electric field is seen which has a period $2\pi/\Omega_{Be}$,



And the power spectrum yields a single tone (corresponding to the electron gyrofrequency).

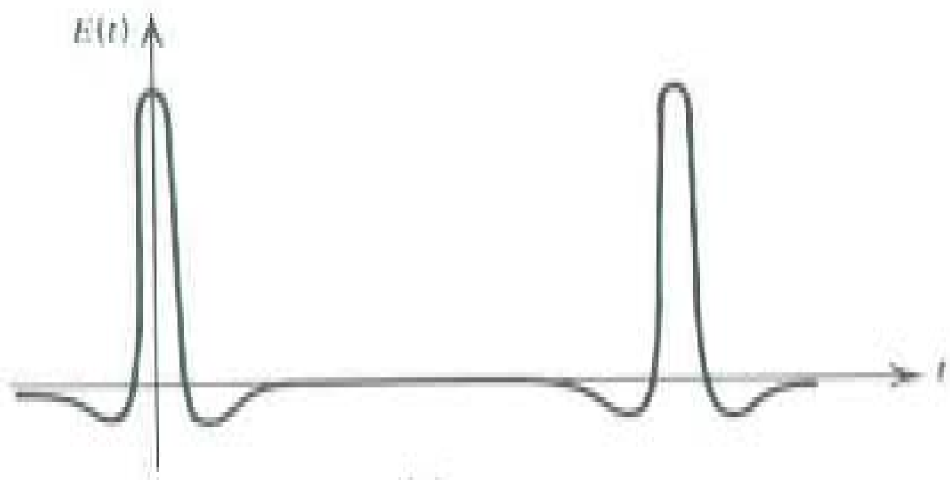
As the electron energy increases, mild beaming begins and the observed variation of the electric field with time becomes non-sinusoidal.

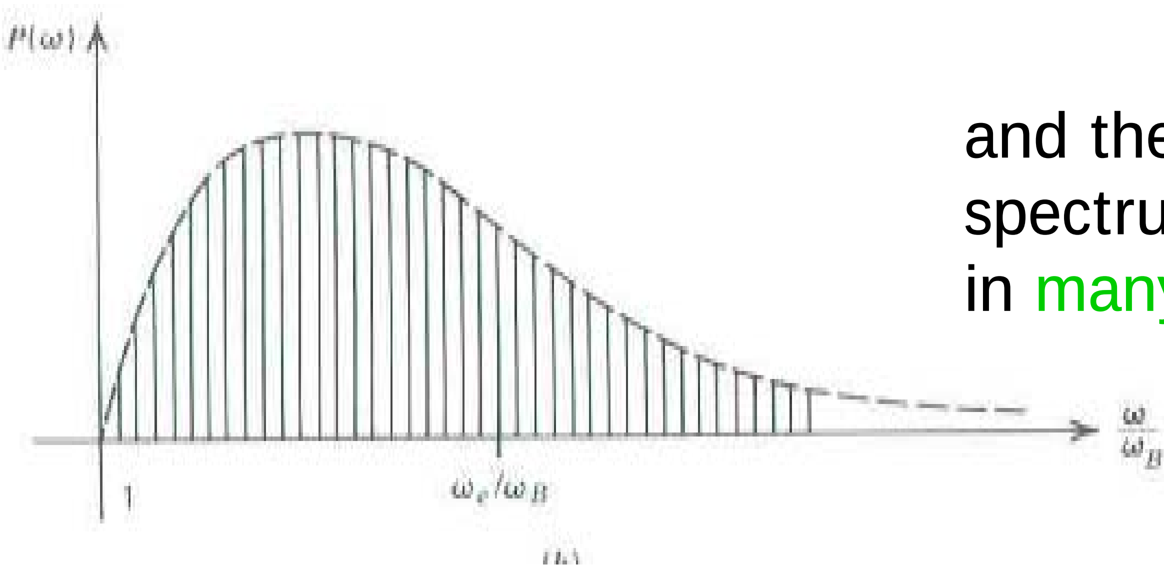


The power spectrum shows power in low harmonics (integer multiples) of the electron gyrofrequency.

Gyroemission at low harmonics of the gyrofrequency is called cyclotron radiation or gyroresonance emission.

When the electron is relativistic the time variation of E is highly non-sinusoidal...





and the power spectrum shows power in many harmonics.

A detailed treatment of the spectral and angular characteristics of electron gyroemission requires a great deal of care.

A precise expression for the emission coefficient that is valid for all electron energies is not available. Instead, expression are derived for various electron energy regimes:

Non-relativistic: γ-1<<1 (thermal)

cyclotron or gyroresonance radiation

Mildly relativisitic: γ-1~1-5 (thermal/non-thermal)

gyrosynchrotron radiation

Ultra-relativisitic: γ-1>>1 (non-thermal)

synchrotron radiation

Synchrotron radiation is encountered in a variety of sources. The electrons involved are generally non-thermal and can often be parameterized in terms of a power law energy distribution:

$$N(E)dE = CE^{-\delta}dE$$

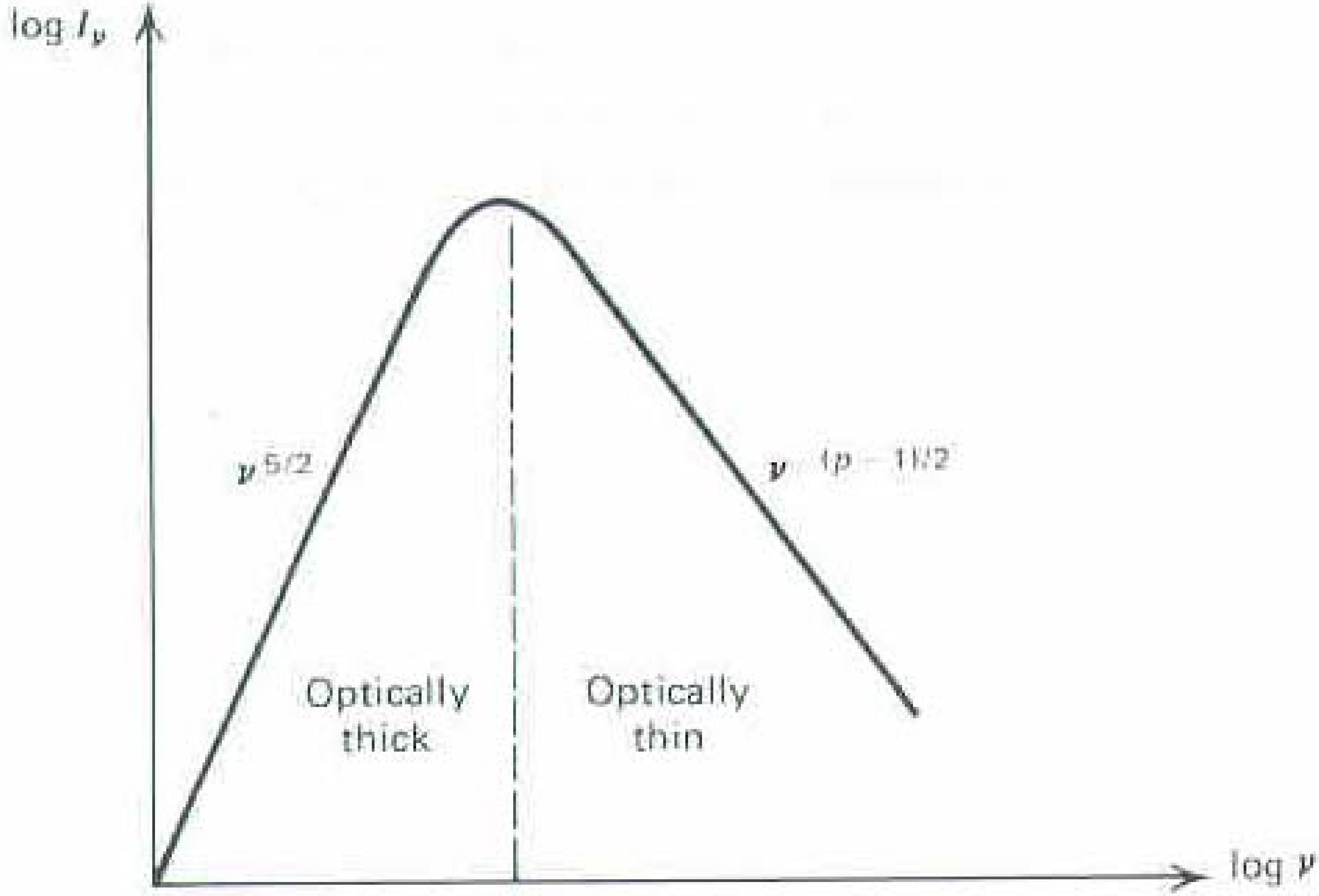
In this case, we have

$$P(\nu) \propto \nu^{-\frac{\delta-1}{2}} \qquad \tau << 1$$

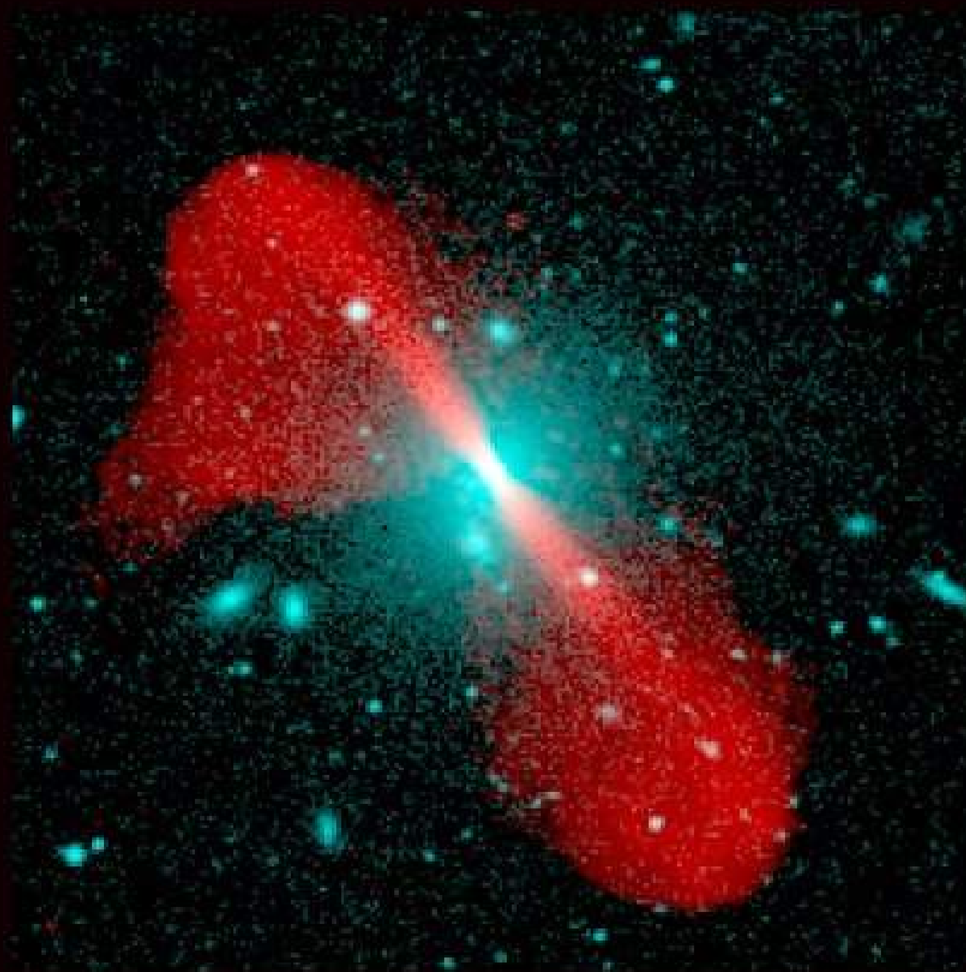
when the source is optically thin and

$$P(\nu) \propto \nu^{5/2} \qquad \tau >> 1$$

when the source is optically thick (or self absorbed).



log I_ν
$\nu^{5/2}$
$\nu^{-(p-1)/2}$
Optically thick
Optically thin
log ν



Radio Galaxy 3C296

Radio/optical superposition

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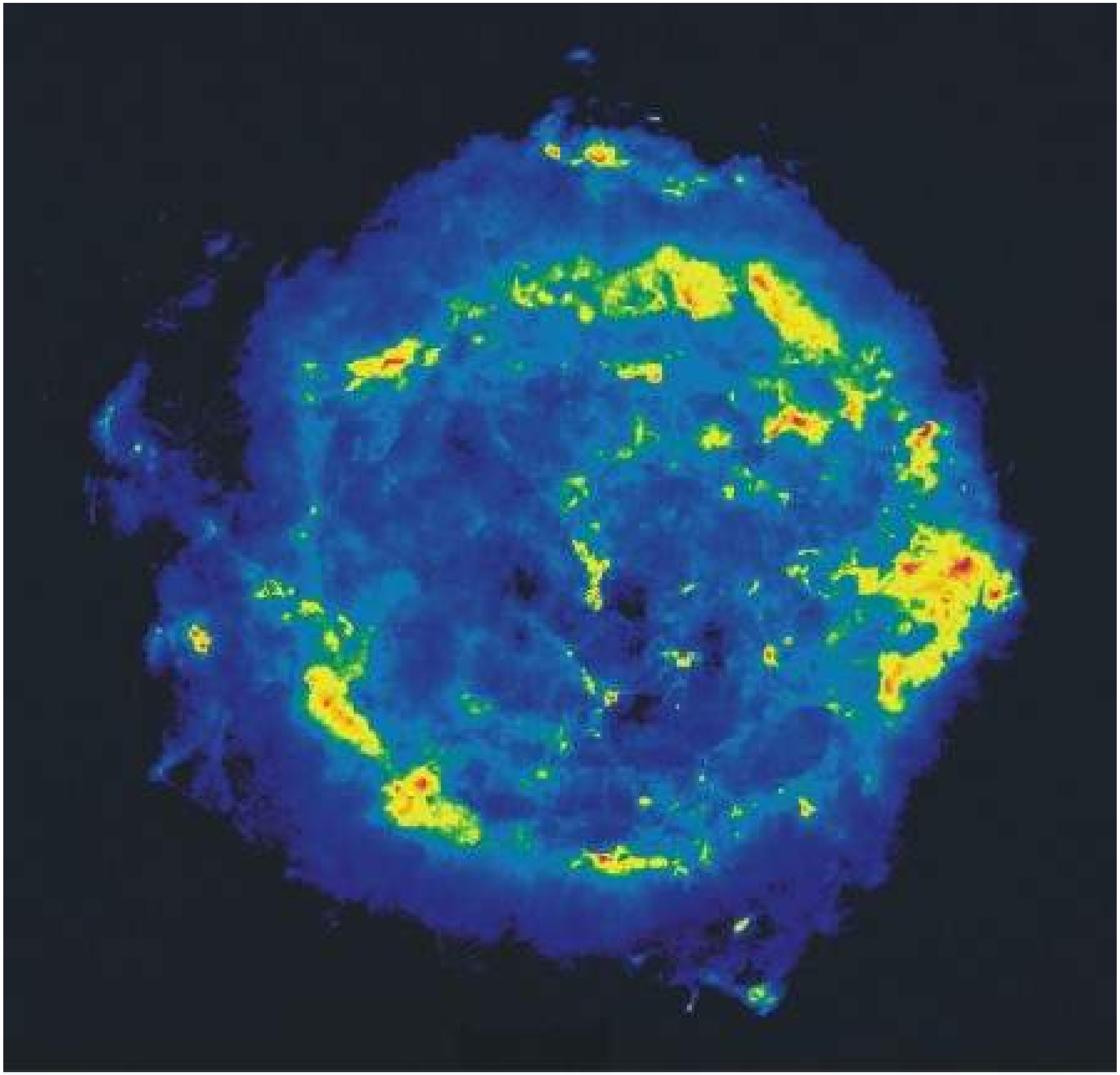


Observers: P.E. Angerhofer, R. Braun, S.F. Gull, R.A. Perley, R.J. Tuffs

Thermal gyroresonance radiation

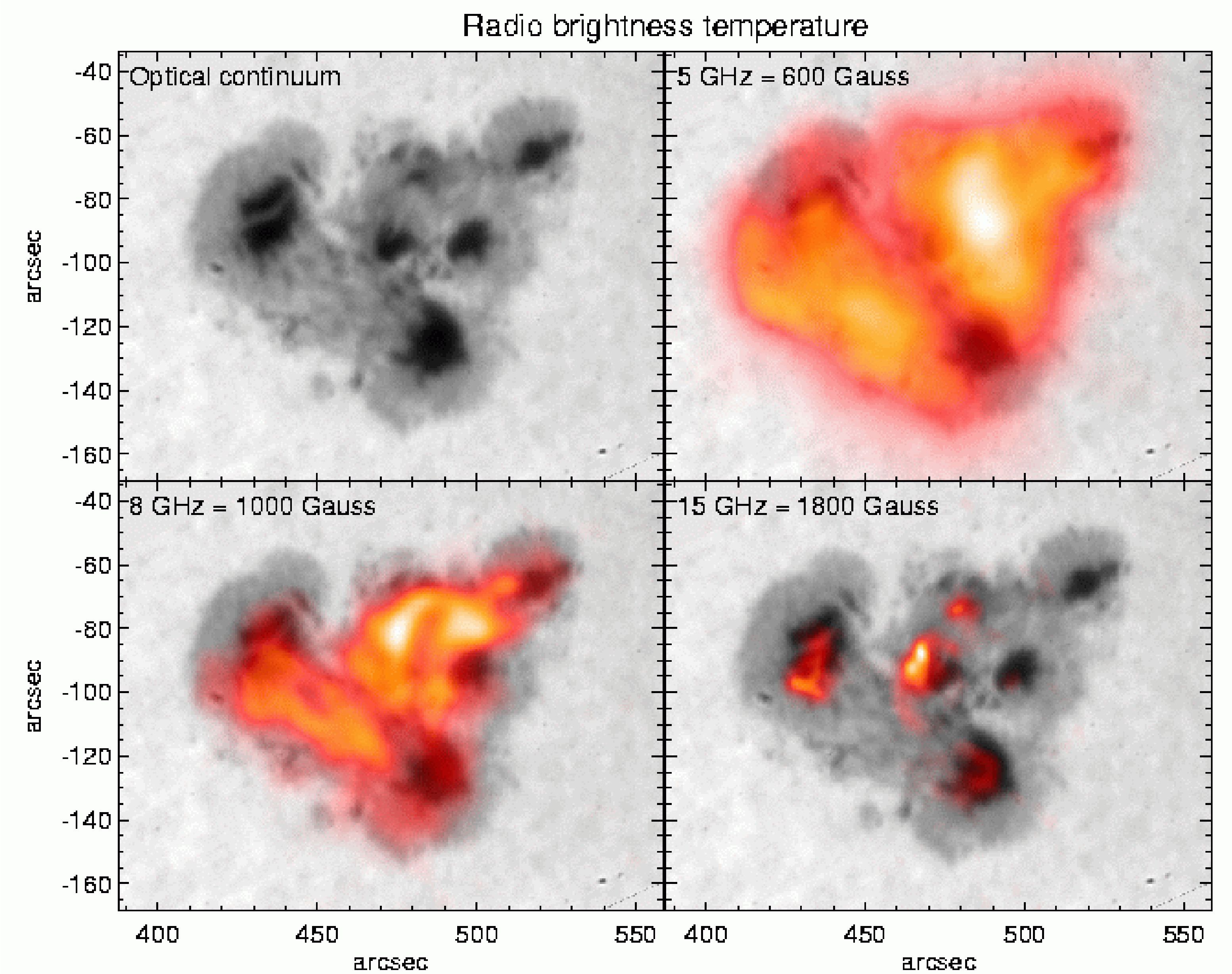
- Harmonics of the gyrofrequency

$$\nu = s\,\nu_B = s\,\frac{eB}{2\pi m_e c} = 2.8\times 10^6\, sB\ \ \mathrm{Hz}$$

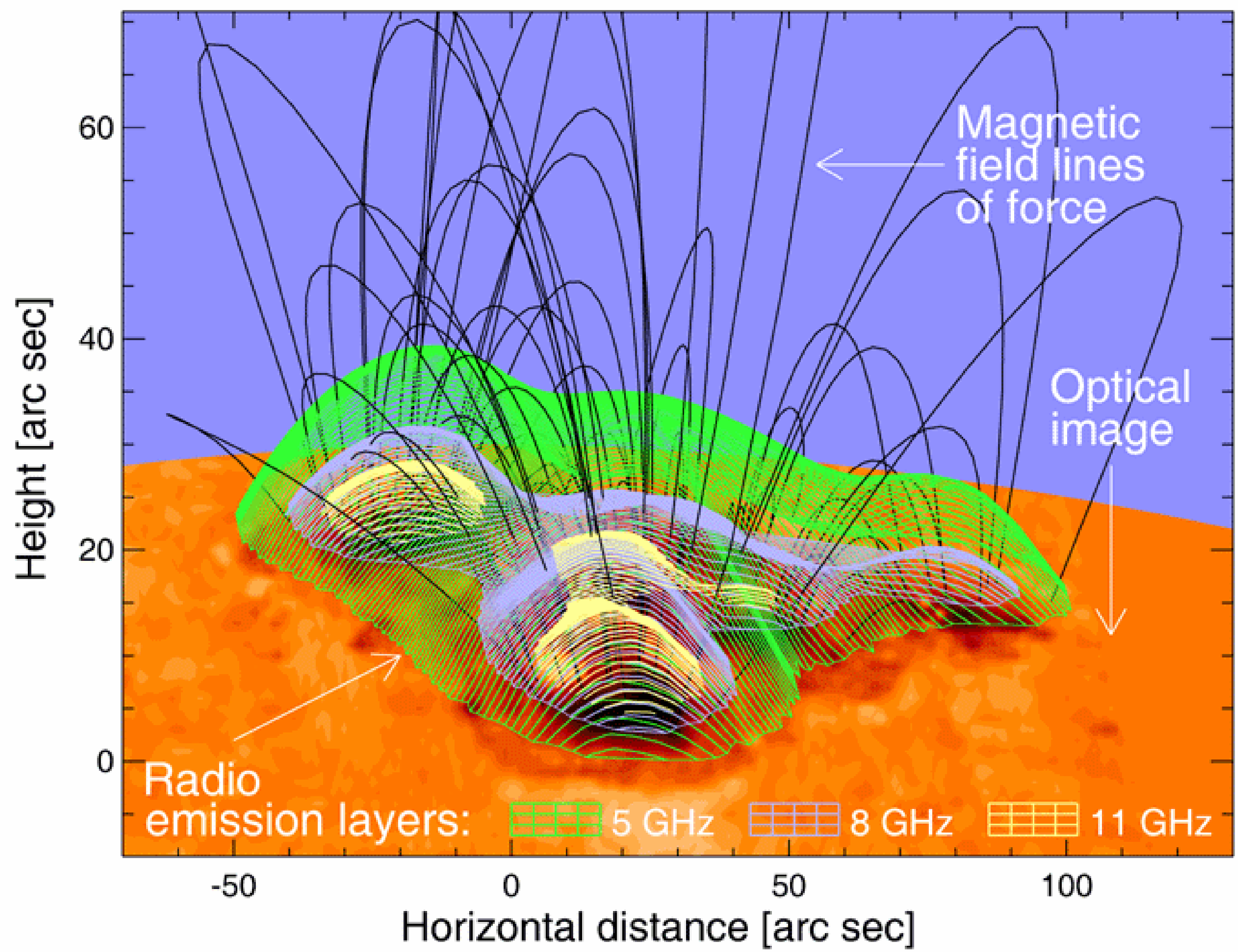
- Two different modes, or circular polarizations (σ=+1 o-mode, σ=-1 x-mode)

$$\alpha_{X,O} = \left(\frac{\pi}{2}\right)^{5/2} \frac{2}{c}\frac{\nu_p^2}{\nu}\frac{s^2}{s!}\left(\frac{s^2\beta_0^2 \sin^2\theta}{2}\right)^{s-1}(1-\sigma\cos\theta)^2$$

- Typically, *s* = 2 (o-mode), *s* = 3 (x-mode)



from Lee et al (1998)

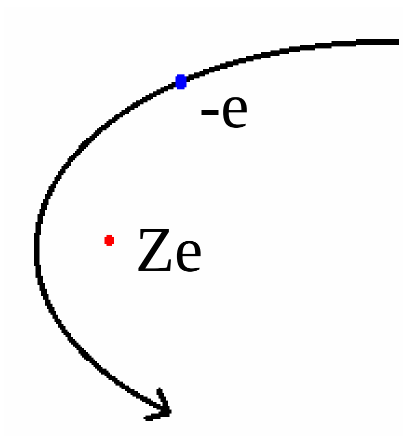


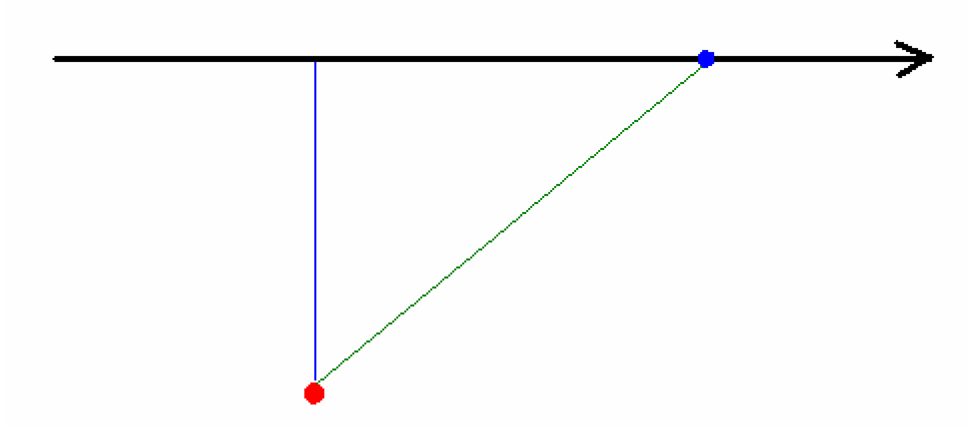
Magnetic field lines of force
Optical image
Radio emission layers:
5 GHz
8 GHz
11 GHz
60
40
20
0
-50
0
50
100
Height [arc sec]
Horizontal distance [arc sec]

Thermal free-free radiation

Now consider an electron's interaction with an ion. The electron is accelerated by the Coulomb field and therefore radiates electromagnetic radiation.

In fact, the electron-ion collision can be approximated by a straight-line trajectory with an impact parameter b. The electron experiences an acceleration that is largely perpendicular to its straight-line trajectory.





For a thermal plasma characterized by temperature T, the absorption coefficient is

$$\alpha_\nu^{ff} = \frac{4\pi e^6}{3mhc}\left(\frac{2\pi}{3km}\right)^{1/2} T^{-1/2} Z^2 n_e n_i \nu^{-3} (1 - e^{-h\nu/kT}) \bar{g}^{ff}$$

In the Rayleigh-Jeans regime this simplifies to

$$\alpha_\nu^{ff} = \frac{4\pi e^6}{3mkc}\left(\frac{2\pi}{3km}\right)^{1/2} T^{-3/2} Z^2 n_e n_i \nu^{-2} \bar{g}^{ff}$$

$$\alpha_\nu^{ff} = 0.018\, T^{-3/2} Z^2 n_e n_i \nu^{-2} \bar{g}^{ff}$$

where g^{ff} is the (velocity averaged) Gaunt factor.

$$\alpha_\nu^{ff} \propto T^{-3/2}\, n_e^2\, \nu^{-2}$$

$$\tau_\nu^{ff} = \alpha_\nu^{ff} L \propto T^{-3/2}\, (n_e^2 \mathrm{L})\, \nu^{-2}$$

The quantity $n_e{}^2L$ is called the column emission measure.

Notice that the optical depth τ^{ff} decreases as the temperature T increases and/or the column emission measure decreases and/or the frequency ν increases.

