Electro-magnetic wave emission

from the Sun

Part - II

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Talk PLAN

1 **Discovery & Nature of solar radio emission**

2 **Quiet Sun, Slowly Varying Component, & the Transients**
     (Observational view point & Very little theory)

3 **Radio → Sun − Earth connection**

Nature of Solar Radio emission

Can the entire radio band be used for observations??

Radio band : ~300 GHz − ~3 kHz

Sun & Earth

Obs. in ≈ 7 – 40 MHz band is difficult because of RFI

**Crucial to establish connectivity between Coronal & IP events**

Sun

$f \lesssim 7$ **MHz**
$\lambda \gtrsim 43$ **m**

$f \gtrsim 7$ **MHz**

Space based Very low-freq. Observations

Ionosphere

Band affected by RFI (up to 40 MHz)

Ground radio-freq. Obs.

Atmosphere

Earth

~7-15 MHz ionospheric Layer (cutoff)
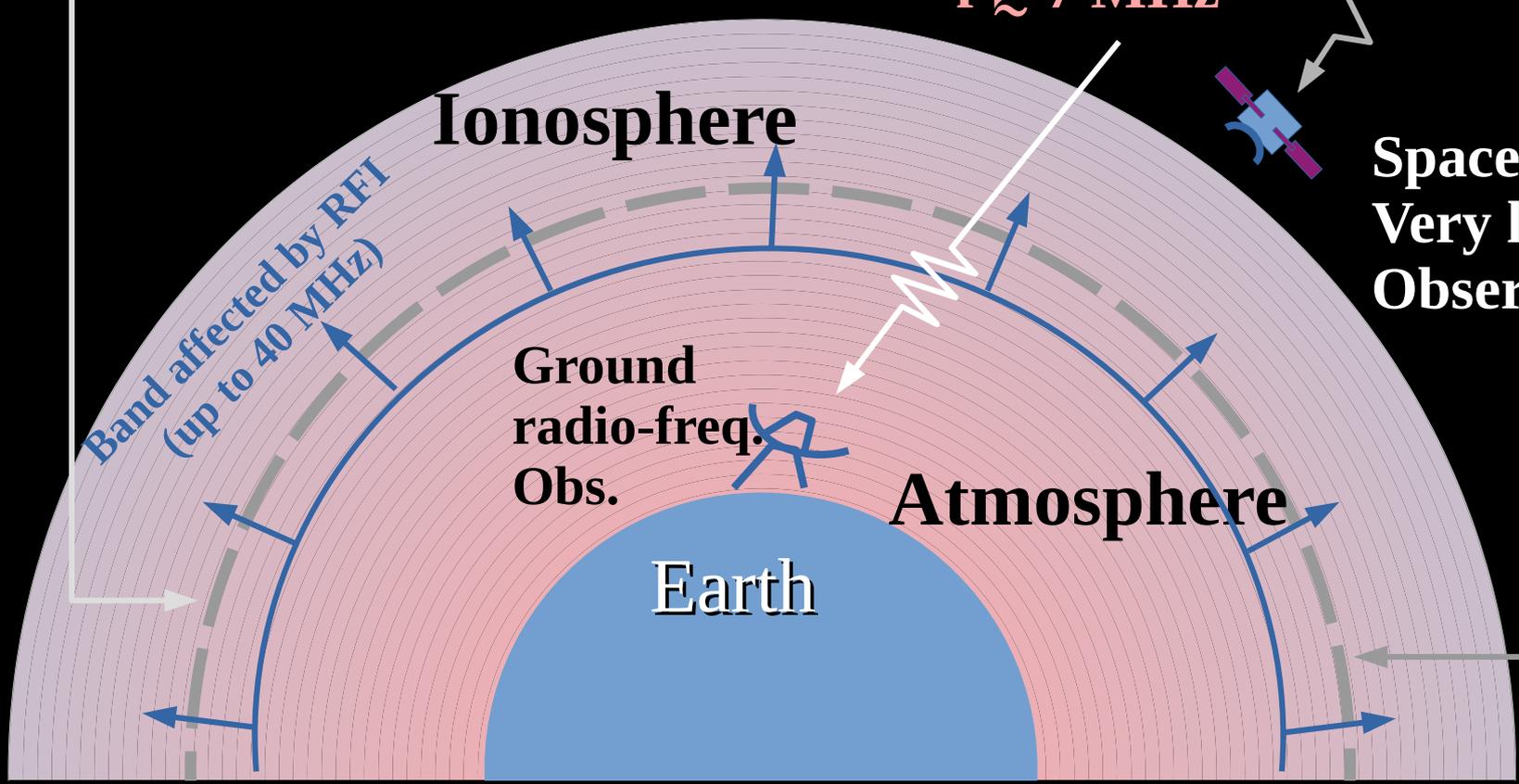
Has the Sun been observed over the entire radio band ??

Yes, Of course …

Can you show some examples ??

Solar Radio Emission

① **Quiet Sun Component (QSC)**
(Thermal)

② **Slowly Varying Component (SVC)**
(Thermal & Non-thermal)

③ **Transient Component (TC)**
(Thermal & Non-thermal)

# How these different Components were found & classified ??

①

The Radio Quiet Sun

1D scan of the Sun : Flux density @ a specific frequency
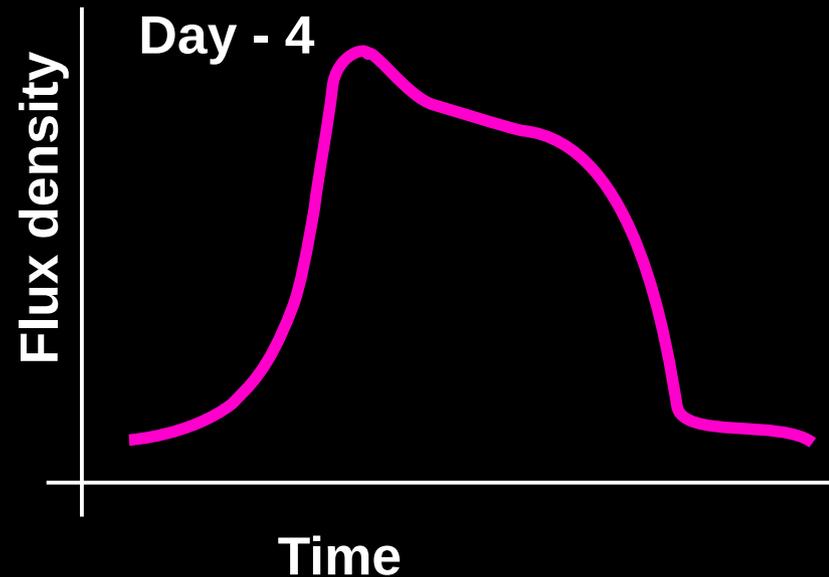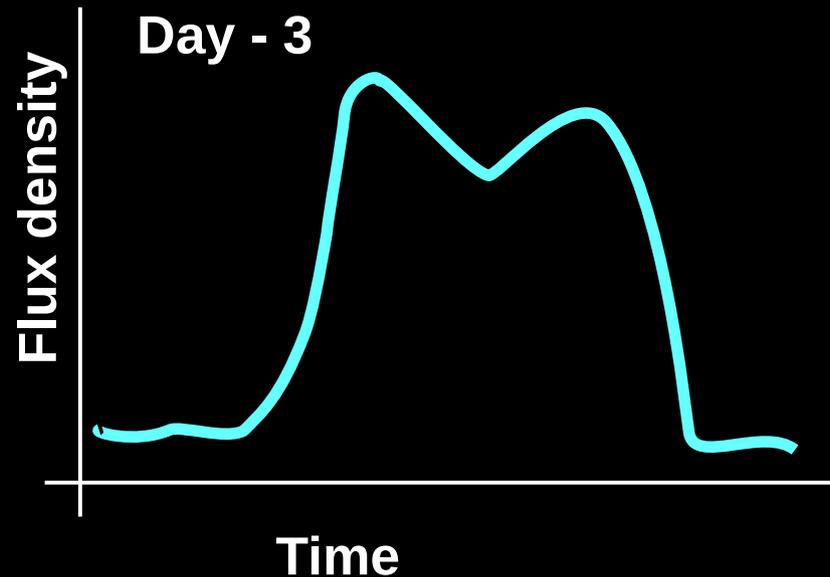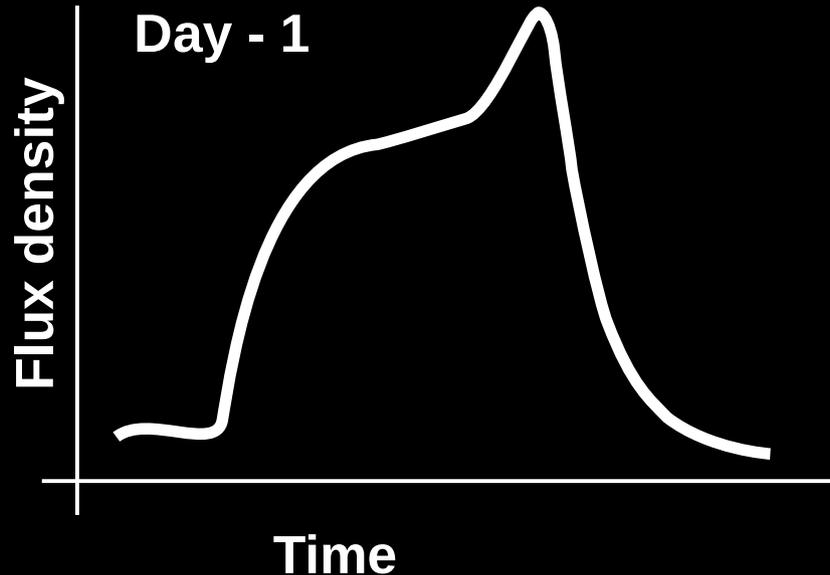
# 1D Scan of the Sun T_b (1.5 m / 200 MHz) Vs Sunspot area
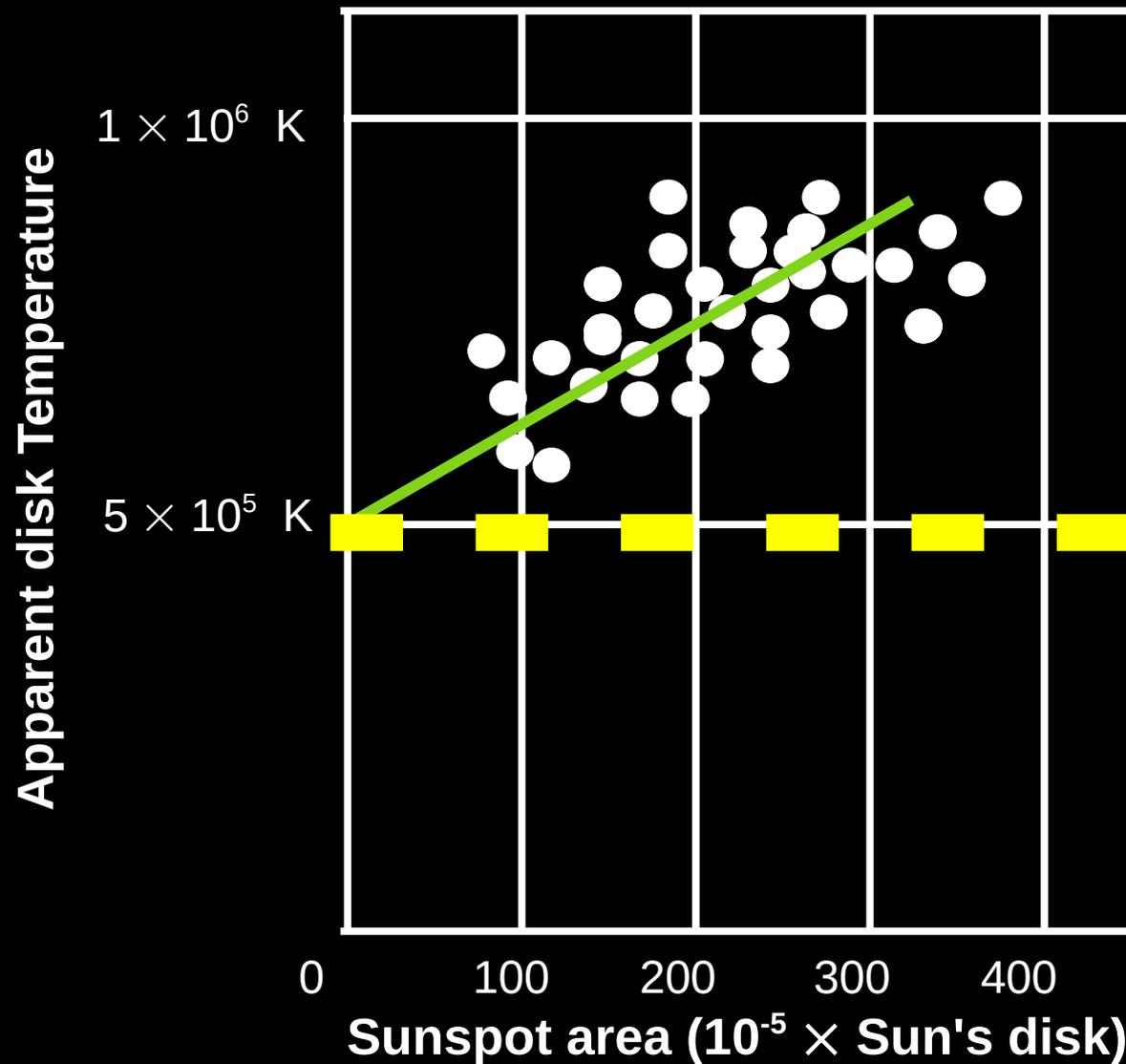
Pawsey et al., Au. J. Sci. Res.-A, 2, 198 (1949)

1D Scan of the Sun T_b (1.5 m / 200 MHz) Vs Sunspot area

1. There is a base level below which the radio intensity (or brightness temperature) never falls.

2. This was obtained by extrapolating the fit to zero sunspot area.

3. Radio astronomers attributed this minimum level to the background corona which is called the quiet Sun brightness temperature as it is independent of solar activity.

Pawsey et al., Au. J. Sci. Res.-A, 2, 198 (1949)

1D Scan of the Sun : Flux density (Superposition)
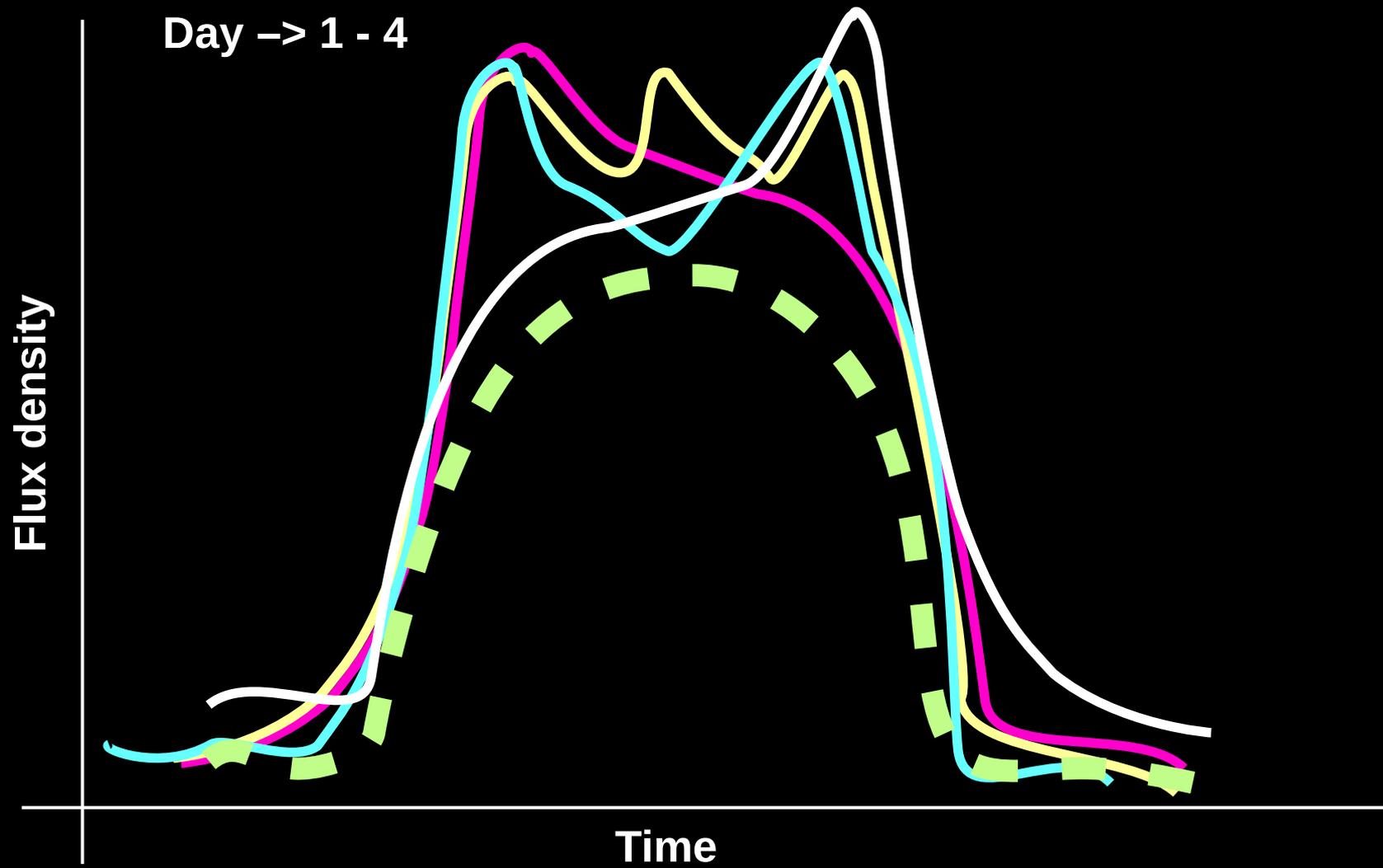
Boischot, A., Ann d' Astrophys., 21, 273 (1958)

1D Scan of the Sun : Flux density (Superposition)

Day –> 1 - 4

If we superpose the flux density distribution, there is an inner envelope and the enhanced emissions are seen above that. This is known as the quiet Sun or background flux density distribution.

Flux density

Time

Boischot, A., Ann d' Astrophys., 21, 273 (1958)

1D Scan of the Sun : Flux density (Superposition)

Day –> 1 - 4

Flux density

Photospheric disk

Chromospheric disk

Time
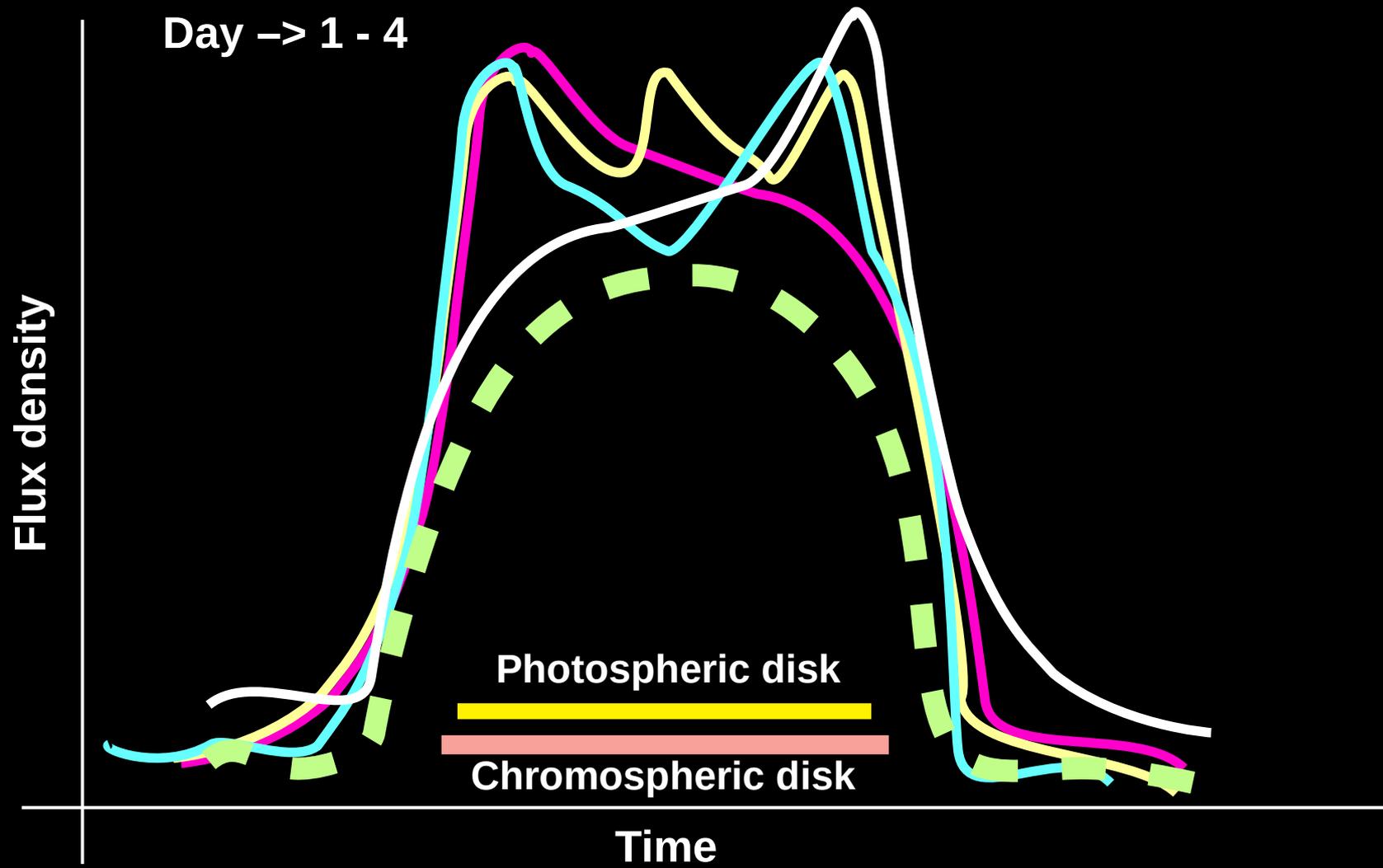
Boischot, A., Ann d' Astrophys., 21, 273 (1958)

1D Scan of the Sun : Flux density (Superposition)

Day –> 1 - 4

Flux density

The size of the radio quiet Sun is more than the size of the Photosphere or Chromosphere which implies that the radio radiation comes above the Photosphere and the Chromosphere.

Photospheric disk

Chromospheric disk

Time

Boischot, A., Ann d' Astrophys., 21, 273 (1958)

Quiet Sun Flux density spectrum : Blackbody

$$S = \left(\frac{2\, k_B\, T_b}{\lambda^2} \right) \Omega_s$$

$S \rightarrow$ flux density of the source

$k_B \rightarrow$ Boltzmann constant

$T_b \rightarrow$ Brightness temperature

$\lambda \rightarrow$ Wavelength

$\Omega_s \rightarrow$ Source solid angle

Frequency (MHz)

Flux density (W m^{-2} Hz^{-1})

Wavelength

Smerd, S. F., Annals of IGY, 34 (1964)

Quiet Sun Flux density spectrum : Blackbody

Frequency (MHz)

10^4 10^3 10^2

$$S = \left(\frac{2 \, k_B \, T_b}{\lambda^2} \right) \Omega_s$$

$S \rightarrow$ Flux density of the source

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$T_b \rightarrow$ Brightness temperature

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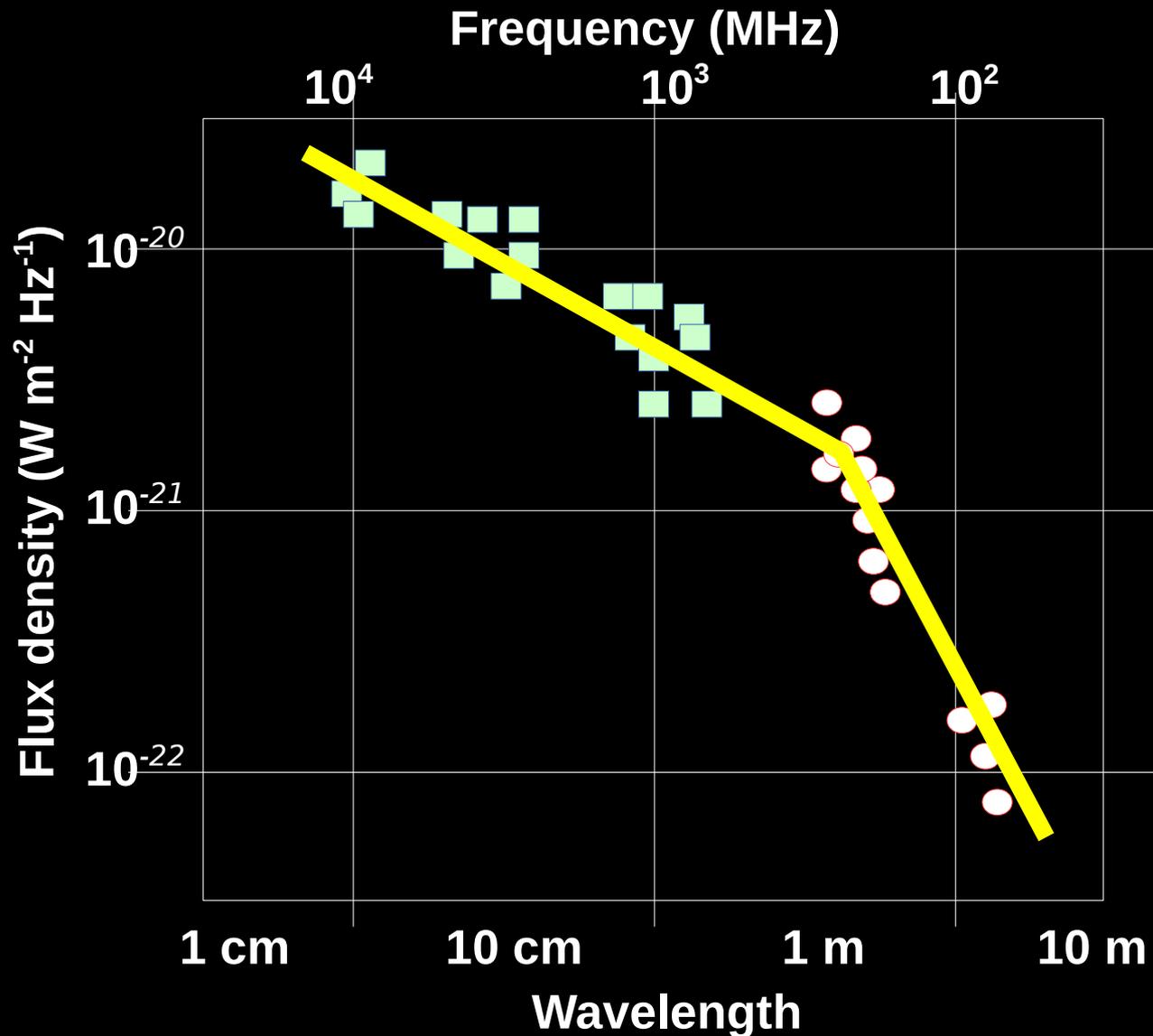
The quiet Sun flux decreases as wavelength increases
OR
The quiet Sun flux increases as frequency increases
– A behaviour of Blackbody.

Flux density (W m⁻² Hz⁻¹)

10^{-20}

10^{-22}

1 cm   10 cm   1 m   10 m

Wavelength

Smerd, S. F., Annals of IGY, 34 (1964)

Quiet Sun flux profiles at different λs (mm – deca-m)

21 cm
9.1 cm
3.2 cm
8.5 mm

Flux density

Heliocentric distance

1.0   2.0 R$_\odot$

3.7 m   **1.4 m**
7.9 m
60 cm

Flux density

Heliocentric distance

1.0   2.0 R$_\odot$
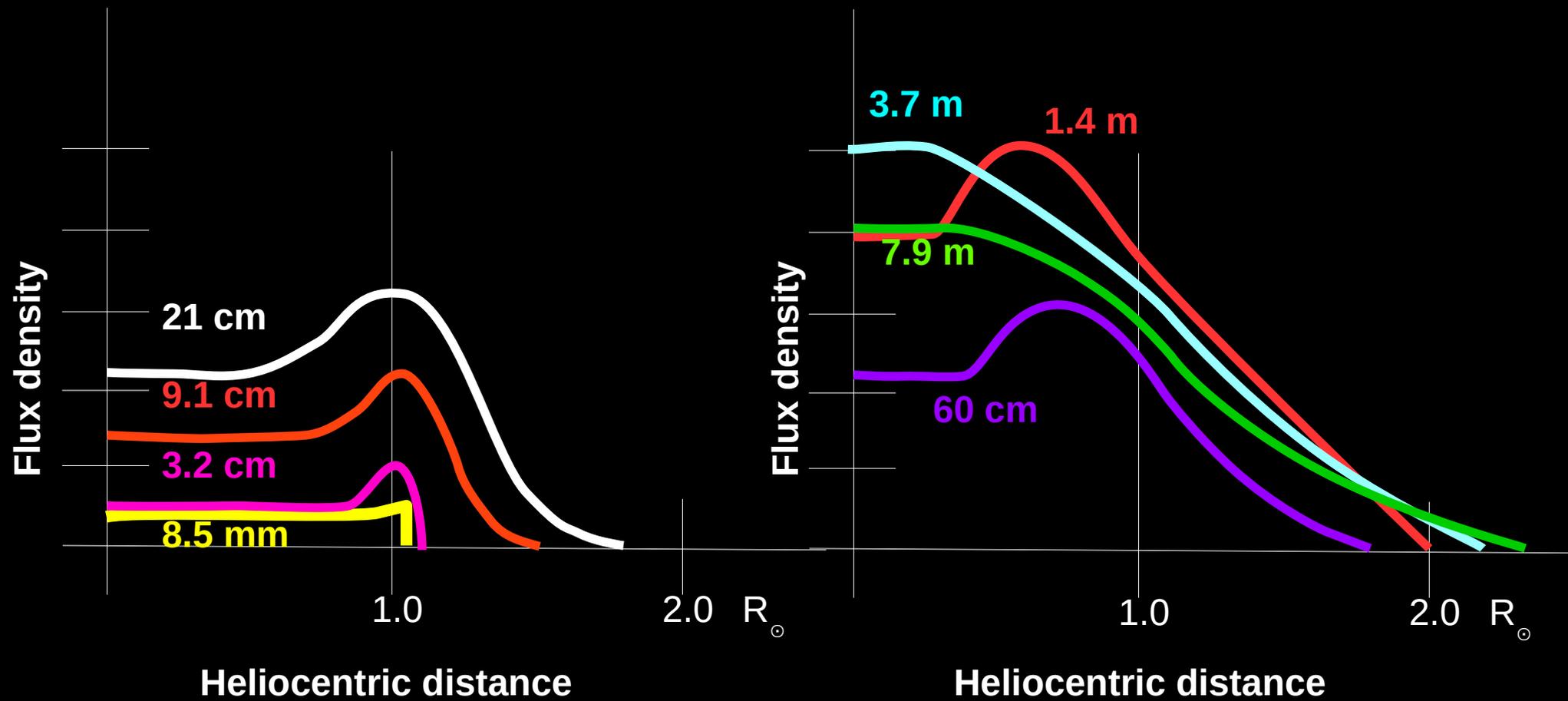
Smerd, S. F., Au. J. Sci. Res.-A, 3, 34 (1950)

Quiet Sun flux profiles at different λs (mm – deca-m)

1. Different wavelengths are emitted at different heights.

2. High frequencies are generated at the inner coronal regions whereas the low frequencies are generated at the outer coronal regions.

3.7 m

7.9 m

8.5 mm

1.0   2.0 $R_\odot$ 1.0   2.0 $R_\odot$

Heliocentric distance   Heliocentric distance
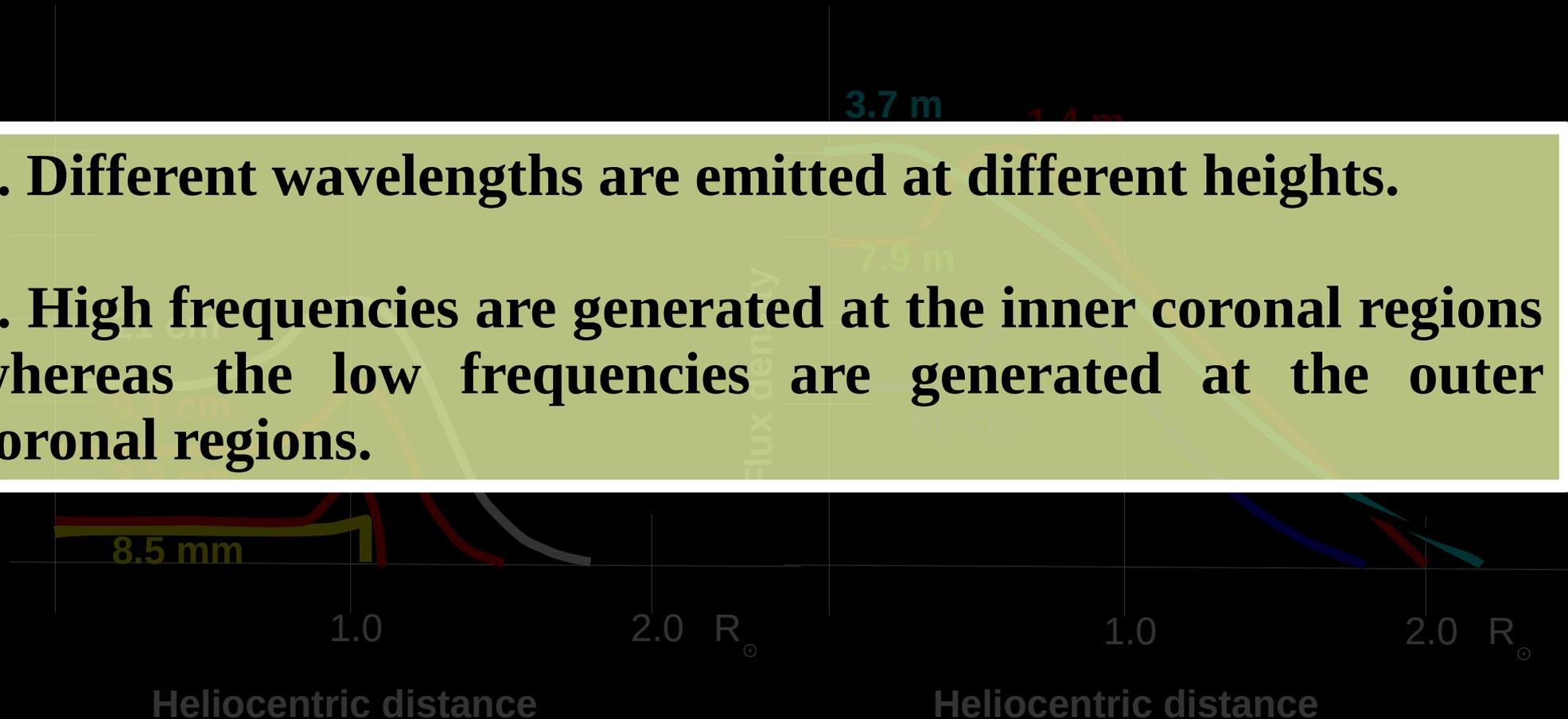
Smerd, S. F., Au. J. Sci. Res.-A, 3, 34 (1950)

Quiet Sun Brightness Temperature (T_b)

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Smerd, S. F., Annals of IGY, 34 (1964)

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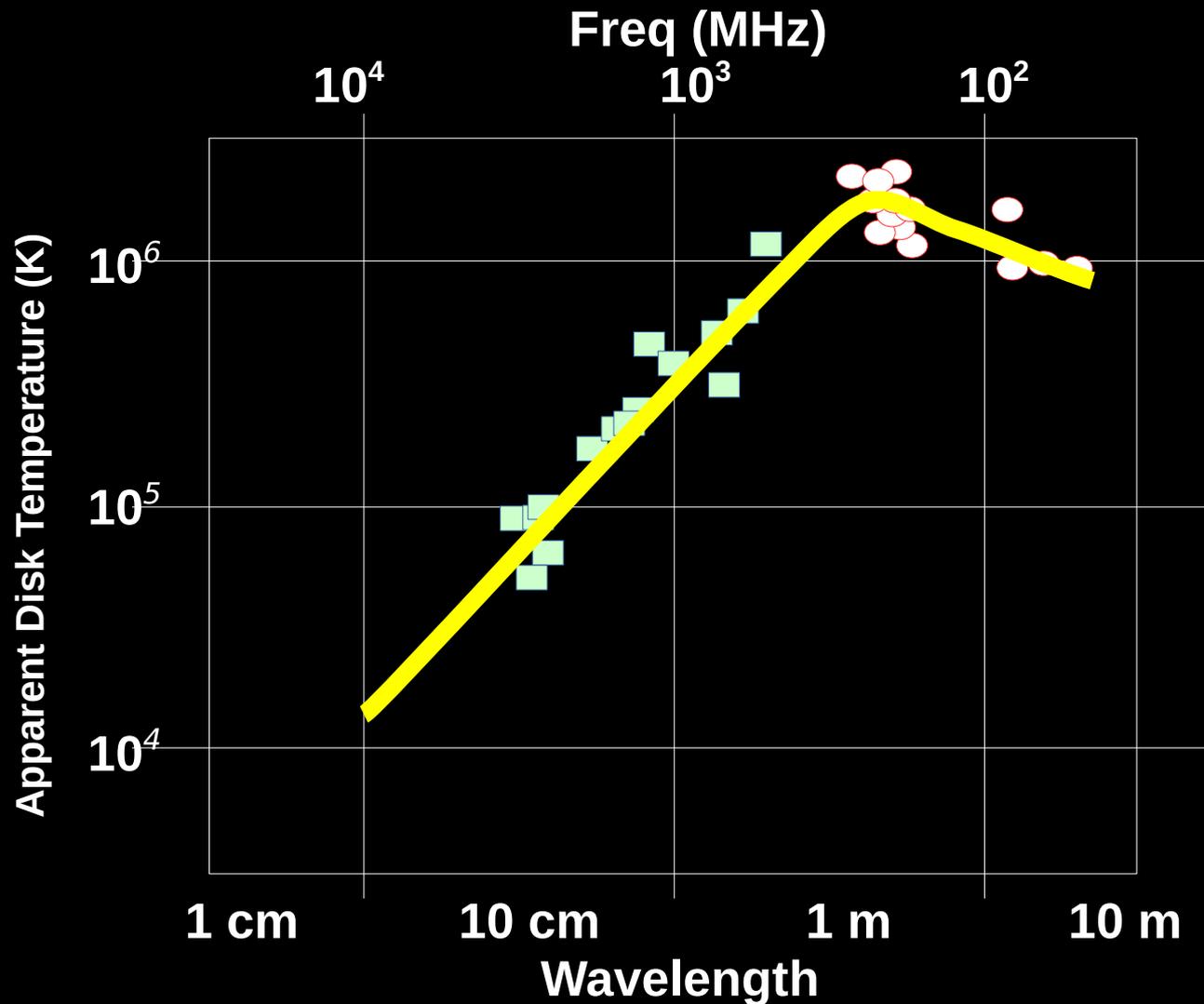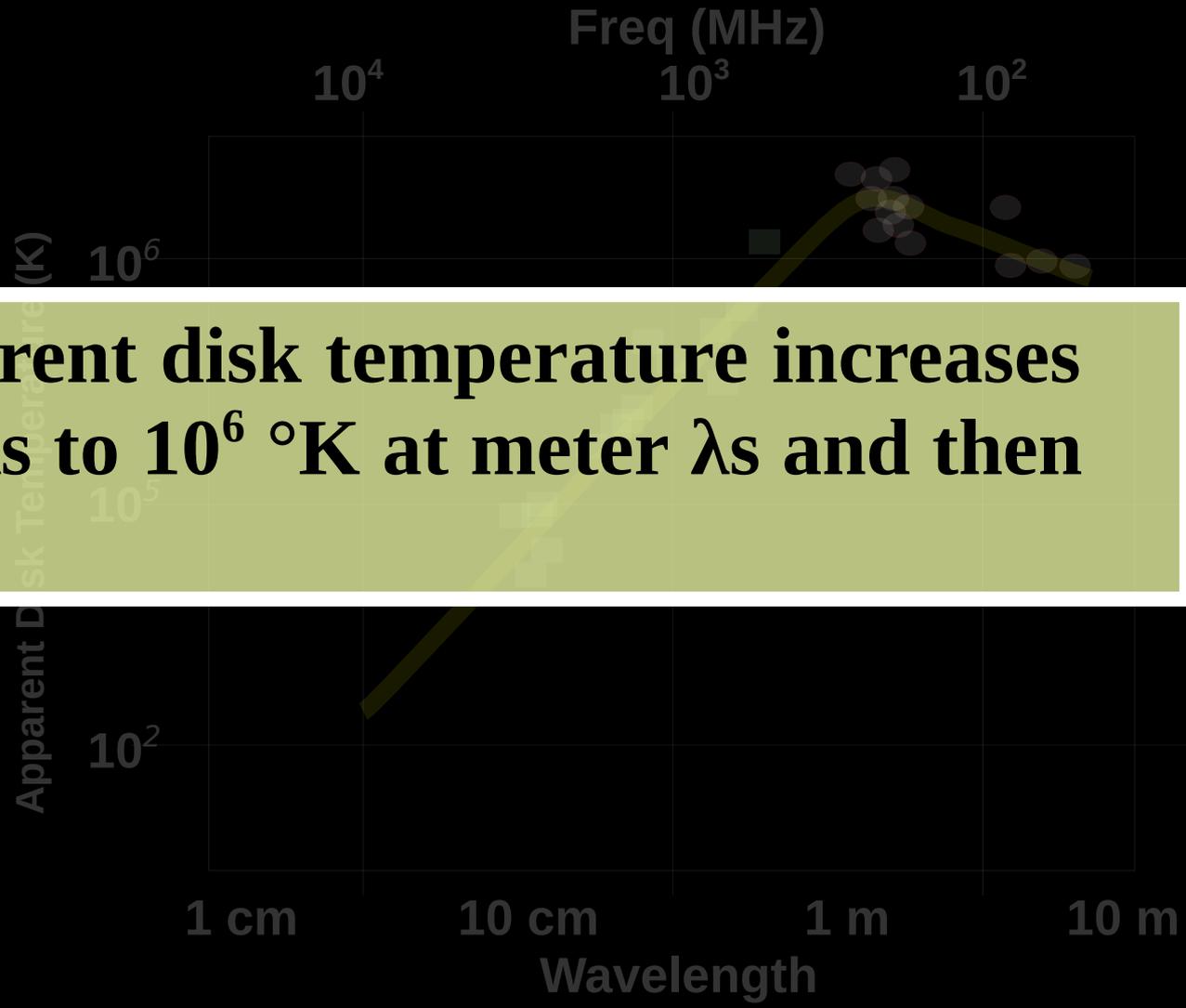
The quiet Sun apparent disk temperature increases from 10^4 °K at cm λs to 10^6 °K at meter λs and then starts decreasing.

Freq (MHz)

10^4 10^3 10^2

Apparent Disk Temperature (K)

10^6

10^5

10^2

1 cm   10 cm   1 m   10 m

**Wavelength**

Smerd, S. F., Annals of IGY, 34 (1964)

Quiet Sun Brightness Temperature at different λs (mm - deca-m)


Smerd, S. F., Au. J. Sci. Res.-A, 3, 34 (1950)

Quiet Sun Brightness Temperature at different λs (mm - deca-m)
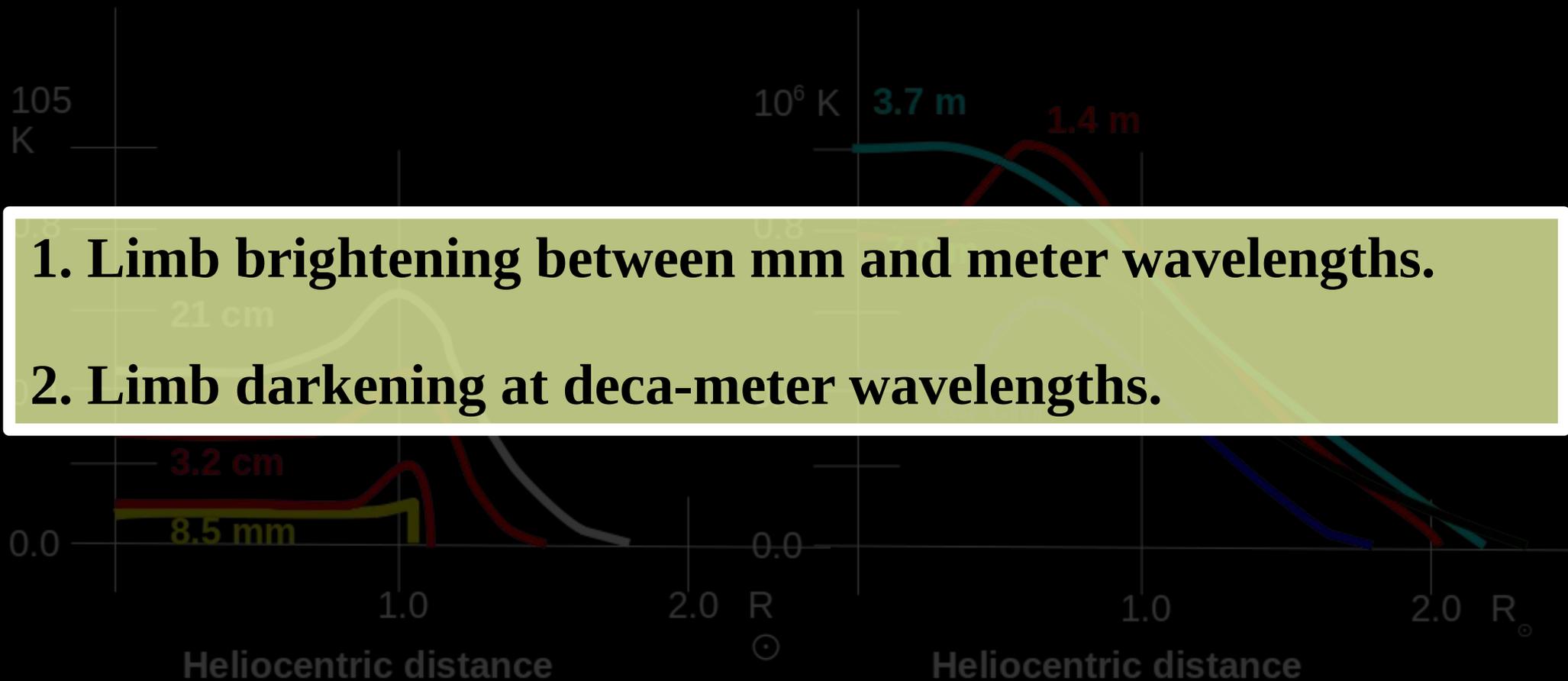
1. Limb brightening between mm and meter wavelengths.

2. Limb darkening at deca-meter wavelengths.

Smerd, S. F., Au. J. Sci. Res.-A, 3, 34 (1950)

Quiet Sun Brightness Temperature (Solar Cycle IGY)
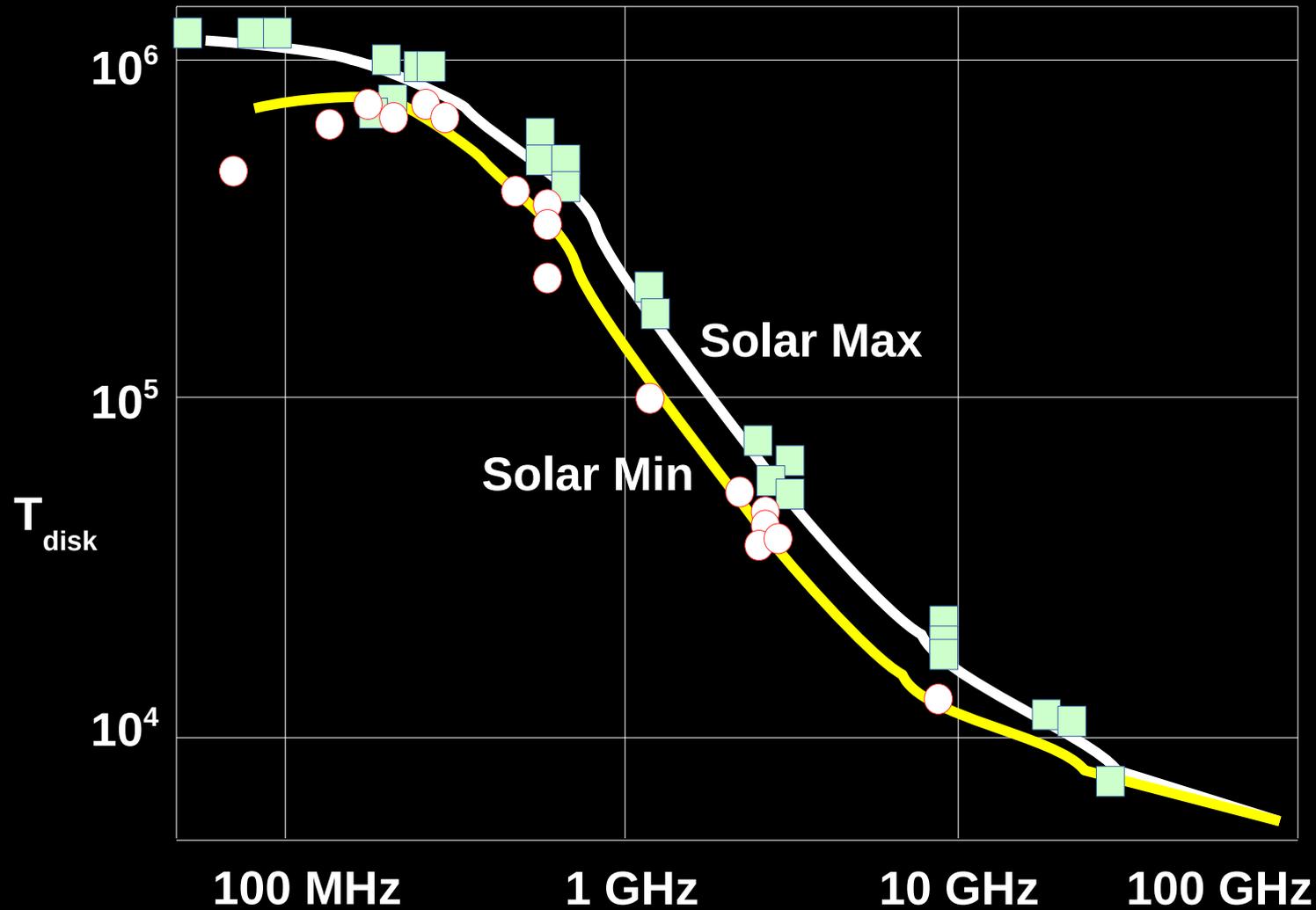
Allen, C. W., IAUS, 4 (1957)

## Quiet Sun Brightness Temperature (Solar Cycle IGY)
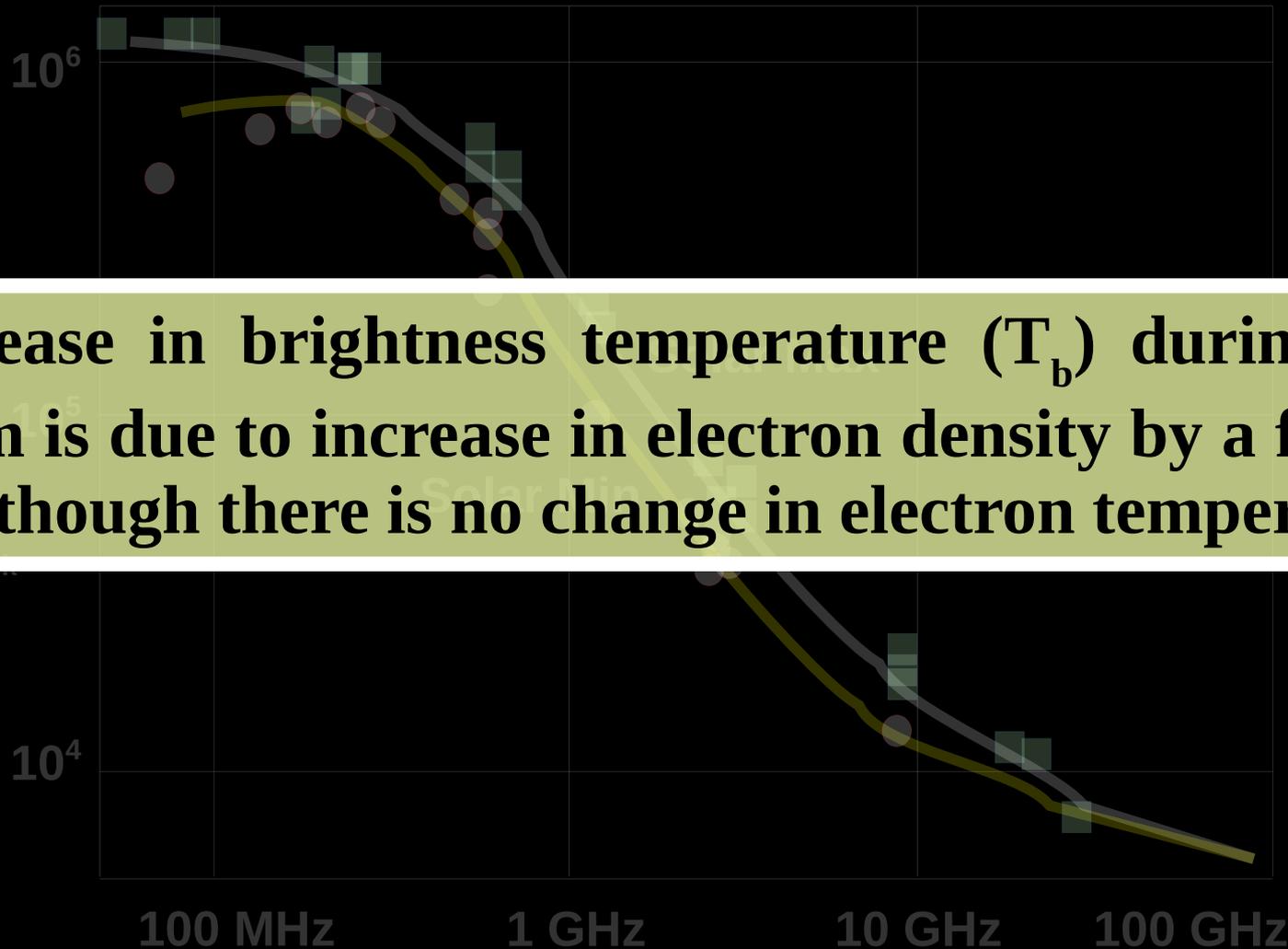
The increase in brightness temperature (T_b) during solar maximum is due to increase in electron density by a factor ≈ 1.5-2.0 although there is no change in electron temperature.