A brief aside

- Radio astronomers express flux density in units of Janskys

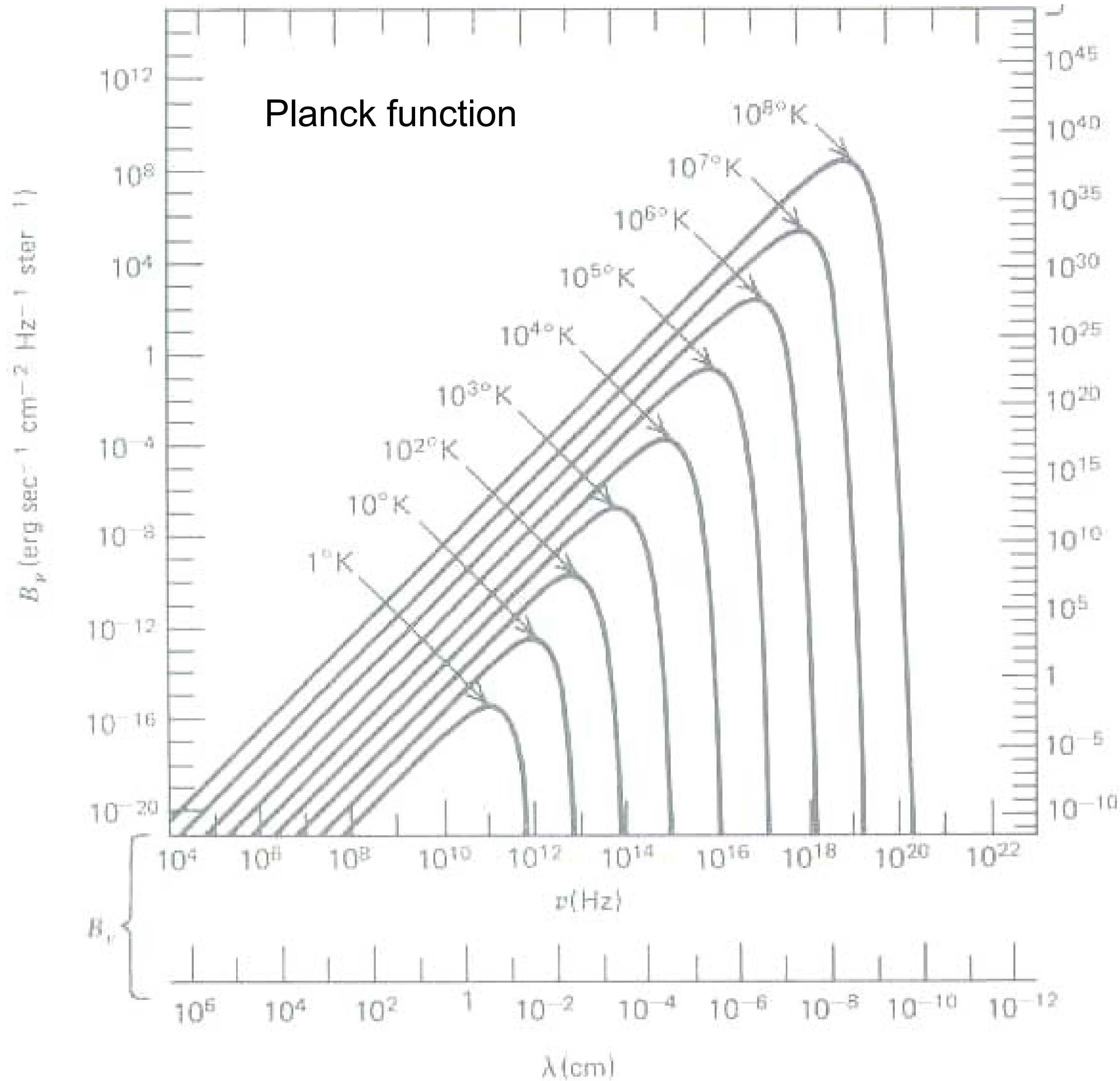
$$1 \text{ Jy} = 10^{-26} \text{ W m}^{-2} \text{ Hz}^{-1}$$

- Solar radio physics tends to employ solar flux units (SFU)

$$1 \text{ SFU} = 10^{4} \text{ Jy}$$

- While specific intensity can be expressed in units of Jy/beam or SFU/beam, a simple and intuitive alternative is brightness temperature, which has units of Kelvin.

Planck function



Note that at radio wavelengths

$$h\nu / kT << 1 \;\rightarrow\; e^{h\nu/kT} - 1 \approx 1 + \frac{h\nu}{kT} - 1 = \frac{h\nu}{kT}$$

The Planckian then simplifies to the Rayleigh-Jeans Law.

$$B_\nu(T) = \frac{2h\nu^3}{c^2}\frac{1}{e^{h\nu/kT} - 1} \approx \frac{2\nu^2}{c^2}kT$$

It is useful to now introduce the concept of brightness temperature T_B, which is defined by

$$I_\nu = B_\nu(T_B) = \frac{2\nu^2}{c^2}kT_B$$

Similarly, we can define an effective temperature T_{eff}:

$$S_\nu = \frac{j_\nu}{\alpha_\nu} = \frac{2\nu^2}{c^2} kT_{eff}$$

The radiative transfer equation is written

$$\frac{dI_\nu}{ds} = -\alpha_\nu I_\nu + j_\nu$$

which describes the change in specific intensity I_ν along a ray. Emission and absorption are embodied in α_ν and j_ν, respectively. The optical depth is defined through $d\tau_\nu = \alpha_\nu ds$ and the RTE can be written

$$\frac{dI_\nu}{d\tau_\nu} = -I_\nu + S_\nu$$

Using our definitions of brightness temperature and effective temperature, the RTE can be recast as

$$\frac{dT_B}{d\tau_\nu} = -T_B + T_{eff}$$

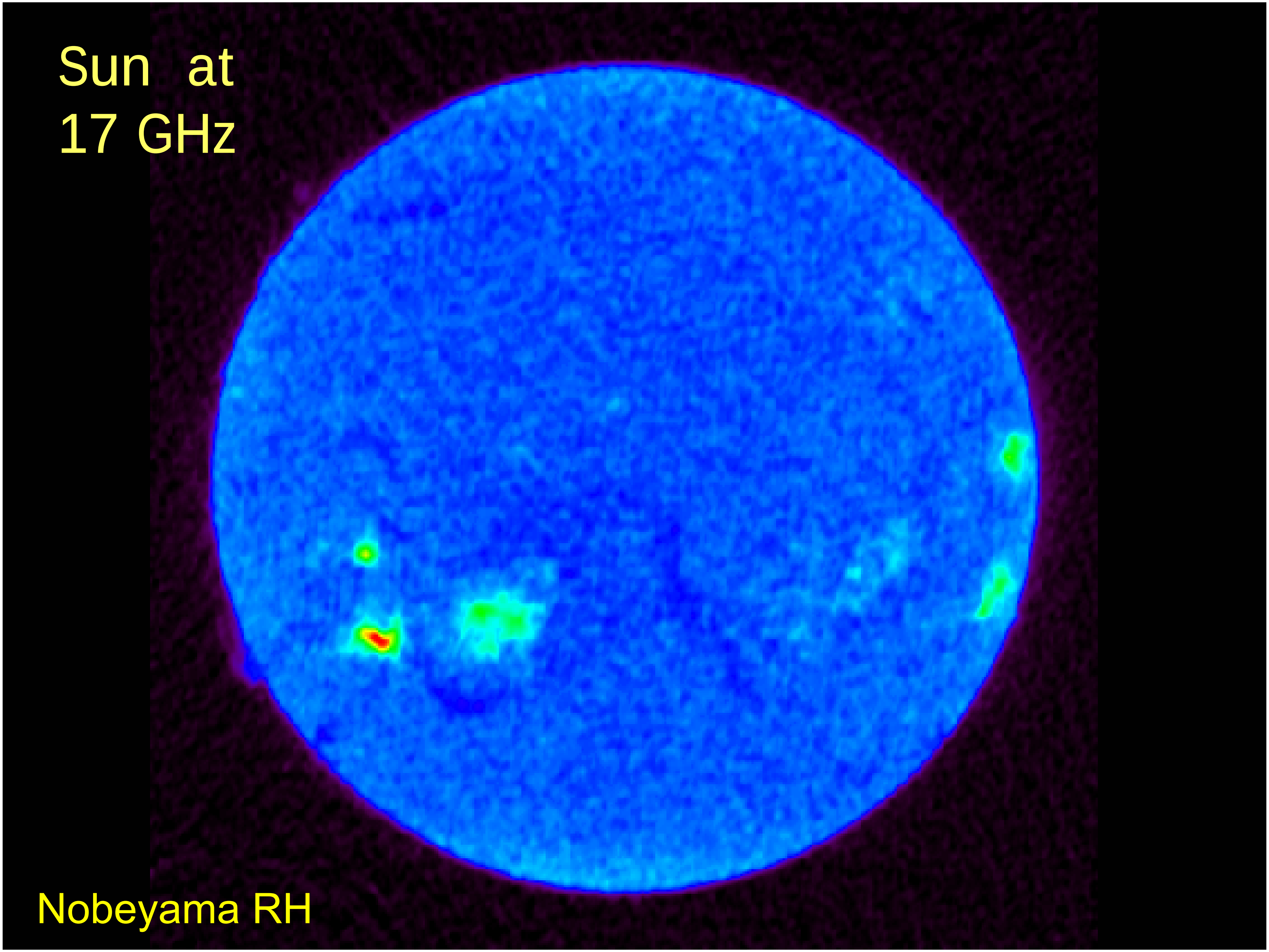
For a homogeneous source it has the solution

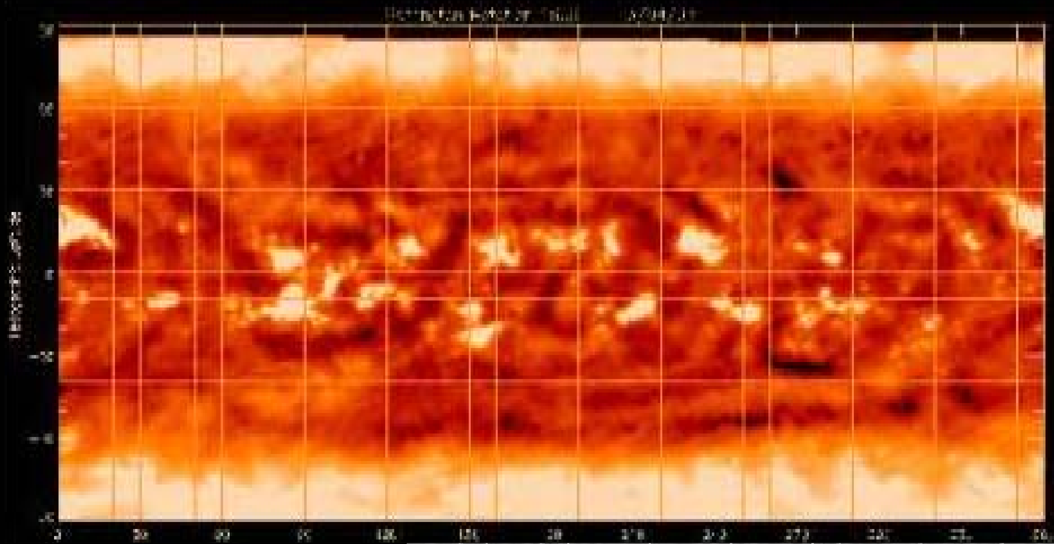
$$T_B = T_{eff}(1 - e^{-\tau_\nu})$$

$$T_B = T_{eff} = T \qquad \tau_\nu >> 1$$

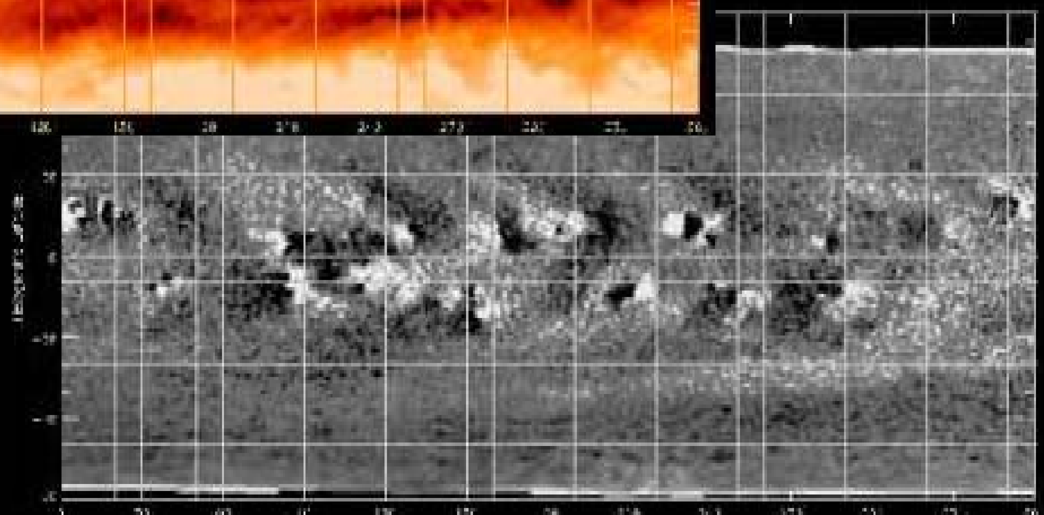
$$T_B = T\tau_\nu^{ff} \propto T^{-1/2}\nu^{-2}n_e^2 L \qquad \tau_\nu << 1$$

Brightness temperature is a simple and intuitive expression of specific intensity.

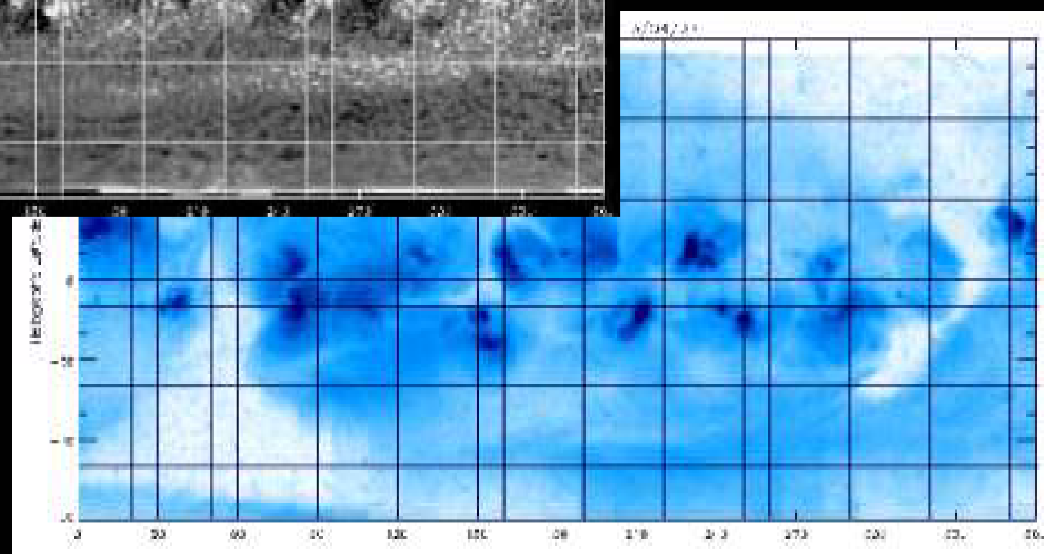

Sun at
17 GHz
Nobeyama RH



17 GHz



B gram



SXR

- A magnetic field renders a plasma "birefringent"

- The absorption coefficient for the two magnetoionic modes, x and o, is

$$\alpha_{x,o} = \left(\frac{2}{\pi}\right)^{1/2} \frac{1}{3c} \frac{\nu_p^2}{(\nu + \sigma\nu_B \cos\theta)^2} \frac{4\pi e^4 \sum_i Z_i^{\,2} n_i}{m^{1/2}(kT)^{3/2}} \Lambda$$

- The x-mode has higher opacity, so becomes optically thick slightly higher in the chromosphere, while o-mode is optically thick slightly lower

- Degree of circular polarization $\rho_c = \dfrac{T_R - T_L}{T_R + T_L}$

Free-Free Opacity

$$\rho_C = \beta \frac{\nu_B}{\nu} \cos\theta \propto B_l$$

$$\beta = \frac{d \ln T}{d \ln \nu}$$

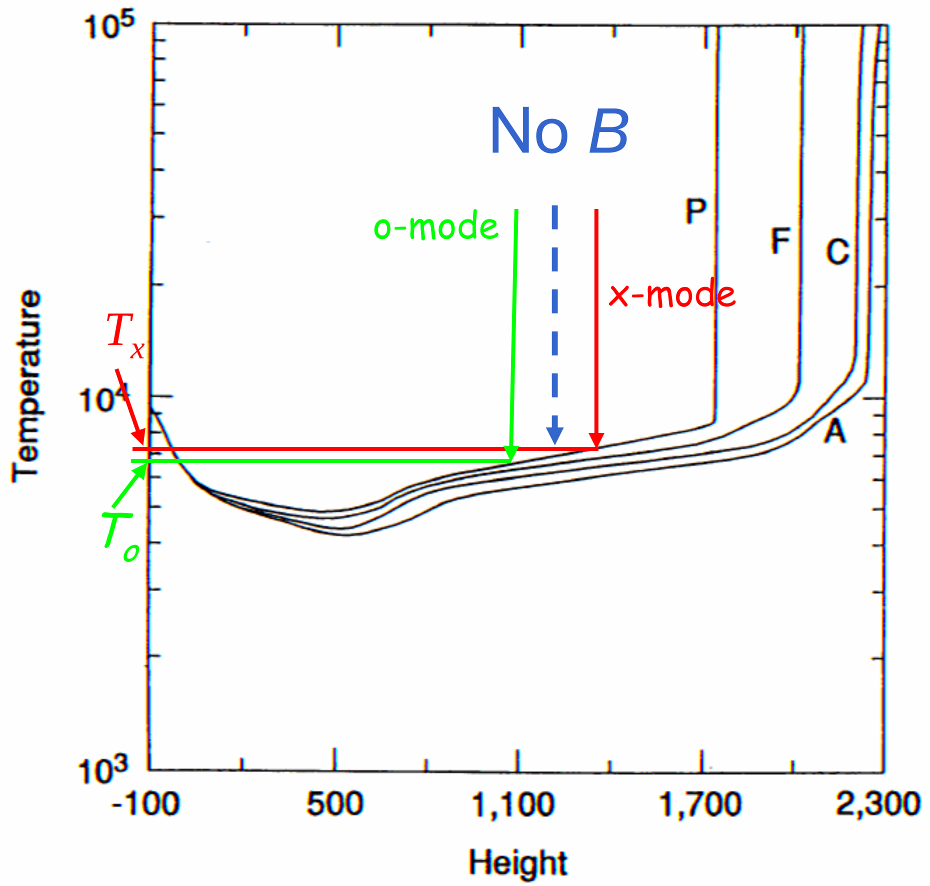


FIG. 3.—Temperature structure of our models A, C, F, and P. The height is measured in kilometers from the level; the temperature is in kelvins.

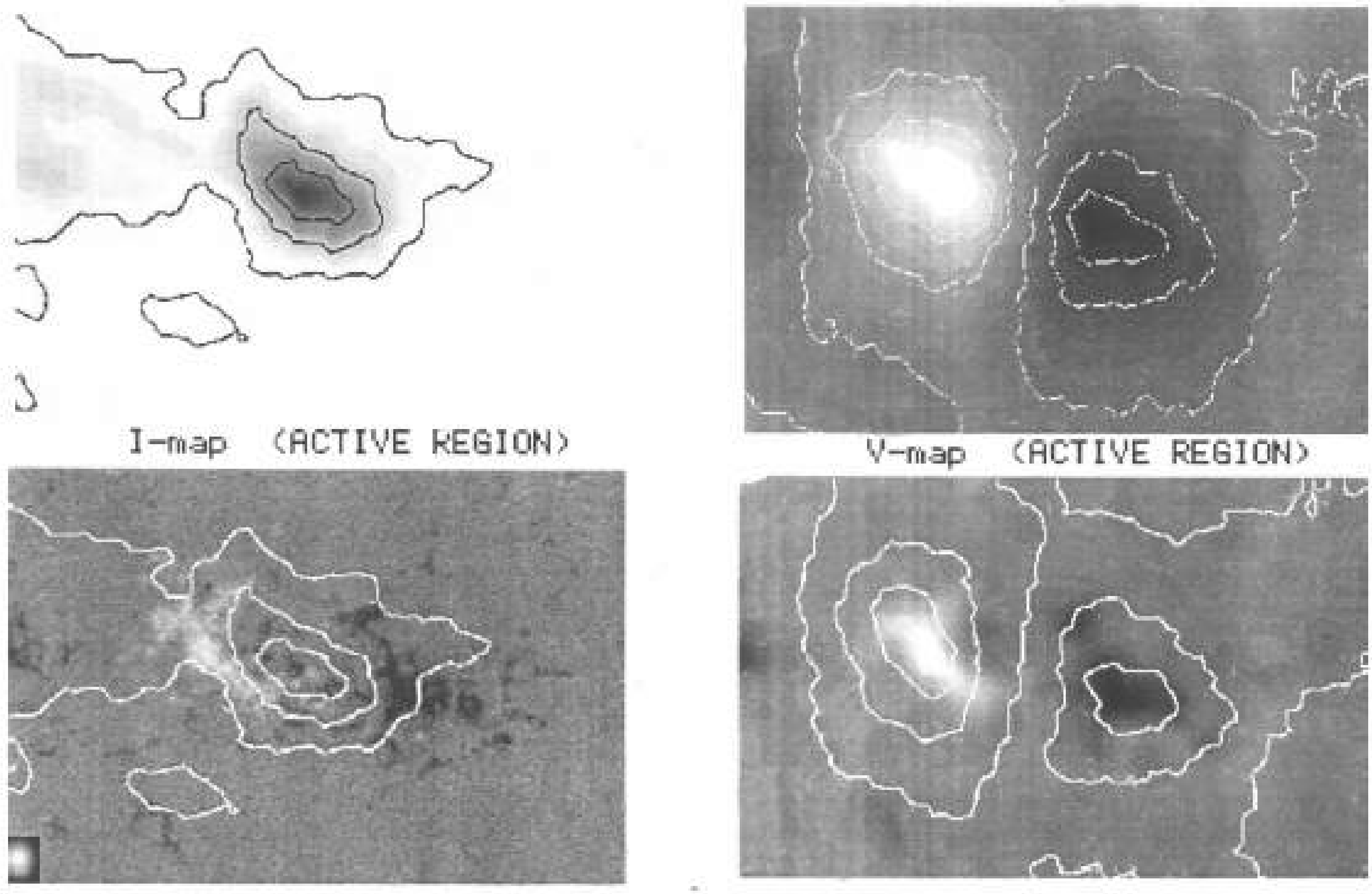


Figure 5.1. Radio maps of the AR observed on June 09, 1995 using Nobeyama radio heliograph at $\lambda = 1.76cm$. Contours present the brightness distribution . Maximum in I channel ($T_b = 27 \cdot 10^3 K$). Maximum in V-channel $T_b^V = 440K$. Maximum degree of polarization $P = 2.8\%$. The region maps are overlapped by gray scale magnetograms . For V-maps they are averaged by the scale of the Nobeyama radio heliograph beam (shown below on the left). The upper V-map present brightness T_b^V, the lower one - percentage $P\%$ of polarization.

Gelfriekh 2004

Plasma radiation

Plasma oscillations (Langmuir waves) are a natural mode of a plasma and can be excited by a variety of mechanisms.

In the Sun's corona, the propagation of electron beams and/or shocks can excite plasma waves.

These are converted from longitudinal oscillations to transverse oscillation through nonlinear wave-wave interactions.

The resulting transverse waves have frequencies near the fundamental or harmonic of the local electron plasma frequency: i.e., ν_{pe} or $2\nu_{pe}$.

Plasma radiation

Plasma radiation is therefore thought to involve several steps:

Fundamental plasma radiation

• A process must occur that is unstable to the production of Langmuir waves

• These must then scatter off of thermal ions or, more likely, low-frequency waves (e.g., ion-acoustic waves)

$$\omega_L + \omega_S = \omega_T \quad \text{and} \quad k_L + k_S = k_T \quad \text{coalescence}$$

or

$$\omega_L = \omega_S + \omega_T \qquad k_L = k_S + k_T \quad \text{decay}$$

Plasma radiation

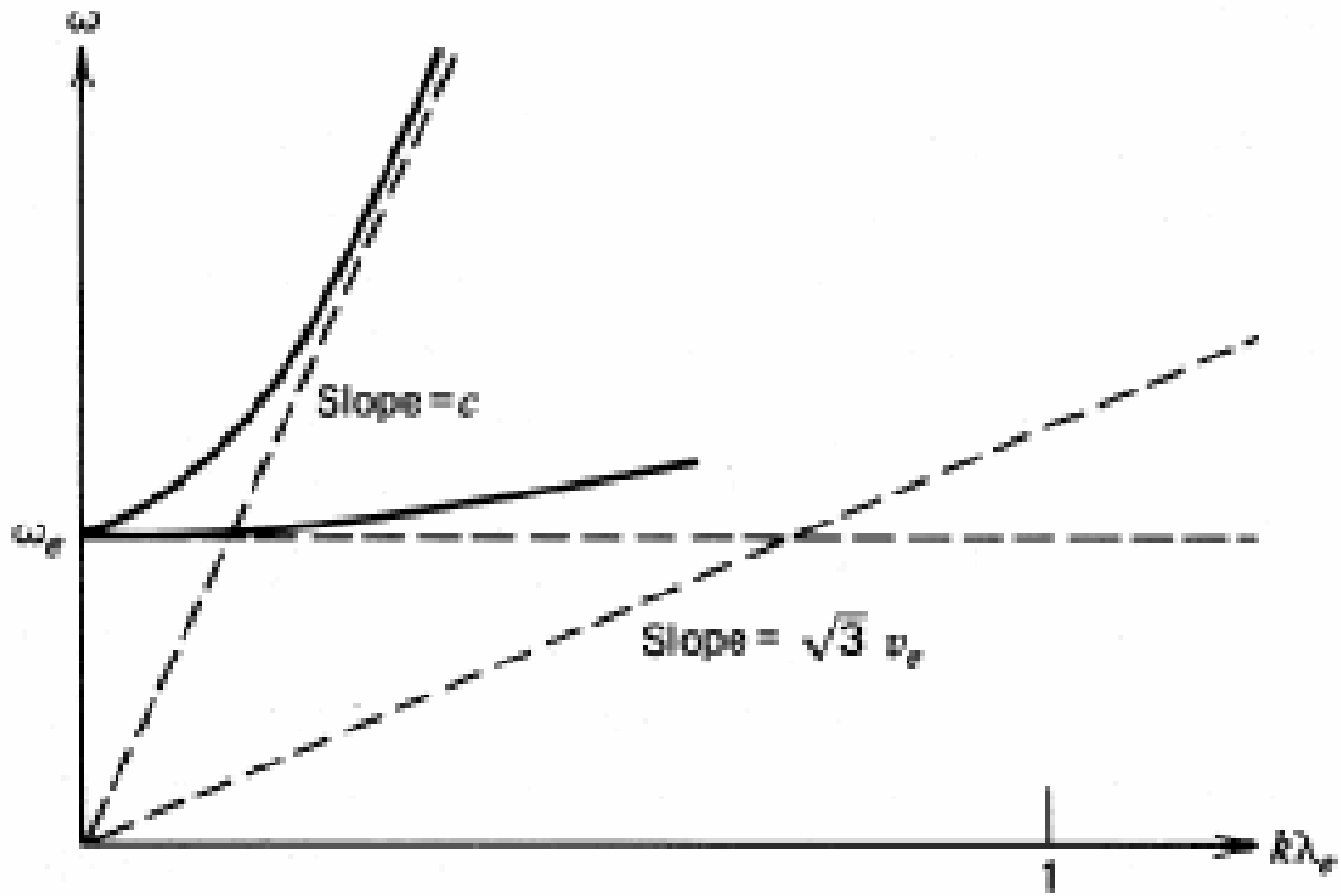
Plasma radiation is therefore thought to involve several steps:

Harmonic plasma radiation

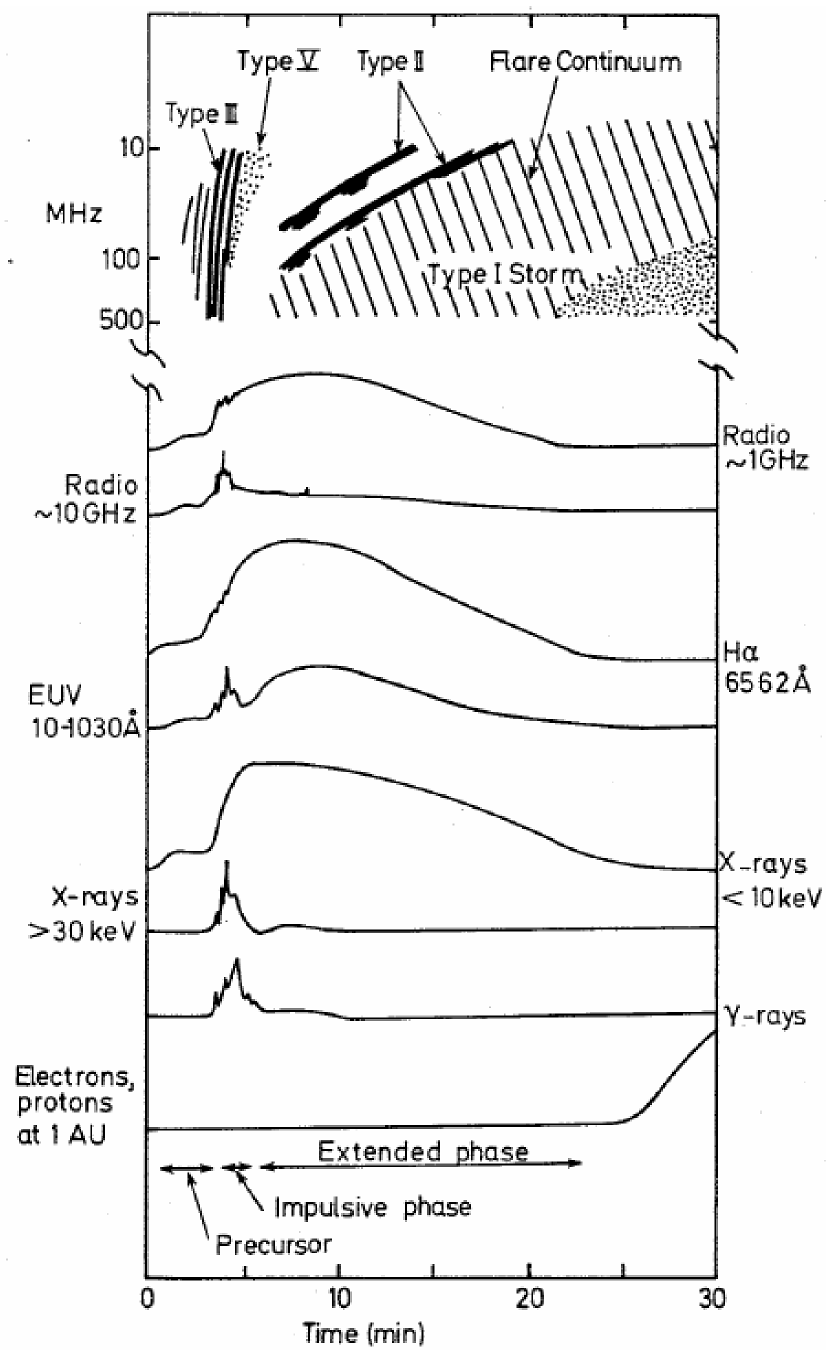
- A process must occur that is unstable to the production of Langmuir waves
- A secondary spectrum of Langmuir waves must be generated
- Two Langmuir waves can then coalesce

$$\omega_L^1 + \omega_L^2 = \omega_T \quad \text{and} \quad k_L^1 + k_L^2 = k_T << k_L$$

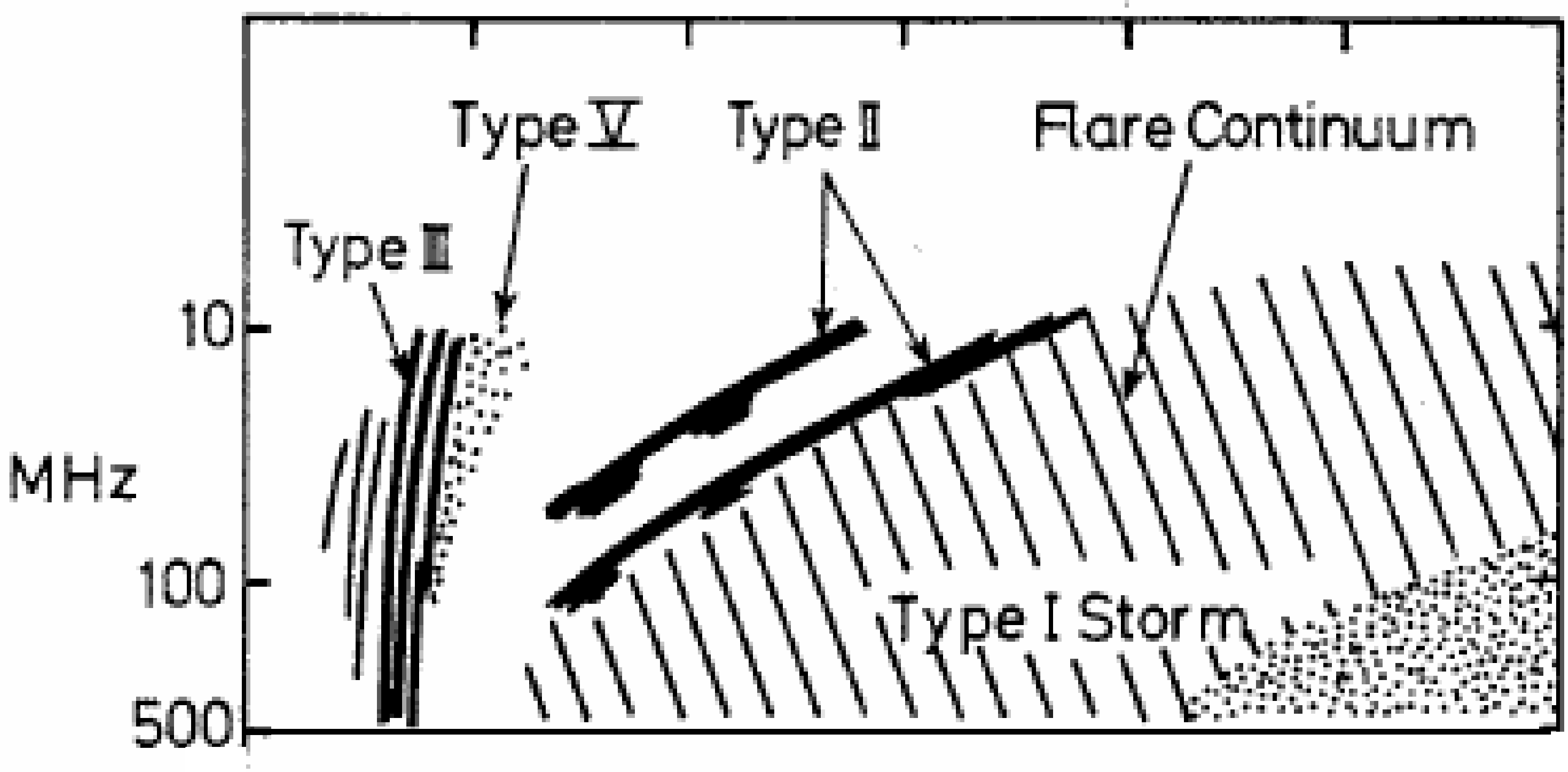
$$\omega_T \approx 2\omega_L \qquad k_L^1 \approx -k_L^2$$



ω
ω_e
Slope = c
Slope = $\sqrt{3}\ v_e$
1
$k\lambda_e$

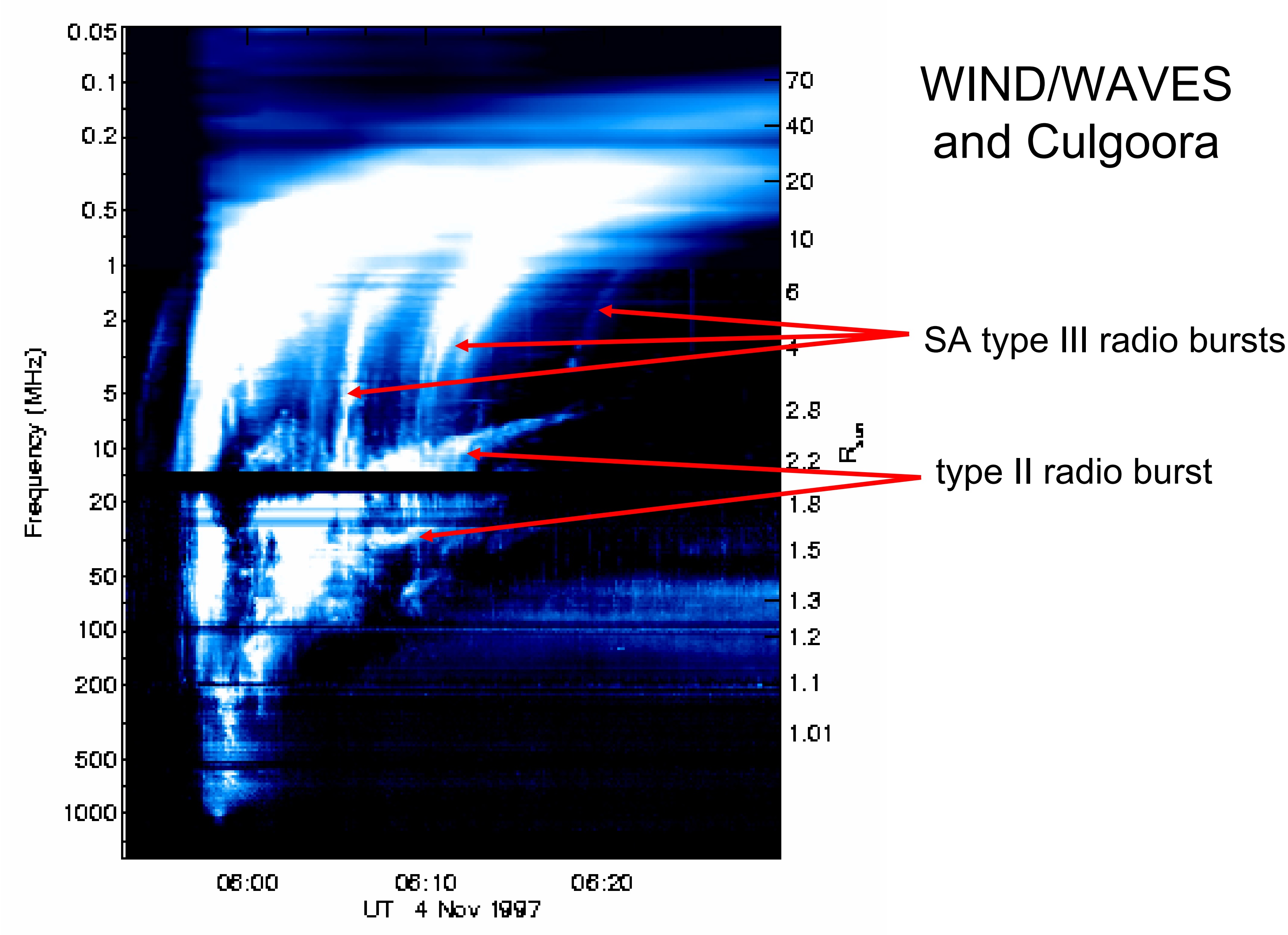


Type V
Type II
Flare Continuum
Type III
10
MHz
100
500
Type I Storm
Radio
~1GHz
Radio
~10 GHz
Hα
6562Å
EUV
10-1030Å
X-rays
< 10 keV
X-rays
> 30 keV
γ-rays
Electrons,
protons
at 1 AU
Extended phase
Impulsive phase
Precursor
0
10
20
30
Time (min)

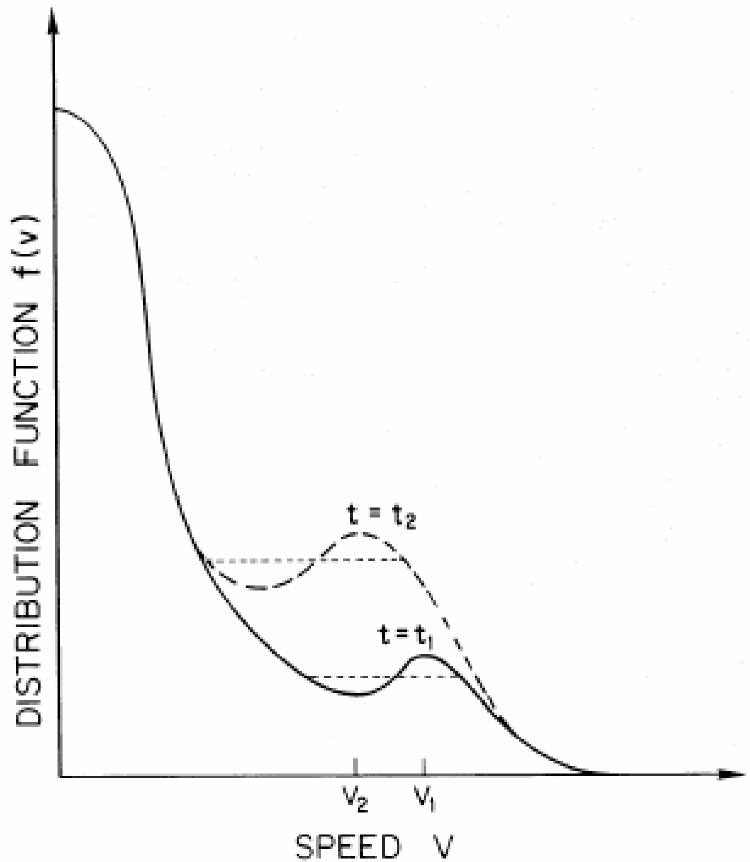


“Classical” radio bursts

WIND/WAVES and Culgoora



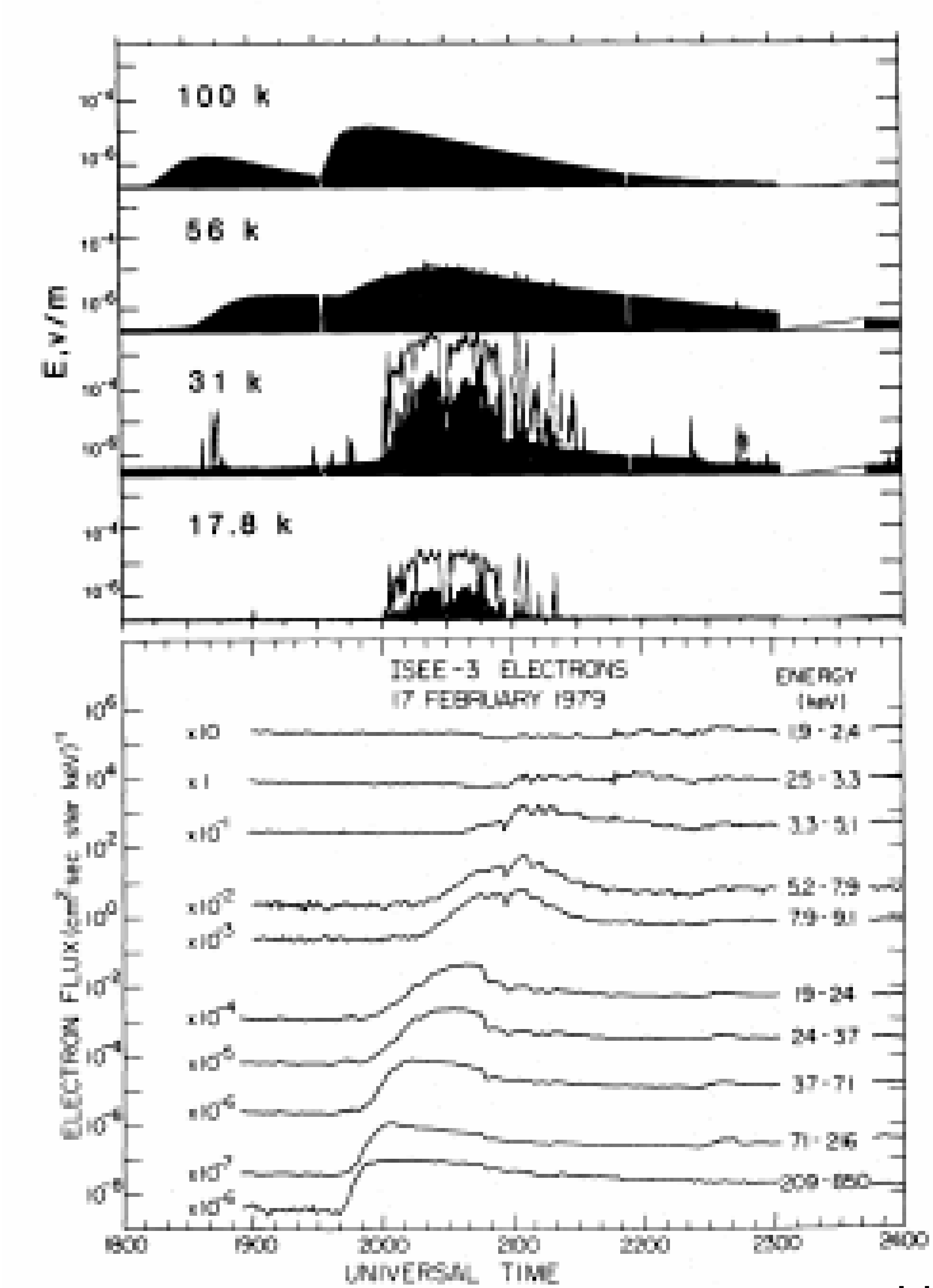
More examples: http://www.nrao.edu/astrores/gbsrbs



DISTRIBUTION FUNCTION f(v)
t = t_2
t = t_1
V_2
V_1
SPEED V

ISEE-3 type III

1979 Feb 17



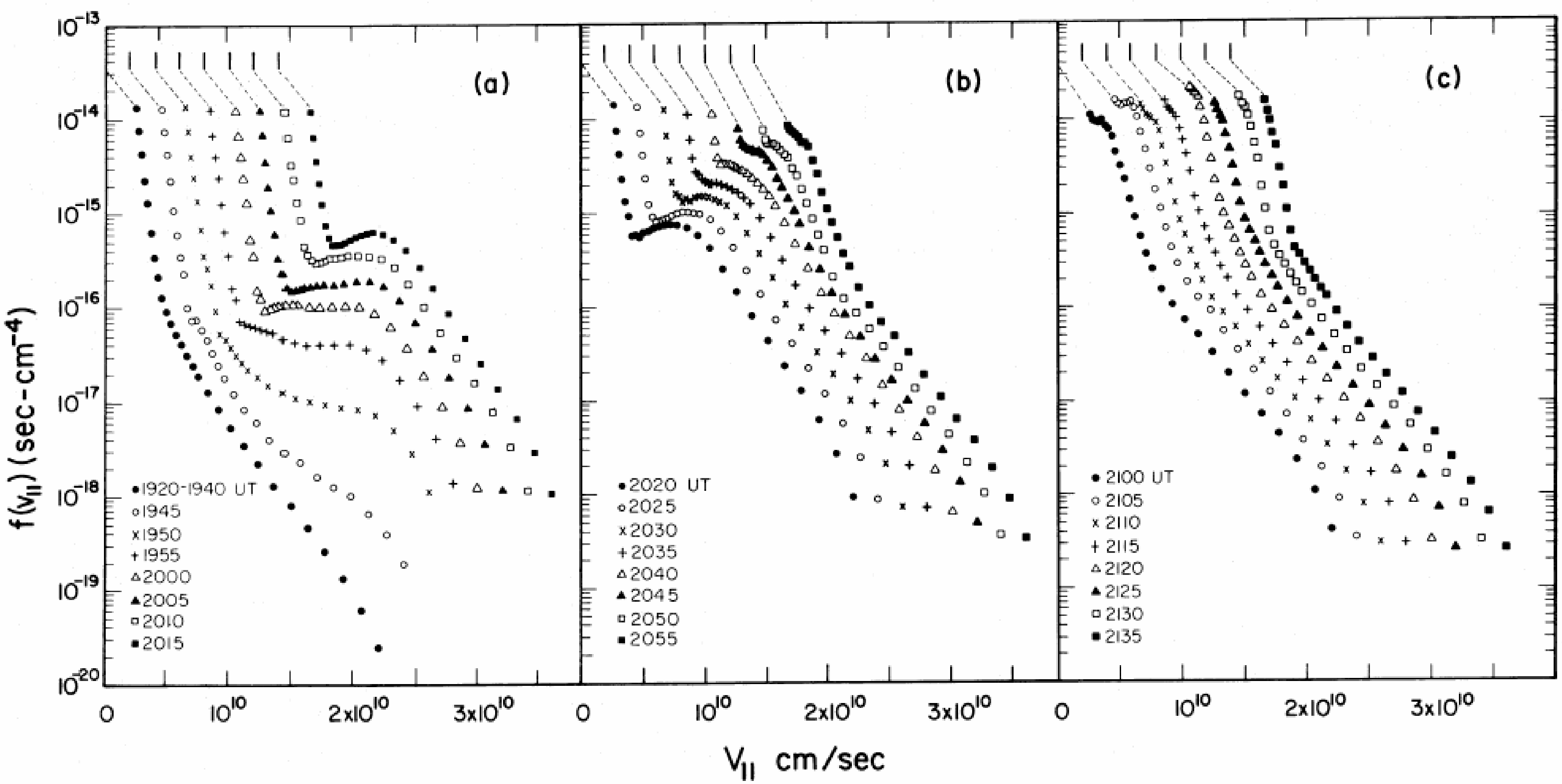
IP Langmuir waves

IP electrons

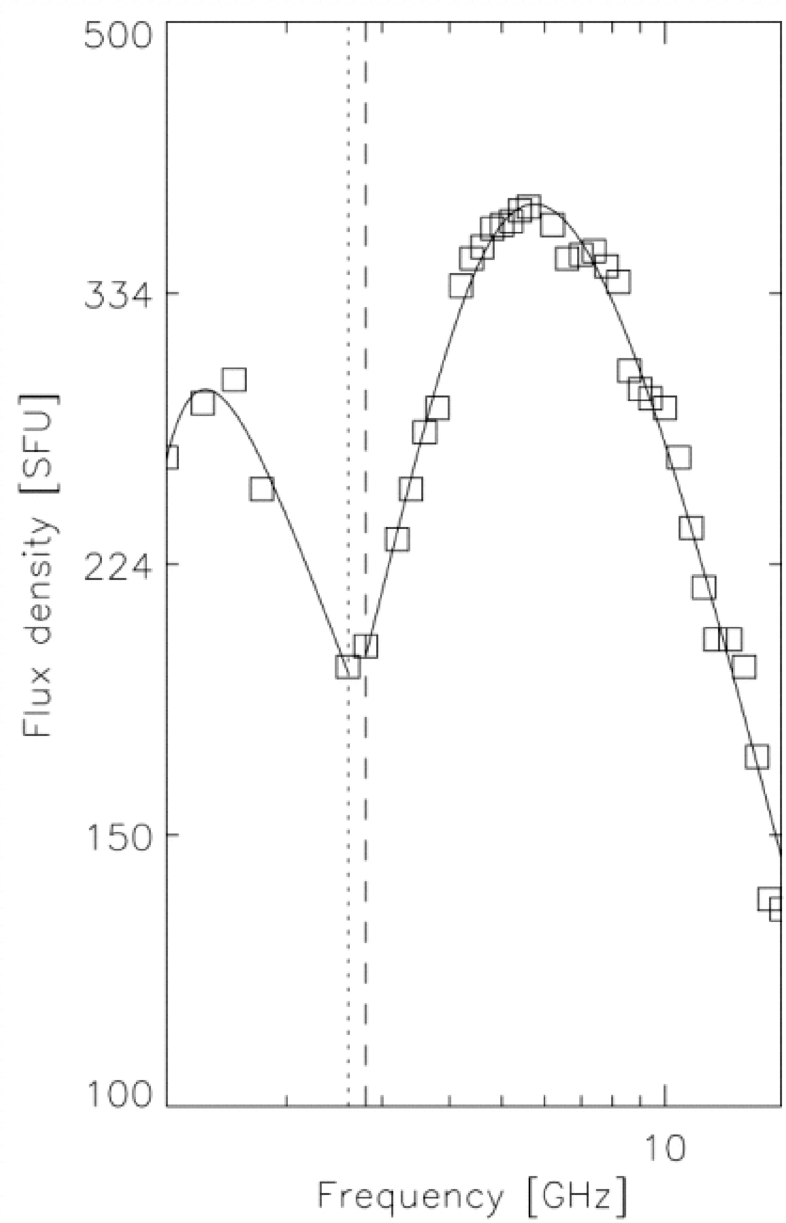
Lin et al. 1981

ISEE-3 type III

1979 Feb 17



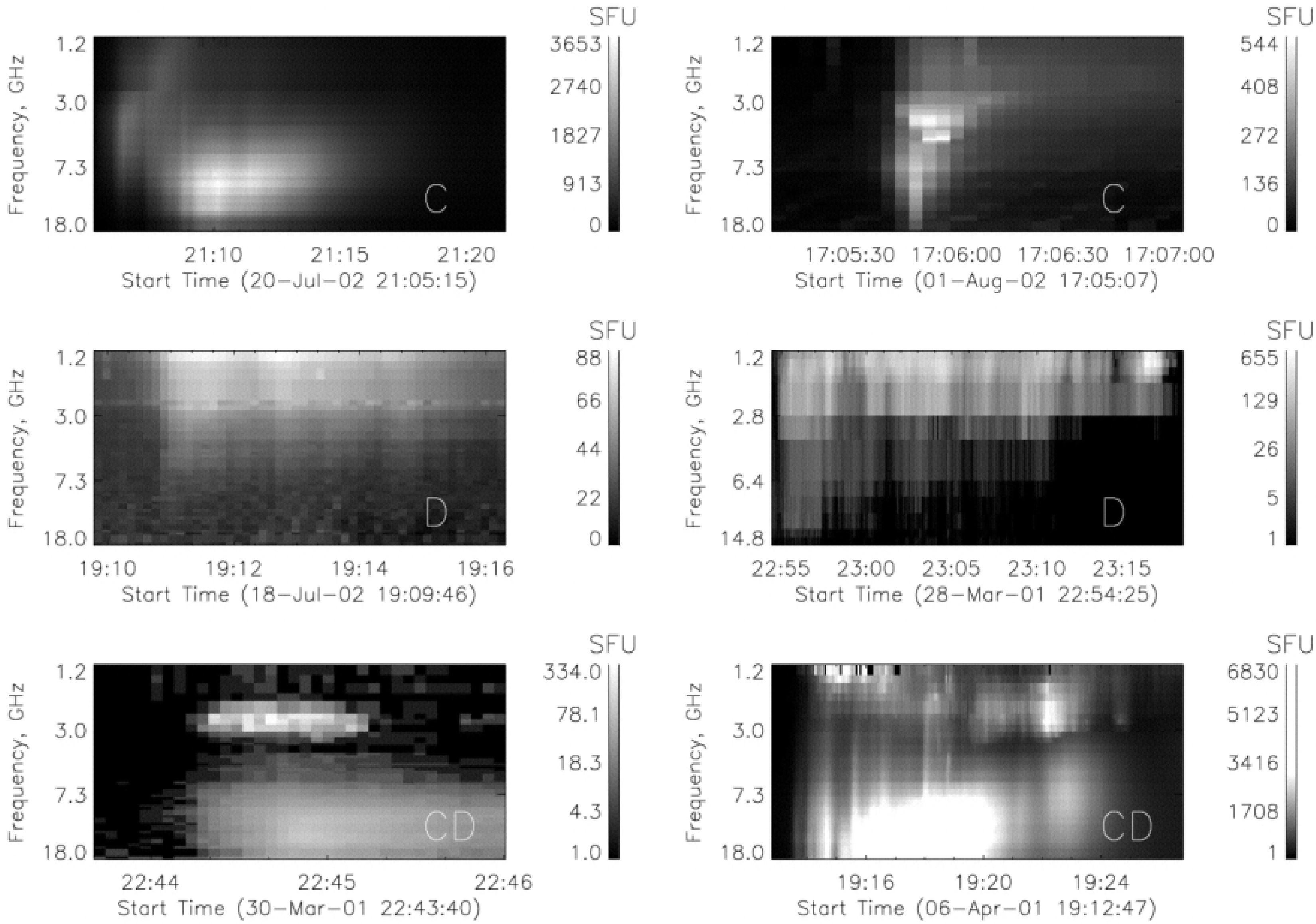
Lin et al. 1981



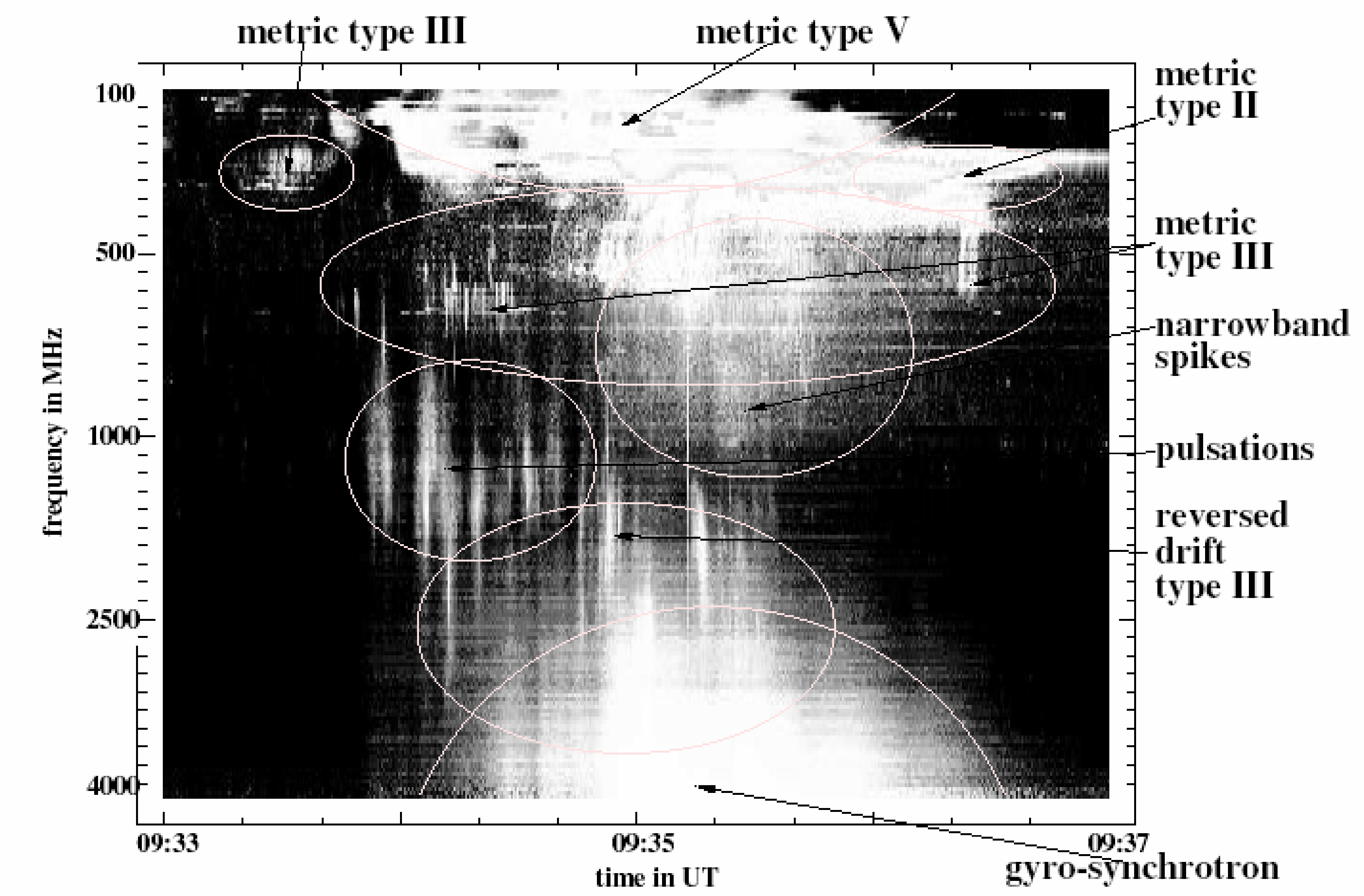
Statistical study of spectral properties of dm-cm λ radio bursts