Allen, C. W., IAUS, 4 (1957)

# Quiet Sun dimension vs Solar Cycle

Solar Maximum

Solar Minimum

52′ ± 4′
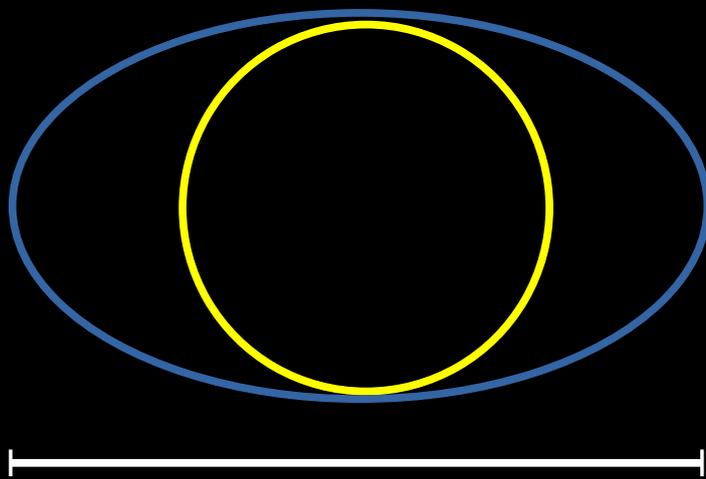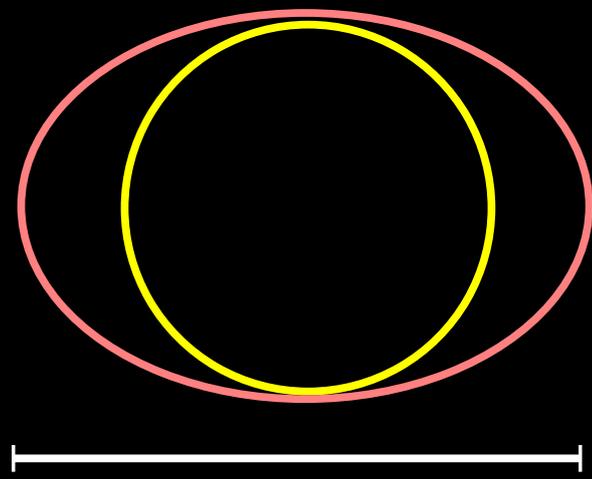
42′ ± 3′

Avignon et al., Compt. Rend., 255, 2859 (1961)

Quiet Sun dimension vs Solar Cycle

1. During solar maximum the equatorial diameter of the radio Sun is maximum and reaches a minimum during solar minimum at any observing frequency (ex: 169 MHz / 1.77 meter) and the polar diameter does not change much.

2. This is not the case with optical observations – during maximum it is spherical.

Avignon et al., Compt. Rend., 255, 2859 (1961)

Coronal electron density models

1. By measuring the diameter of the Quiet Sun at different radio frequencies (from radio observations with frequencies greater than 15 MHz) and using the corresponding electron densities, the background coronal electron density models can be generated.

2. One should carefully remove the contribution from other structures to minimize the errors.

3. The active Sun data are used to determine density estimates with frequencies less than 15 MHz.

Coronal electron density model (from Corona to 1 AU)
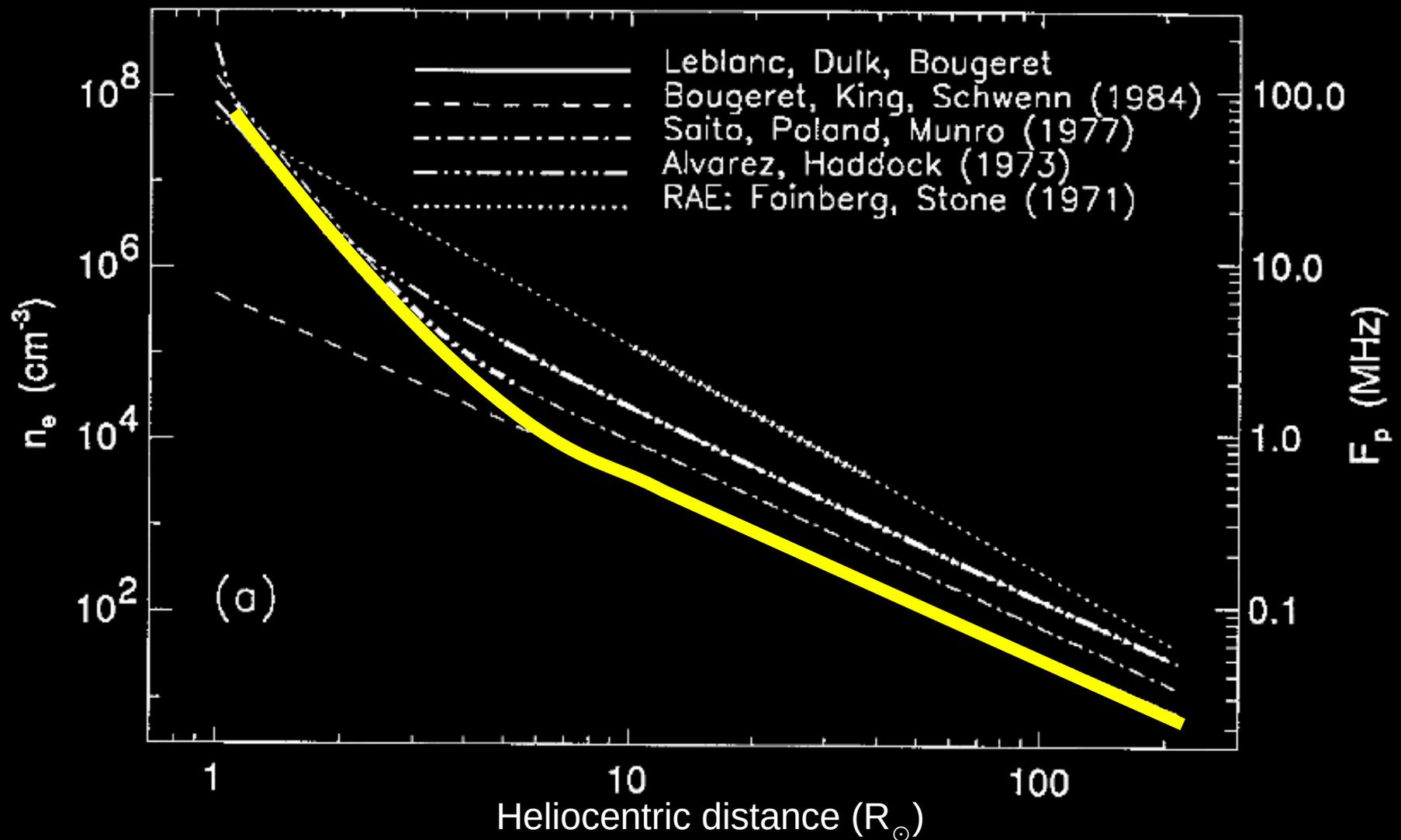
Leblanc et al., Sol. Phy., 183, 165 (1998)

Coronal electron density model (from Corona to 1 AU)

$$N_e = 3.3 \times 10^5 \, r^{-2} + 4.1 \times 10^6 \, r^{-4} + 8.0 \times 10^7 \, r^{-6} \, cm^{-3}$$

$$N_e \rightarrow \text{Electron number density}$$

$$r \rightarrow \text{heliocentric distance} \left(\text{in Units of } R_\odot \right)$$

Leblanc et al., Sol. Phy., 183, 165 (1998)

Coronal electron density model (from Corona to 1 AU)

MEX 2008 conjunction

$$Ne = \frac{0.89 \times 10^6}{r^{2.40}}$$

$$Ne = \frac{0.10 \times 10^8}{r^4} + \frac{0.22 \times 10^6}{r^2}$$

Electron density (cm^{-3})

MDLOS in solar radii
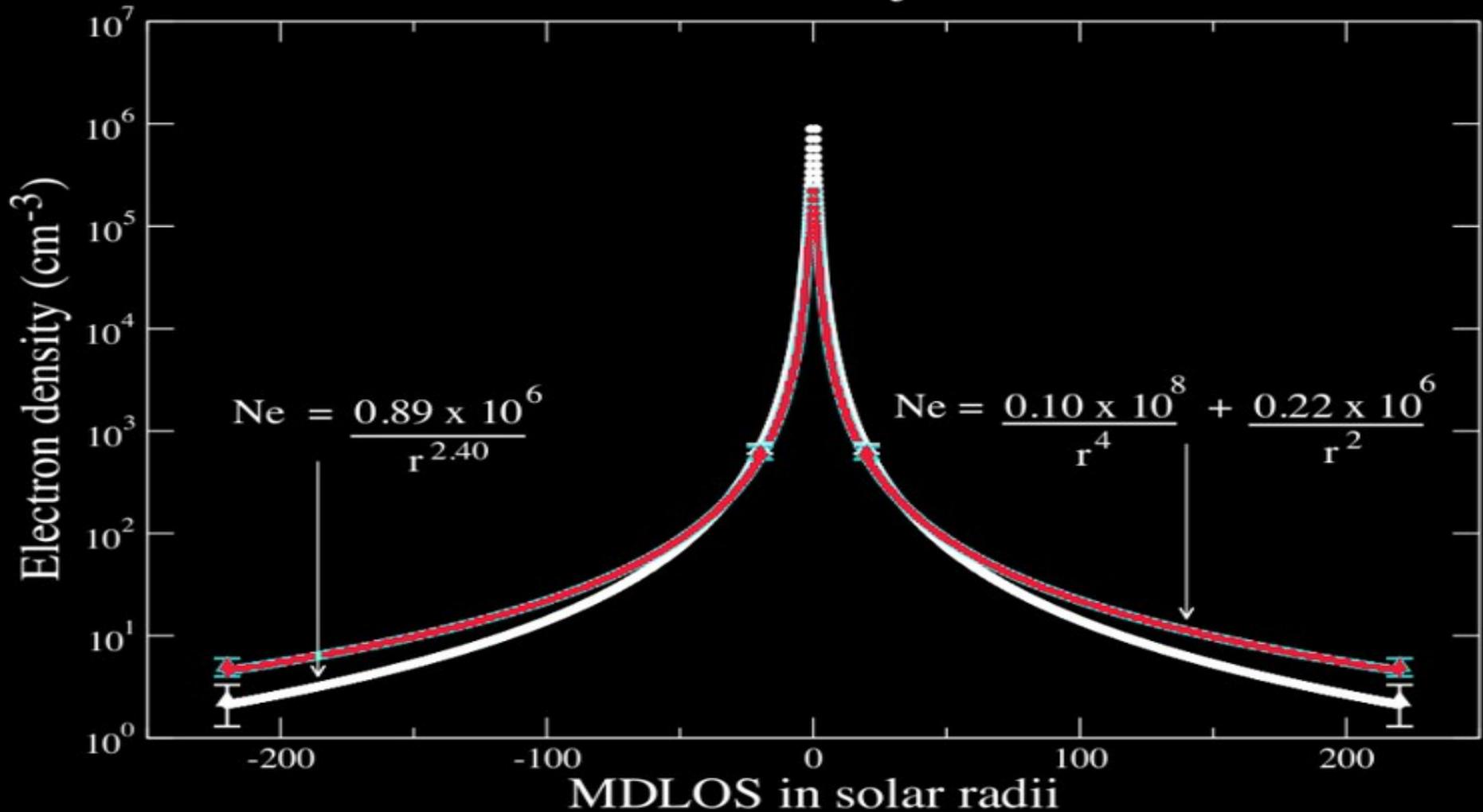
Verma et al., A&A, 550, A124 (2013)

Coronal electron density model (from Corona to 1 AU)

This method measures the travel-time delay of radio signals between the spacecraft and the Earth station to determine the electron number density.

$$\Delta\tau = \frac{1}{2cn_{critic}(f)} \int_E^S N_e(L)\, dl$$

$\Delta\tau \rightarrow$ Travel-time delay

E $\rightarrow$ Earth Station

S $\rightarrow$ Satellite location $\left(\text{in Units of } R_\odot\right)$

$c \rightarrow$ Velcocity of light

$n_{critic} \rightarrow$ Critical ELectron density

$f \rightarrow$ Carrier frequency

Verma et al., A&A, 550, A124 (2013)

There are other models from radio / WL observations

Not discussed due to time constraint

Why Sun behaves differently at different frequency bands ??

Radio wave propagation in a plasma

Plasma oscillations – Plasma frequency

Protons

Electrons
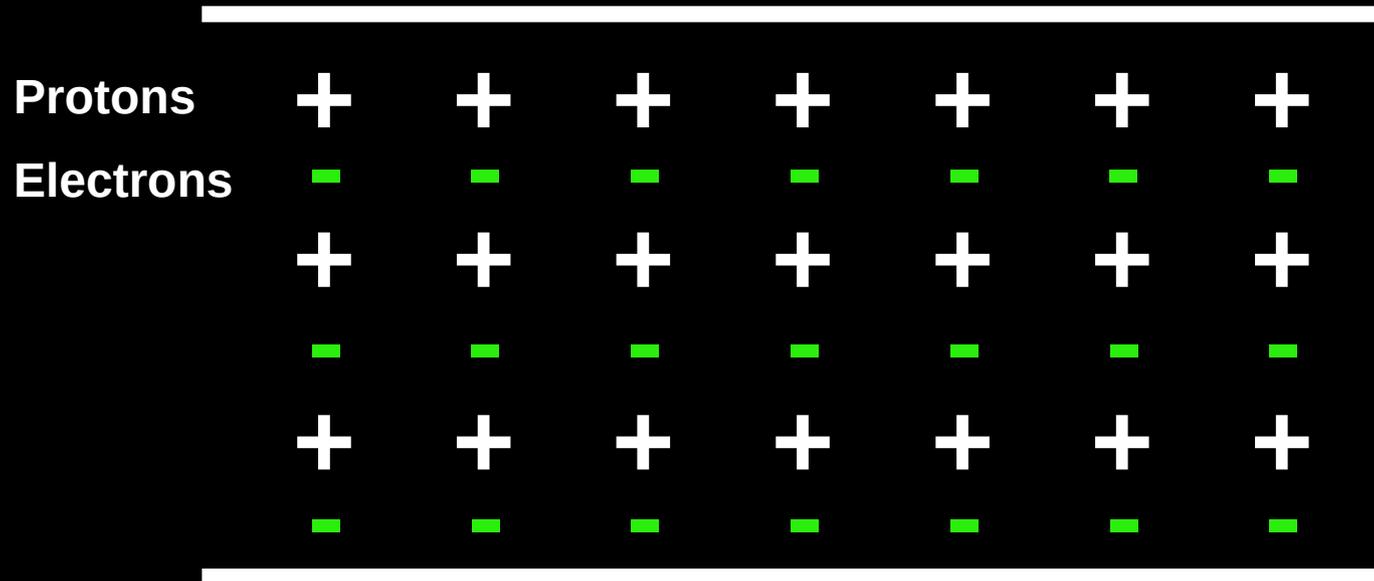
Unit volume (Charge Neutrality) → Net Charge = 0

Plasma oscillations – Plasma frequency

Protons

Electrons

Displacement (x)
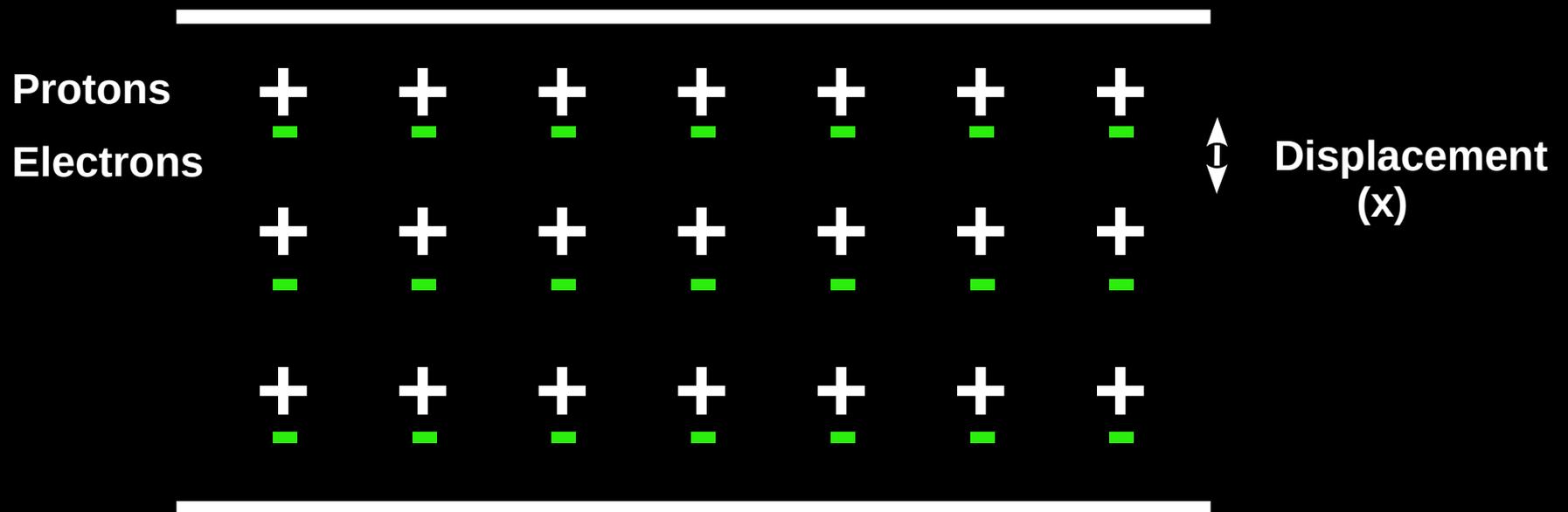
$F = ma = -eE$ $x \sim A \sin \omega t$ $\omega \rightarrow 2\pi f_p$

$a = d^2x/dt^2$ $\omega \rightarrow$ **angular plasma frequency** $f_p = (e^2 N_e / \pi m_e)^{1/2} \approx 9 N_e^{1/2}$

Radio wave propagation in a plasma medium

$$\mu = \sqrt{1 - \left(\frac{f_p^2}{f^2}\right)} \qquad\qquad f_p = \sqrt{\frac{N_e\, e^2}{\pi\, m_e}}$$

μ ➔ Refractive Index $\qquad\qquad N_e$ ➔ electron number density

f_p ➔ plasma frequency $\qquad\qquad e$ ➔ electron charge

f ➔ Observing frequency $\qquad\qquad m_e$ ➔ electron mass

1. In a plasma medium the propagation of the radio wave is decided by the refractive index.
2. The plasma frequency to observing frequency ratio decides the nature of propagation.
3. The plasma frequency is dependent on N_e

Radio wave propagation in a plasma medium

The nature of propagation is decided by f_p and f.

1. f_p < f → Propagation (normal & Oblique)
2. f_p = f → Absorption
3. f_p > f → Reflection

Radio wave propagation in a plasma medium
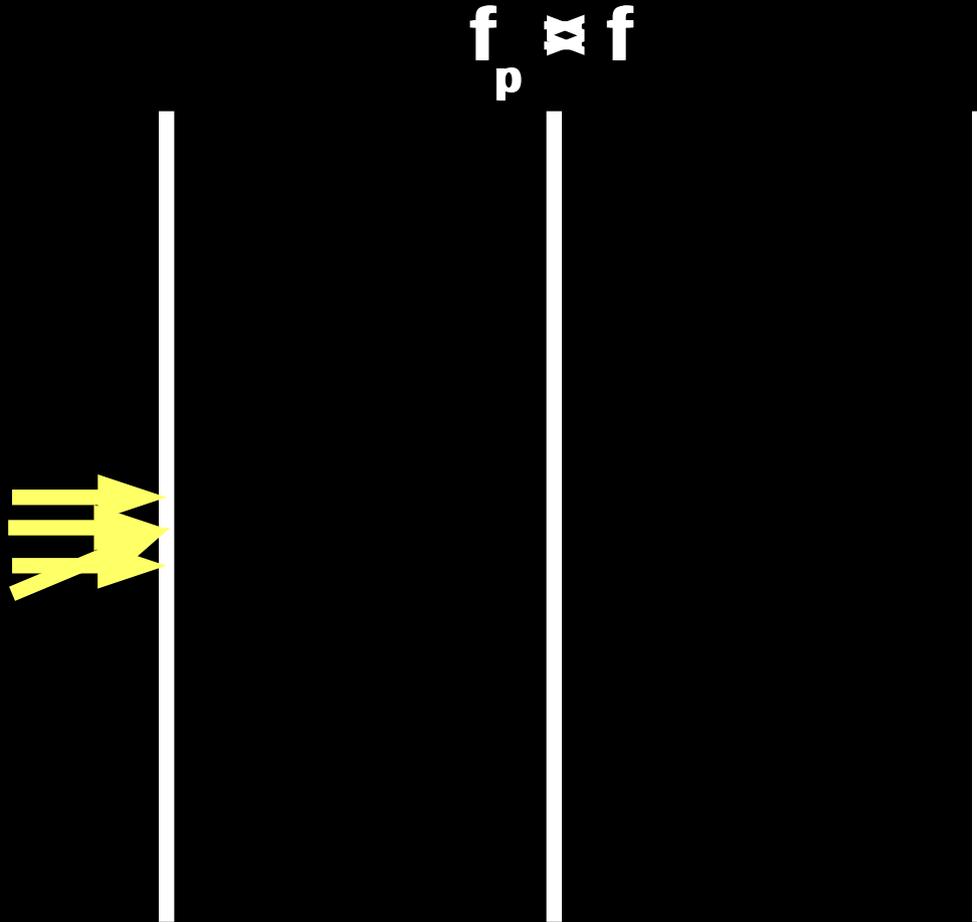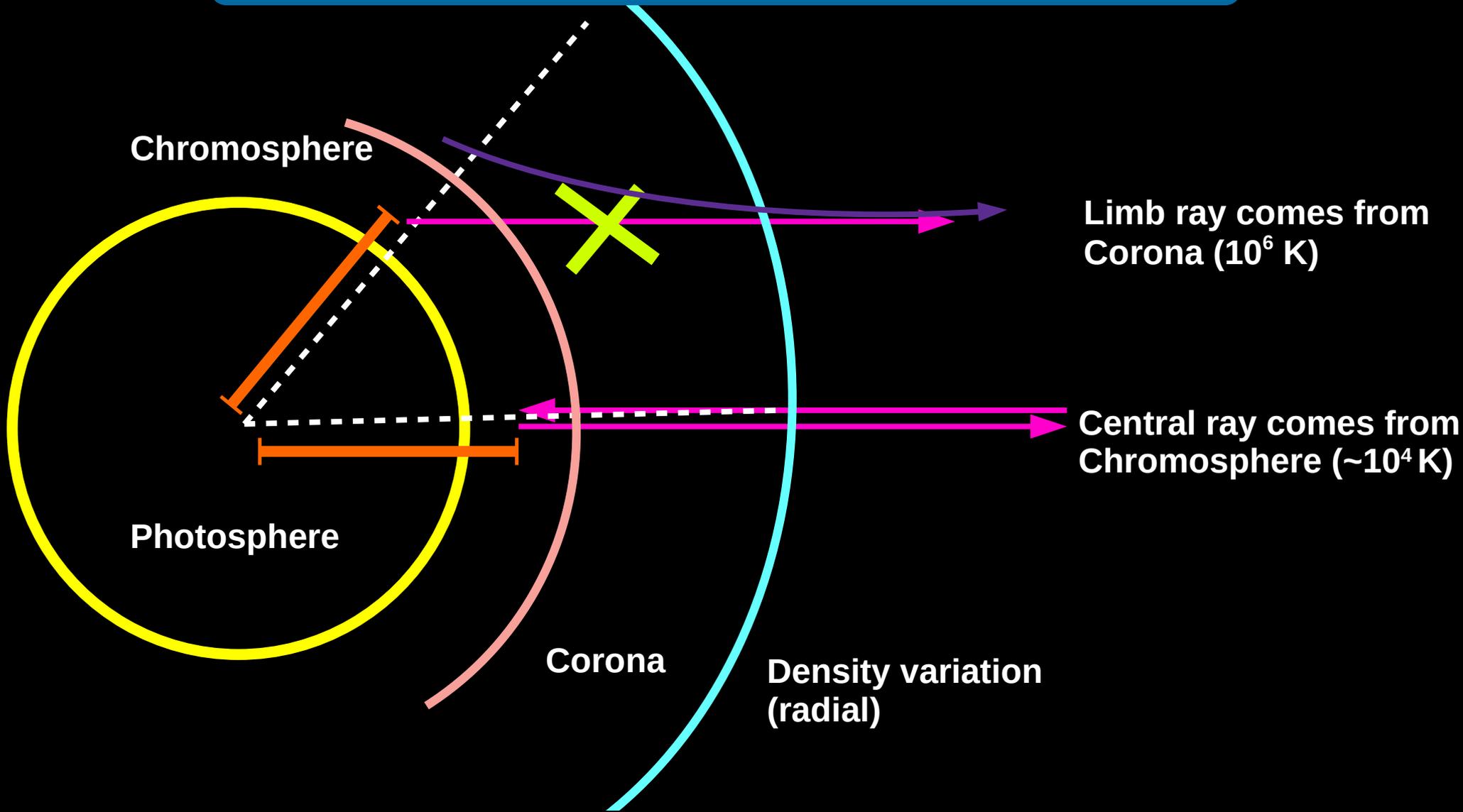
$$f_p \bowtie f$$

Limb brightening at cm wavelengths

Chromosphere

Photosphere

Corona

Density variation
(radial)

Limb ray comes from
Corona (10^6 K)

Central ray comes from
Chromosphere (~10^4 K)

Jager et al., Au. J. Sci. Res.-A, 2, 322 (1949)   **Aubier et al., A&A, 12, 435 (1971)**

Limb brightening at cm wavelengths

Chromosphere

The central ray at cm λs reach up to the Chromosphere whereas the limb ray at cm λs reach only the Corona. Hence limb brightening can be seen at cm λs.