Nita et al 2004

- Sample of 412 OVSA events (1.2-18 GHZ)
- Events are the superposition of cm-λ (>2.6 GHz) and dm-λ (<2.6 GHz) components
- Pure C: 80%; Pure D: 5%; Composite CD: 15%
- For CD events: 12% (<100 sfu); 19% (100-1000 sfu); 60% (>1000 sfu)
- No evidence for harmonic structure

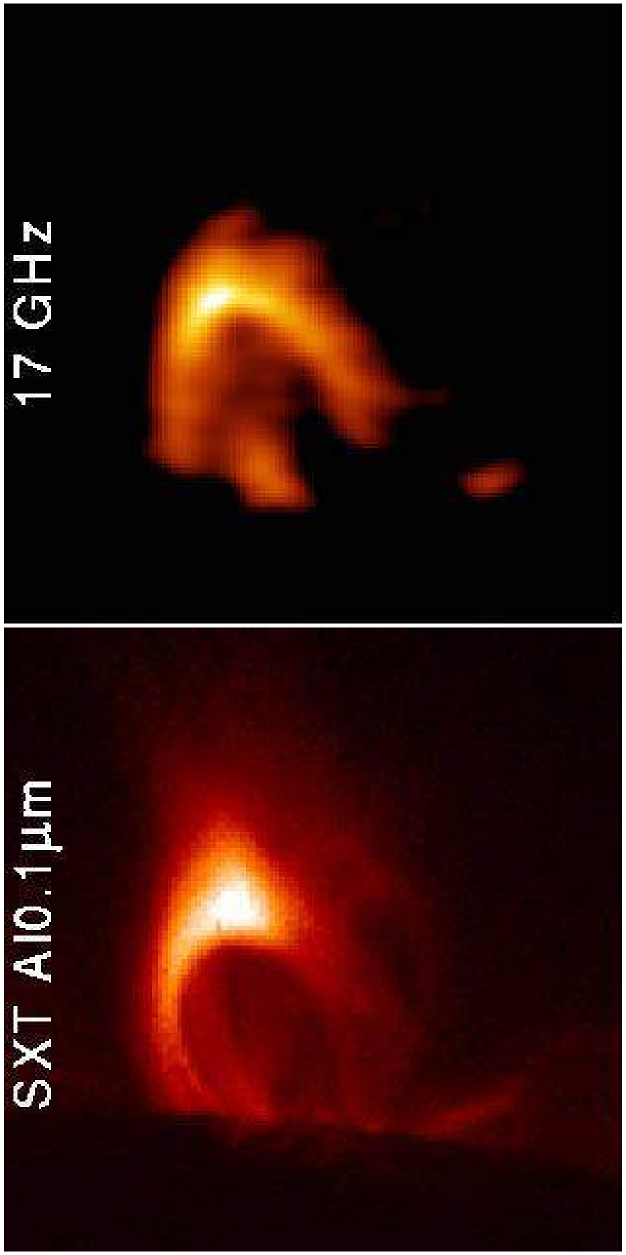


from Nita et al 2004

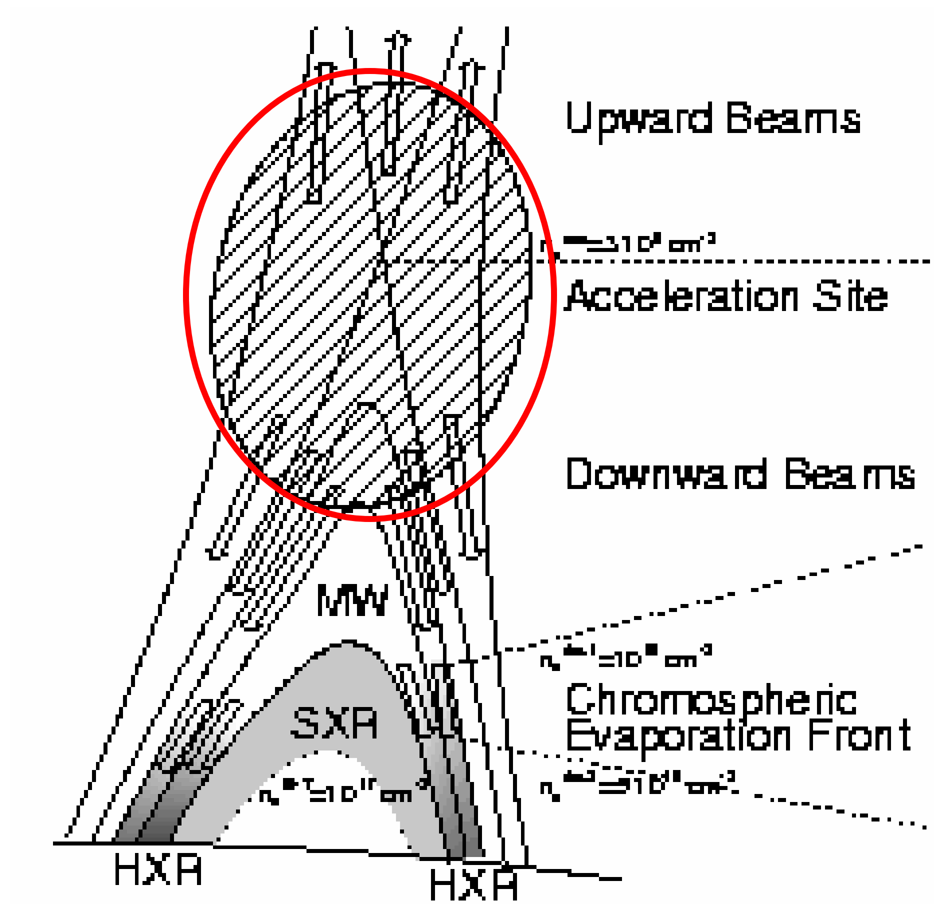


from Benz, 2004

Long duration flare observed on west limb by Yohkoh and the Nobeyama radioheliograph on 16 March 1993.

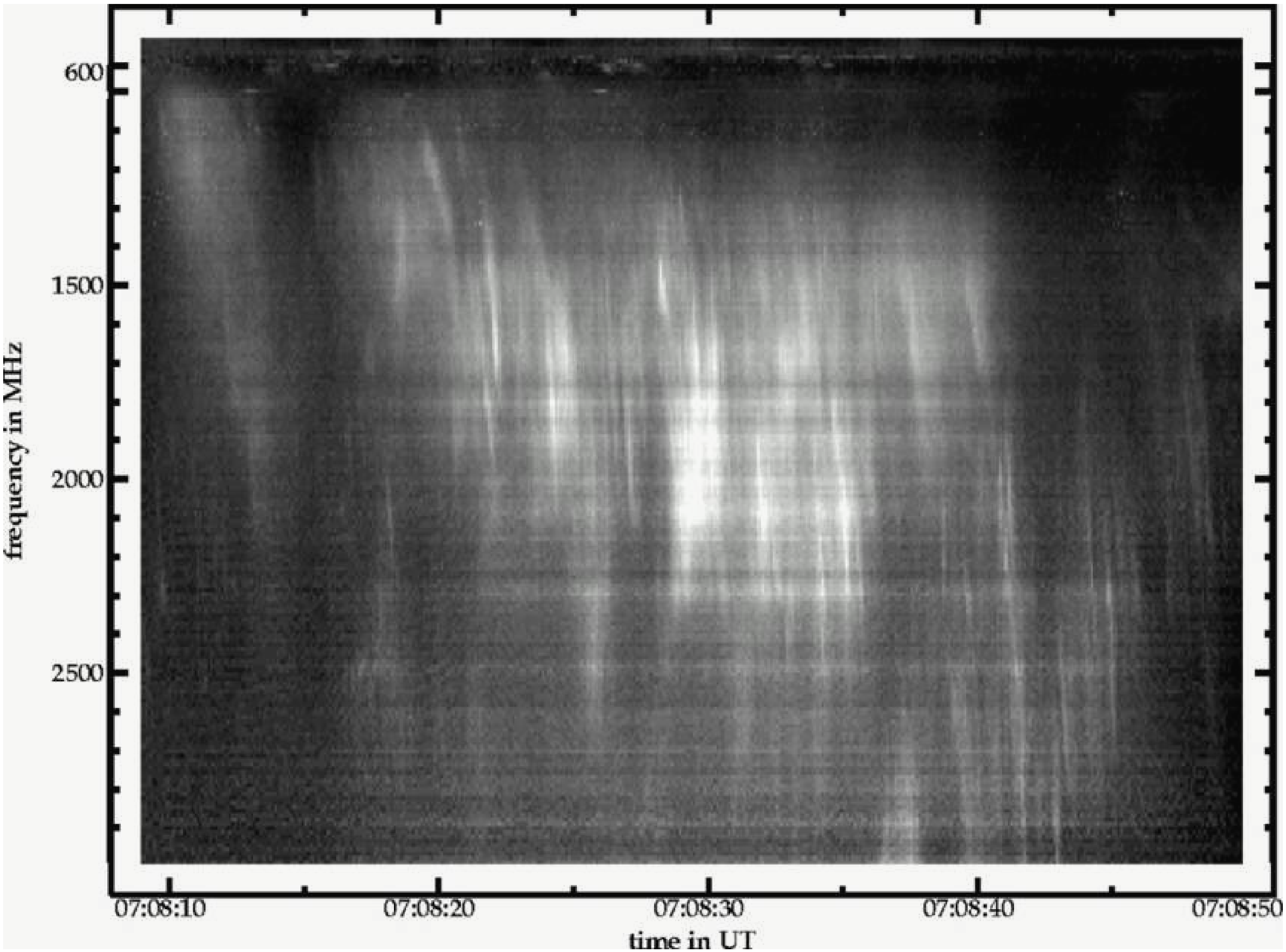


Y. Hanaoka

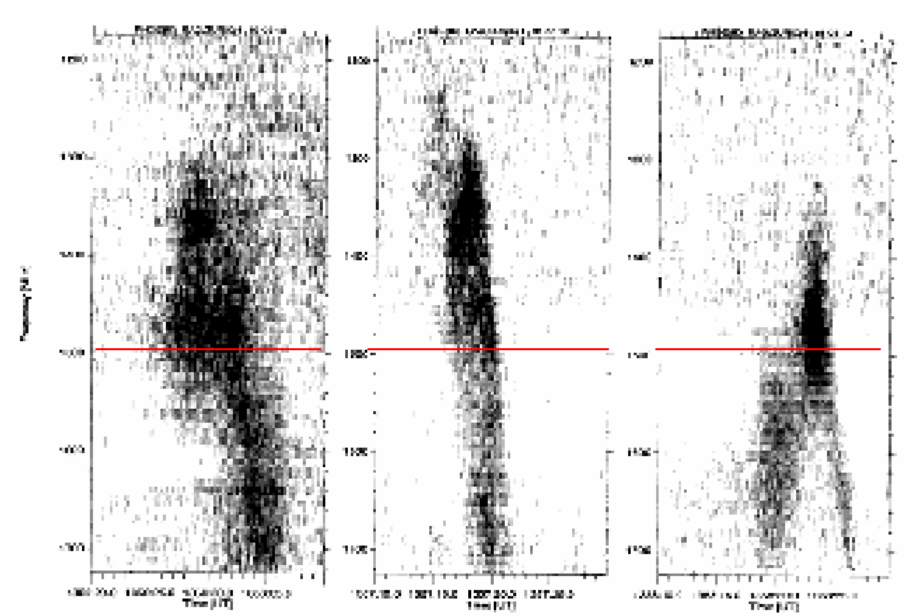


Aschwanden & Benz 1997

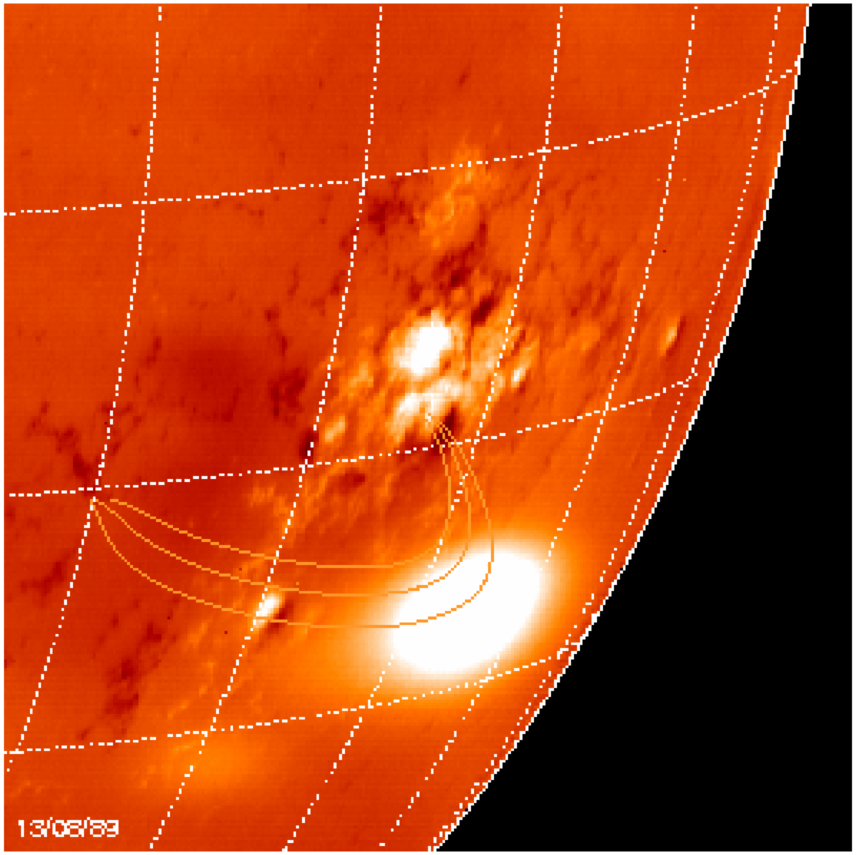
Reverse slope type IIIdm radio bursts



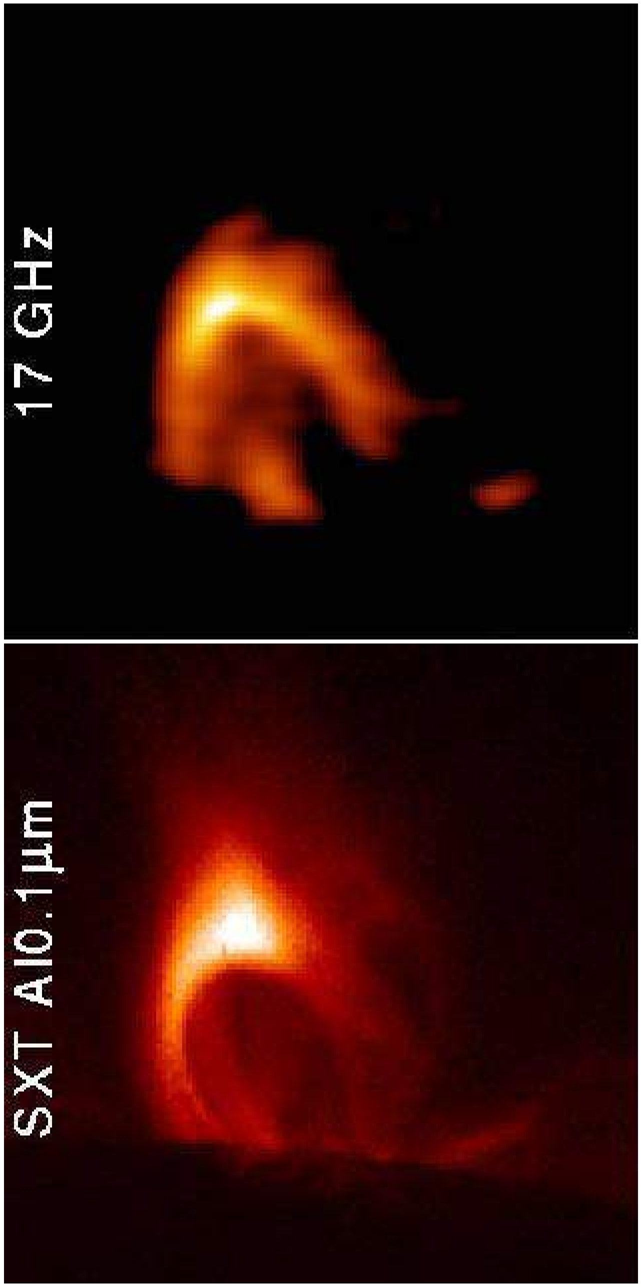
Isliker & Benz 1994



Type U bursts observed by Phoenix/ETH and the VLA.

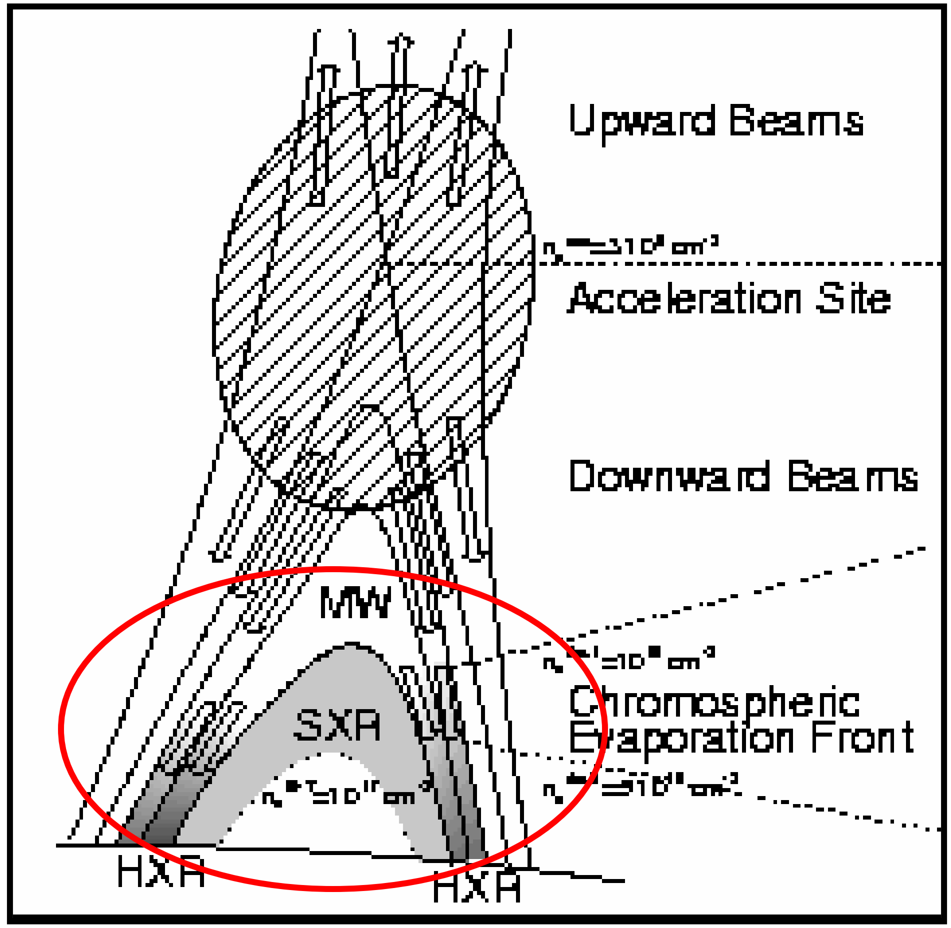


Aschwanden et al. 1992



Y. Hanaoka

Long duration flare observed on west limb by Yohkoh and the Nobeyama radioheliograph on 16 March 1993.



Aschwanden & Benz 1997

Gyrosynchrotron Radiation

$$I_{\pm}(\nu, \theta) = \frac{j_{\pm}}{\kappa_{\pm}} [1 - \exp(-\kappa_{\pm} D)] \text{ ergs (s sr Hz cm}^2)^{-1}$$

$$\begin{aligned} n_{\pm}^2(\theta) = 1 &+ 2\nu_p^2(\nu_p^2 - \nu^2) \\ &\times \{\pm[\nu^4 \nu_b^4 \sin^4\theta + 4\nu^2\nu_b^2(\nu_p^2 - \nu^2)^2 \cos^2\theta]^{1/2} \\ &- 2\nu^2(\nu_p^2 - \nu^2) - \nu^2\nu_b^2 \sin^2\theta\}^{-1} . \end{aligned}$$

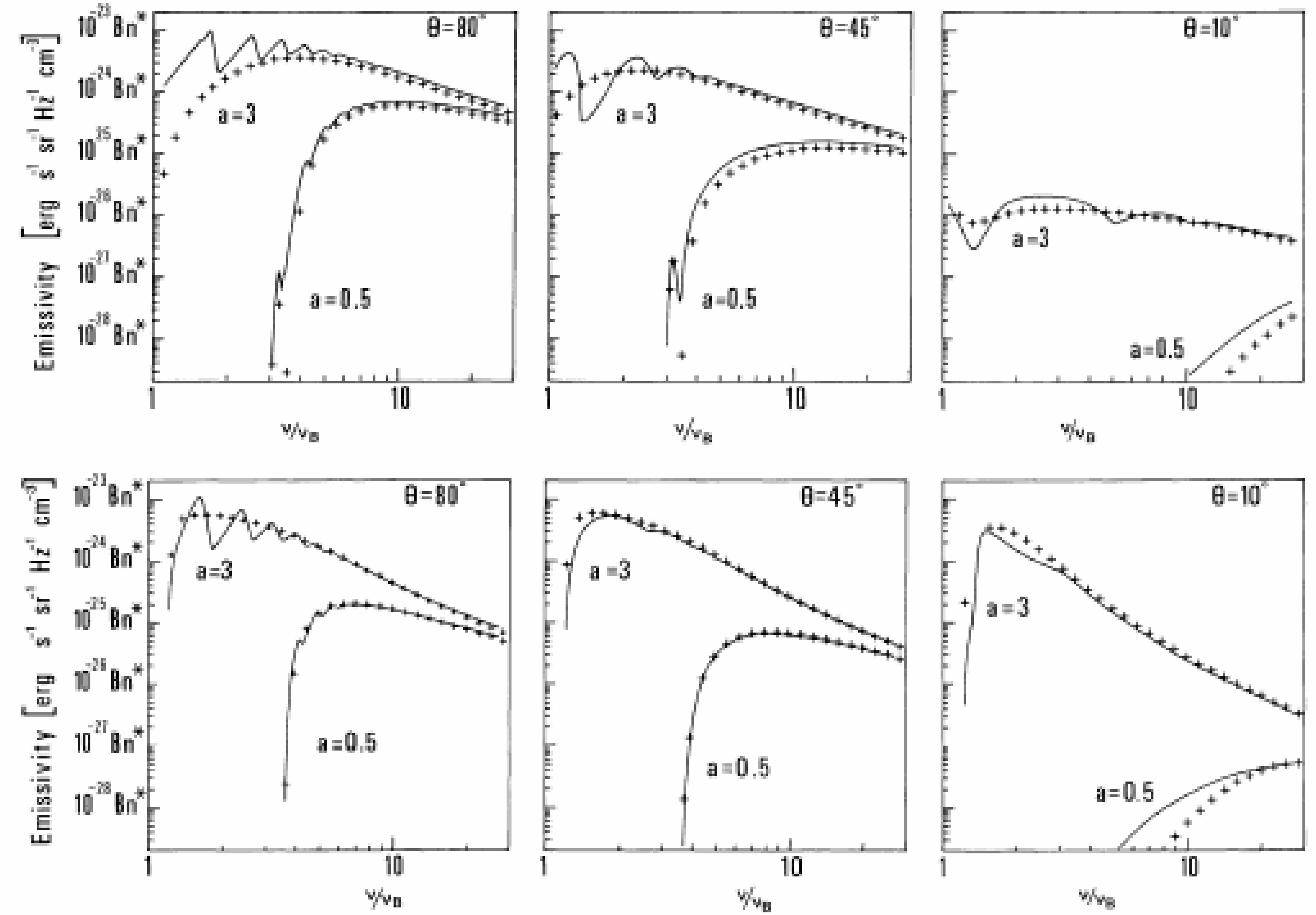
"exact"	approximate
Ramaty 1969	Petrosian 1981
Benka & Holman 1992	Dulk & Marsh 1982, 1985
	Klein 1987

$$2\pi \int_{1}^{\infty} d\gamma \int_{-1}^{1} d(\cos\,\phi) f(\gamma,\,\phi) = 1$$

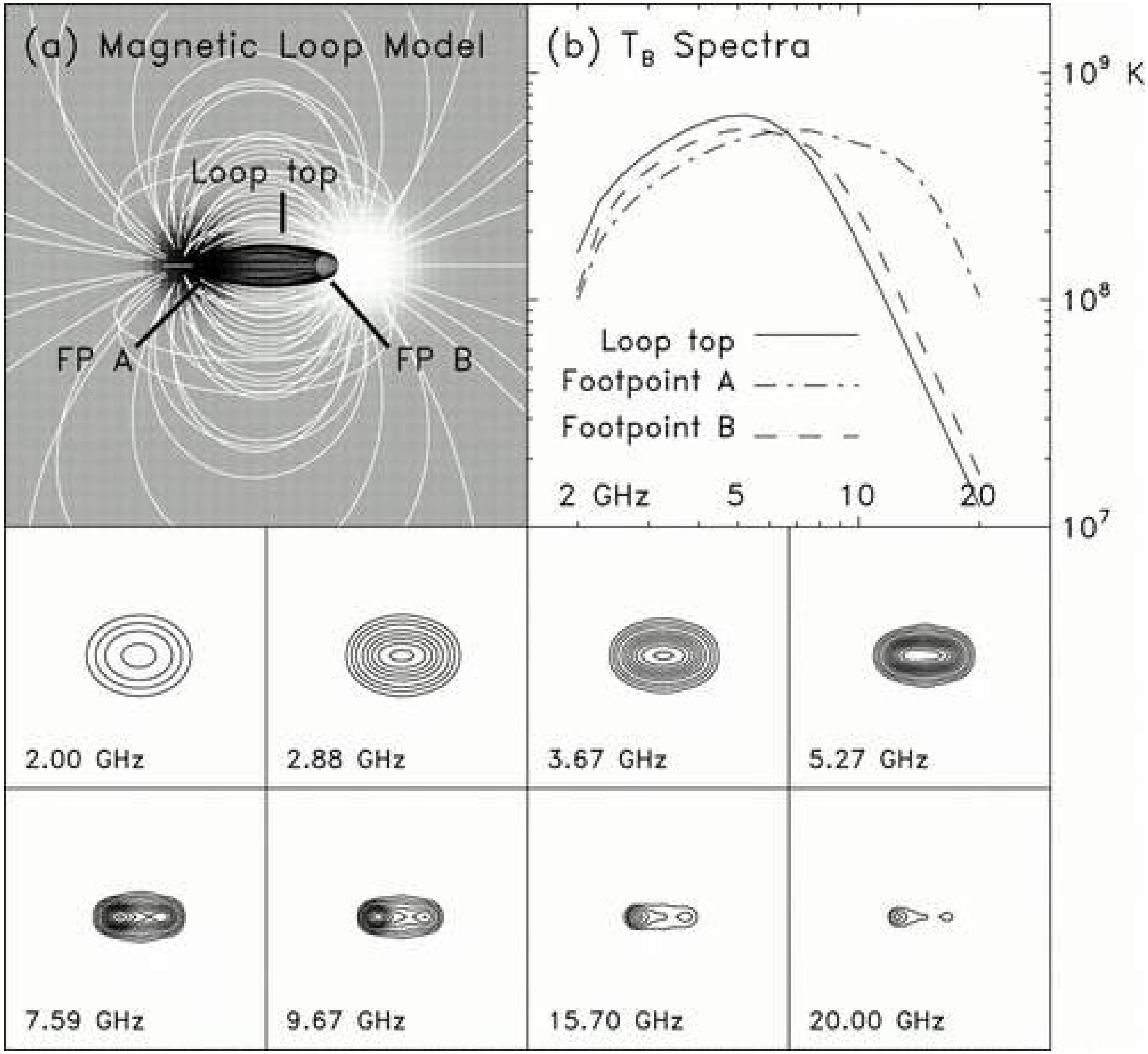
$$j_{\pm}(\nu, \theta) = \frac{4\pi^2 e^2 \nu N_r}{|\cos\,\theta| c} \frac{1}{1 + a_{\theta\pm}^2} \sum_{s_{\min}}^{\infty} \int_{\gamma_1}^{\gamma_2} \Bigg\{ d\gamma\, f(\gamma,\,\phi_s) \beta^{-1} \times \left[\alpha_{\theta\pm} \left(\frac{\cot\,\theta}{n_{\pm}} - \beta \frac{\cos\,\phi_s}{\sin\,\theta} \right) J_s(x_s) - \beta \sin\,\phi_s\, J_s'(x_s) \right]^2 \Bigg\} ,$$

$$\kappa_{\pm}(\nu, \theta) = \frac{4\pi^2 e^2 N_r}{mc\nu |\cos\,\theta|} \frac{1}{n_{\pm}(1 + a_{\theta\pm}^2)} \sum_{s_{\min}}^{\infty} \int_{\gamma_1}^{\gamma_2} d\gamma\, \beta^{-1} \times \left\{ -\beta\gamma^2 \frac{\partial}{\partial\gamma} \left[\frac{f(\gamma,\,\phi)}{\beta\gamma^2} \right] + \frac{n_{\pm}\,\beta \cos\,\theta - \cos\,\phi}{\beta^2 \gamma \sin\,\phi} \frac{\partial}{\partial\phi} f(\gamma,\,\phi) \right\}_{\phi=\phi_s} \times \left[a_{\theta\pm} \left(\frac{\cot\,\theta}{n_{\pm}} - \beta \frac{\cos\,\phi_s}{\sin\,\theta} \right) J_s(x_s) - \beta \sin\,\phi_s\, J_s'(x_s) \right]^2$$

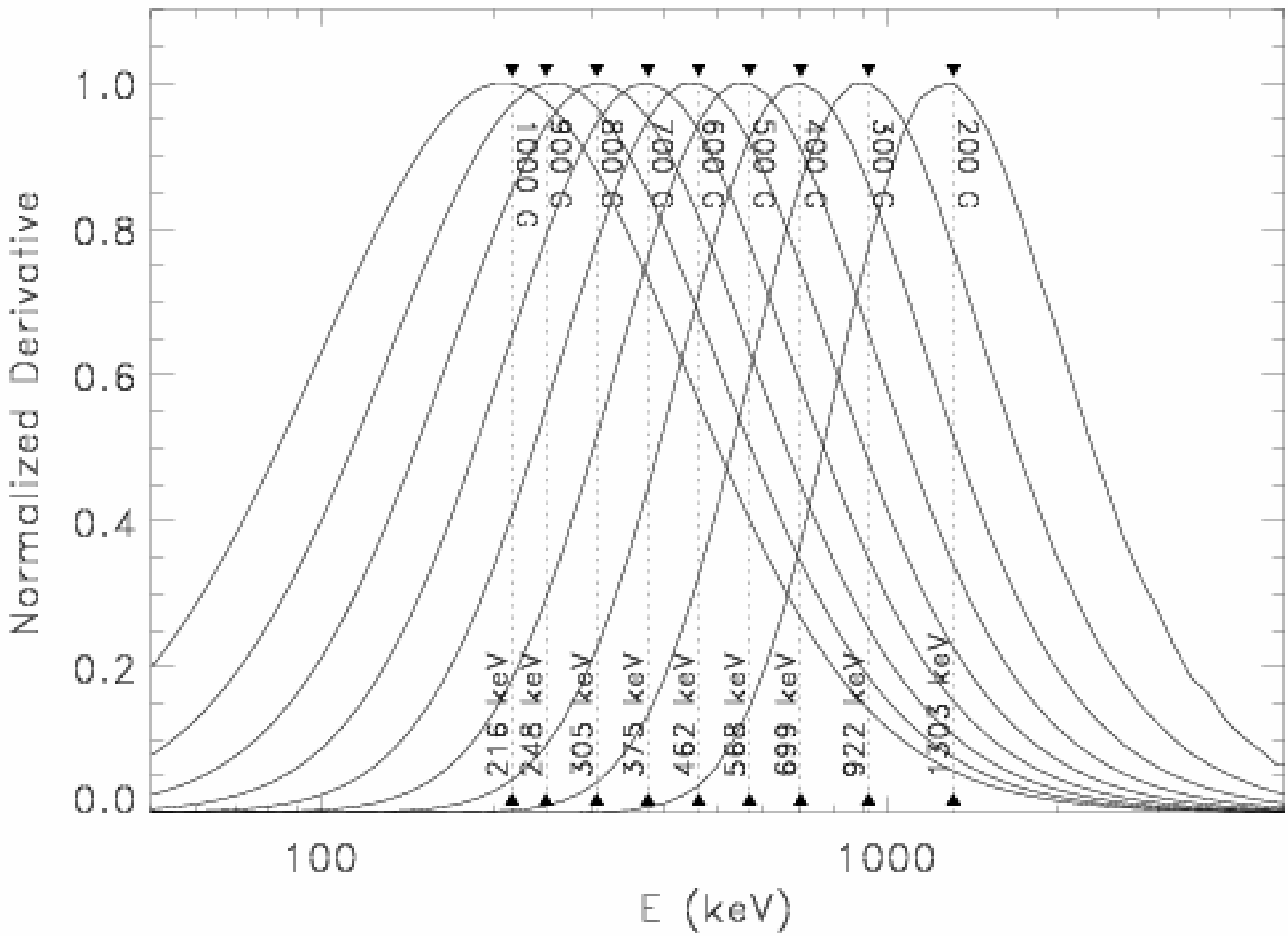
e.g., Klein (1987)



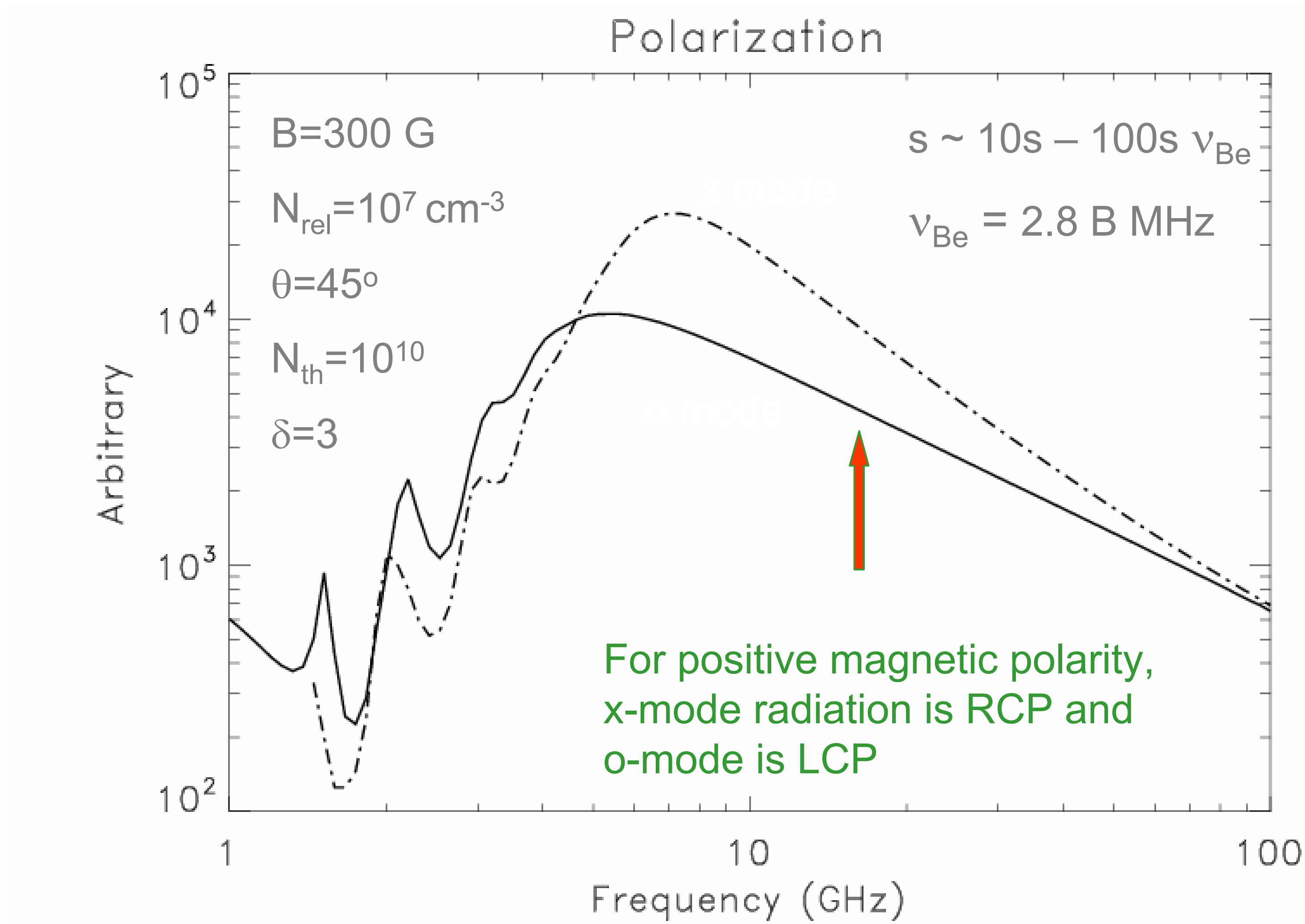
A Schematic Model



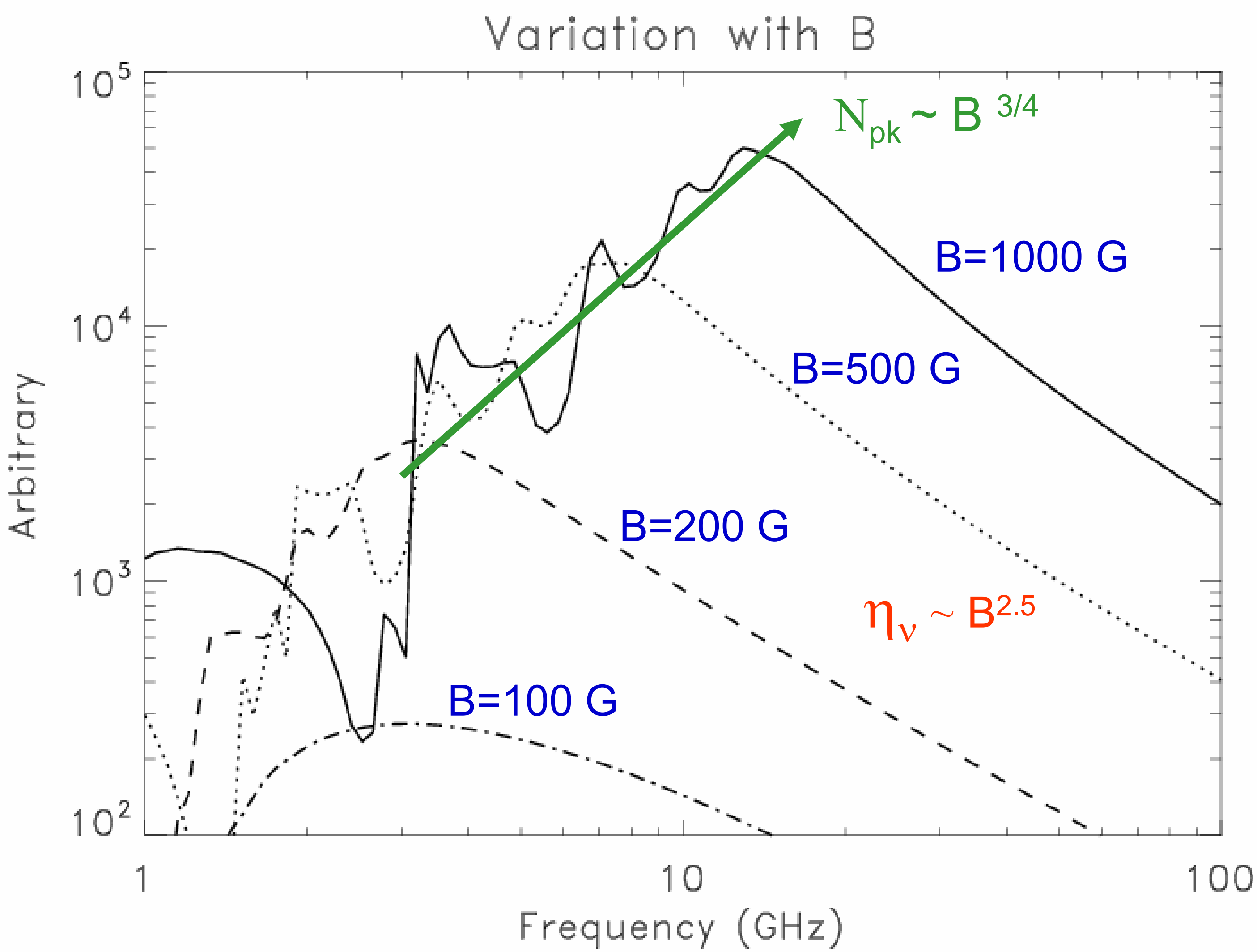
Bastian et al 1998



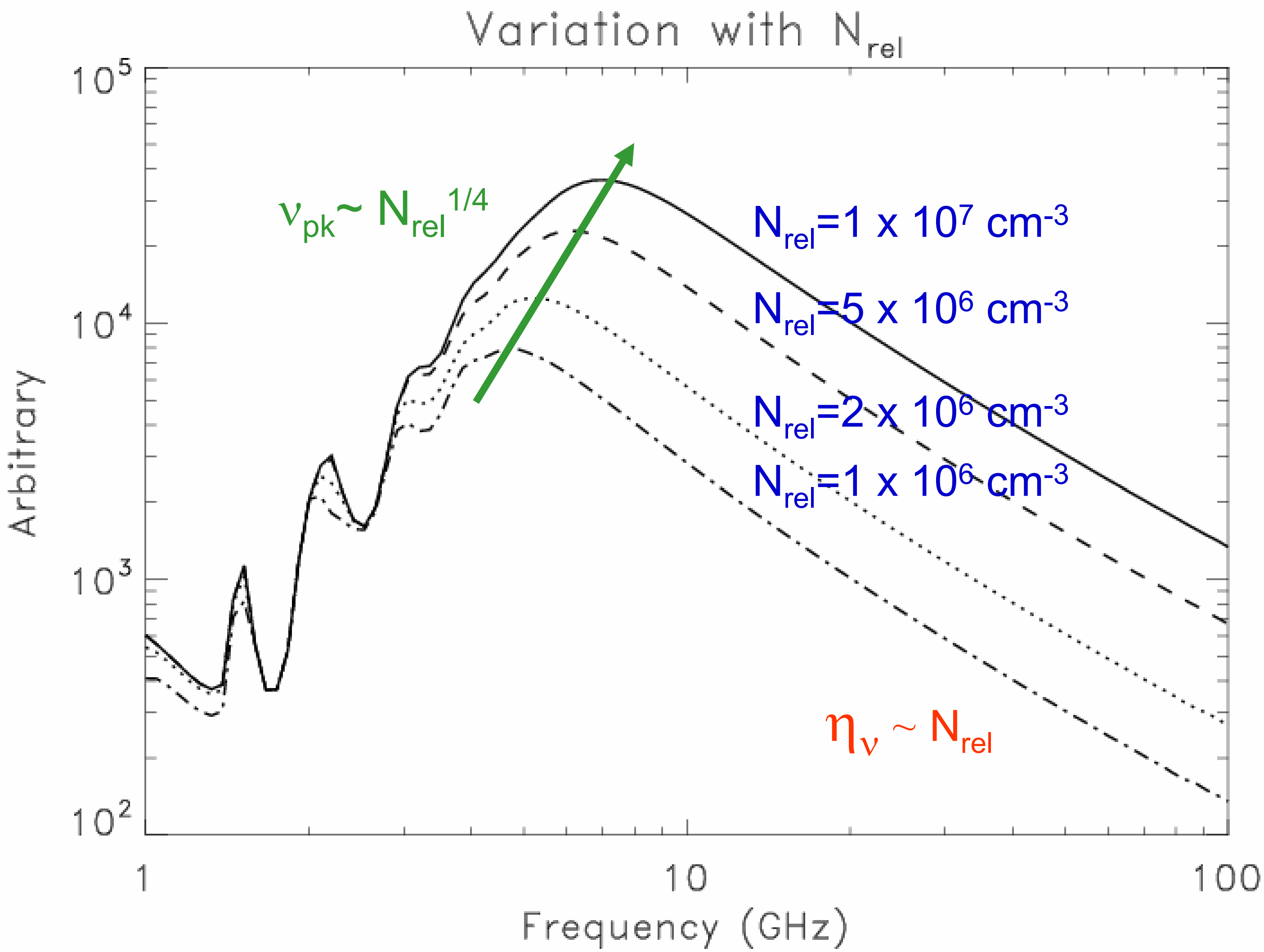
Normalized Derivative
E (keV)
1.0
0.8
0.6
0.4
0.2
0.0
100
1000
1000 G
900 G
800 G
700 G
600 G
500 G
400 G
300 G
200 G
216 keV
248 keV
305 keV
375 keV
462 keV
568 keV
699 keV
922 keV
1303 keV



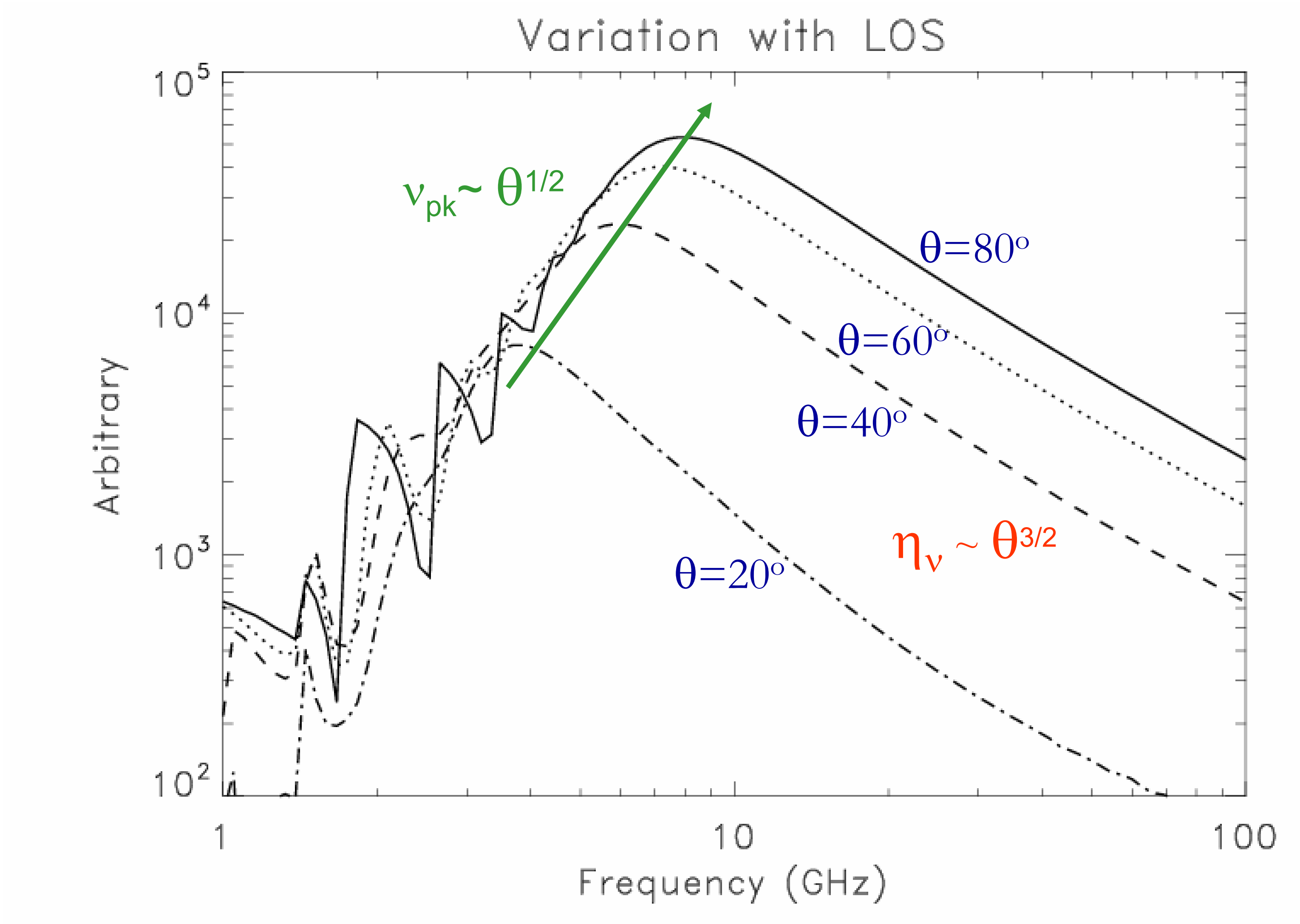
Polarization
B=300 G
N_rel=10^7 cm^-3
θ=45°
N_th=10^10
δ=3
s ~ 10s – 100s ν_Be
ν_Be = 2.8 B MHz
For positive magnetic polarity,
x-mode radiation is RCP and
o-mode is LCP
Arbitrary
Frequency (GHz)
10^5
10^4
10^3
10^2
1
10
100



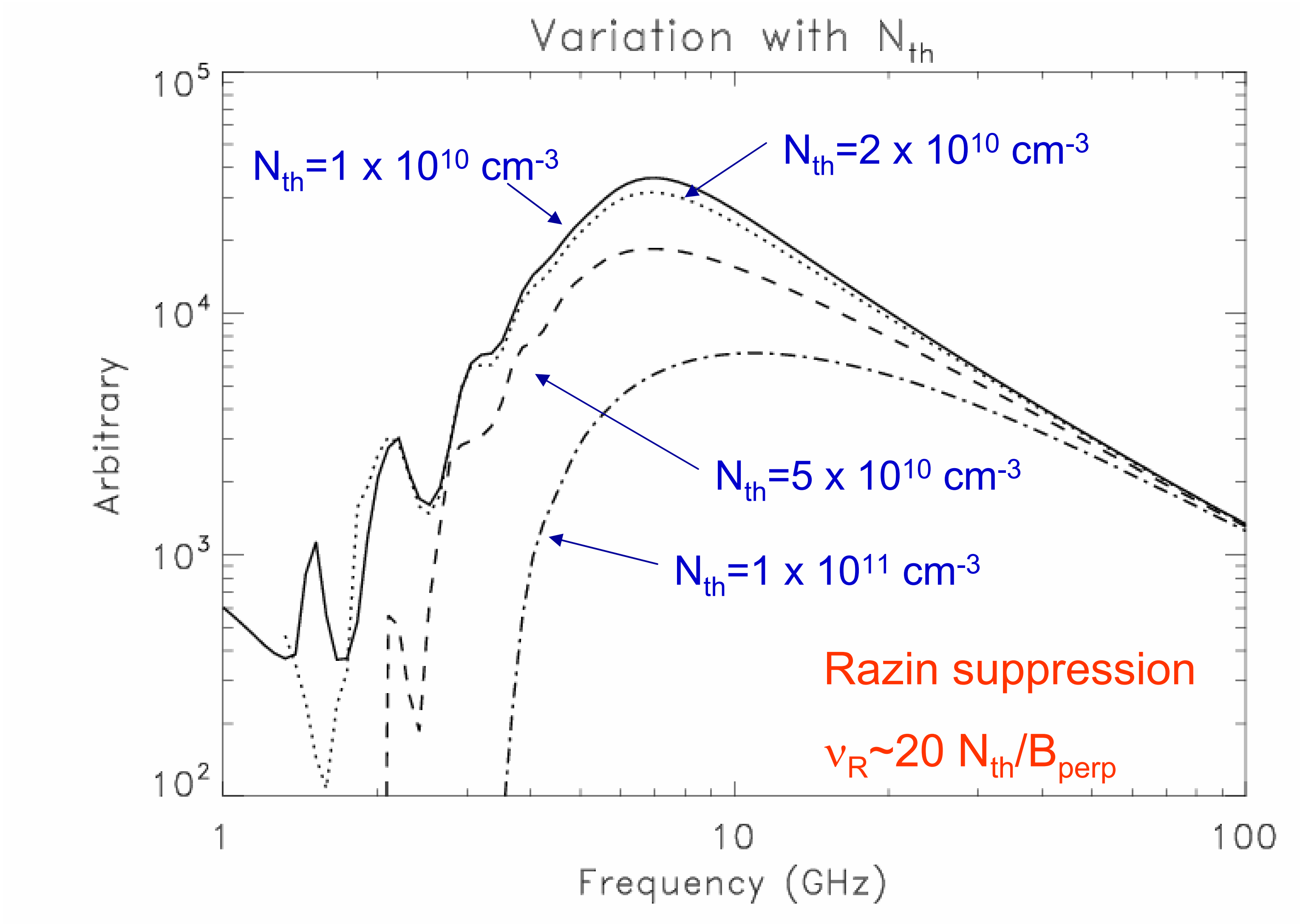
Variation with B
$N_{pk} \sim B^{3/4}$
B=1000 G
B=500 G
B=200 G
$\eta_\nu \sim B^{2.5}$
B=100 G
Arbitrary
Frequency (GHz)
10^5
10^4
10^3
10^2
1
10
100



Variation with N_{rel}
$\nu_{pk} \sim N_{rel}^{1/4}$
$N_{rel}=1 \times 10^{7}$ cm^{-3}
$N_{rel}=5 \times 10^{6}$ cm^{-3}
$N_{rel}=2 \times 10^{6}$ cm^{-3}
$N_{rel}=1 \times 10^{6}$ cm^{-3}
$\eta_\nu \sim N_{rel}$
Arbitrary
Frequency (GHz)
10^2
10^3
10^4
10^5
1
10
100



Variation with LOS
Arbitrary
Frequency (GHz)
10^5
10^4
10^3
10^2
1
10
100
$\nu_{pk} \sim \theta^{1/2}$
$\theta = 80^o$
$\theta = 60^o$
$\theta = 40^o$
$\theta = 20^o$
$\eta_\nu \sim \theta^{3/2}$



Variation with N$_{th}$
Arbitrary
Frequency (GHz)
10^5
10^4
10^3
10^2
1
10
100
N$_{th}$=1 x 10^{10} cm^{-3}
N$_{th}$=2 x 10^{10} cm^{-3}
N$_{th}$=5 x 10^{10} cm^{-3}
N$_{th}$=1 x 10^{11} cm^{-3}
Razin suppression
$\nu_R \sim 20\ N_{th}/B_{perp}$

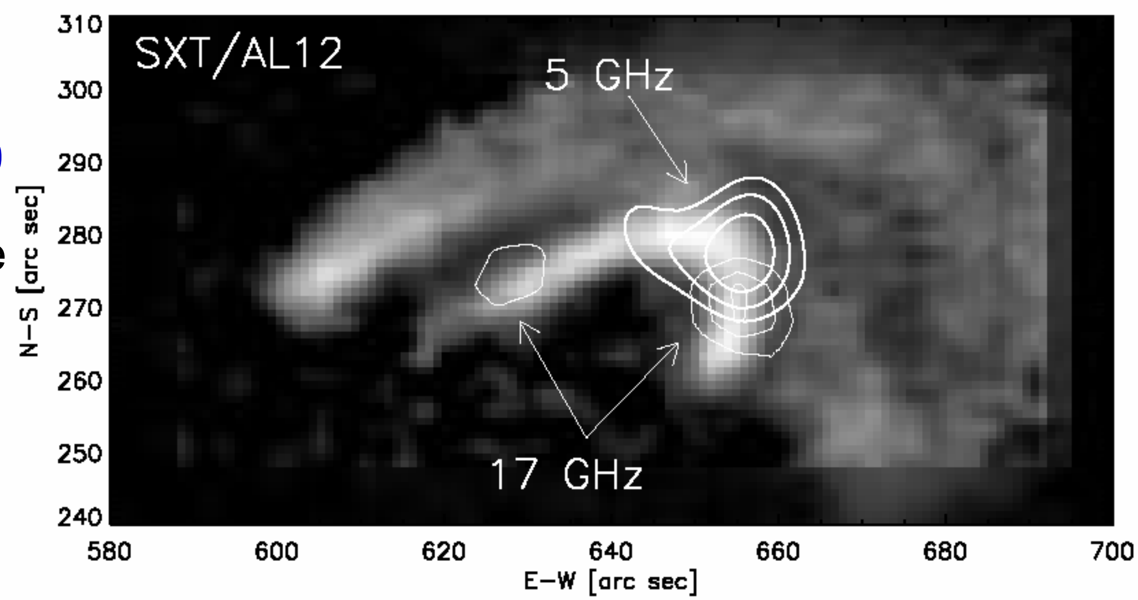
1993 June 3

OVSA/NoRH

Trap properties

Lee, Gary, & Shibasaki 2000

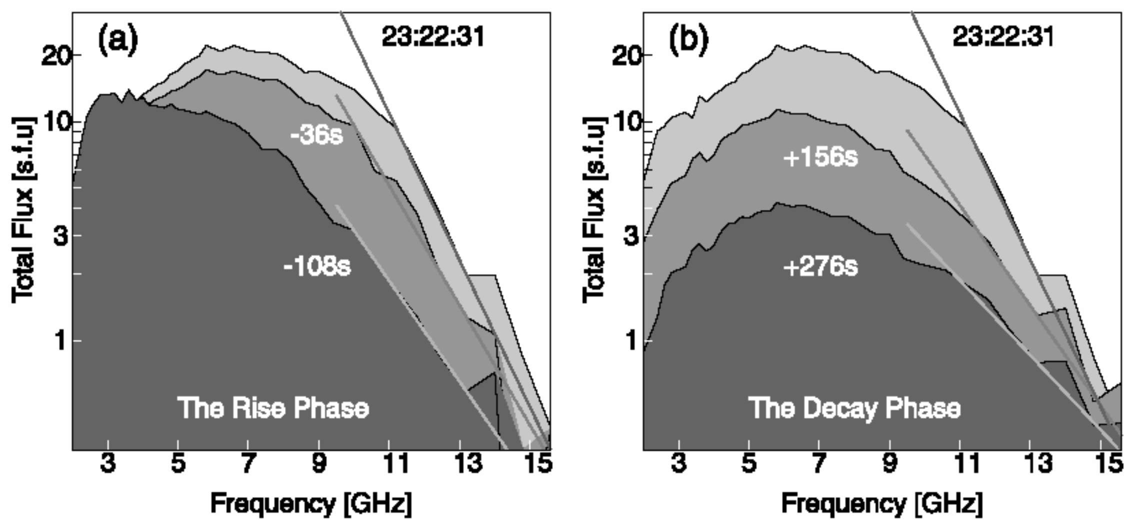
A comparison of successive flares yielded trap densities of 5 x 10^9 cm^{-3} in the first, and 8 x 10^{10} cm^{-3} in the second.