But, both central and limb rays at meter λs reach up to the Corona. Hence limb darkening can only be seen at meter λs.

Corona　　　Density variation (radial)

Jager et al., Au. J. Sci. Res.-A, 2, 322 (1949)　　　Aubier et al., A&A, 12, 435 (1971)

Limb brightening at cm wavelengths (Imaging)

N

18000 K

26000 K

23000 K

20000 K

15000 K

10000 K

λ = 6 cm

Photosphere size

N

20000 K

43000 K

66000 K

50000 K

10000 K

35000 K

λ = 11 cm

Photosphere size
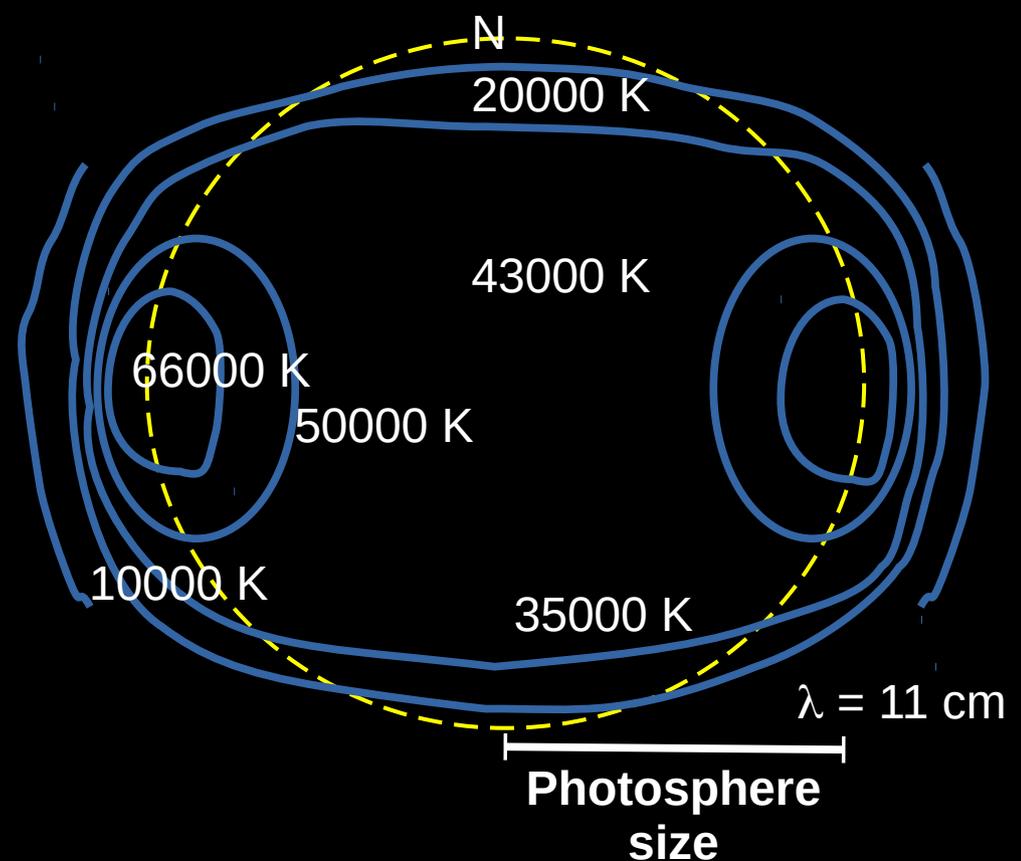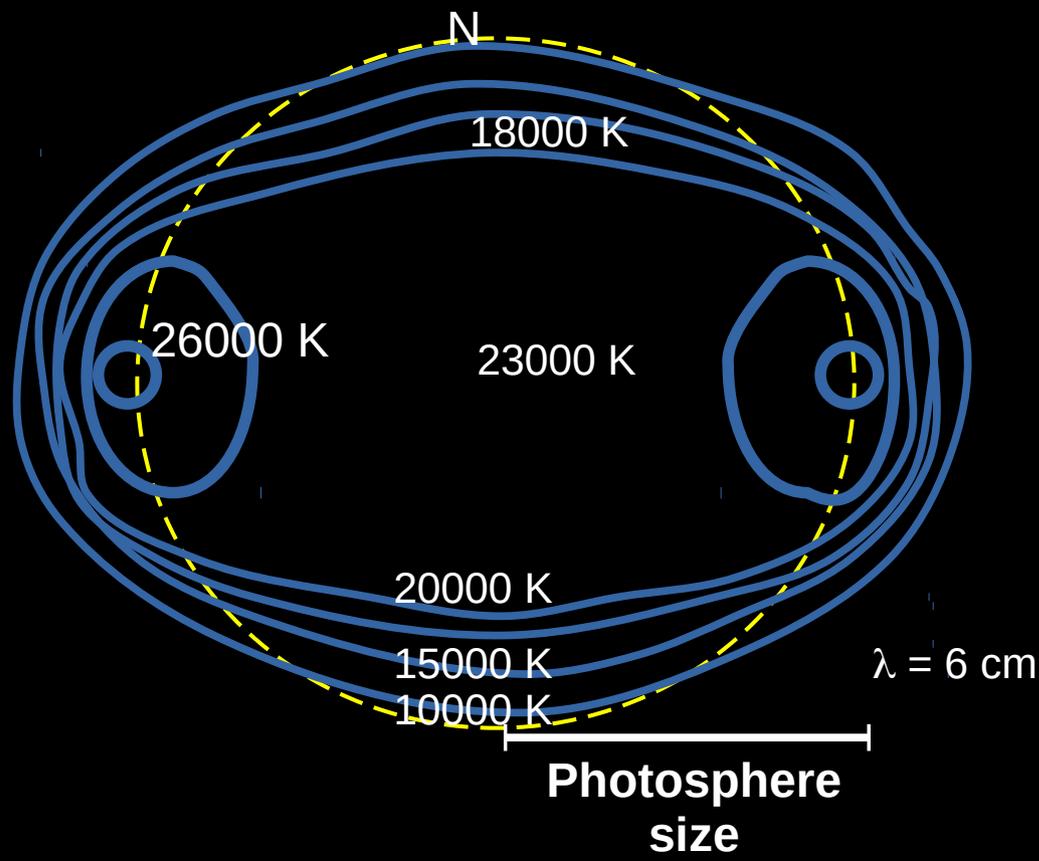
Ceballos, J. C. et al, SoPh, 22, 142 (1972)

Hα & cm-λ radio observations

Nobeyama Radioheliograph 17 GHz (R+L)   **BBSO Hα**
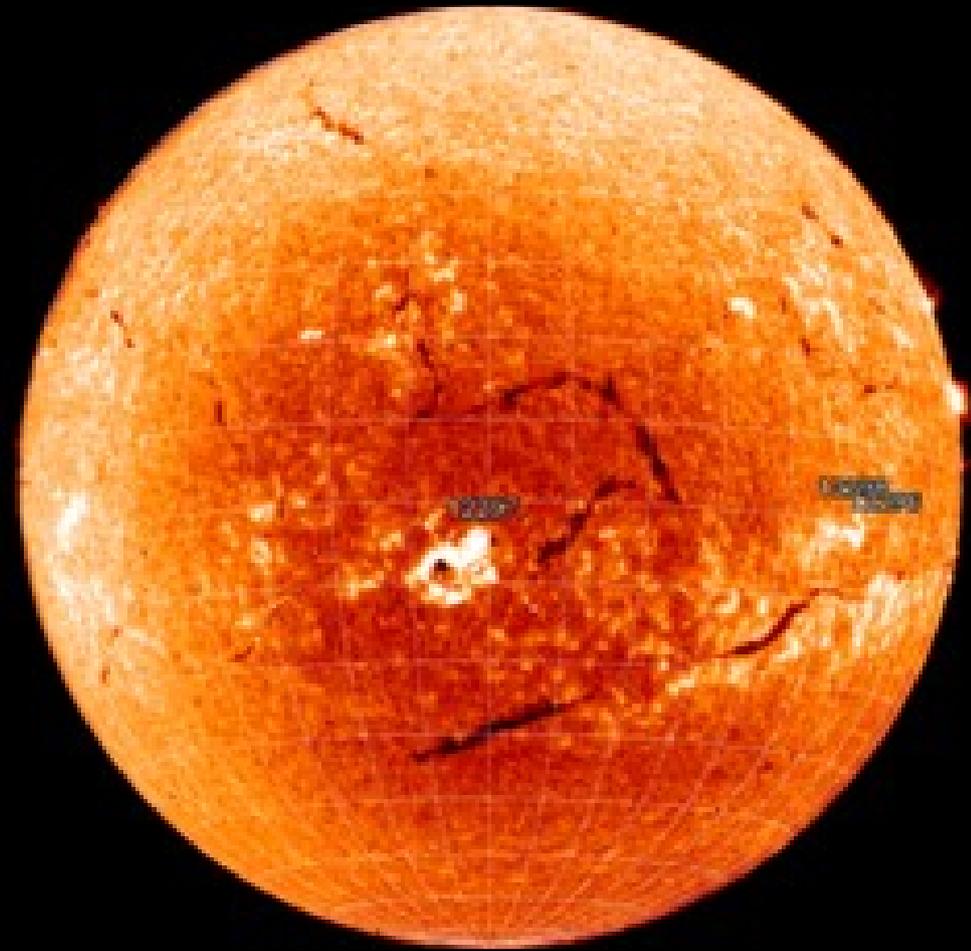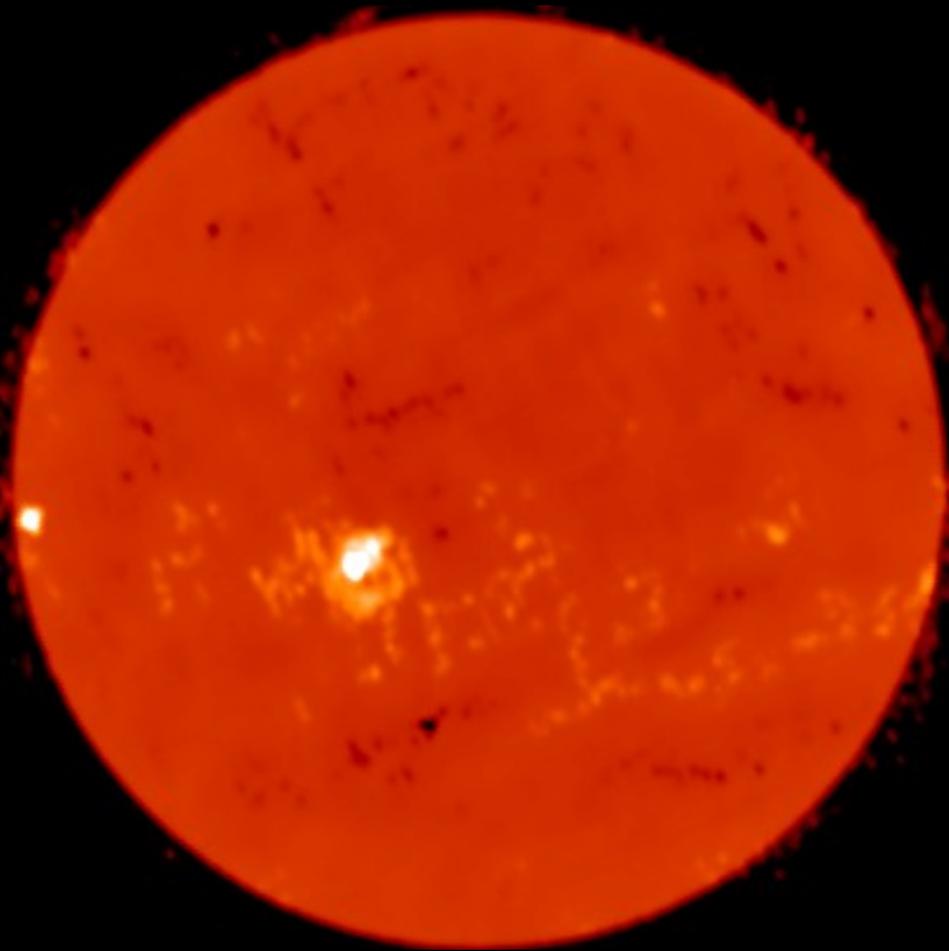
12/03/2015

2D radio observations (RATAN)
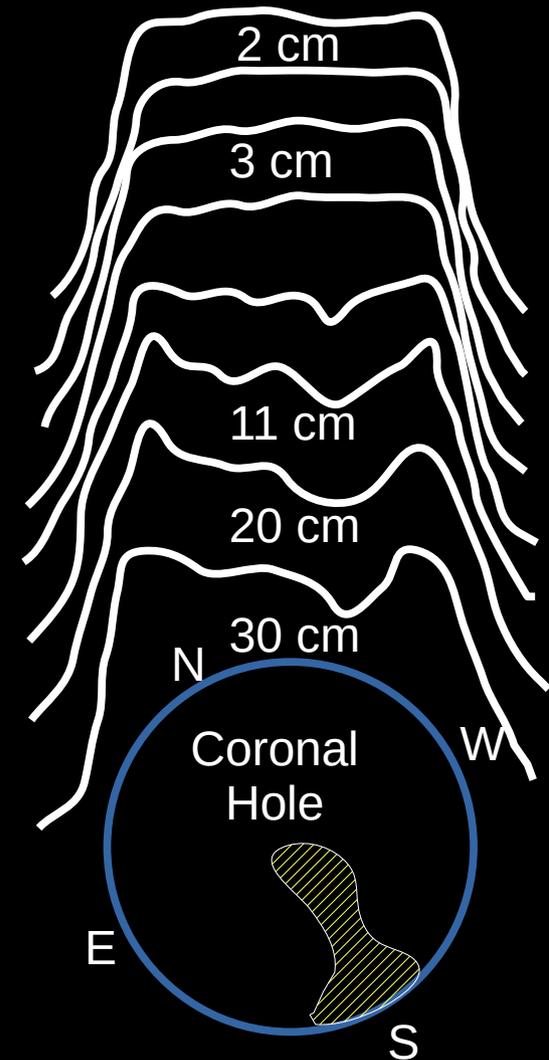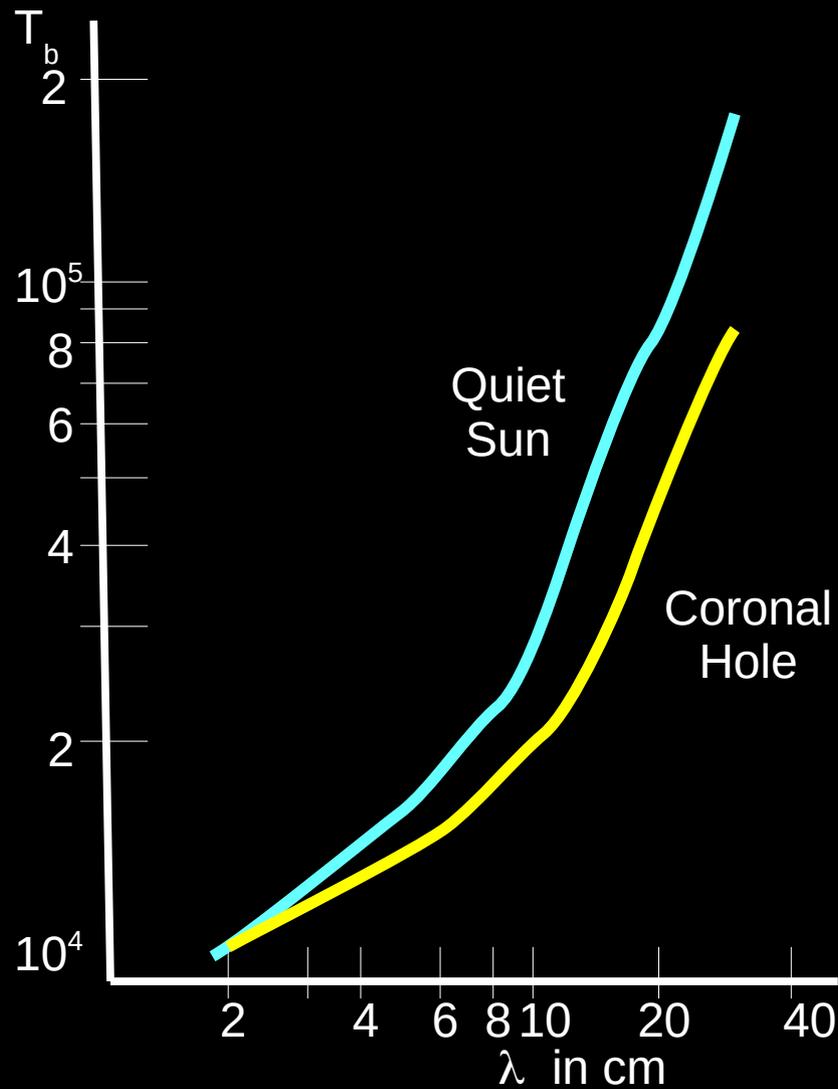
Ceballos, J. C. et al, SoPh, 22, 142 (1972)   **Borovik, V. N et al. Sov. Ast. 34, 522 (1990)**

EUV & decimeter-λ radio observations

NANCAY RADIOHELIOGRAPH
327.0 Mhz
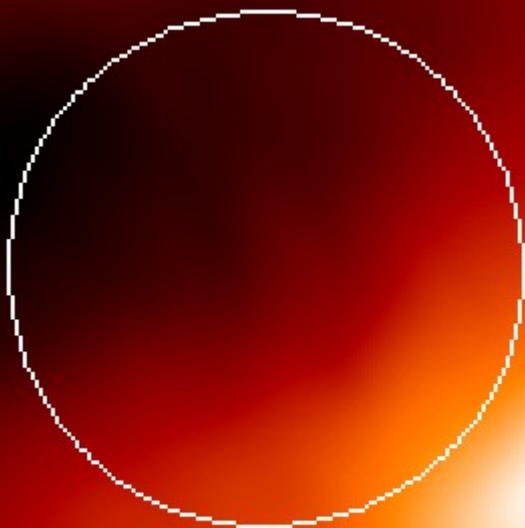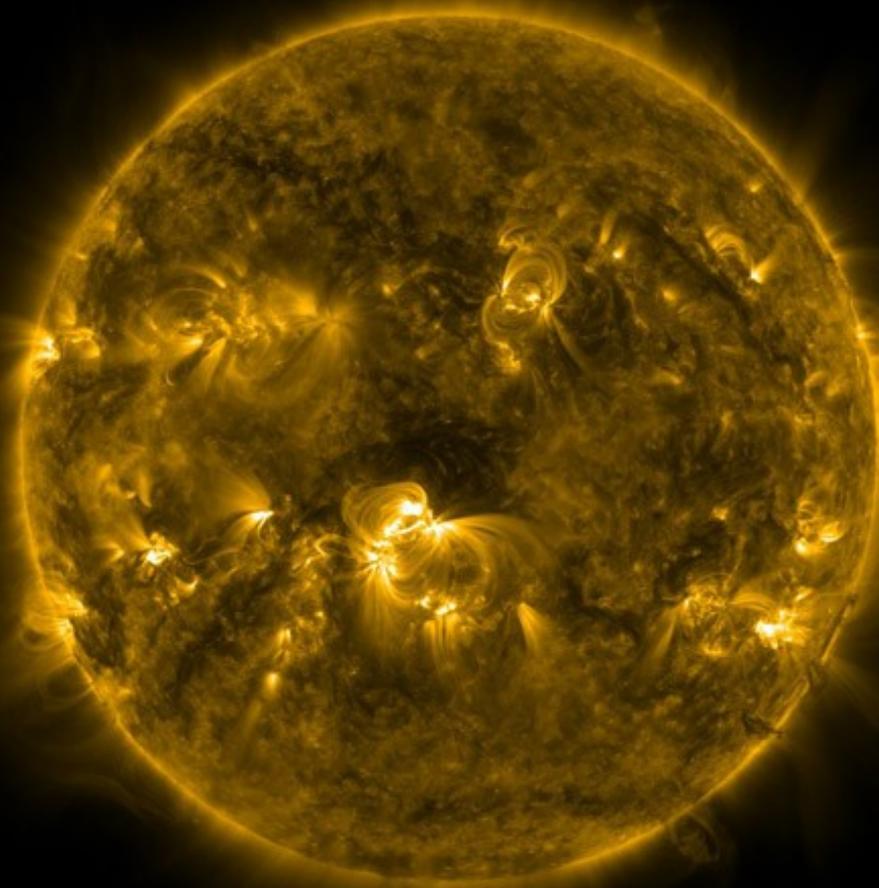
20-Jan-2015 13:43:41 UT

SDO AIA / 171 Å

EUV & meter-λ radio observations

GRAPH

53 MHz　　　　**14/08/2020**

N

W

Visible disk

Interval = 10% peak
T_b = 1.0 M
K
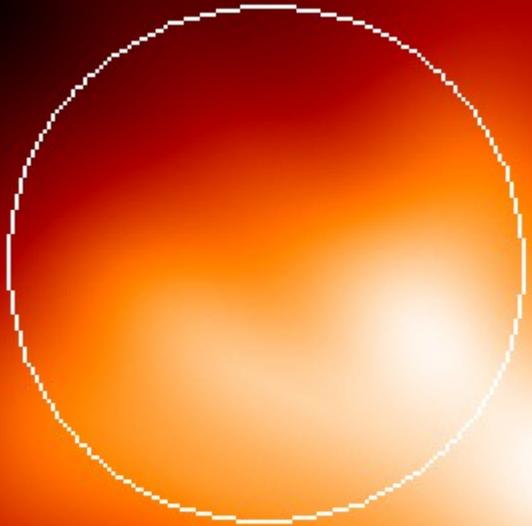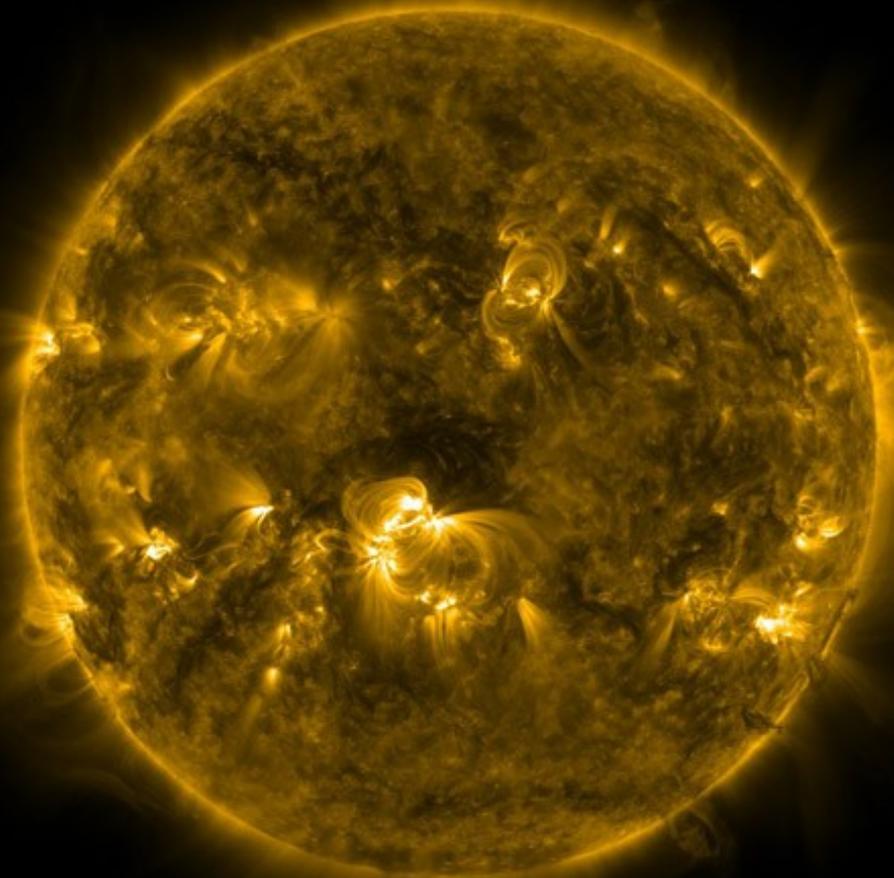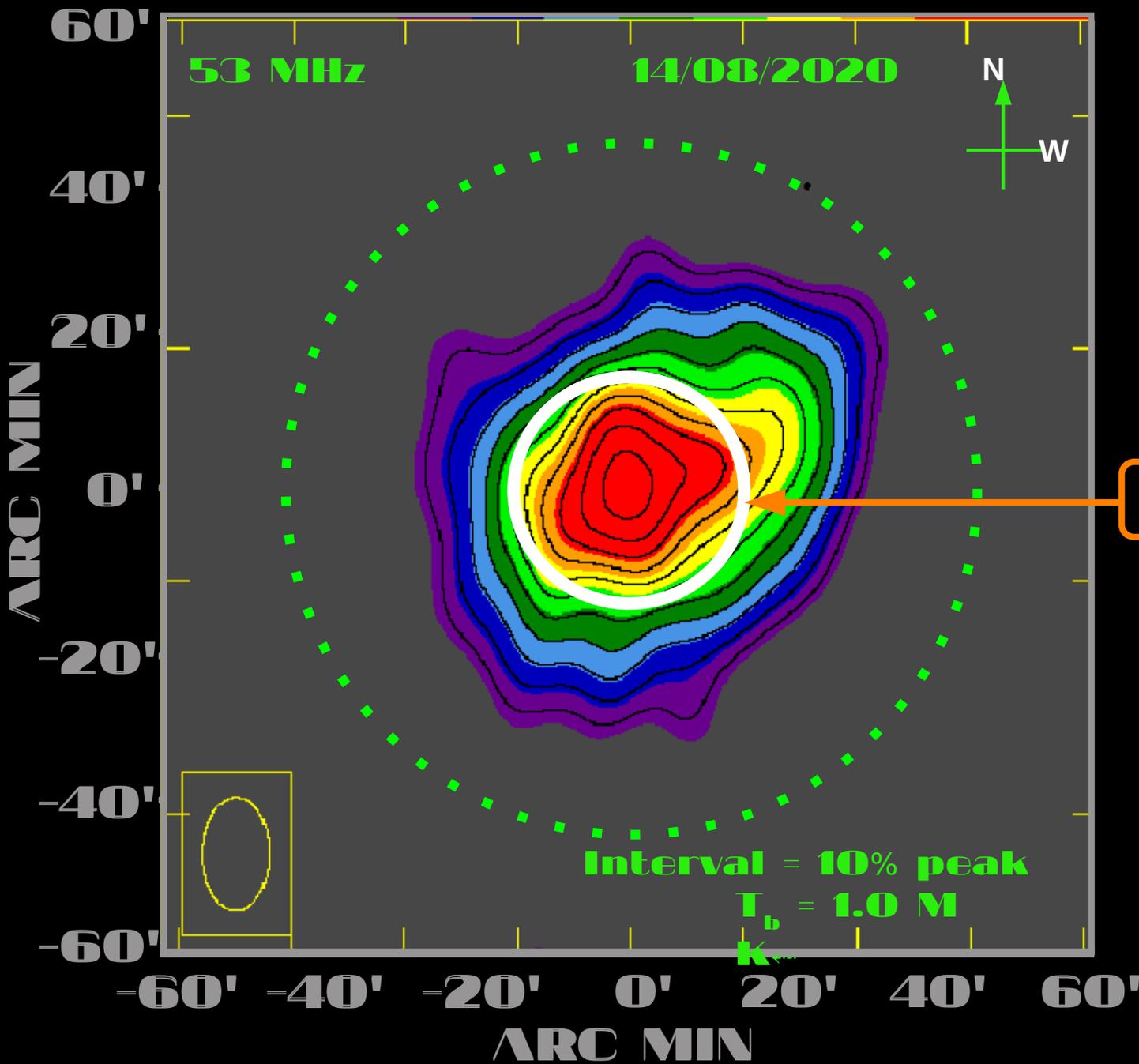
Snap shots over
Wide frequency range
Coronal Tomography