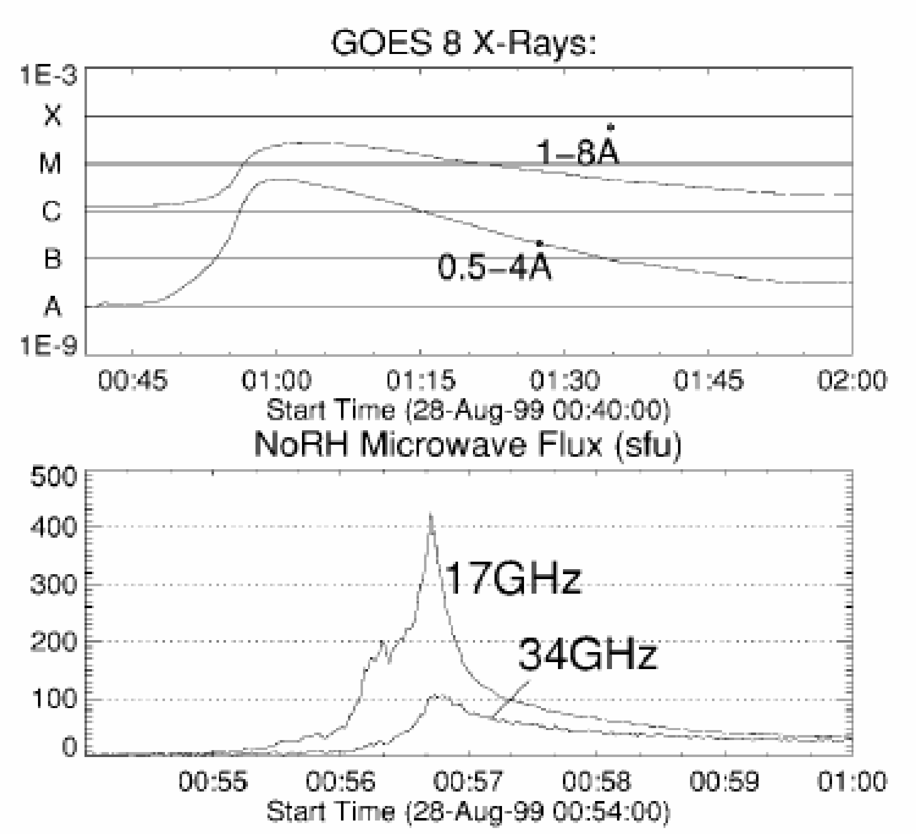
Anisotropic injection

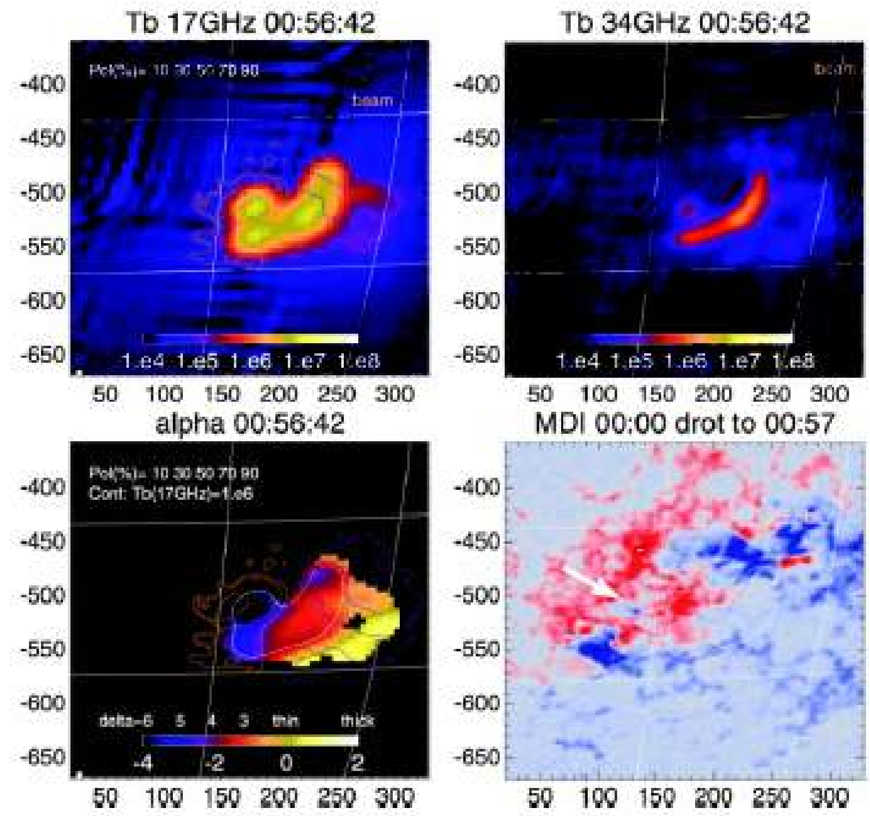
Lee & Gary 2000

Showed that the electron injection in the first flare was best fit by a beamed pitch angle distribution.

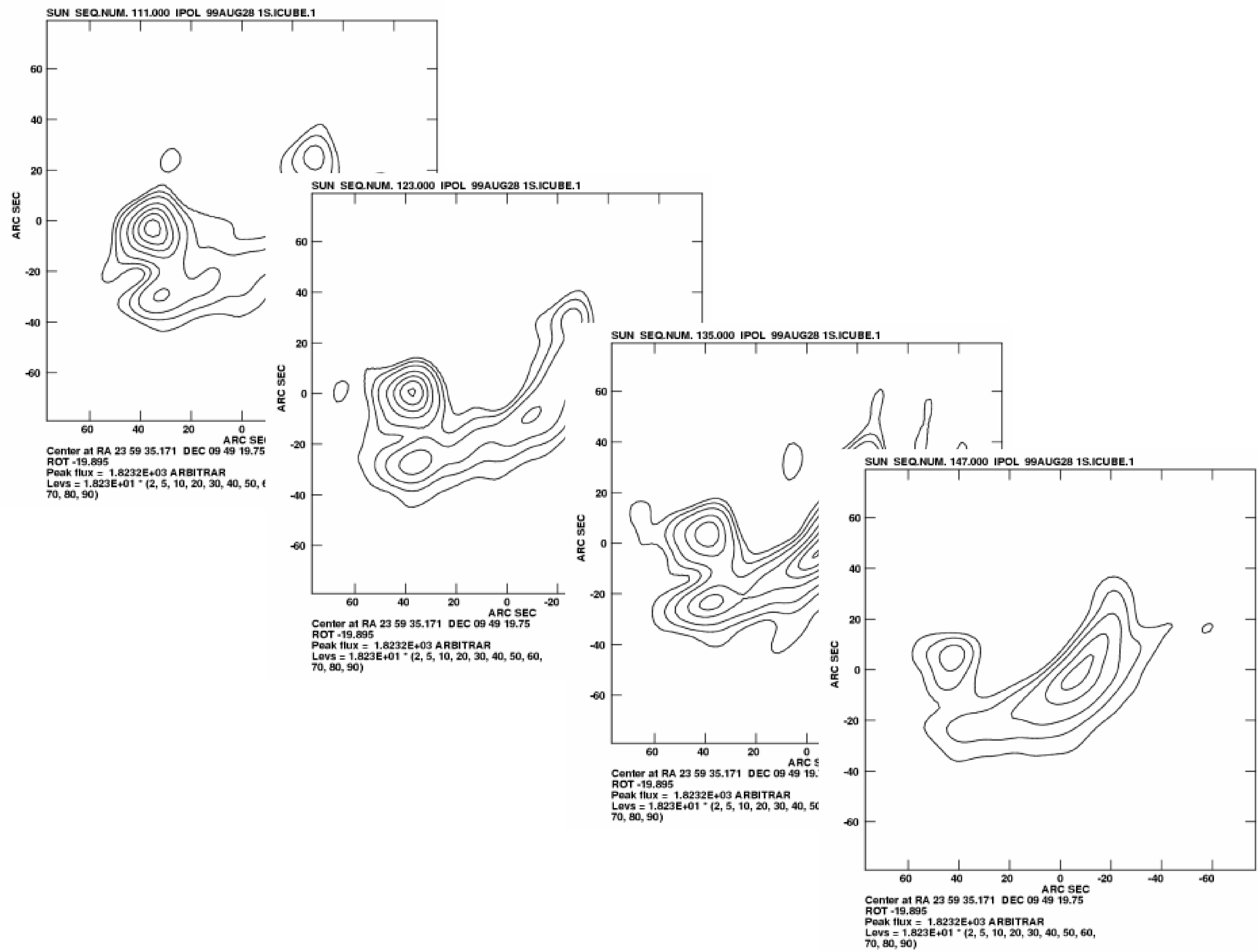


1999 August 28

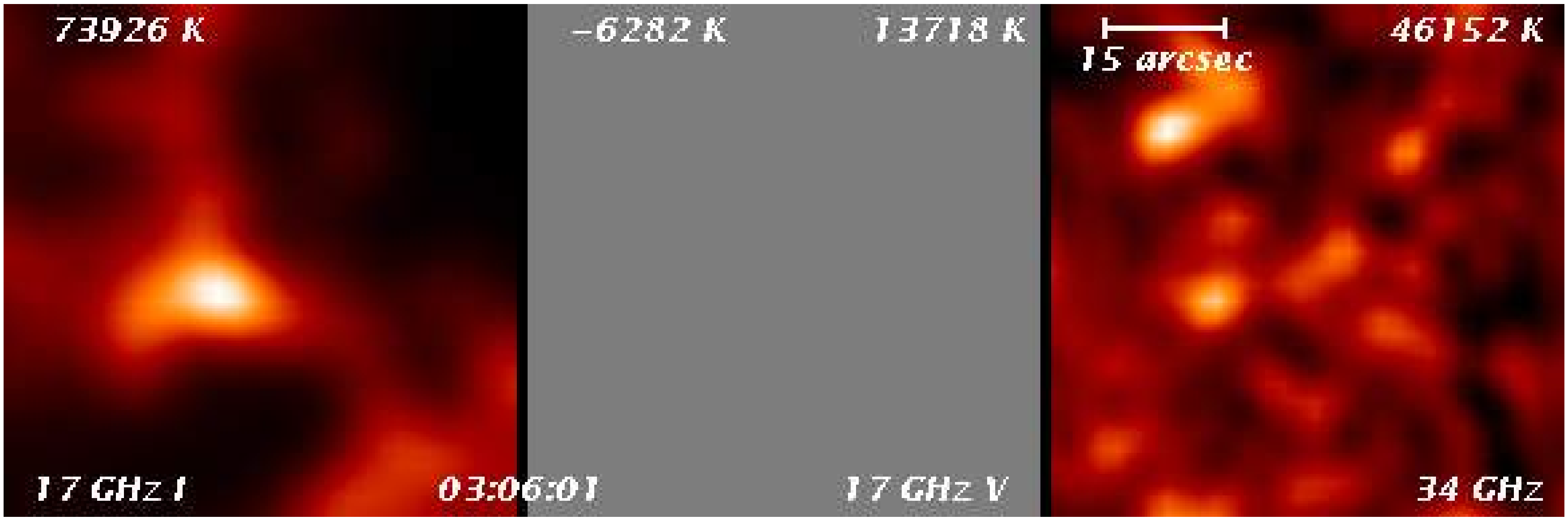




Yokoyama et al 2002

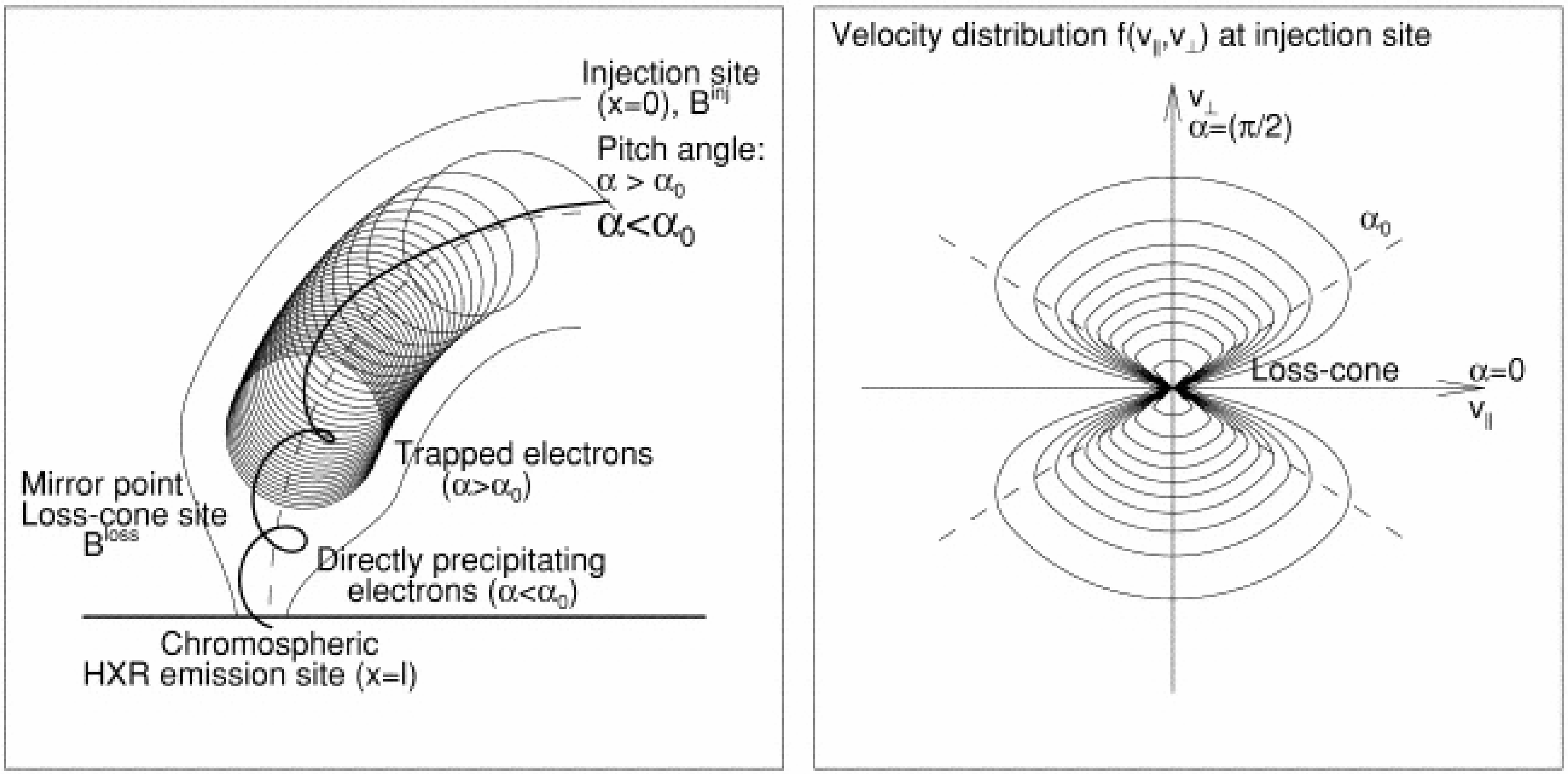

SUN SEQ.NUM. 111.000 IPOL 99AUG28 1S.ICUBE.1
ARC SEC
Center at RA 23 59 35.171 DEC 09 49 19.75
ROT -19.895
Peak flux = 1.8232E+03 ARBITRAR
Levs = 1.823E+01 * (2, 5, 10, 20, 30, 40, 50,
70, 80, 90)
SUN SEQ.NUM. 123.000 IPOL 99AUG28 1S.ICUBE.1
ARC SEC
Center at RA 23 59 35.171 DEC 09 49 19.75
ROT -19.895
Peak flux = 1.8232E+03 ARBITRAR
Levs = 1.823E+01 * (2, 5, 10, 20, 30, 40, 50, 60,
70, 80, 90)
SUN SEQ.NUM. 135.000 IPOL 99AUG28 1S.ICUBE.1
ARC SEC
Center at RA 23 59 35.171 DEC 09 49 19.
ROT -19.895
Peak flux = 1.8232E+03 ARBITRAR
Levs = 1.823E+01 * (2, 5, 10, 20, 30, 40, 50
70, 80, 90)
SUN SEQ.NUM. 147.000 IPOL 99AUG28 1S.ICUBE.1
ARC SEC
Center at RA 23 59 35.171 DEC 09 49 19.75
ROT -19.895
Peak flux = 1.8232E+03 ARBITRAR
Levs = 1.823E+01 * (2, 5, 10, 20, 30, 40, 50, 60,
70, 80, 90)

17 GHz intensity 17 GHz circ. pol. 34 GHz intensity

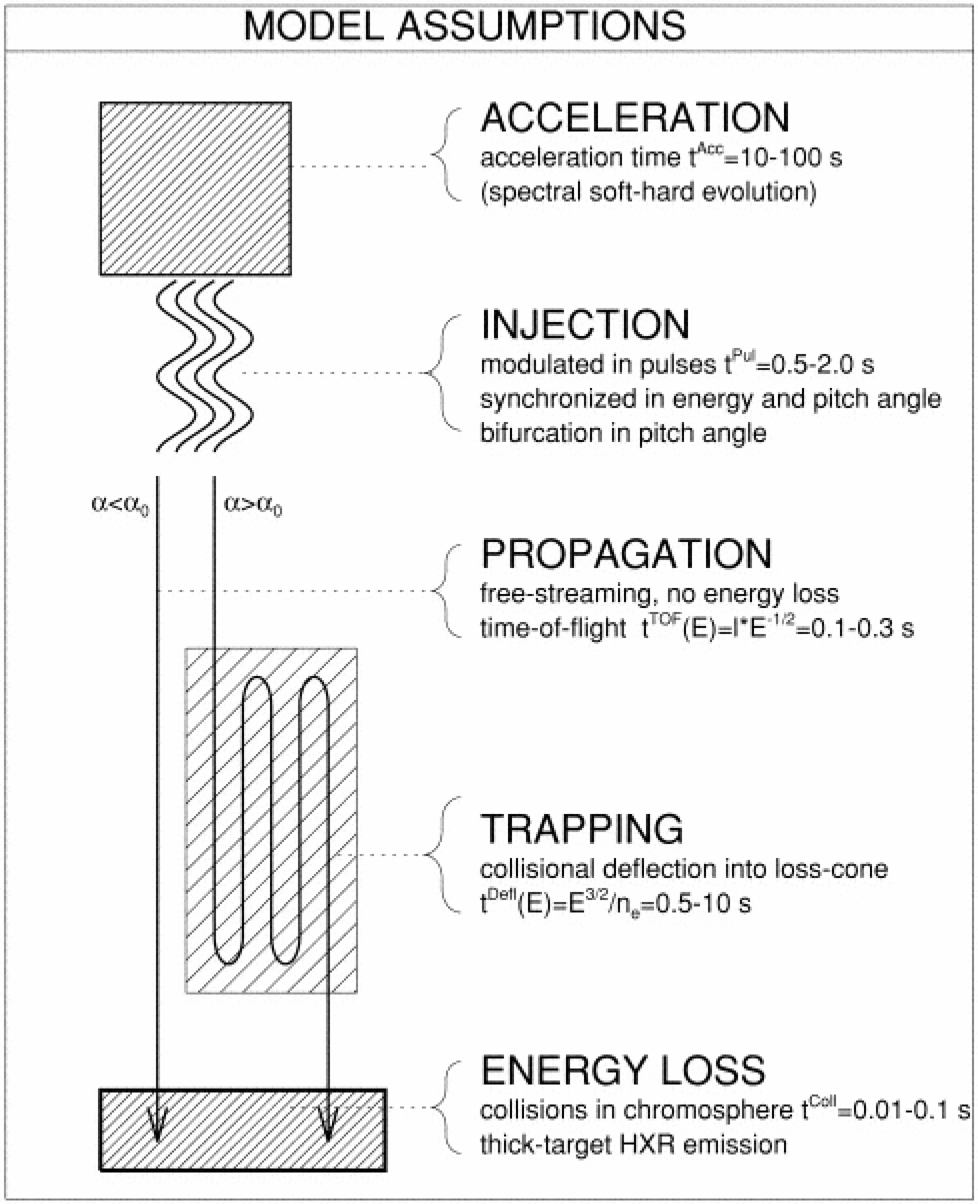


Magnetic field lines in the solar corona illuminated by gyrosynchrotron emission from nonthermal electrons.

Nobeyama RH



Injection site
(x=0), B^{inj}
Pitch angle:
$\alpha > \alpha_0$
$\alpha<\alpha_0$
Trapped electrons
($\alpha>\alpha_0$)
Mirror point
Loss-cone site
B^{loss}
Directly precipitating
electrons ($\alpha<\alpha_0$)
Chromospheric
HXR emission site (x=l)
Velocity distribution $f(v_{\parallel},v_{\perp})$ at injection site
$v_{\perp}$
$\alpha=(\pi/2)$
α_0
Loss-cone
$\alpha=0$
$v_{\parallel}$

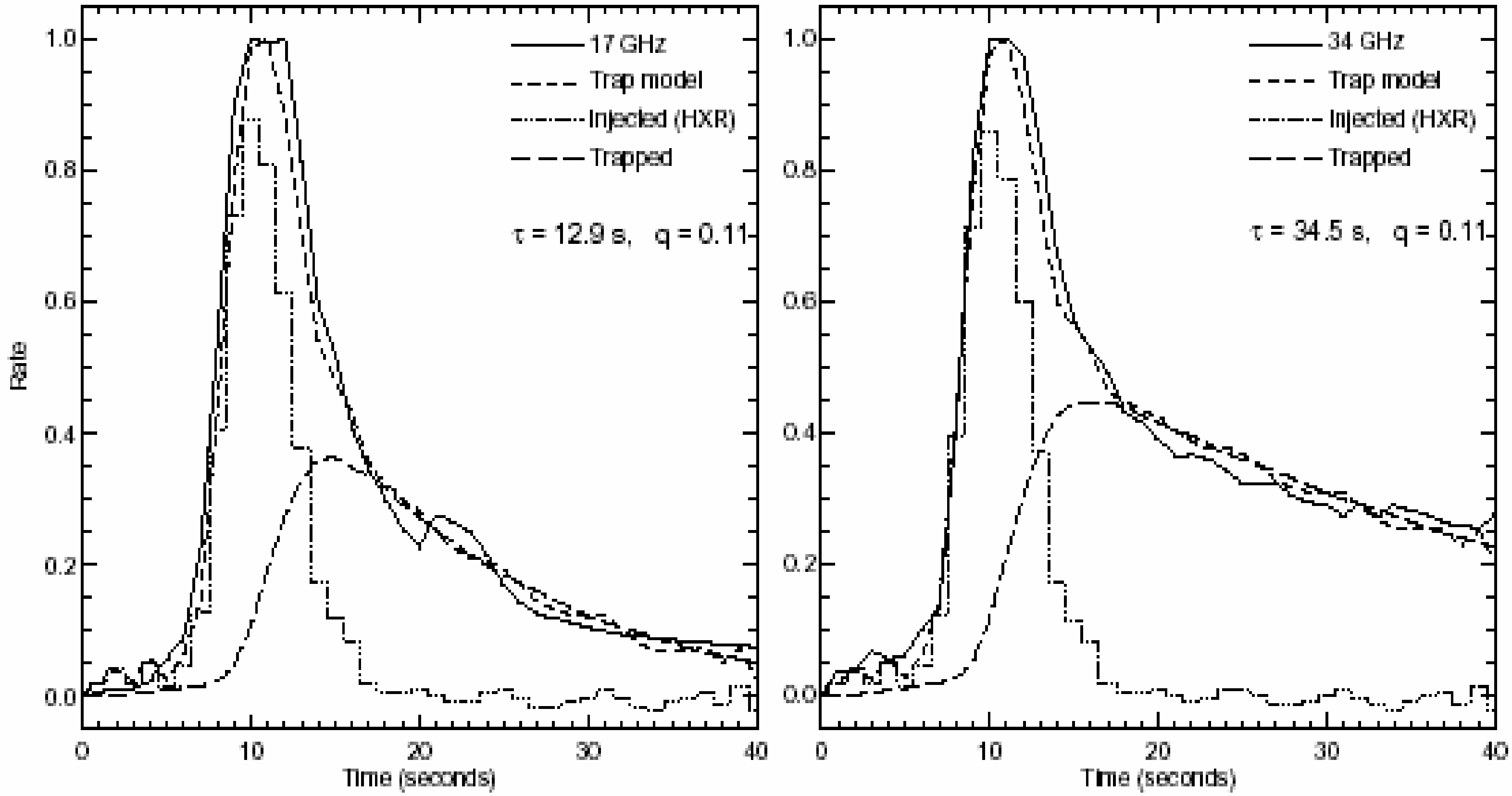


TPP/DP Model

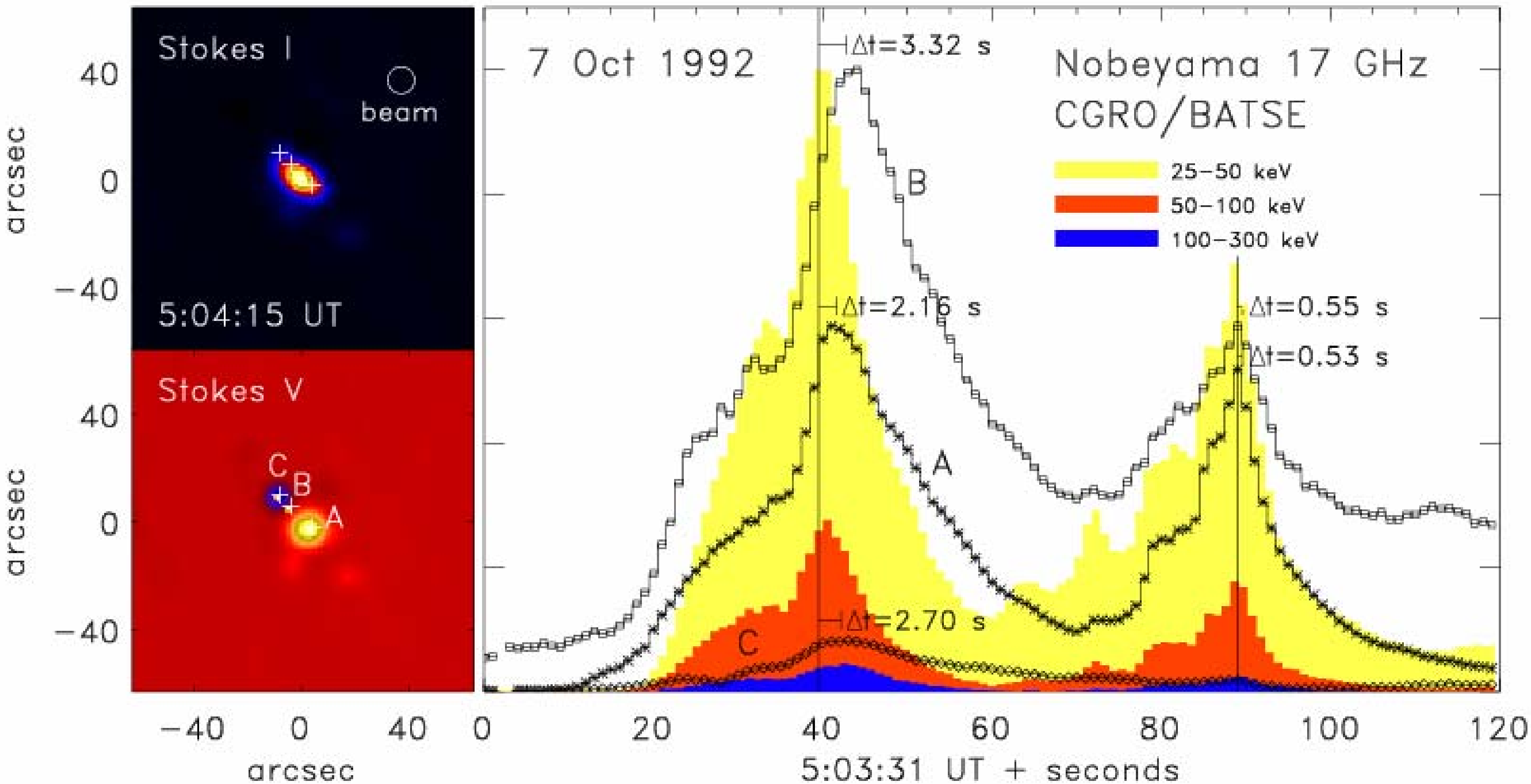
$$\nu_D \propto \nu_E \propto E^{-3/2}$$

from Aschwanden 1998

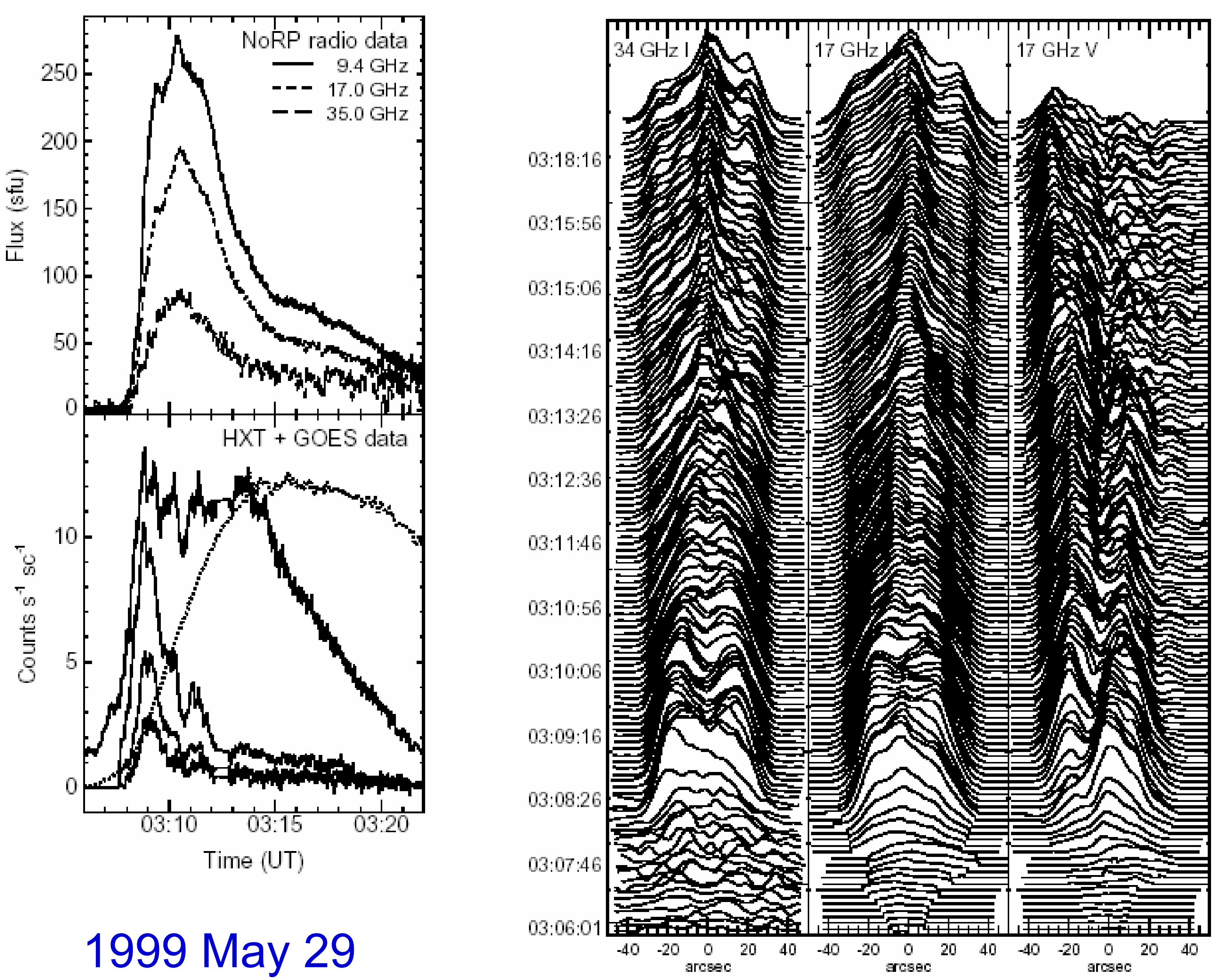
1998 June 13



Kundu et al. 2001



Bastian et al 1998

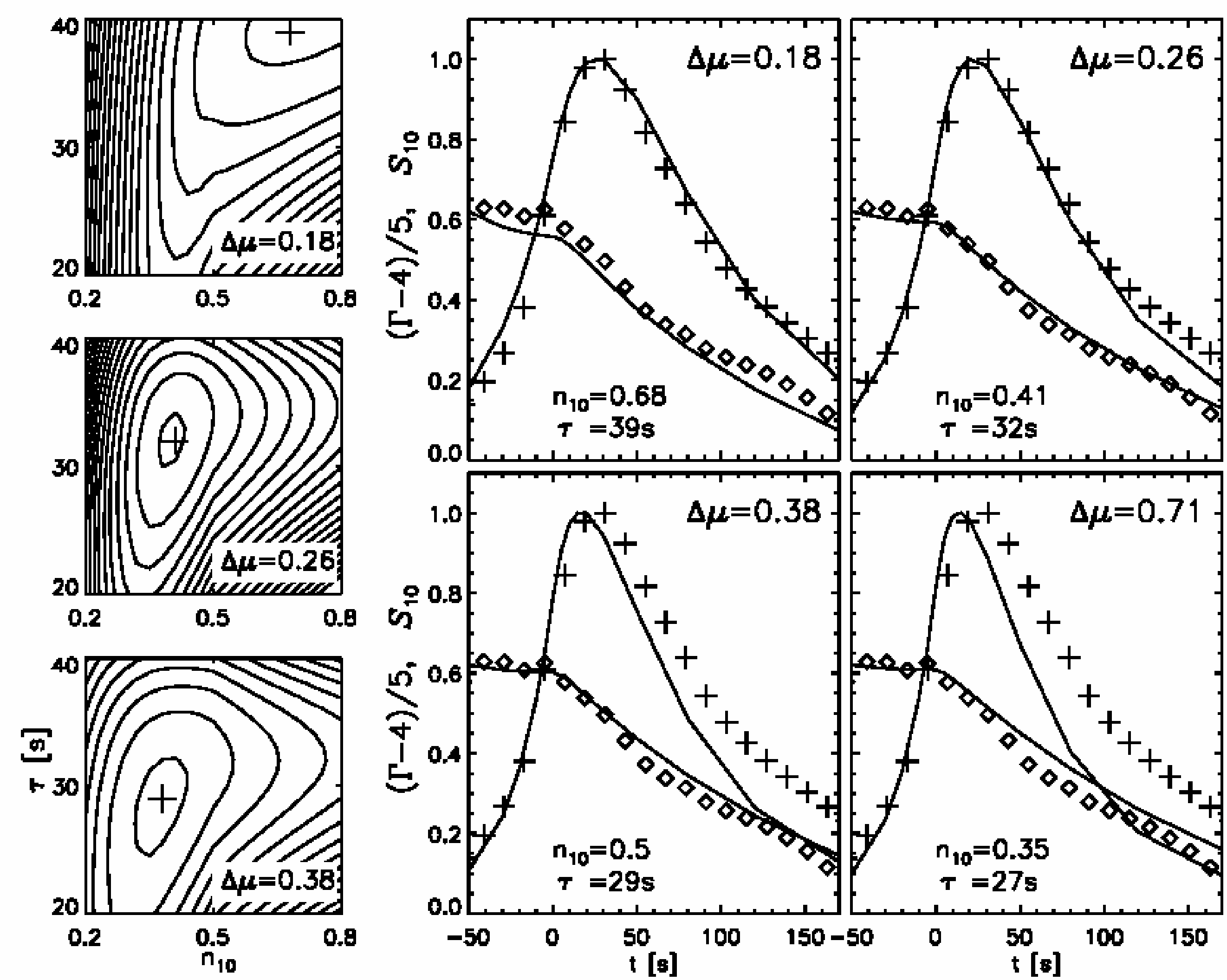


1999 May 29

White et al 2002

1993 June 3

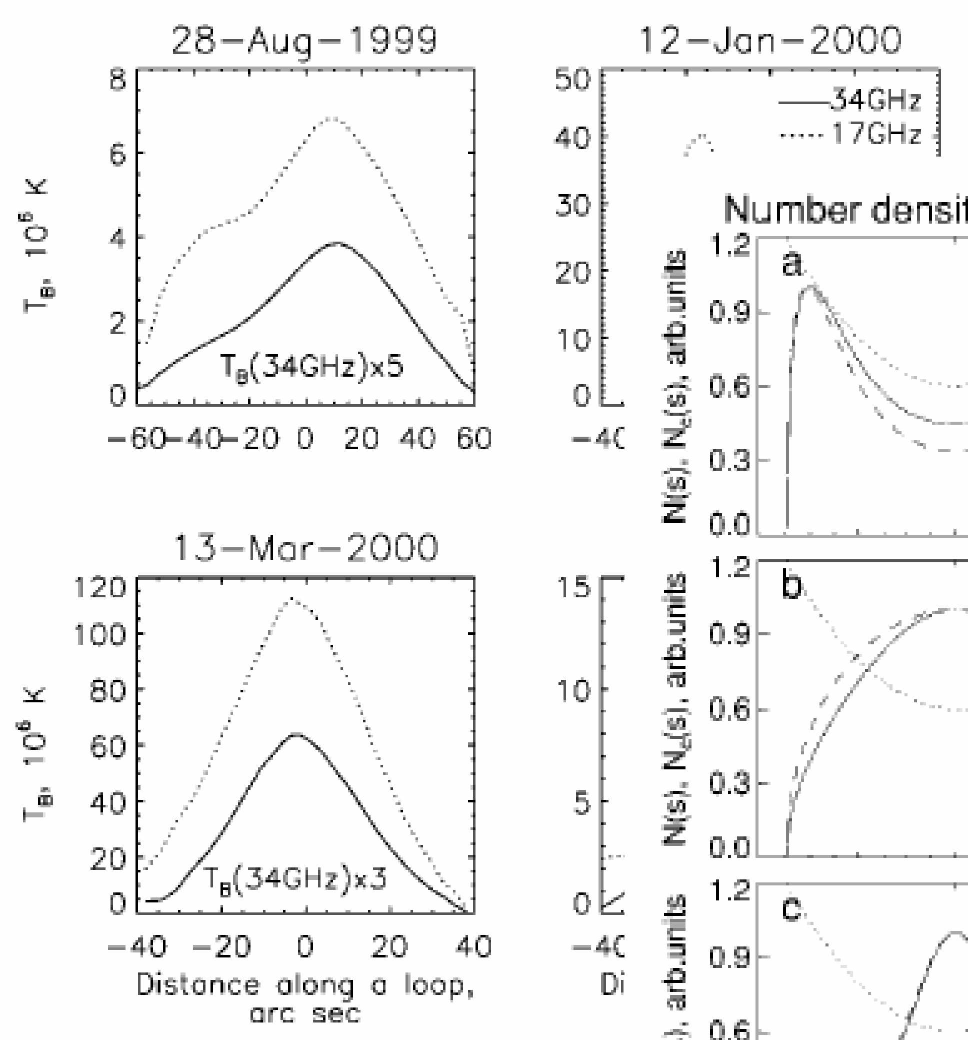
OVSA

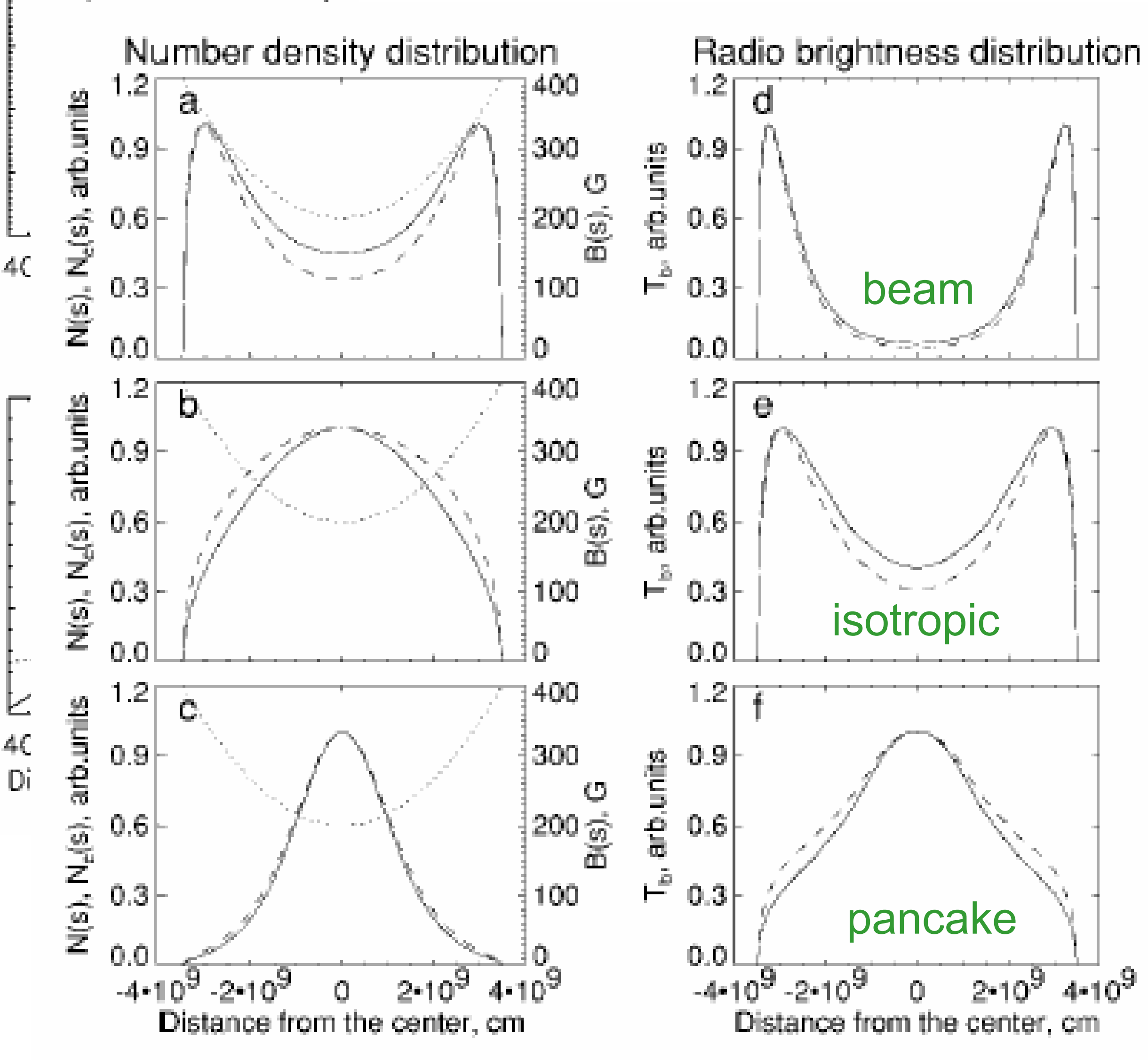


$\mu_o=0$

$$P_\gamma(\mu)\,|_{s=0} = \frac{1}{\sqrt{\pi}\Delta\mu} \exp\left[-4\,\frac{(\mu-\mu_0)^2}{\Delta\mu^2}\right].$$

Lee & Gary 2000





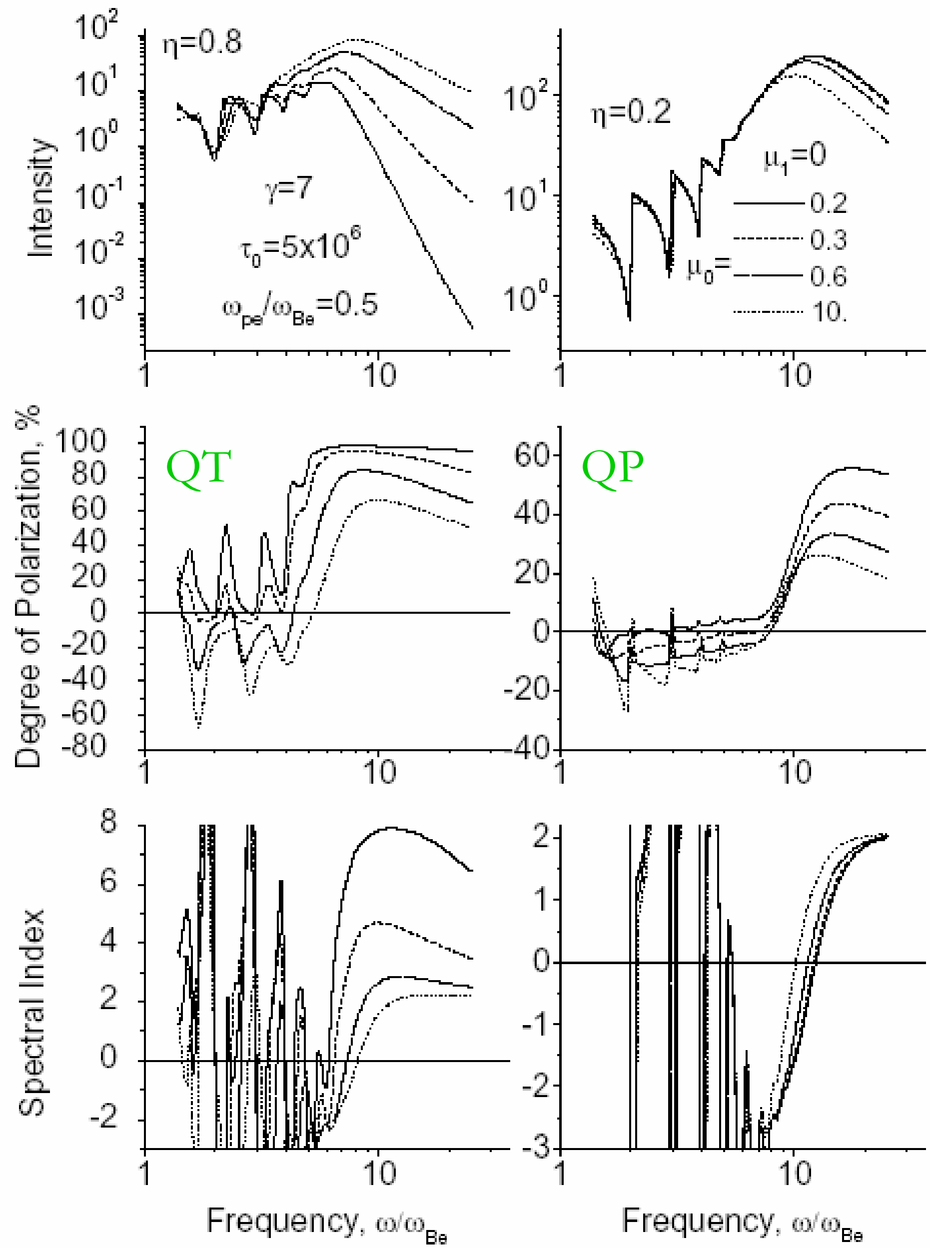
Melnikov et al 2002

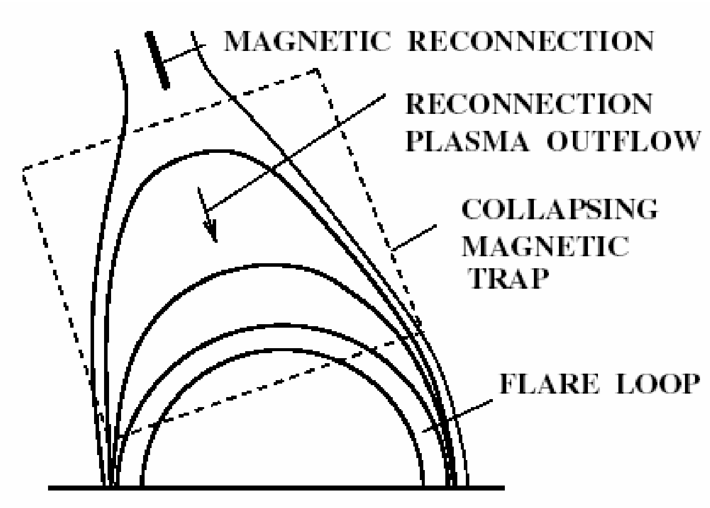
Gyrosynchrotron radiation from anisotropic electrons

Fleishman & Melnikov 2003a,b

Properties of the emitted radiation – e.g., intensity, optically thin spectral index, degree of polarization – depend sensitively on the type and degree of electron anisotropy

$$\eta = \cos \theta$$

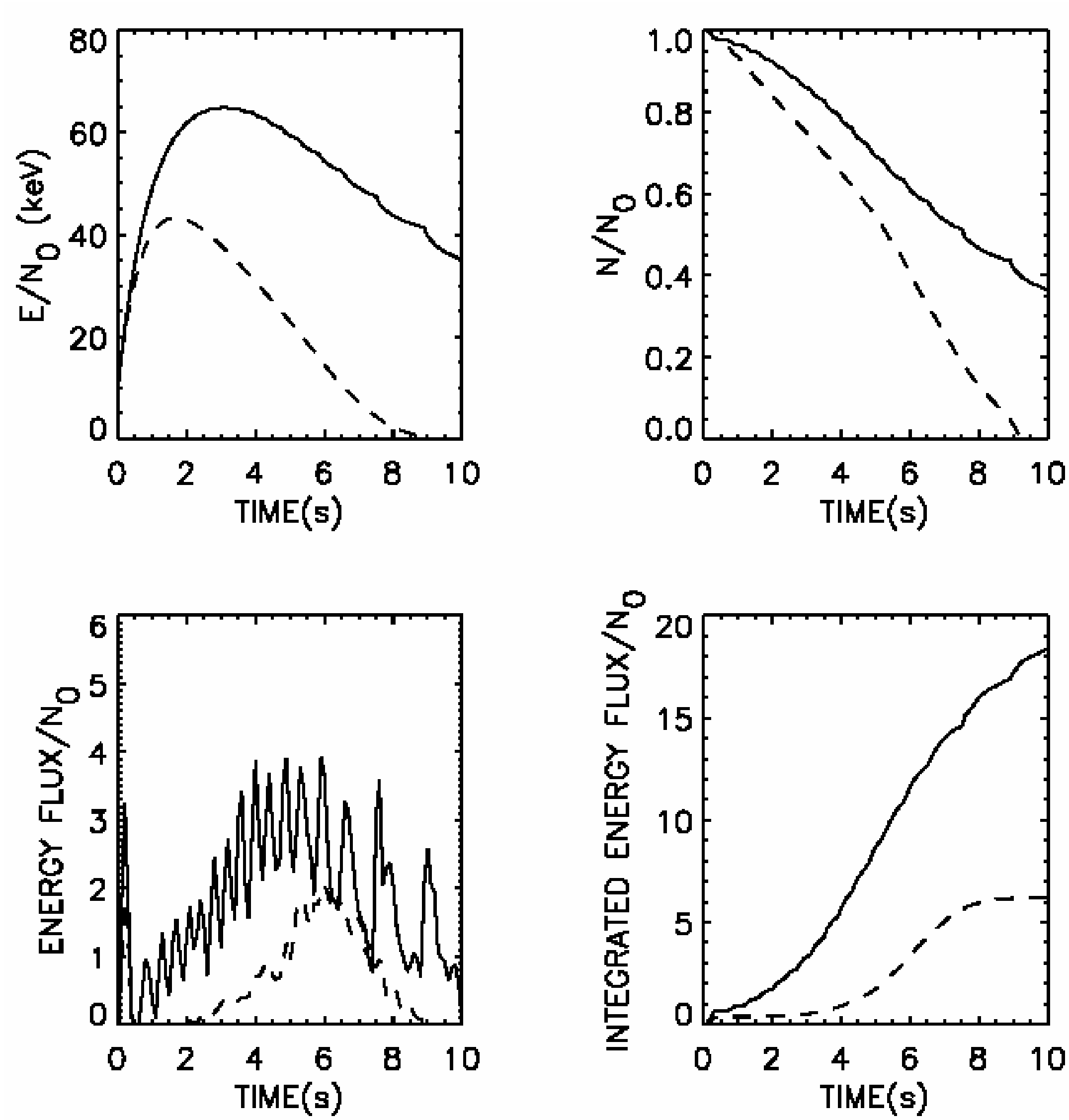




"Collapsing trap"

Karlický & Kosugi 2004

- Analysis of betatron acceleration of electrons due to relaxation of post-reconnection magnetic field lines.
- Energies electrons and producers highly anisotropic distribution



Model electron properties near "footpoint"

Observations of Radio emission from flares

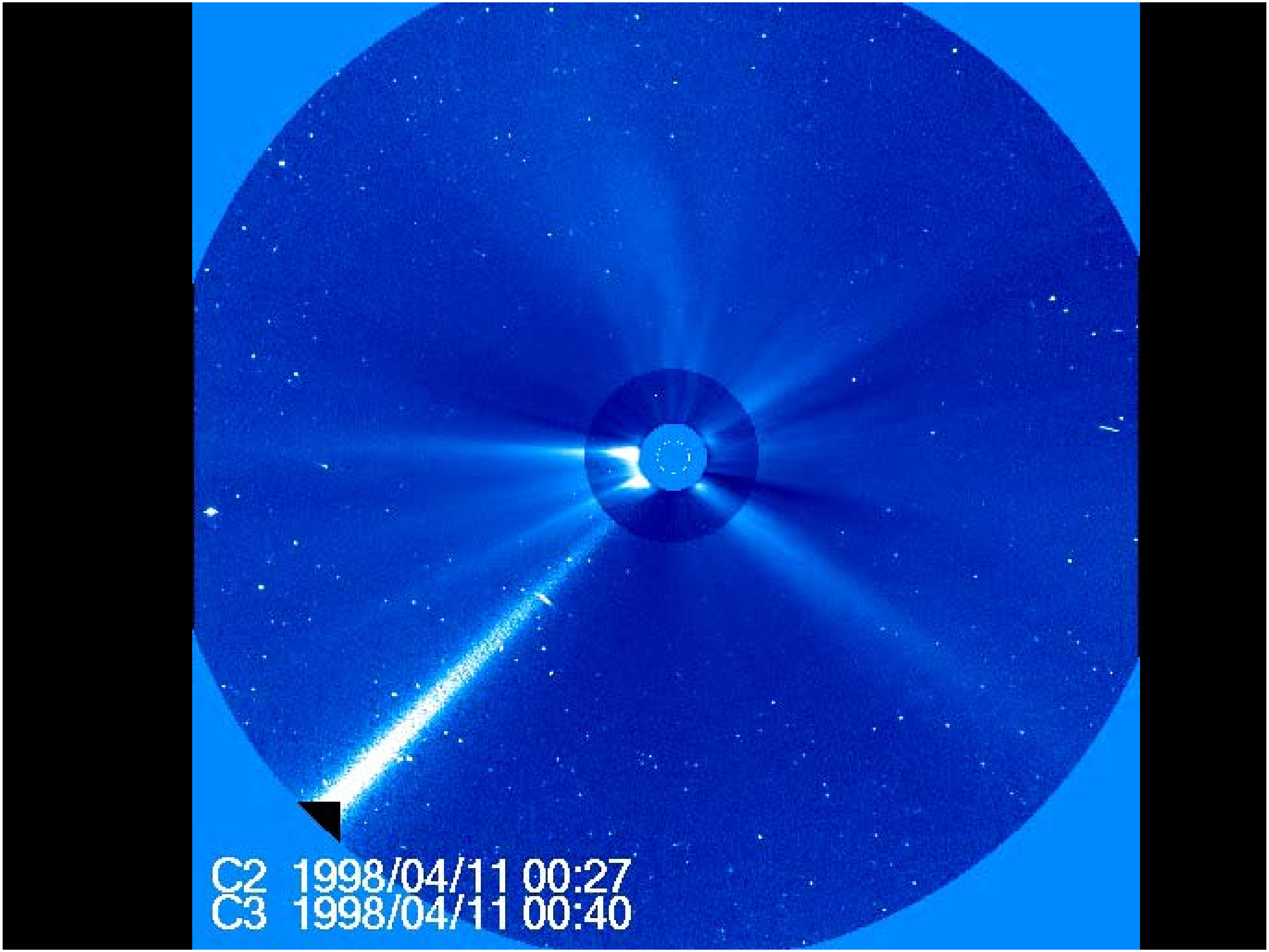
- Access to nonthermal electrons throughout flaring volume: magnetic connectivity