Simultaneous
53 MHz & 80 MHz

Quiet Sun
Image

LASCO C2 & GRAPH radio observations

14/08/2020

So, one can have the following simplified background coronal schematic

Just to remember / recollect easily

Radio Layers

**mm & cm waves
(Chromosphere)
~ 10^{13} ele./cm³ (~30 GHz)**

Bg. Corona

Photosphere

**Plasma frequency
∝ Electron Density**

$$f_p(kHz) = 9\sqrt{N_e(cm^{-3})}$$

**Meter waves
(inner + mid Corona)
~10^9 ele./cm³ (~300 MHz)**

Chromosphere

**Deca-Hecto-kilo meter waves
(outer Corona+IP medium)
~10^7 − 10^1 ele./cm³ (~30 MHz − ~30 kHz)**

**Decimeter waves
(Transition Region)
~ 10^{11} ele./cm³ (~3 GHz)**

②
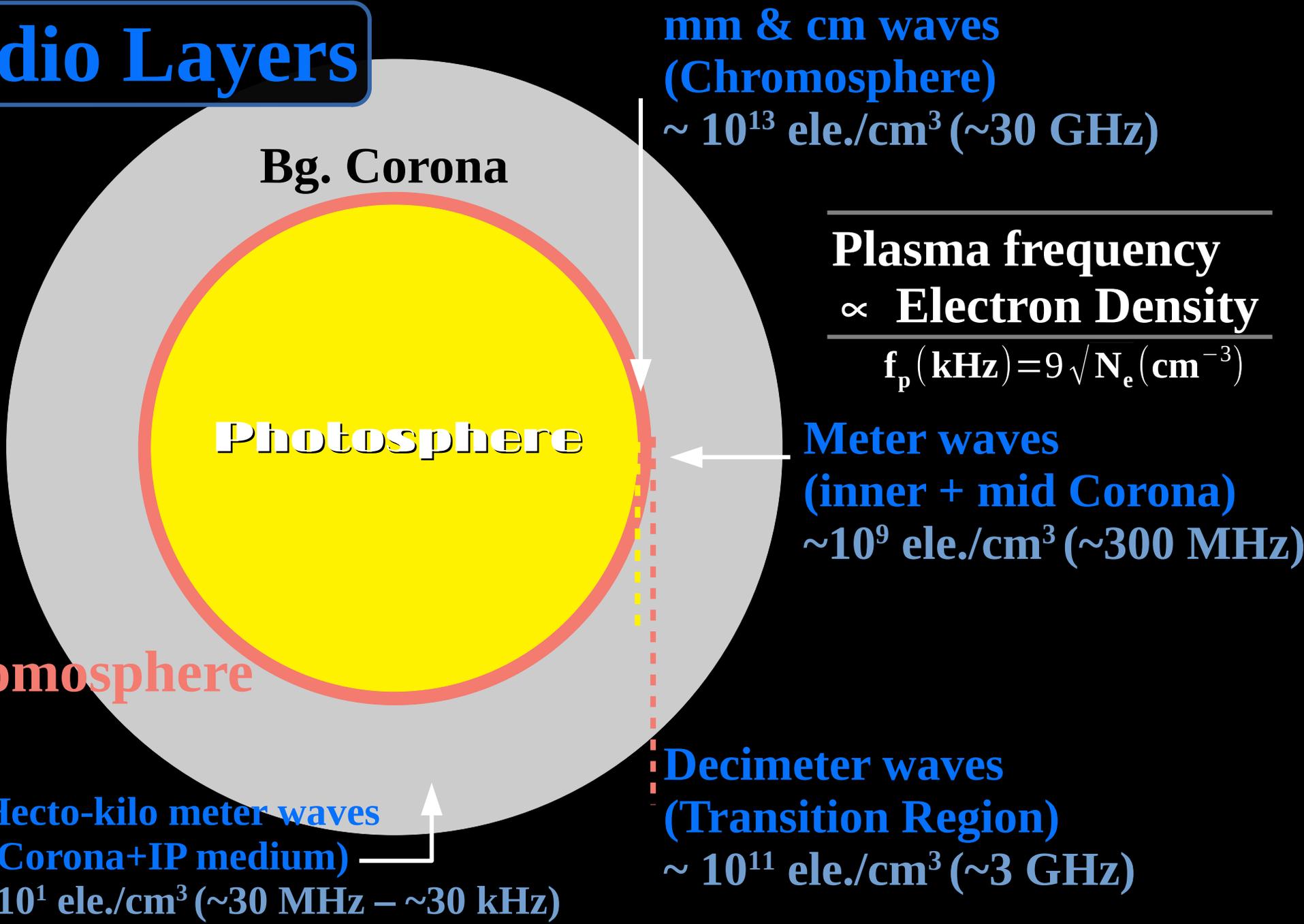
The Slowly Varying Component

Components above the Quiet Sun

Day –> 1 - 4

Flux density

(SVC)

Photospheric disk

Chromospheric disk

Time
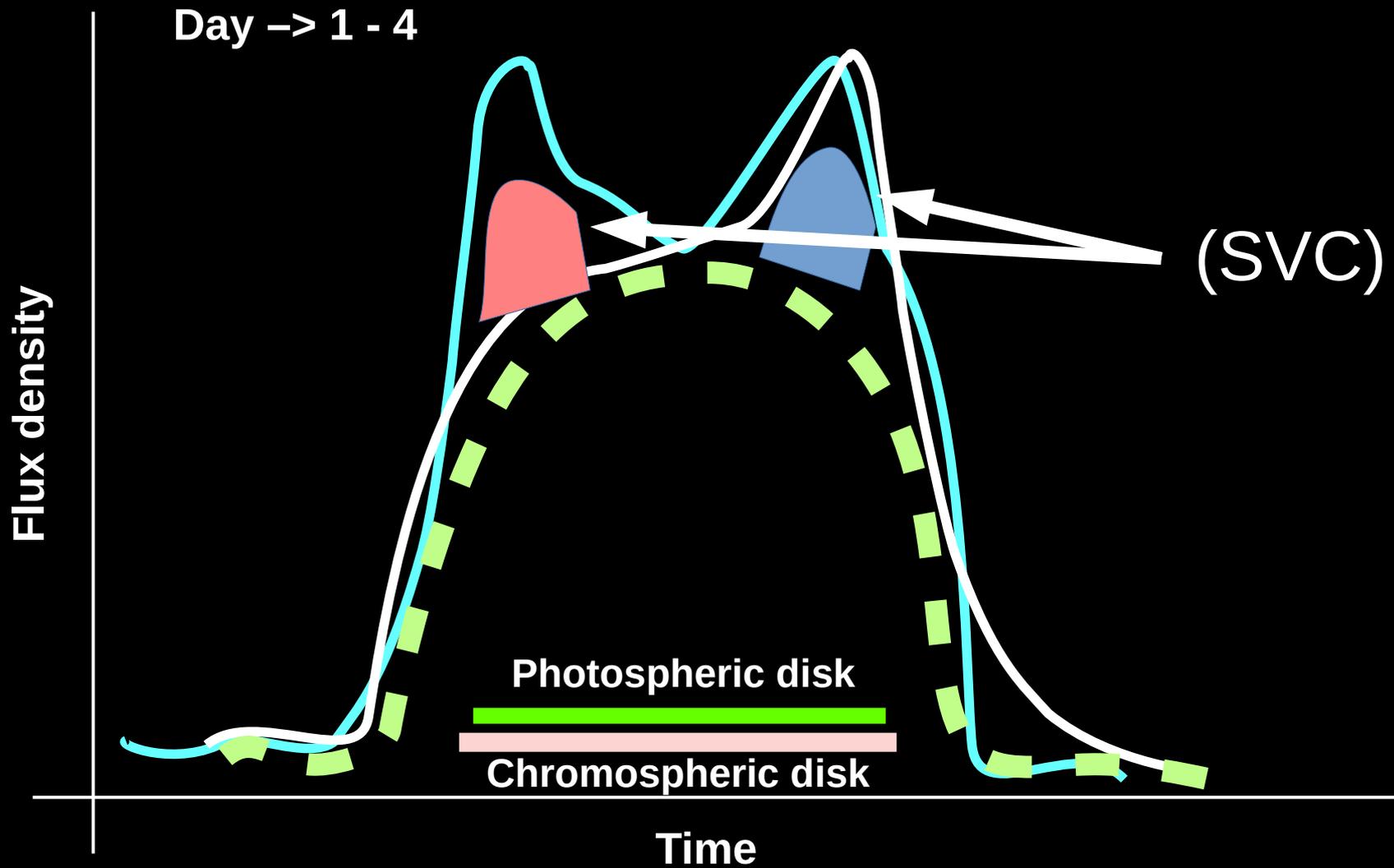
Boischot, A., Ann d' Astrophys., 21, 273 (1958)

Components above the Quiet Sun

Day –> 1 - 4

Slowly Varying Component :

Sources that remain after the background is removed. These correspond to the active centers present above the photosphere.

These last for few hours to days and were found to vary slowly and hence the name SVC.

Time

Boischot, A., Ann d' Astrophys., 21, 273 (1958)

If the SVCs have lifetime of hours to days, then are they related to Sunspots ??

Since Sunspots live for a solar rotation !!

Slowly Varying Component (SVC)
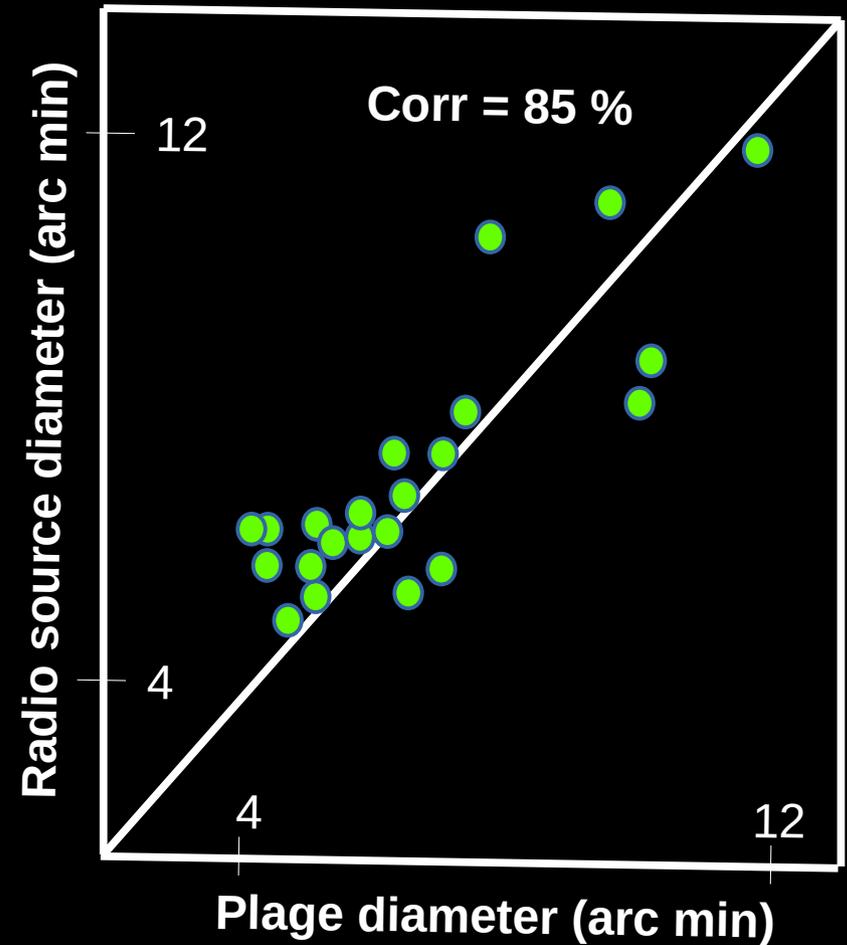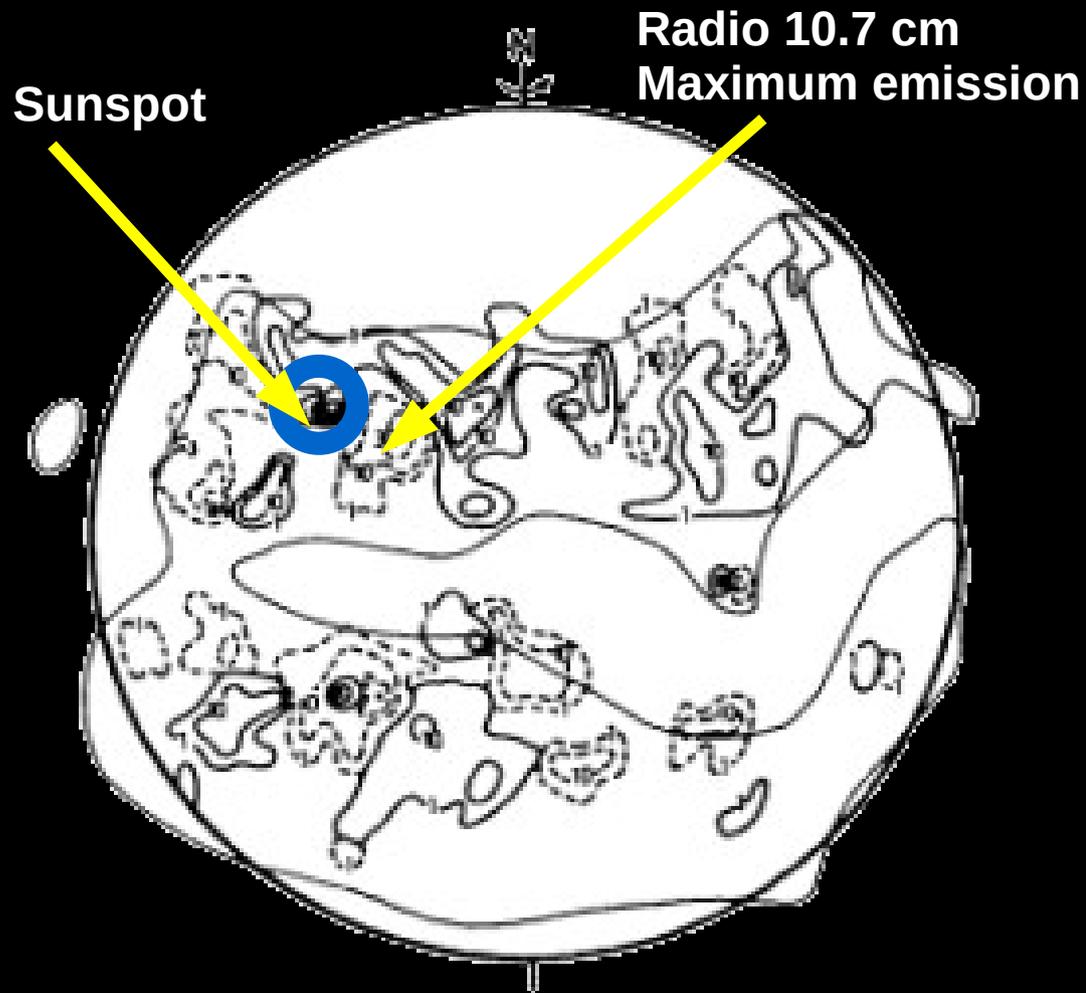
Christiansen et al., IAU, 9, 108 (1959)

Slowly Varying Component (SVC)

Slowly Varying Component :

Superposition of radio contours on the magnetogram and plage image implies the radio emission is closely associated with plages around sunspots rather than the sunspots themselves.

The higher correlation coefficient between the plage and the radio source diameter is an indication of their close association.

Christiansen et al., IAU, 9, 108 (1959)

# SVC – Brightness temperature

cm wavelengths
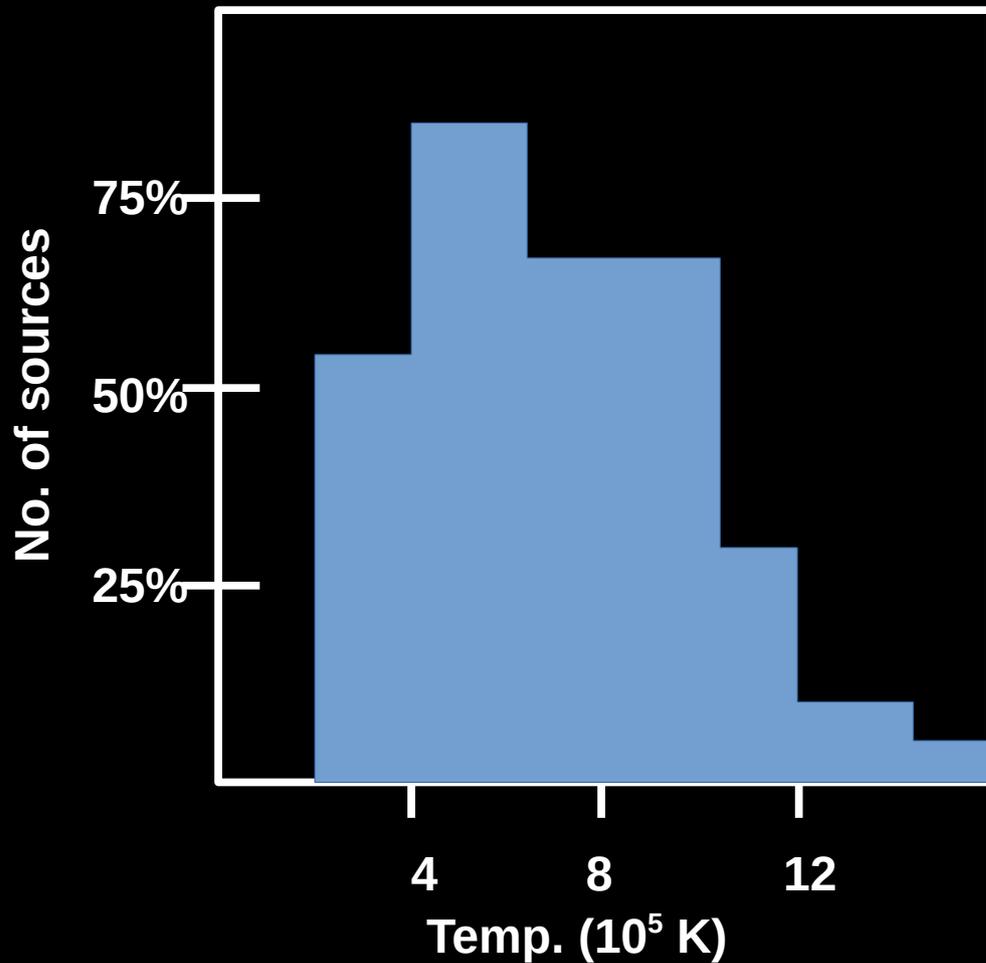
meter wavelengths
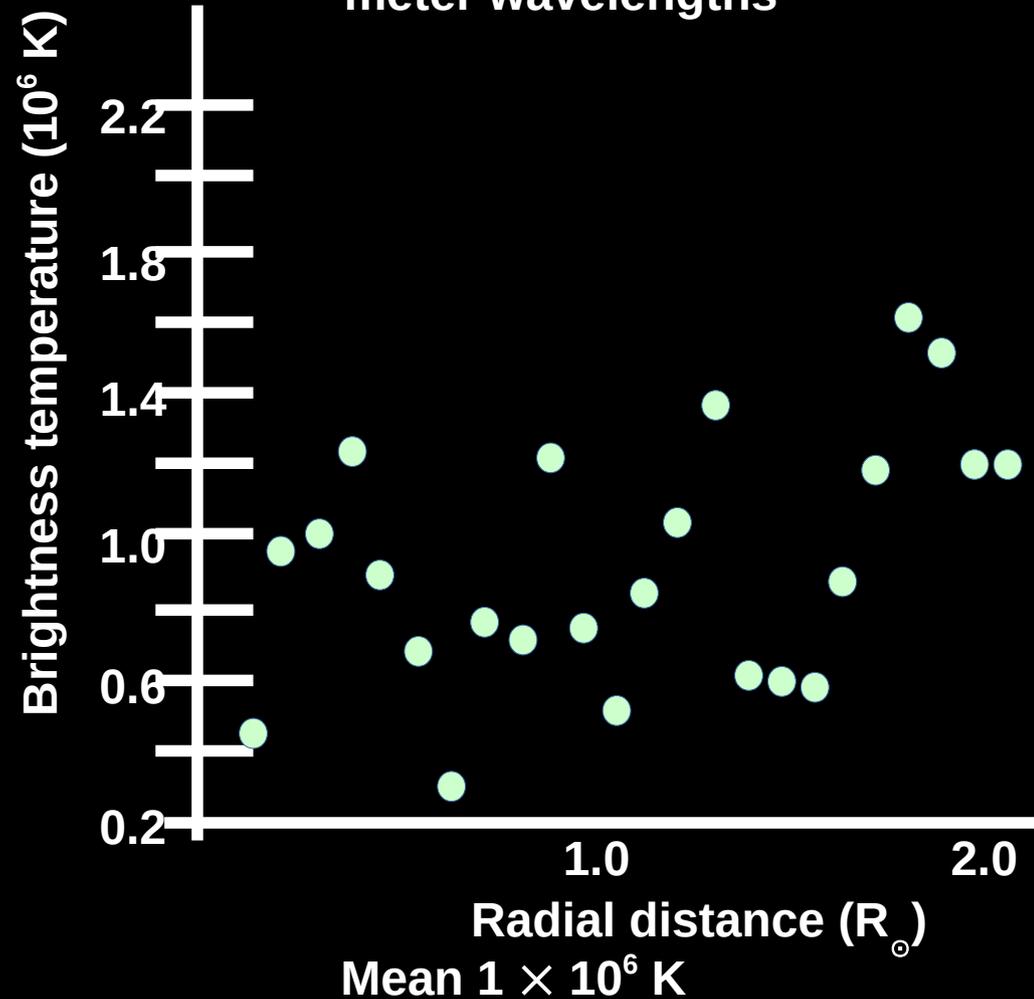
Christiansen et al., IAU, 9, 108 (1959)   **Sastry et al., SoPh, 73, 363 (1981)**

SVC – Source heights
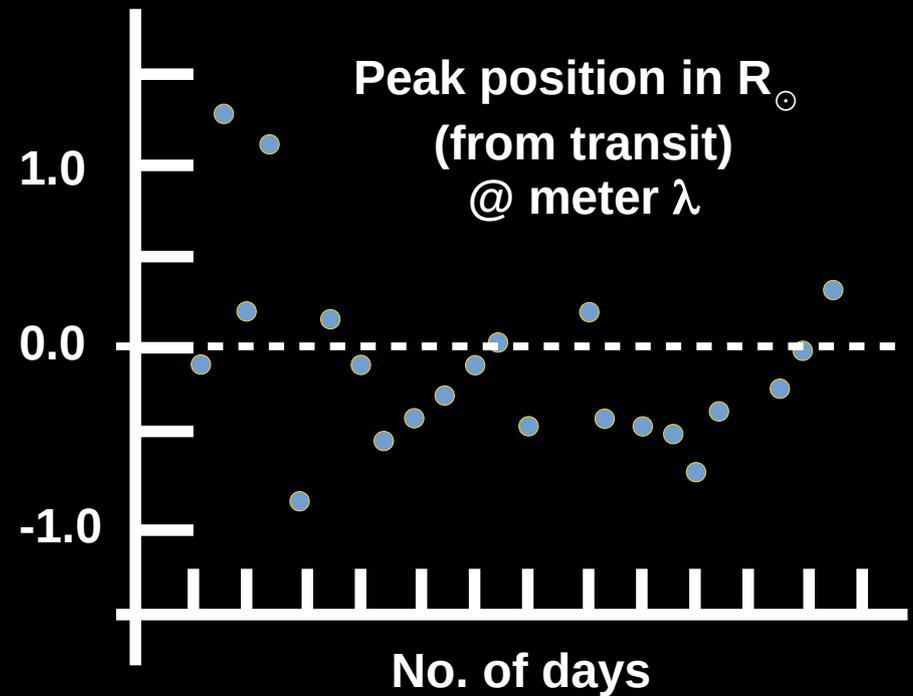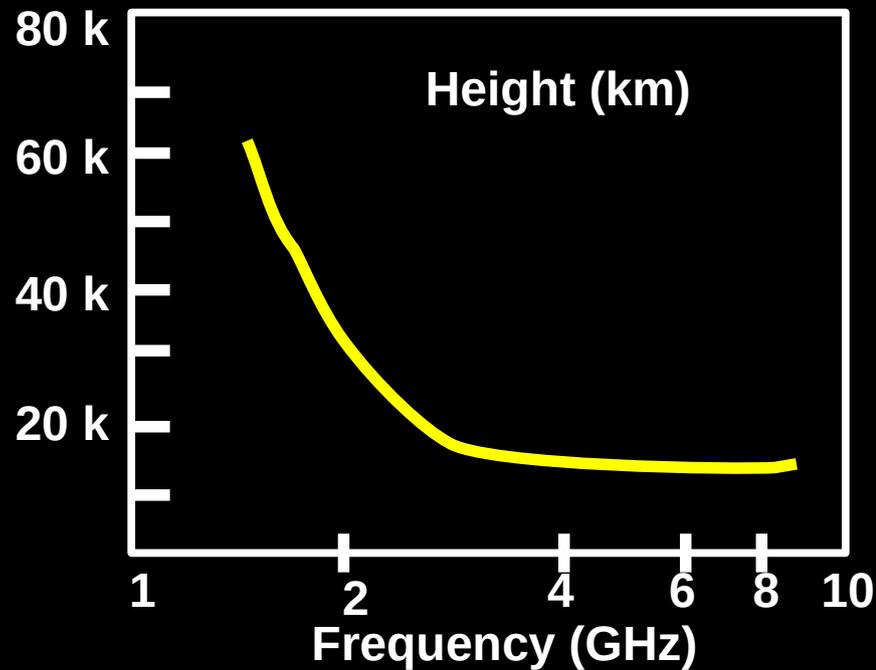
At high frequencies the source height is lesser as compared to that of low frequencies. The high frequency sources are in the chromosphere and the low frequency sources are in the corona.

Christiansen et al., IAU, 9, 108 (1959)   Sastry et al., SoPh, 73, 363 (1981)

SVC – Source Structure
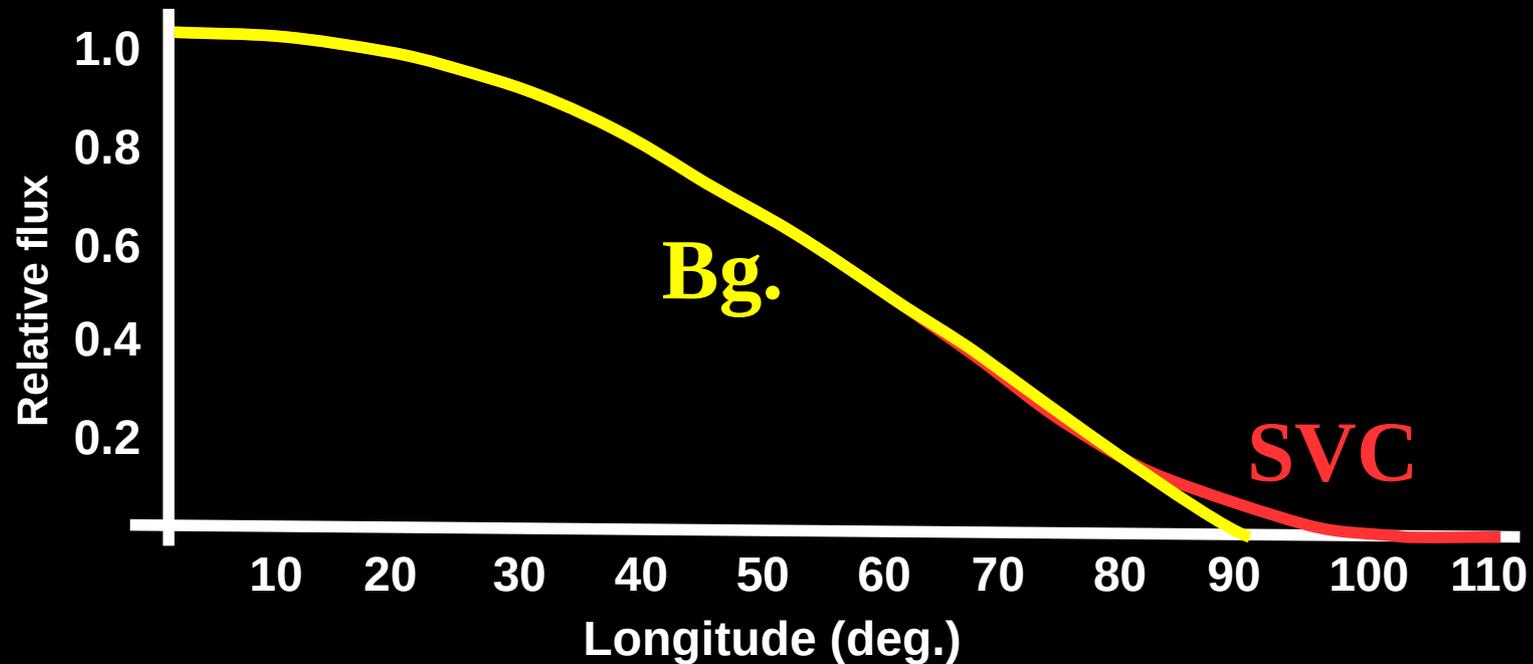
The SVC source diameter is very small (about 10°-20°) - This implies that the source is likely a narrow current sheet located above coronal streamers.

SVC – Imaging Observations
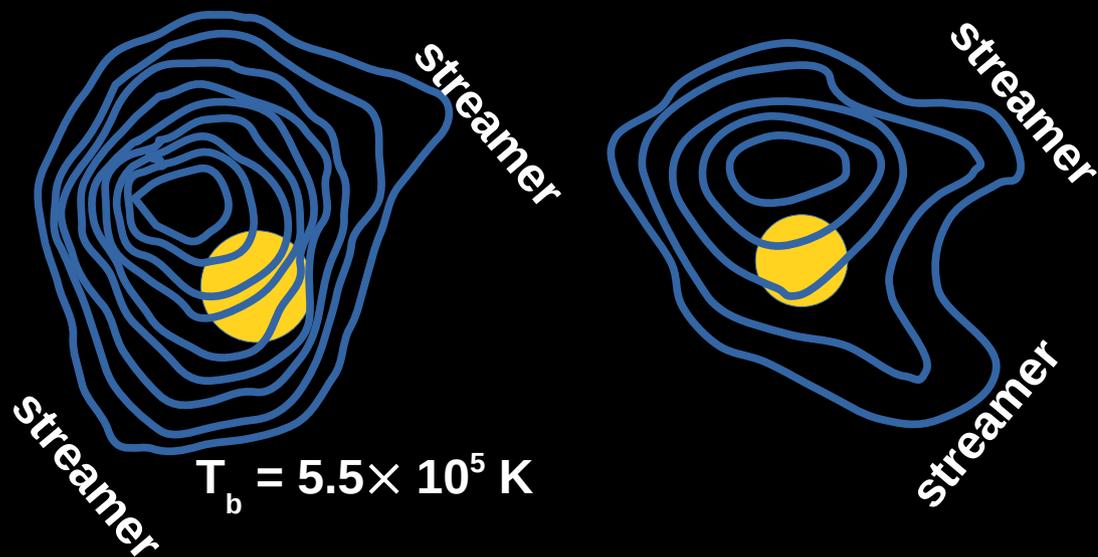
Meter wave (169 MHz) observations

Decameter (34.5 MHz) observations

streamer

streamer

streamer

streamer

$T_b = 5.5 \times 10^5$ K
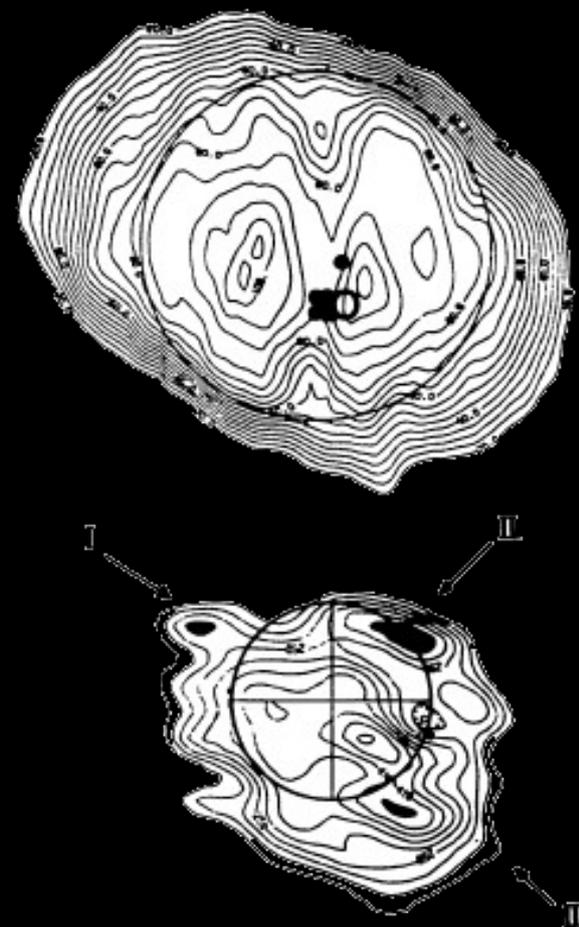
Sastry, Ch. V. et al., SoPh, 87, 391, 1983   **Lantos, P. et al. SoPh, 112, 325, 1987**

SVC – Imaging Observations

Meter wave (169 MHz) observations

Decameter (34.5 MHz) observations

Radioheliograms made at 169 MHz / meter & decameter (34.5 MHz) wavelengths show the presence of SVC components on top of coronal loops, streamers, etc. This is in addition to those radio emission above plage areas of the chromosphere.

Sastry, Ch. V. et al., SoPh, 87, 391, 1983   Lantos, P. et al. SoPh, 112, 325, 1987

SVC – Polarization & Nature of Emission
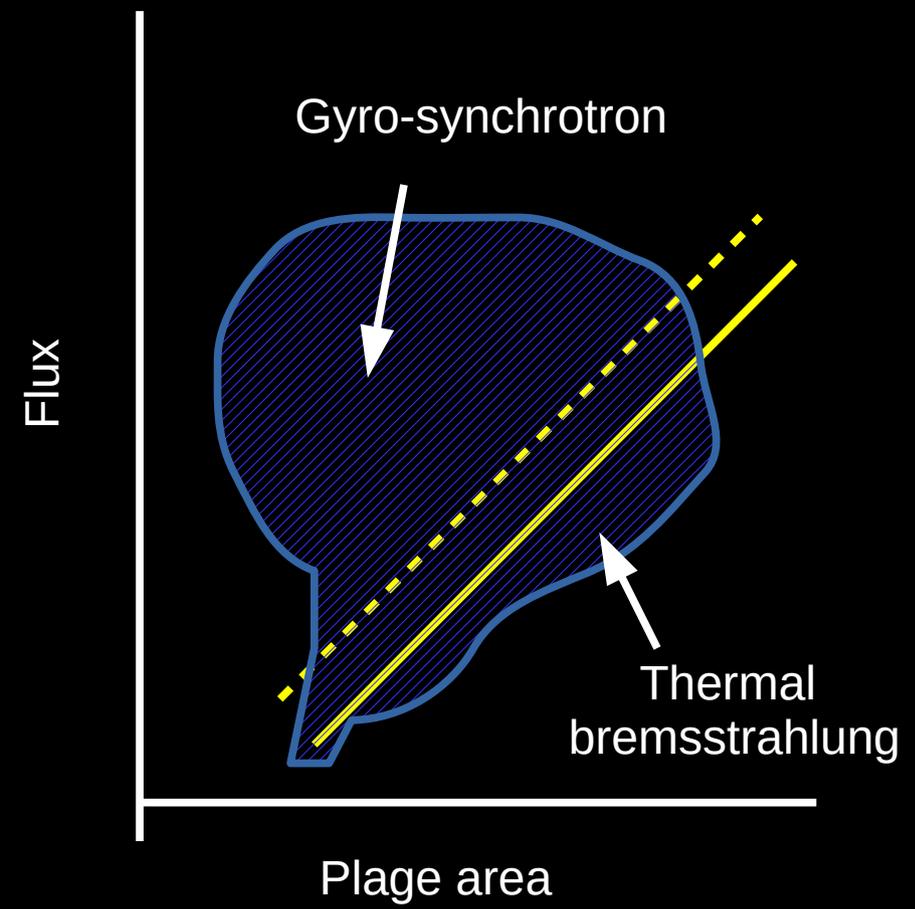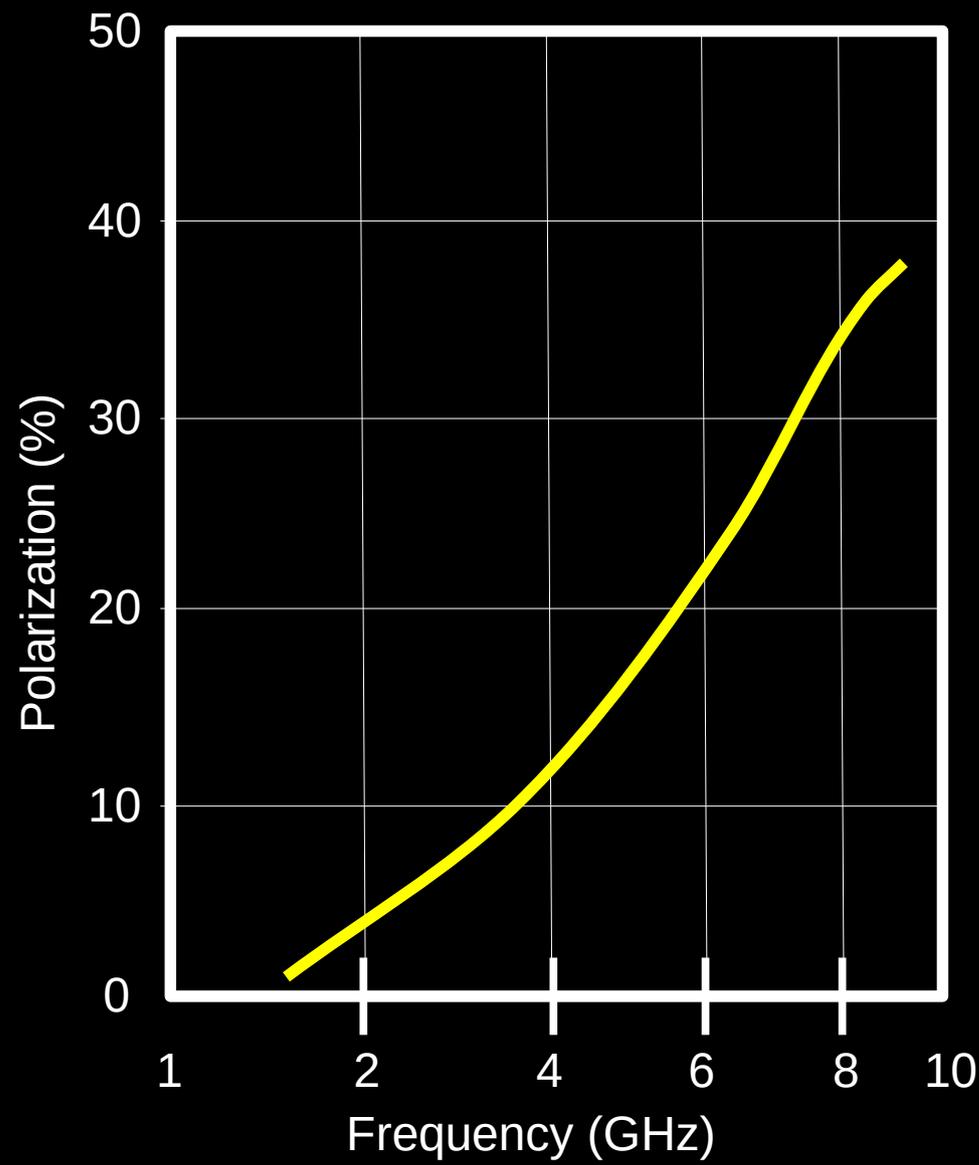
Tapping et al., SoPh, 199, 217, 2001

SVC – Polarization & Nature of Emission

1. The electron gyro-resonance theory explains satisfactorily about the observed degree of circular polarization.

2. It appears that radiation at the gyro-frequency ($\omega_g = eB/m$) and its harmonics emitted by thermal electrons in a dense region over the sunspot group can account for the intensity and polarization spectrum. The mechanism requires an average magnetic field of 500 Gauss at about 20000 km above photosphere and an electron temperature of ~ 2×10^6 K.

③

The Transient Component

The Transient Component / Outburst

TC / Components with short lifetime.

Flux density

Time
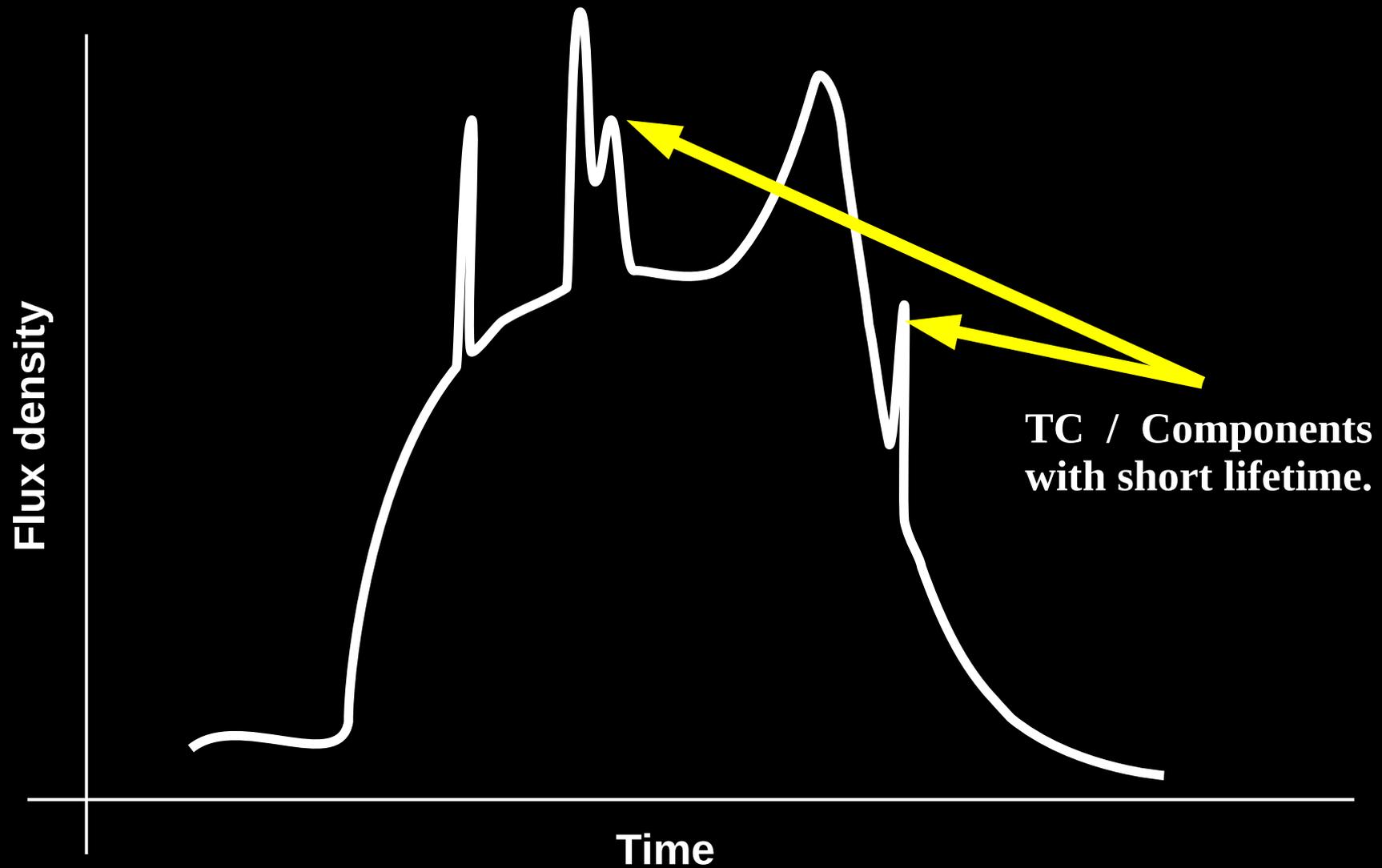
The Transient Component / Outburst

1. A sudden increase in the observed radio brightness ($T_b >>> 10^6$ K).

2. It lasts for few seconds to minutes.
3. It is called as a radio surge or transient or outburst or simply radio burst. One can call this as a radio flare as well.

Based on the wavelength of origin they are classified into :

1. Centimeter wave radio bursts
2. Decimeter wave radio bursts
3. Meter & Decameter wave radio bursts
4. Hecto & kilometer wave radio bursts

Time

The cm-λ radio bursts

cm–λ radio bursts
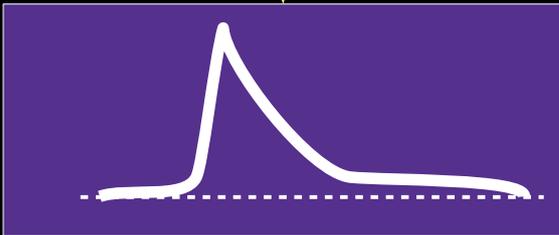
| Type-A : Simple burst | Type-B : Post- burst | Type-C : Gradual rise and fall |
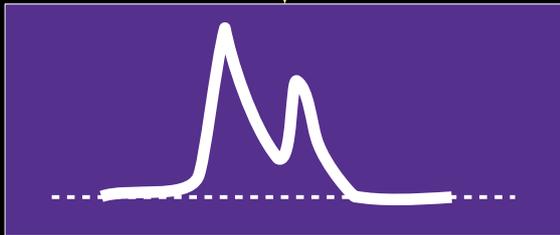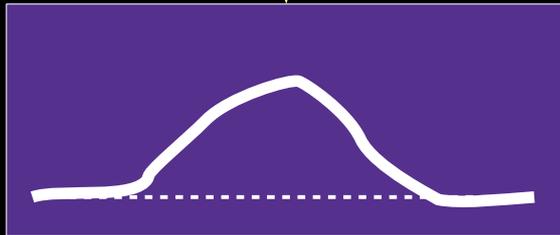
Nature → Rise very rapidly and fall gradually
Duration →1-5 minutes
Polarization → partially circular
Source size → 1´.5
T_b → 10^6 K (for weak)
Emission → non-thermal
 gyro-synchrotron

Nature → group of simple bursts
Duration →several minutes
Polarization → partially circular
Source size → > 3´.0
T_b → 10^5 – 10^7 K (for strong)
Emission → thermal bremsstrahlung

Nature → increase and decrease gradually
Duration →few tens of minutes
Polarization → partially circular
Source size → < 1´.0
T_b → 10^6 K
Emission → thermal bremsstrahlung