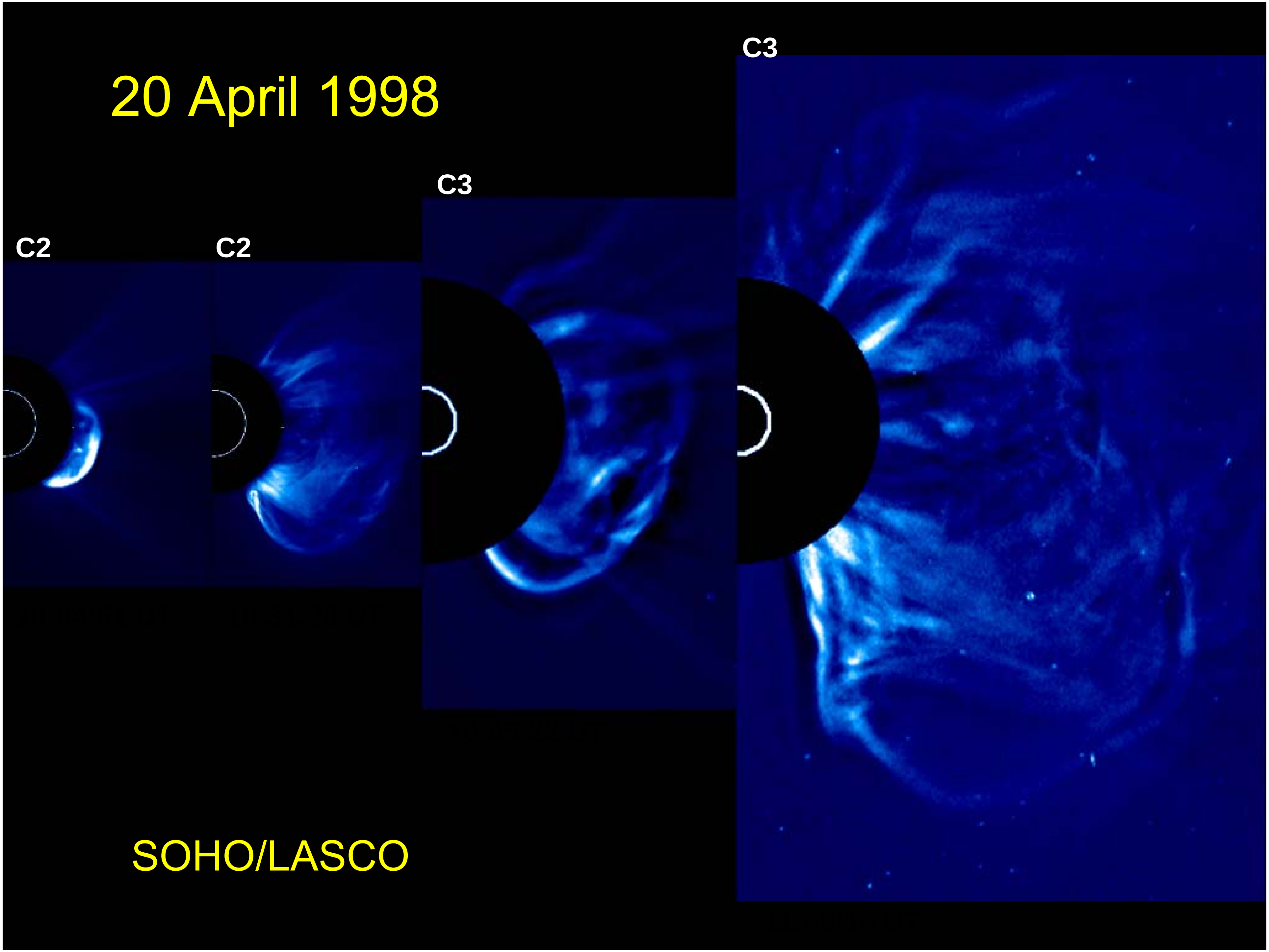
- Sensitive to electron distribution function and magnetic vector, ambient density and temperature

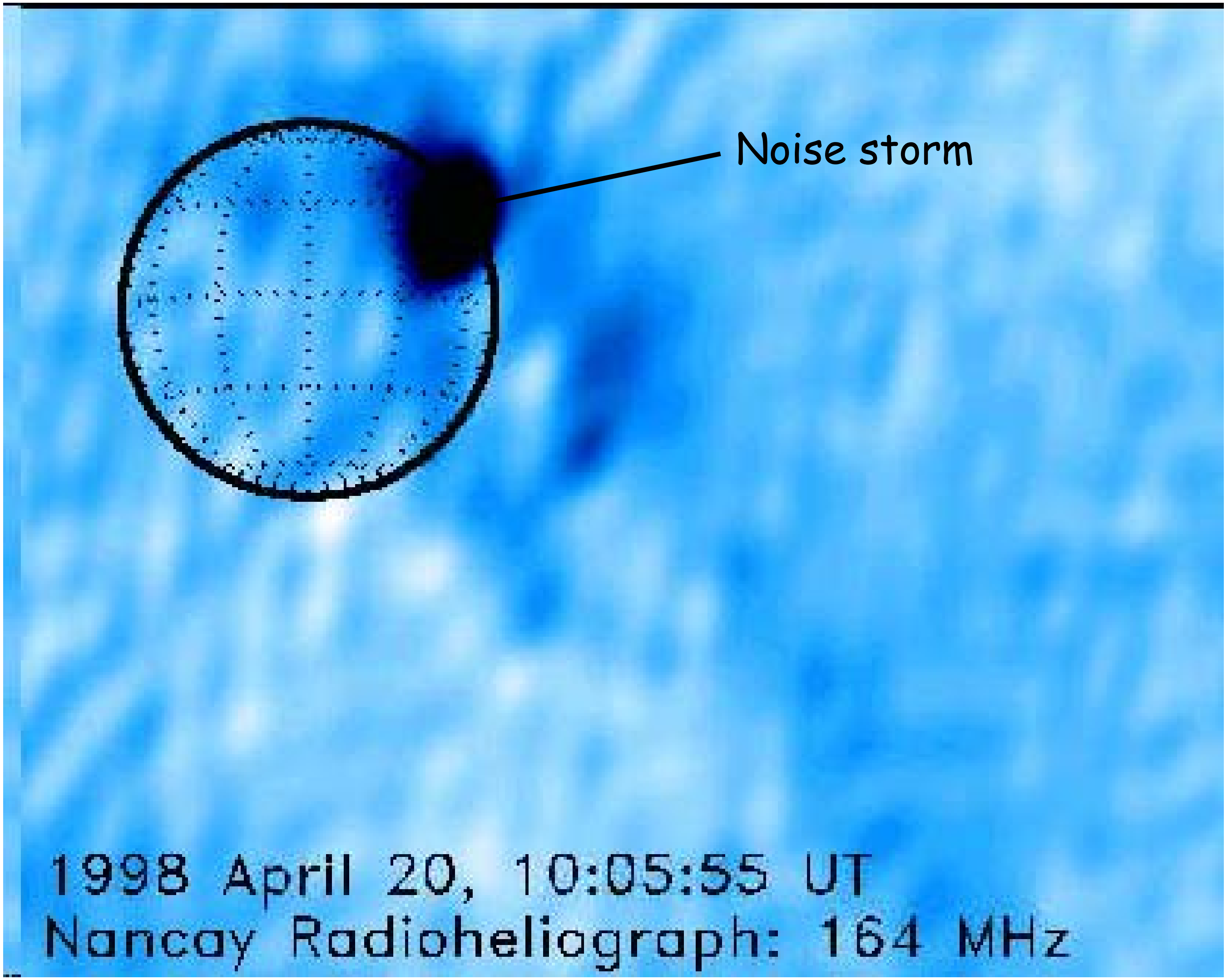
- Observations over past decade have clarified relation of microwave-emitting electrons to HXR-emitting electrons: FP, LT, spectral properties

- Recent work has emphasized importance of particle anisotropies

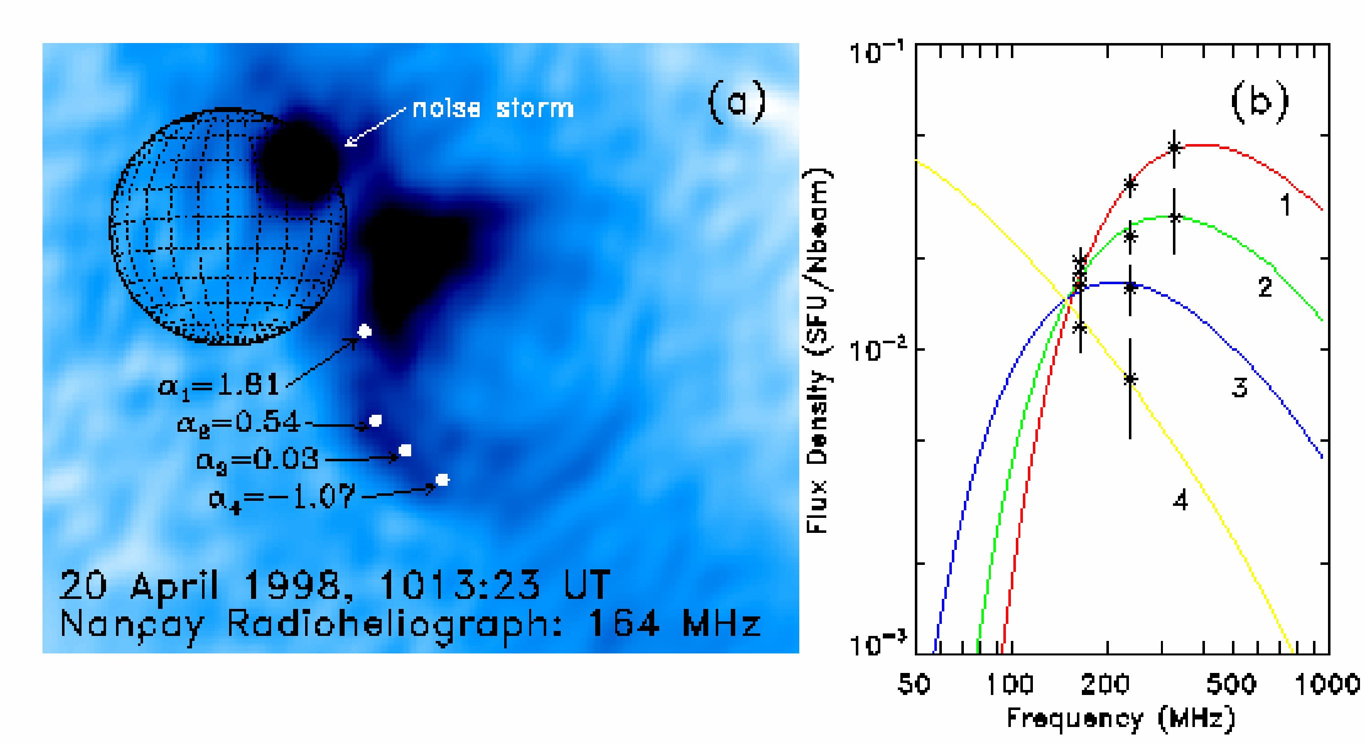
Need an instrument capable of time-resolved broadband imaging spectroscopy to fully exploit radio diagnostics!


C2 1998/04/11 00:27
C3 1998/04/11 00:40


20 April 1998
C2
C2
C3
C3
SOHO/LASCO

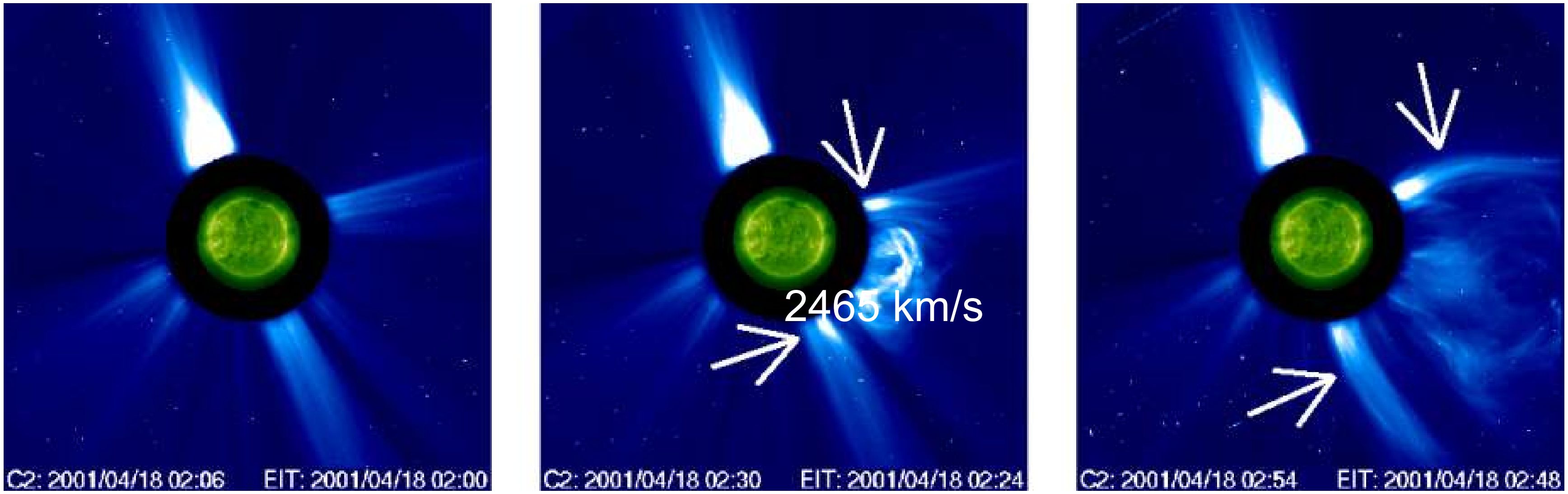


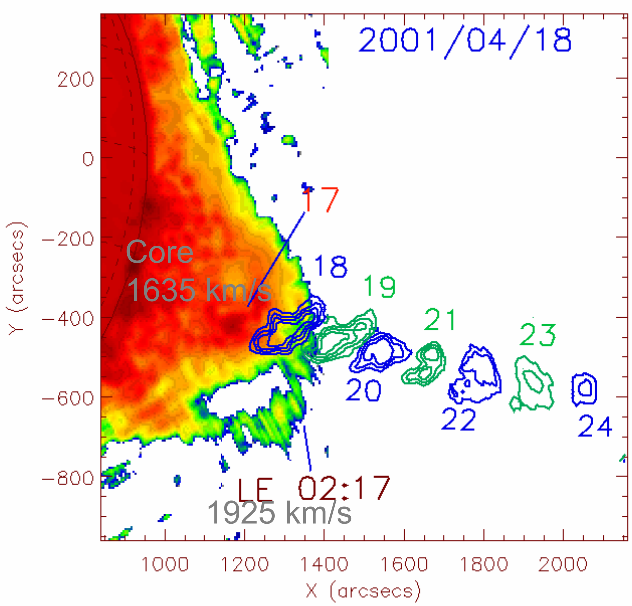
Bastian et al. (2001)



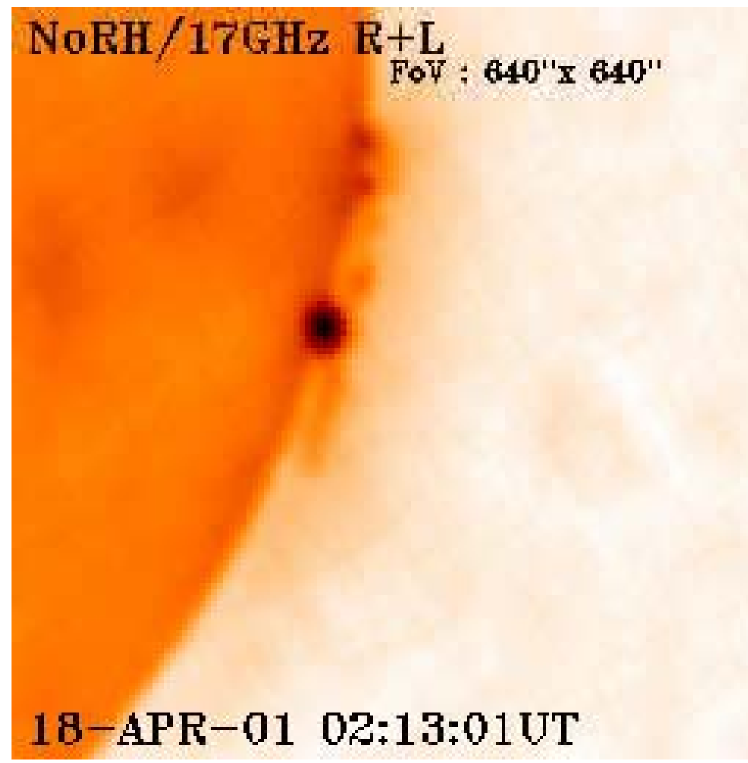
LoS	α	R_{sun}	ϕ (deg)	n_e (cm^{-3})	B(G)	ν_{RT} (MHz)
1	1.81	1.45	234	2.5×10^7	1.47	330
2	0.54	2.05	218.5	1.35×10^7	1.03	265
3	0.03	2.4	219.5	6.5×10^6	0.69	190
4	-1.07	2.8	221	5×10^5	0.33	30

Bastian et al. (2001)

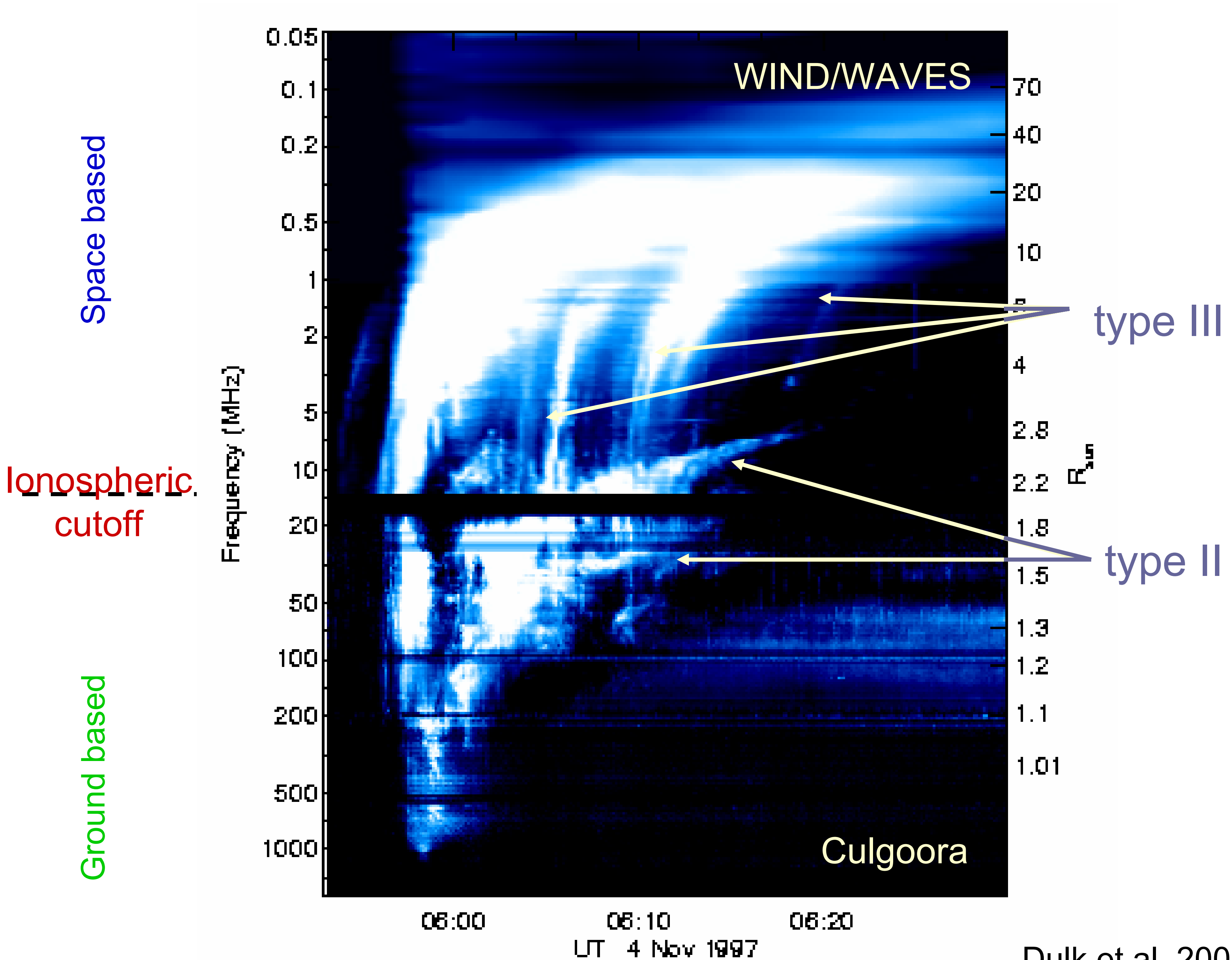




see Hudson et al. 2001



Gopalswamy et al 2004



Dulk et al. 2001

Observations of Radio emission from CMEs

- Unique access to the nascent stages of CMEs
- Sensitive to both gyrosynchrotron (leading edge) and thermal (core) emission
- Provides means of measuring speed, acceleration, width etc.
- Can also measure B (CME), n_{th} (CME), n_{rel} (CME), nth (core), T (core)

Need an instrument capable of time-resolved broadband imaging spectroscopy to fully exploit radio diagnostics!

[redacted]

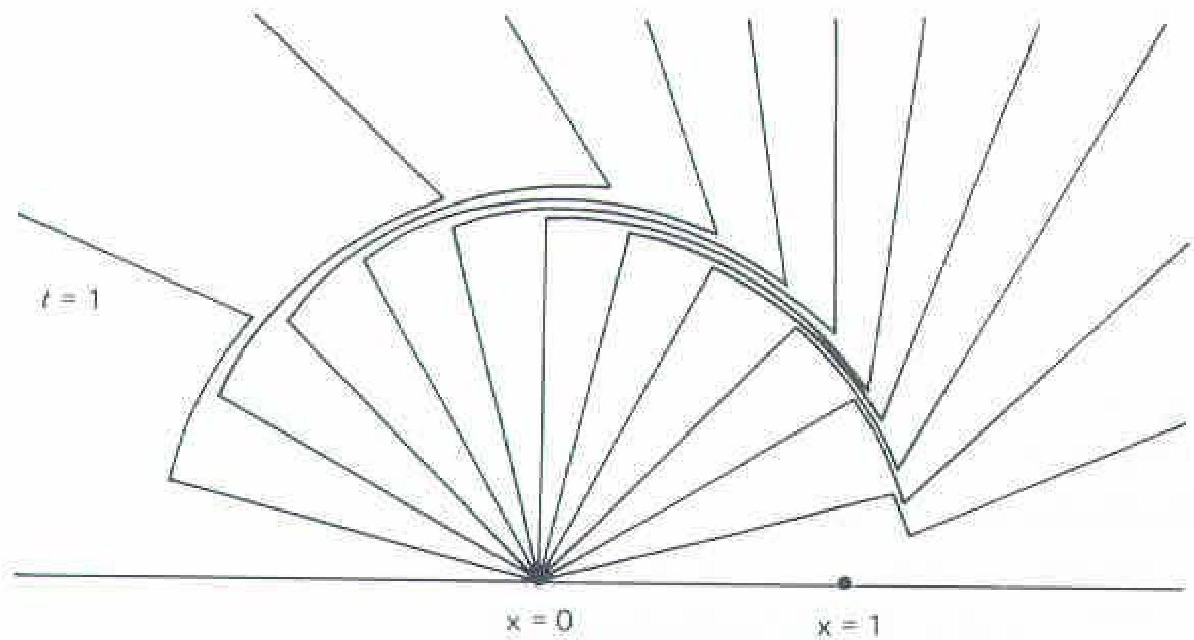
Larmor Formula

For the time being, we are going to consider continuum emission mechanisms, deferring emission and absorption in spectral lines until later.

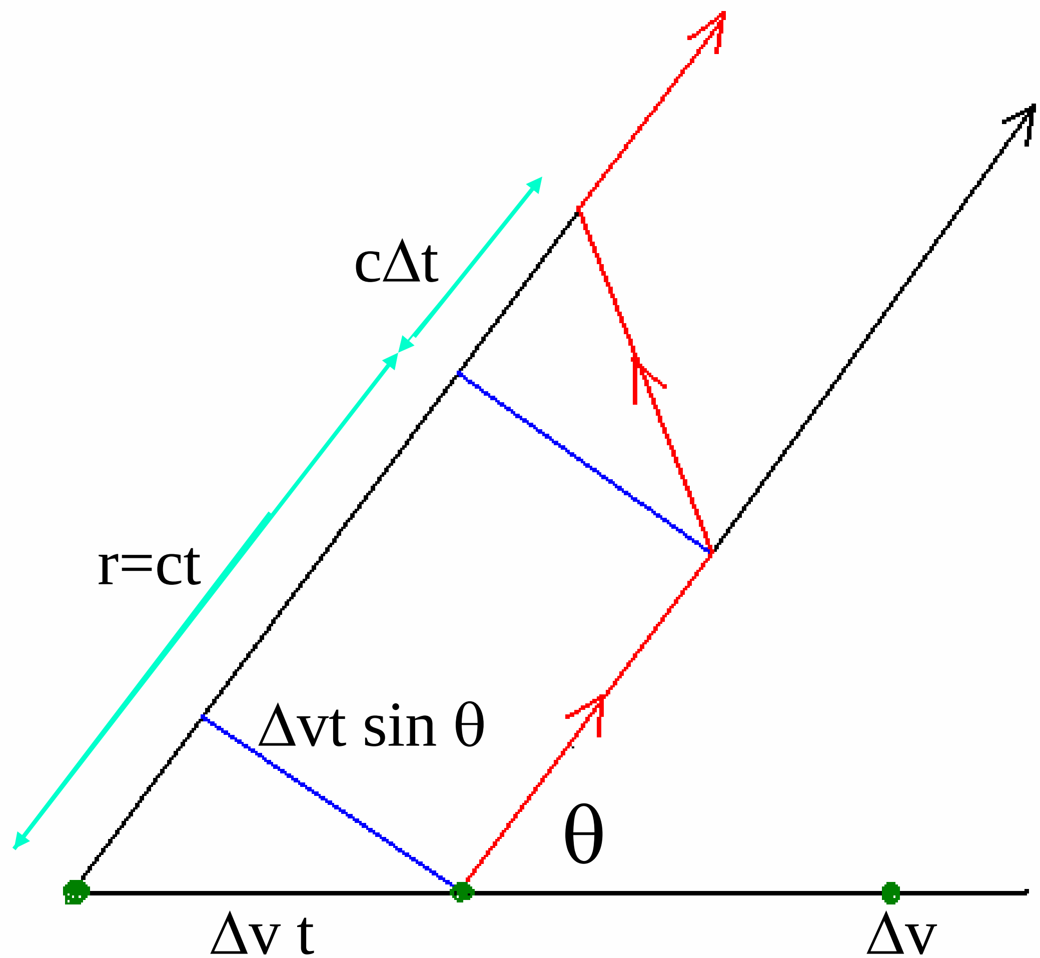
We are therefore going to ignore radiation processes involving atomic and molecular transitions and instead think about radiation from free charges.

A derivation of radiation from free charges is somewhat involved. I'm just going to sketch out the underlying physical ideas using a simple derivation due to J.J Thomson.

First, consider a charged particle q moving at some velocity v from left to right. It is suddenly brought to a stop at point x at time $t=0$; I.e., it is decelerated.



Alternatively, a charge can be accelerated. We'll analyze this case...



cΔt
r=ct
Δvt sin θ
θ
Δv t
Δv

The ratio of the perpendicular component of the electric field to the radial component is

$$\frac{E_\theta}{E_r} = \frac{\Delta v\, t \sin\theta}{c\Delta t}$$

$$E_r = \frac{q}{r^2}$$

from Coulomb's Law. Since $r=ct$, we can substitute and rearrange terms to get

$$E_\theta = \frac{q}{rct}\frac{\Delta v}{\Delta t}\frac{t\sin\theta}{c} = \frac{q\dot{v}\sin\theta}{rc^2}$$

Note that E_r is proportional to $1/r^2$, while E_θ is proportional to $1/r$, so $E_\theta \gg E_r$ far from the charge q.

The radiation power is given by the Poynting Flux (power per unit area: ergs cm^{-2} s^{-1} or watts m^{-2})

$$\mathbf{S} = \frac{c}{4\pi}\mathbf{E}\times\mathbf{H} = \frac{c}{4\pi}E^2$$

Substituting our expression for E_θ for E, we obtain

$$|\mathbf{S}| = \frac{c}{4\pi}\left(\frac{q\dot{v}\sin\theta}{rc^2}\right)^2 = \frac{q^2\dot{v}^2\sin^2\theta}{4\pi c^3 r^2}$$

The power pattern is determined by the factor $\sin^2\theta$, which yields a “donut” (dipole pattern) whose axis is coincident with the vector along which the charge was accelerated.

To compute the total radiation power P produced by the accelerated charge, we integrate over the sphere of radius r:

$$P = \iint S\, dA = \frac{q^2 \dot{v}^2}{4\pi c^3} \int_{\phi=0}^{2\pi} \int_{\theta=0}^{\pi} \frac{\sin\theta}{r^2}\, \mathrm{r}\, d\theta\, \mathrm{r} \sin\theta\, \mathrm{d}\theta$$

$$P = \frac{q^2 \dot{v}^2}{2c^3} \int_{\theta=0}^{\pi} \sin^3\theta\, \mathrm{d}\theta = \frac{2}{3} \frac{q^2 \dot{v}^2}{c^3}$$

The last expression is called Larmor's Equation. Note that the power is proportional to the square of the charge and the square of the acceleration.