The cm-λ radio bursts – Flux & duration statistics
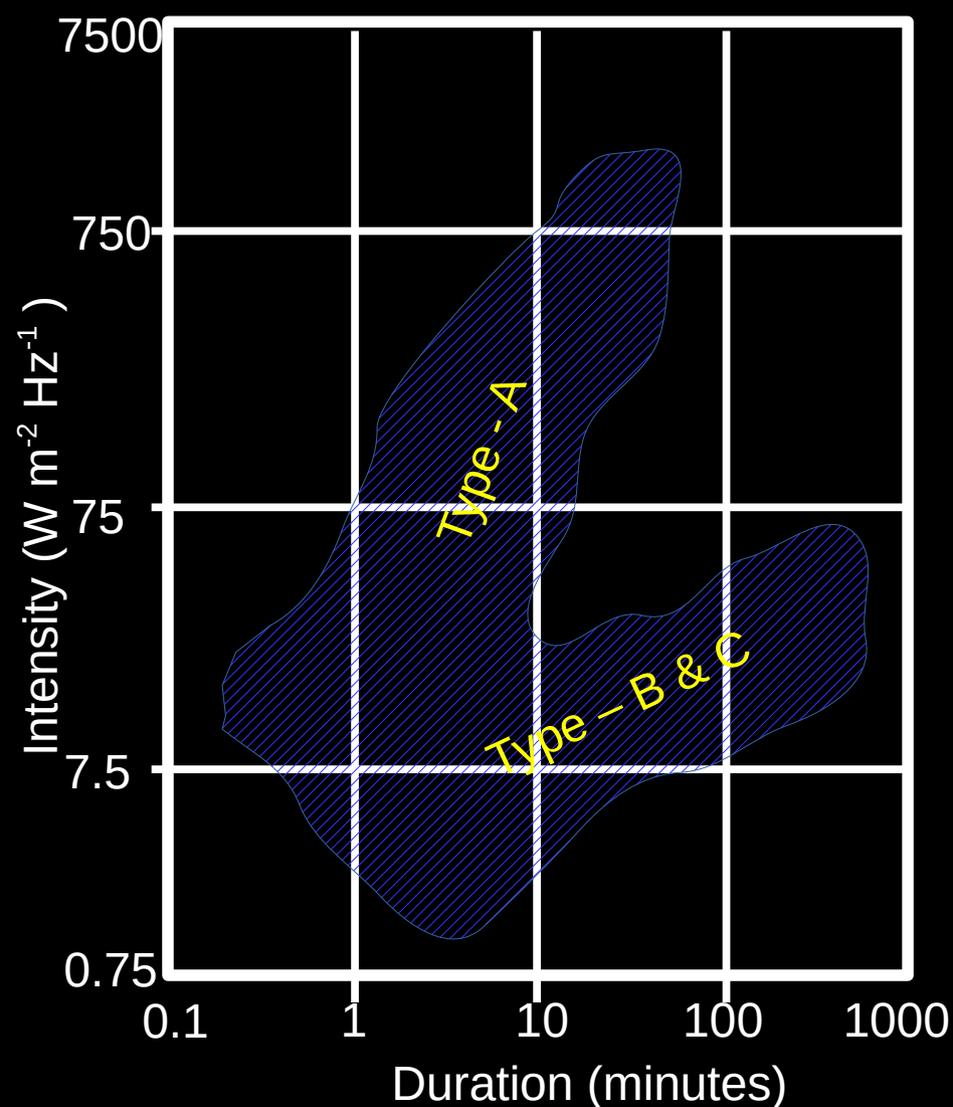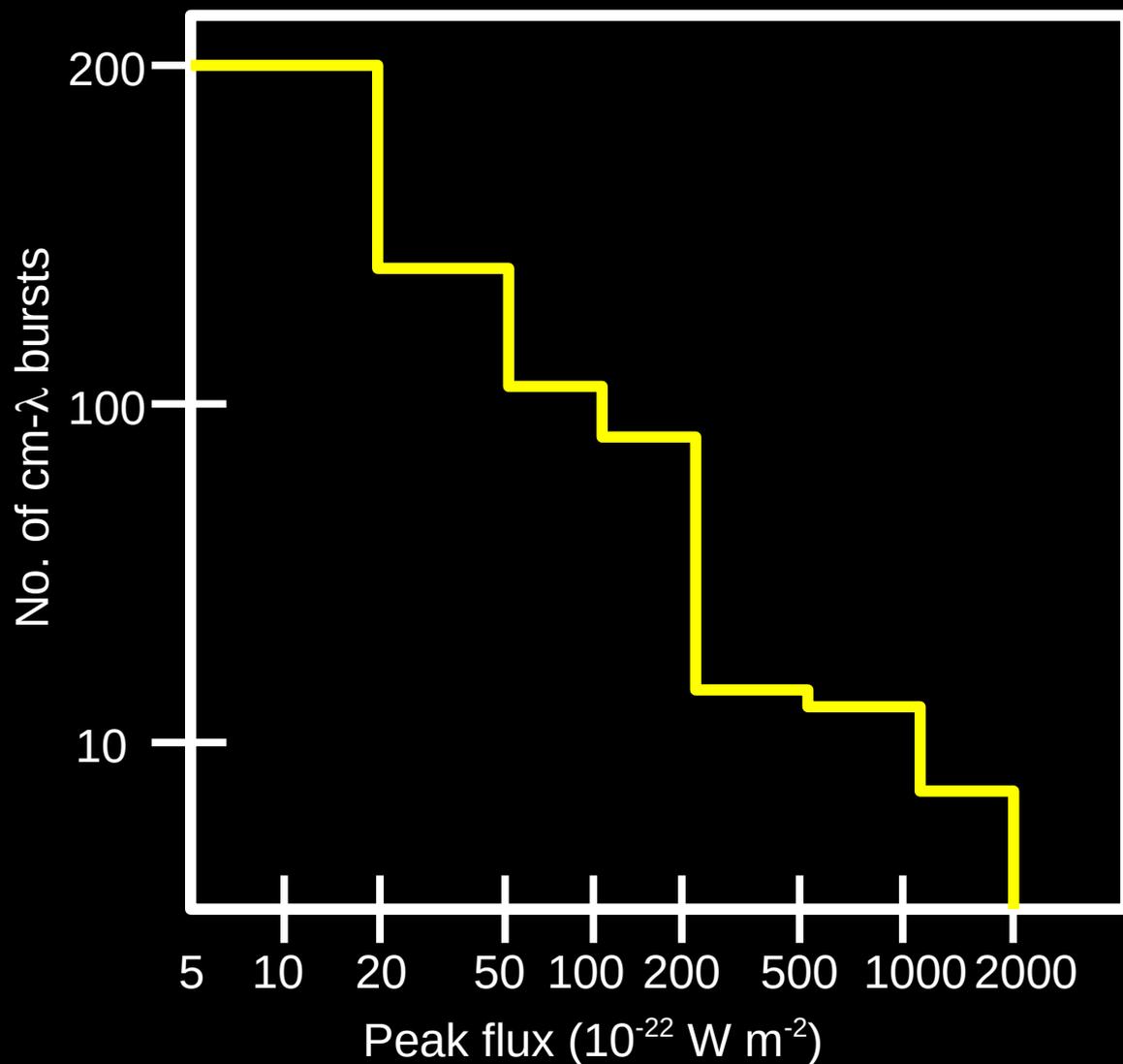
Covington, C. Paris symposium on Radio Astronomy, 159 (1959)

The cm-λ radio bursts : General Properties

1. The location of the sources : 4′ – 6′ above photosphere and move rarely; Size : 1′ - 4′; Polarization : 5 % - 40 %.

2. Bursts that gradually rise and fall often occur near simultaneously with H-alpha flare indicate the heating and compression of the flare region.

3. The weak impulsive bursts originate in the coronal plasma of Chromospheric density with a local temperature of 10^6 K.

4. The strong impulsive bursts are either due to gyro-synchrotron or non-thermal bremsstrahlung by super-thermal electrons from flare ejected plasma.

5. The electrons producing cm bursts by bremsstrahlung and synchrotron also produce bremsstrahlung x-ray bursts of low and high energy.

The cm-λ radio bursts : Microwave bursts

1. Type-A - called microwave outbursts.

2. Intensity > 100 times higher than usual cm bursts

3. Have several peaks during the rise phase (few minutes) and follow a gradual decay for few tens of minutes to hours.

4. Source size : 1′ – 2′. But increases after the post-burst phase to >3′.

5. Temperature can go up to 10^9 K.

6. 70 % of them are partially circularly polarized.

Many more properties can be discussed further

Limited it due to time constraint

The decimeter-λ radio bursts

decimeter–λ radio bursts

Fast drifting   Intermediate drifting   Continuum

Decimeter type   meter type
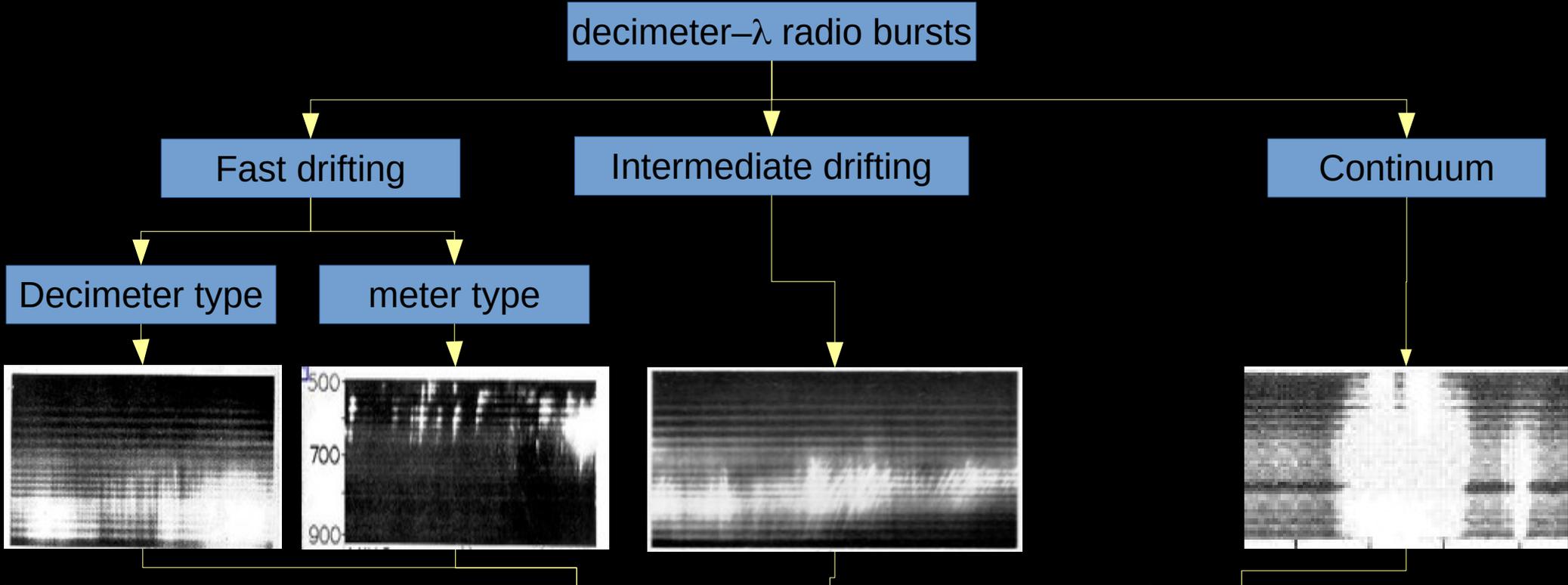

Both are fast drifting > 2 GHz / s with shorter duration (ta
Positive and reverse drifts are seen
Decimeter type does not extend in to meter wave domain (500 – 600
MHz / 3 – 60 cm)
Meter type continues into meter wave domain
Reason → plasma oscillation like type-III

Intermediate drift rate < 150 MHz/s
Bandwidth ~ 10 MHz
Exists below 600 MHz
Reason → plasma oscillations like type-II

Continuum – no drifts seen
Bandwidth ~ 500 MHz
Exists from 900 - 500 MHz
Reason → plasma oscillations within specific layers

Young et al., ApJ, 133, 243 (1961)

Decimeter-λ radio bursts : Source size & Brightness
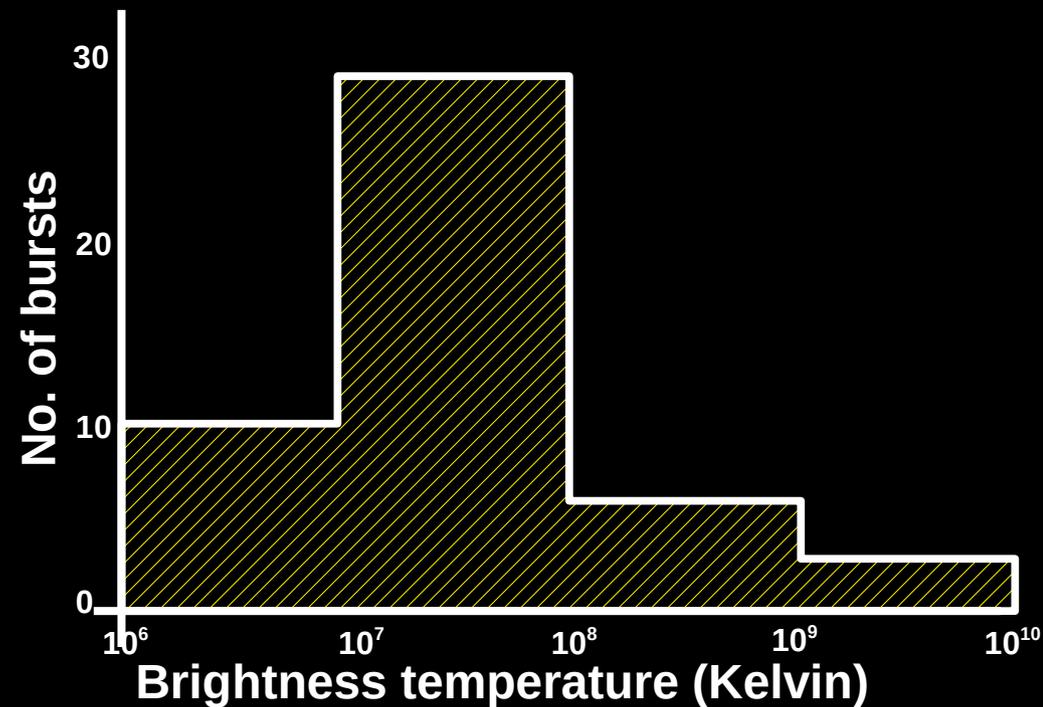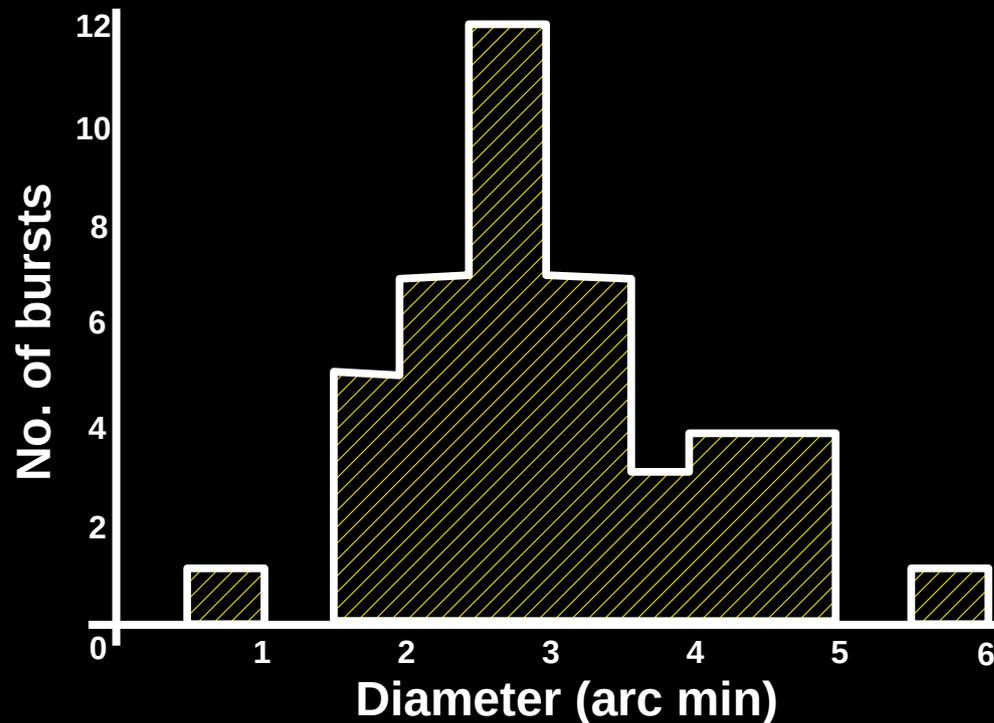
1. Mean source diameter : ~2′ (2′-5′)

2. Mean brightness temperature : ~ 10^7 °K (10^6 – 10^{10} °K).

Mullaly, R. F. et al., Au. J. Ph, 16, 8 (1963)

Decimeter-λ radio bursts : Polarization
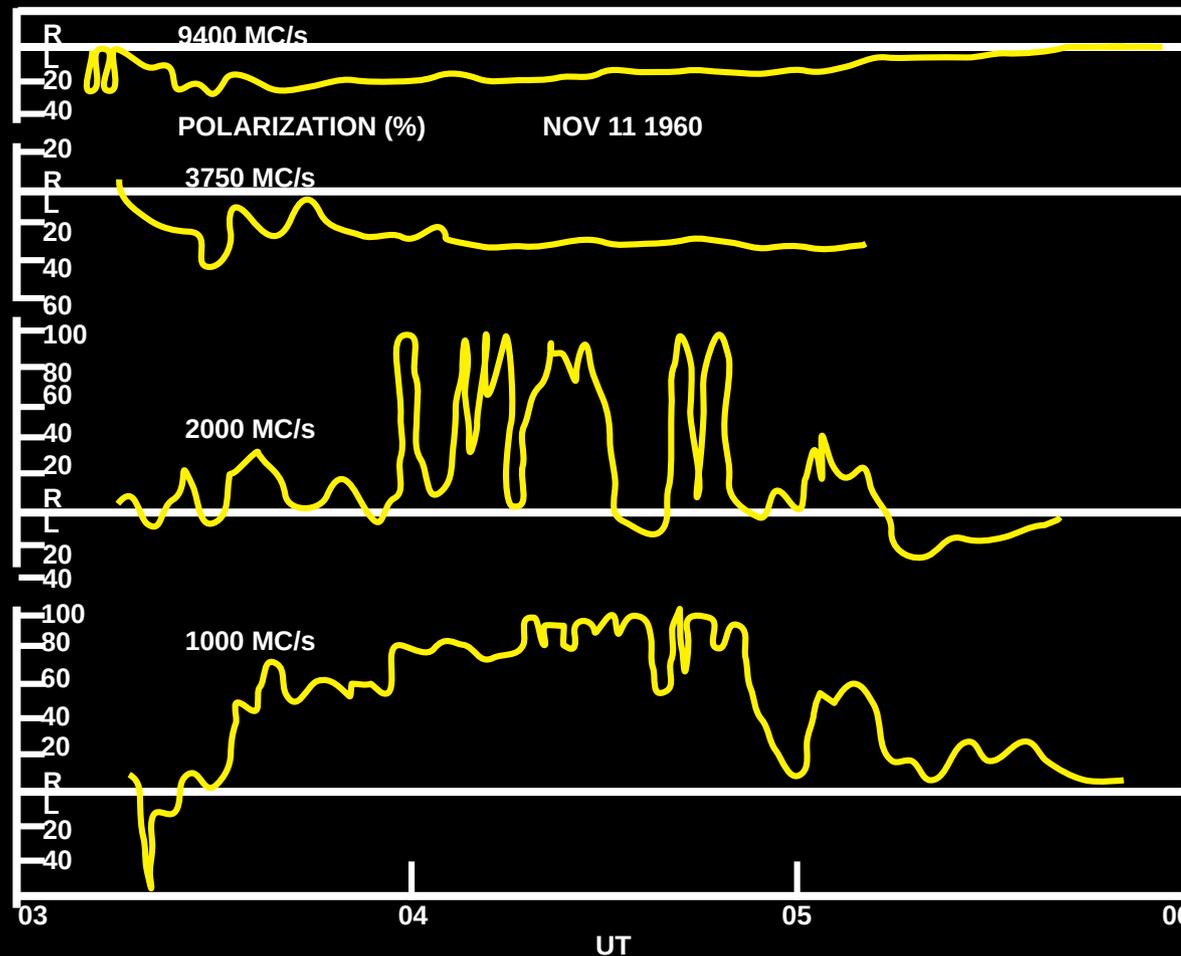
Tanaka, H., Proc. Res. Inst. Atmosph., Nagoya Univ. Japan, 8, 1 (1961)

Decimeter-λ radio bursts : Polarization
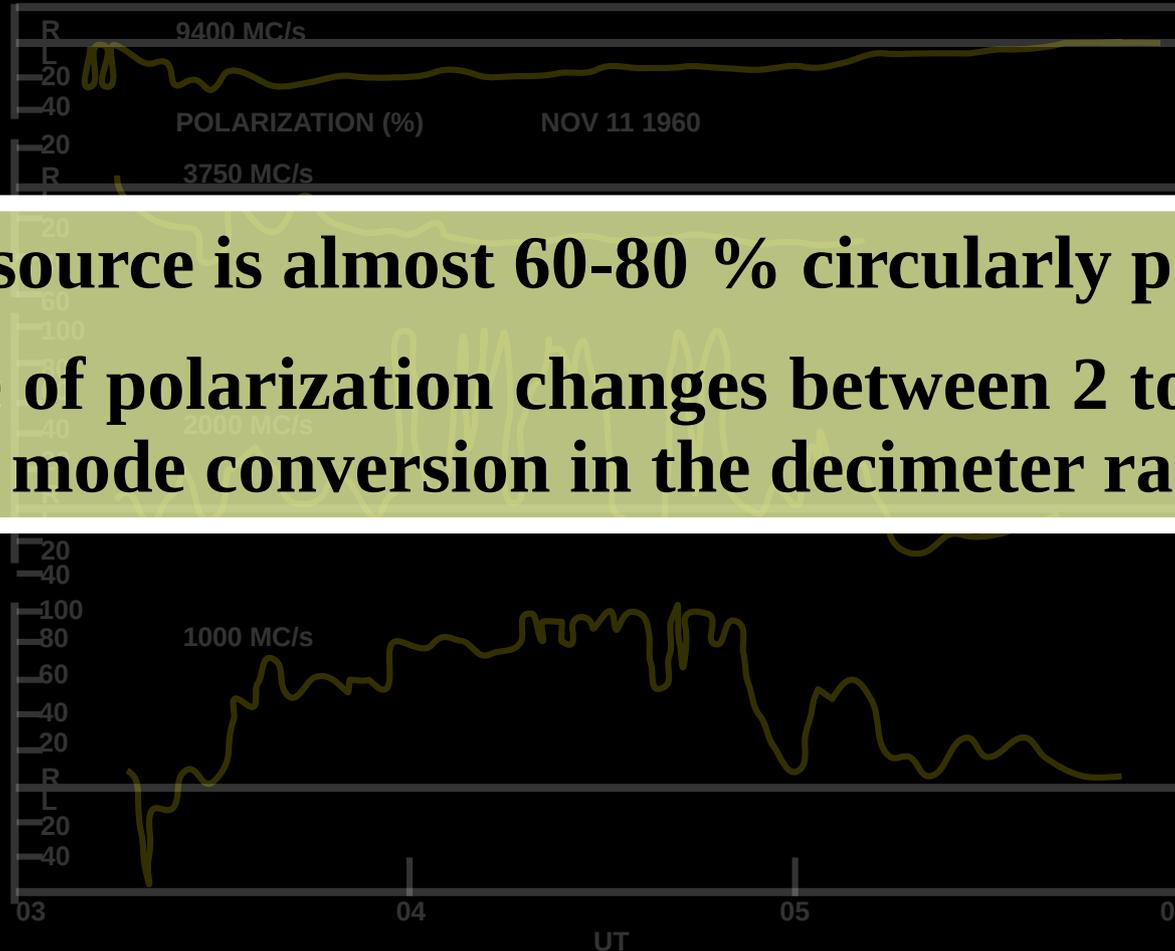
1. The dcm source is almost 60-80 % circularly polarized.

2. The sense of polarization changes between 2 to 3.7 GHz, indicating a mode conversion in the decimeter radiation.

Tanaka, H., Proc. Res. Inst. Atmosph., Nagoya Univ. Japan, 8, 1 (1961)

Decimeter-λ radio pulsations

Oscillation / Pulsation Signature
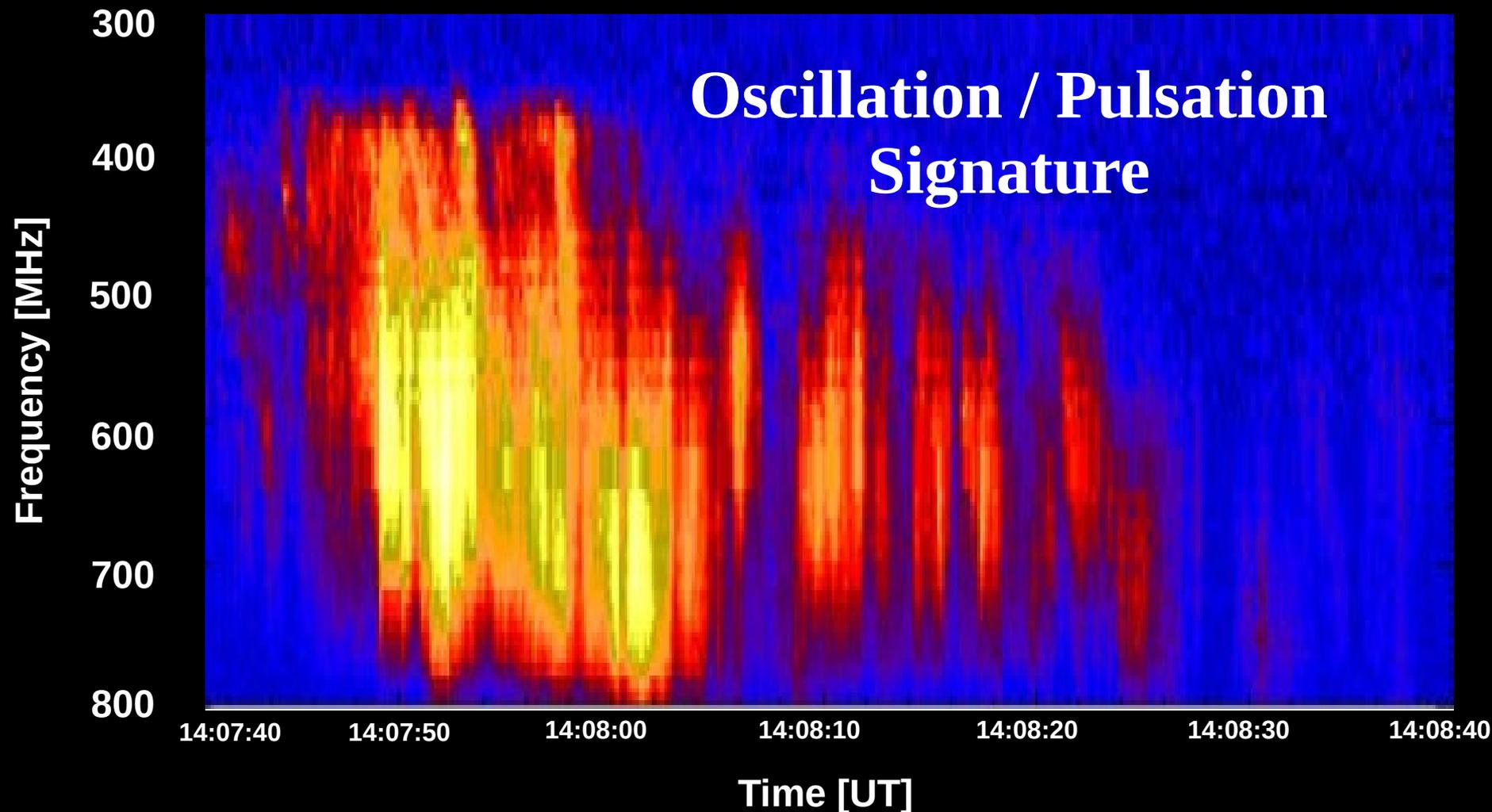
Radio Dynamic Spectrum

Benz, A. O. SoPh, 273, 363 (2011)

Decimeter-λ radio pulsations
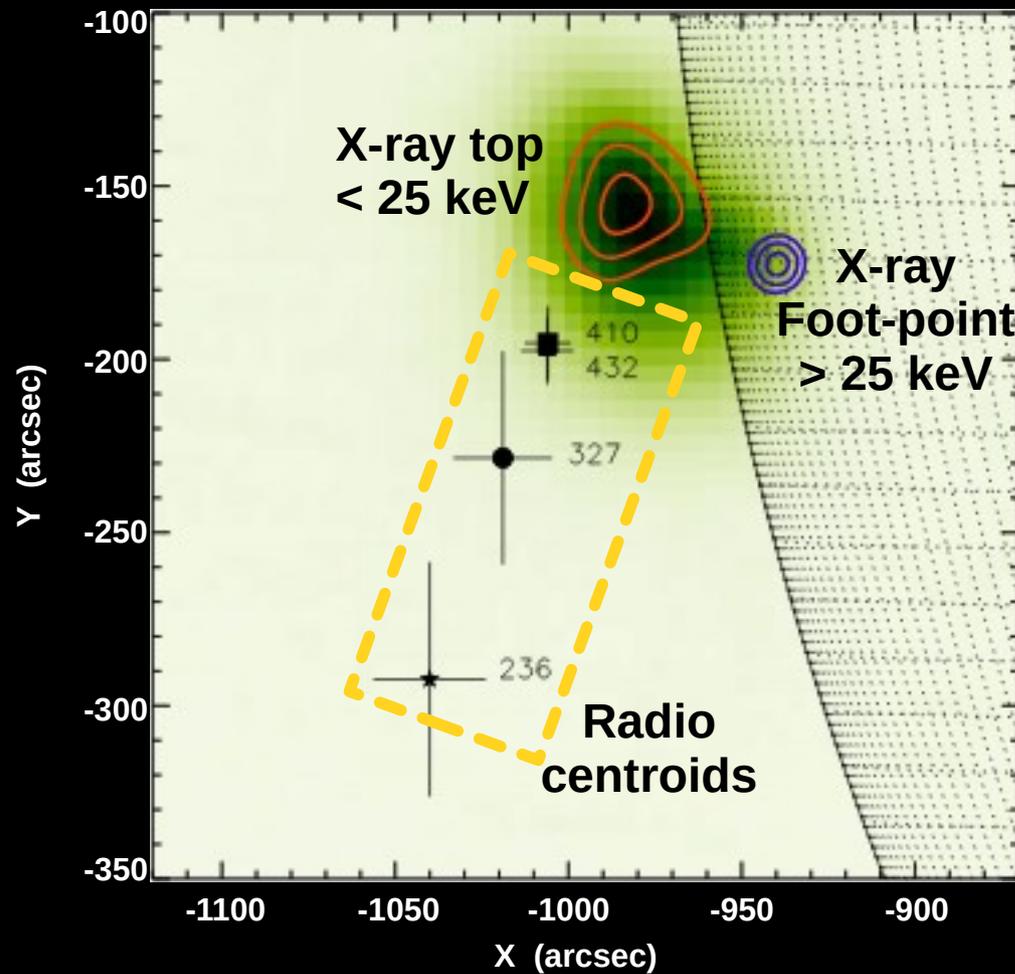
X-Ray & Radio superposition

Benz, A. O. SoPh, 273, 363 (2011)

Decimeter-λ radio pulsations

1. X-rays and coherent radio emissions are due to particle accelerations.

2. The dcm pulsation observations combined with RHESSI X-ray and radio imaging (Nancay) observations indicate that the radio sources are in line with the X-ray source.

3. A common source responsible for X-ray and radio gave rise to pulsation in the lower atmosphere.

Benz, A. O. SoPh, 273, 363 (2011)

Many other dcm-λ bursts can be discussed further

Limited it due to time constraint

Meter & deca-m λ radio bursts : Classification

Meter wave Radio bursts

Type – I → Long lived broad-band continuum with short lived narrow-band burst of non-thermal emission

Type – II → Slow-drifting broad-band non-thermal emission

Type – III → Fast-drifting broad-band non-thermal emission

Type – IV → Slow / Very slow-drifting broad-band non-thermal emission (sometimes stationary)

Type – V → Fast-drifting broad-band non-thermal emission (type-III like)

Meter & deca-m λ type-I radio burst / Noise Storms
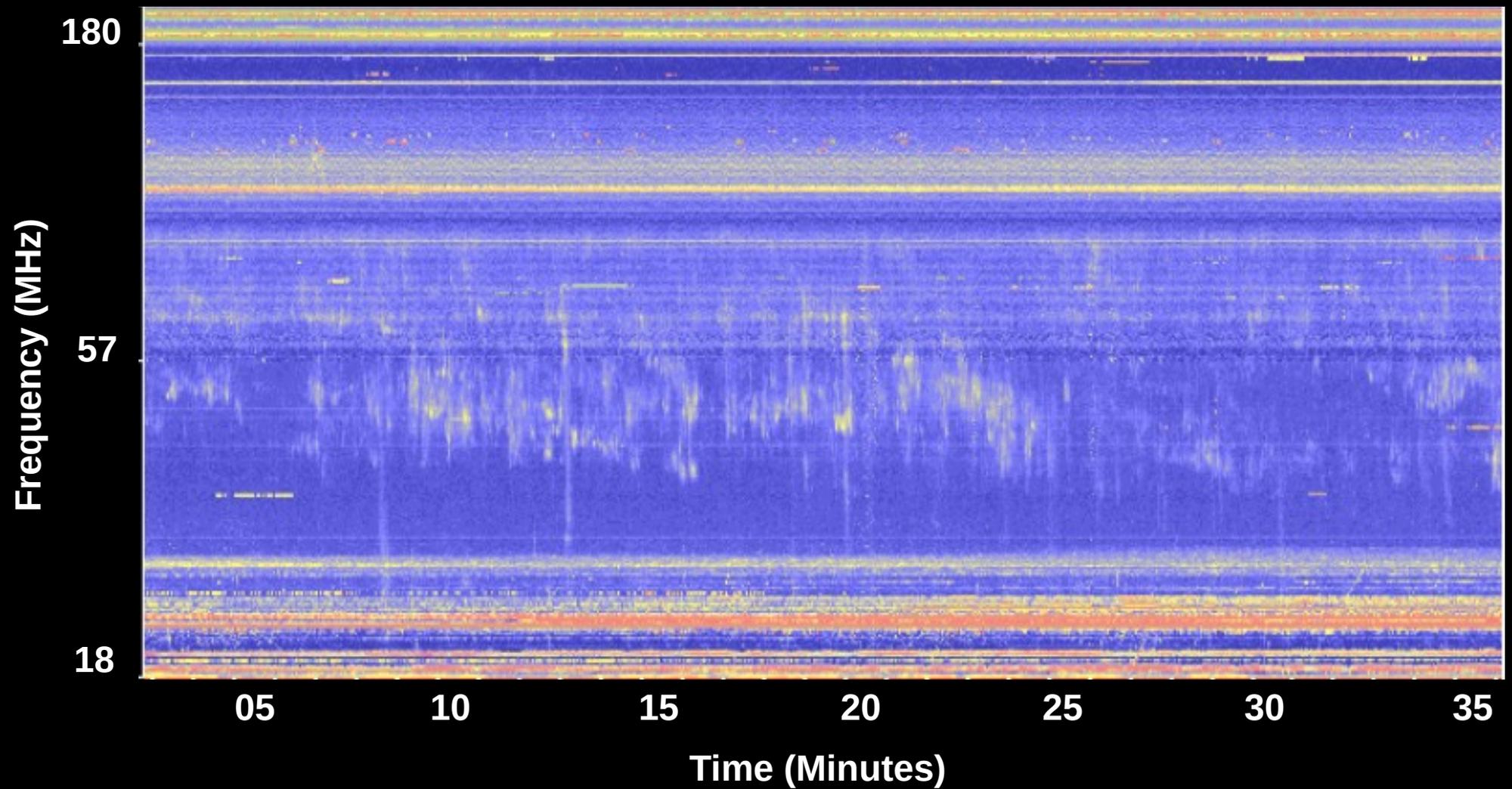
Meter & deca-m λ type-I – Bandwidth & lifetime

N
100

50

Ntot = 616

0.1　0.2　0.3　0.4　0.5　0.6　0.7
Duration (sec.)

274 Mc/s

20

10

Number

0　1　2　3　4　5　6　7　8　9　10　11　12
Bandwidth (Mc/s)
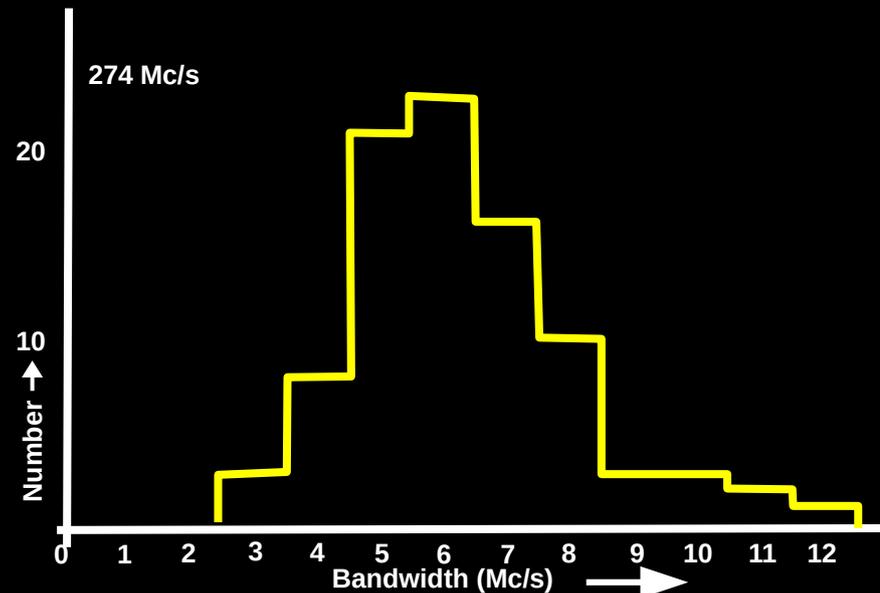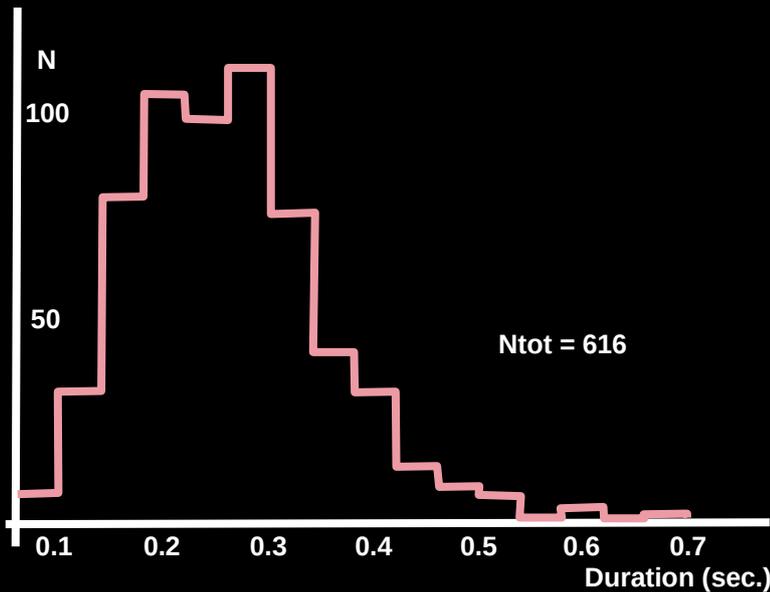
Majority of the type-I bursts have :

1. Duration in the range 0.2 – 0.4 second (274 MHz) & 1 second (77 MHz).

2. Bandwidth in the range 5 – 8 MHz.

Elgaroy, O., Astrophysica Norvegica, 7, 123 (1961)　　Ramesh et al., ApJ, 89, 762 (2013)

Meter & deca-m λ type-I – Energy distribution
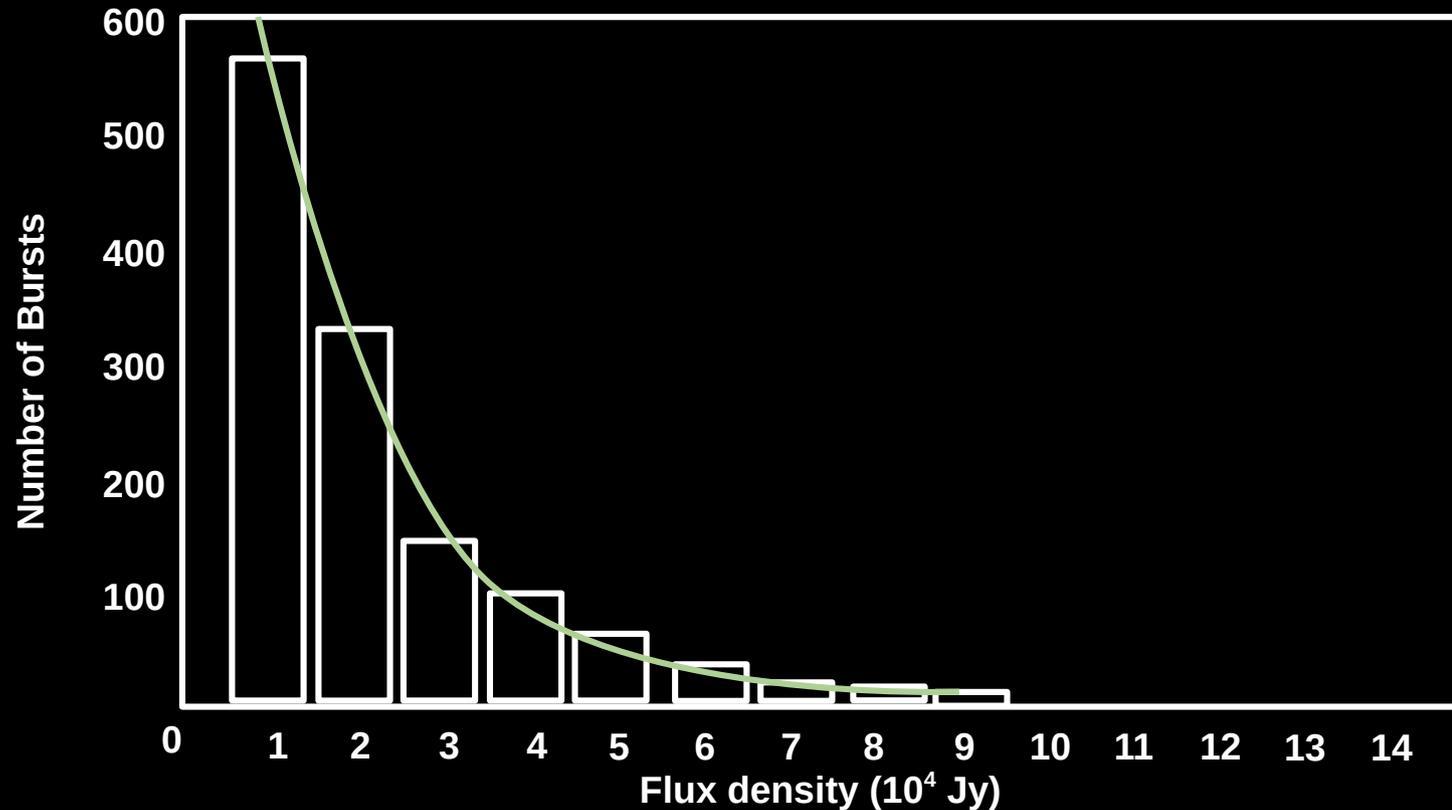
Majority of the type-I bursts have flux density < 30 kJy.

Elgaroy, O., Astrophysica Norvegica, 7, 123 (1961)　　　Ramesh et al., ApJ, 89, 762 (2013)

Meter & deca-m λ type-I – Storm center size

Wild, J. P., Proc. IRE, 46, 160, 1958

Mercier et al., A&A, 576, 136, (2015)

Meter & deca-m λ type-I – Storm center size

N

50

169 MHz
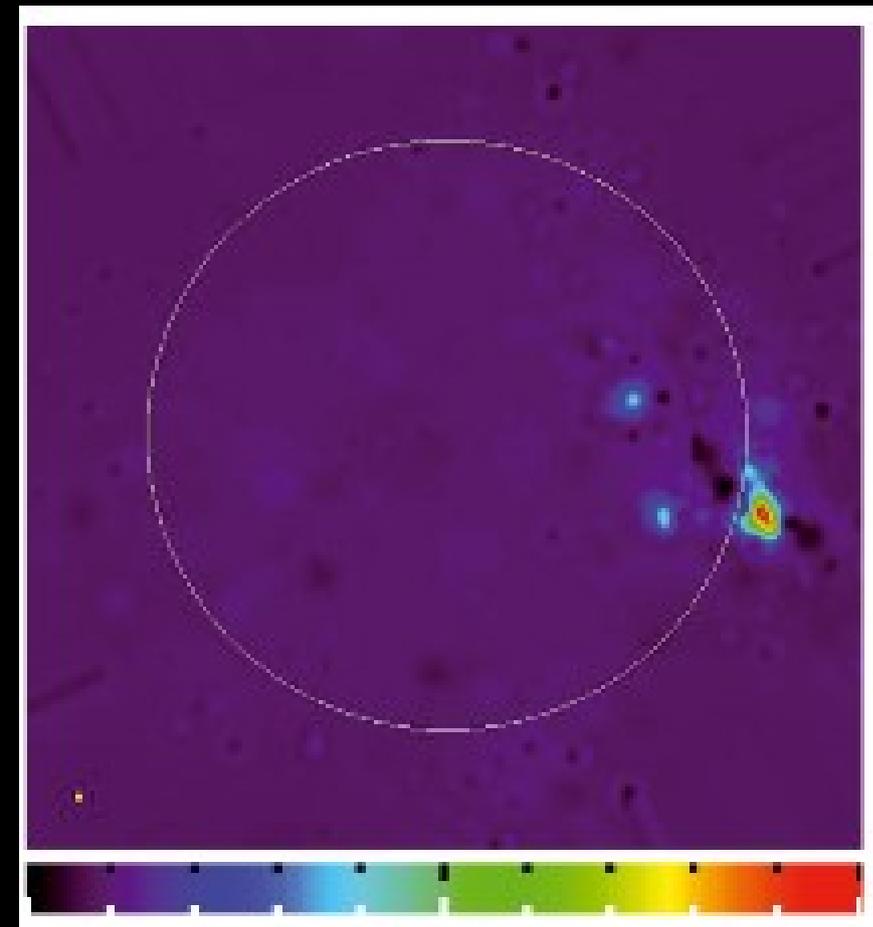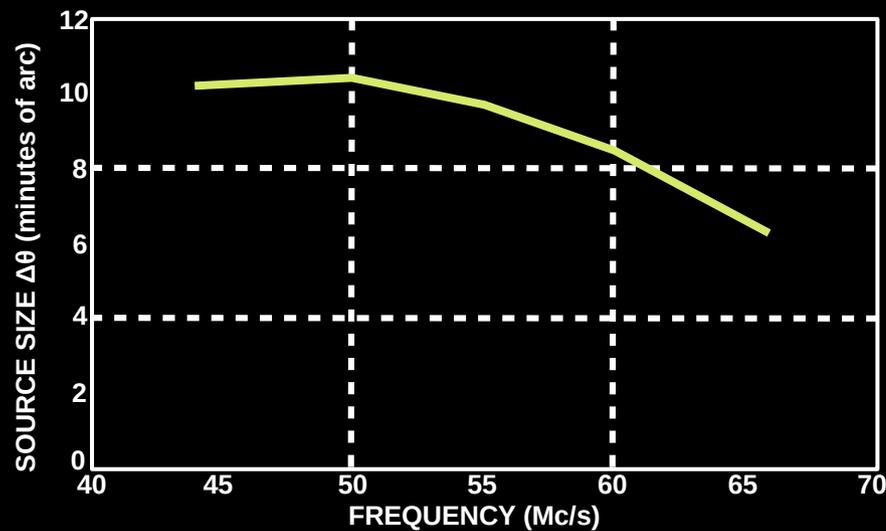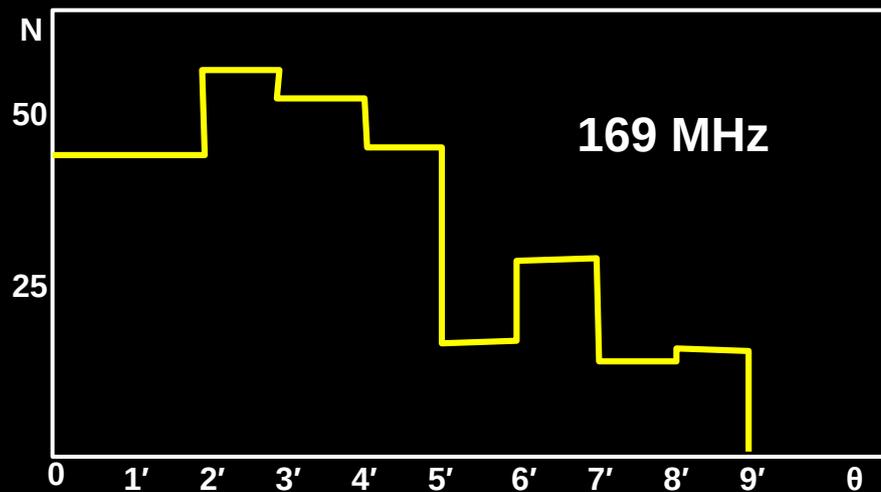
1. **The overall angular size of the source varies from 30″ – 90″ with an inner core size of 30″-60″ at 237 MHz.**

2. **However, the source size is higher at low frequencies. And it continues to increase as a function of decreasing frequency (or increasing altitude in the atmosphere).**

SOURCE SIZE Δθ (min

12

10

8

6

4

2

0

40   45   50   55   60   65   70

FREQUENCY (Mc/s)
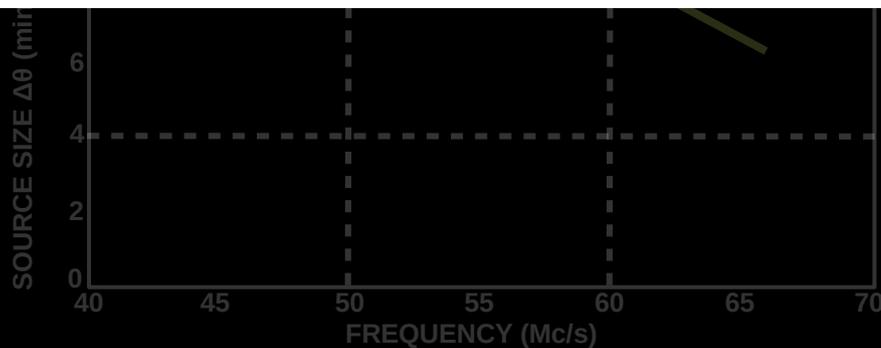
Wild, J. P., Proc. IRE, 46, 160, 1958   **Mercier et al., A&A, 576, 136, (2015)**

Meter & deca-m λ type-I : Polarization
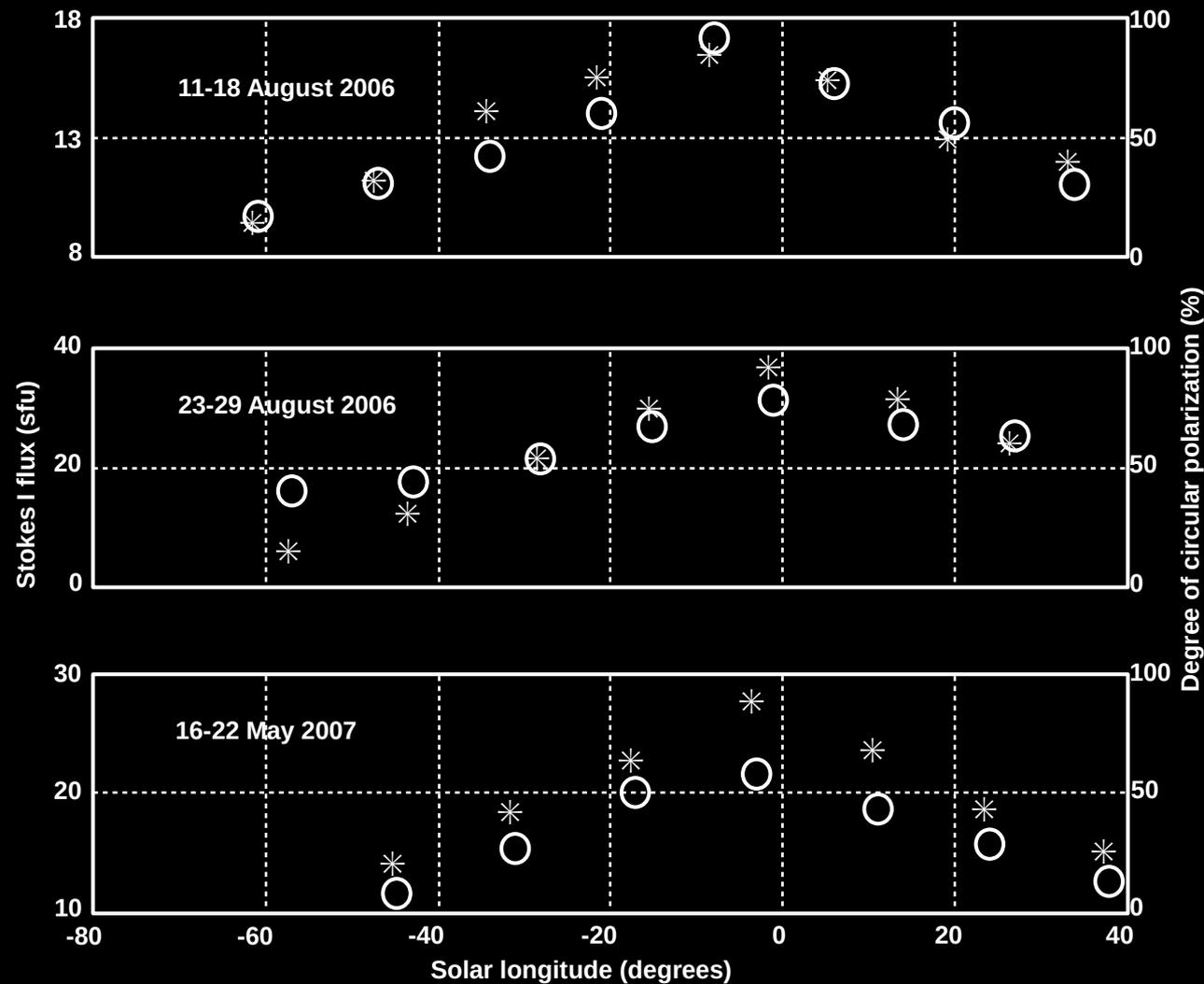
Ramesh et al., ApJ, 734, 39 (2011)

Meter & deca-m λ type-I : Polarization

1. The fall of polarization on either side of the disk center implies that the source is highly directive.

2. The magnetic field of the noise-storm active regions estimated are 0.6 – 1.1 G

3. The emerging magnetic flux and the changes in the existing active region magnetic fields inevitably lead to field reconnection and generation of type-I bursts – So, these are associated with these small sites of reconnection.

Ramesh et al., ApJ, 734, 39 (2011)

Meter & deca-m λ type-II radio bursts
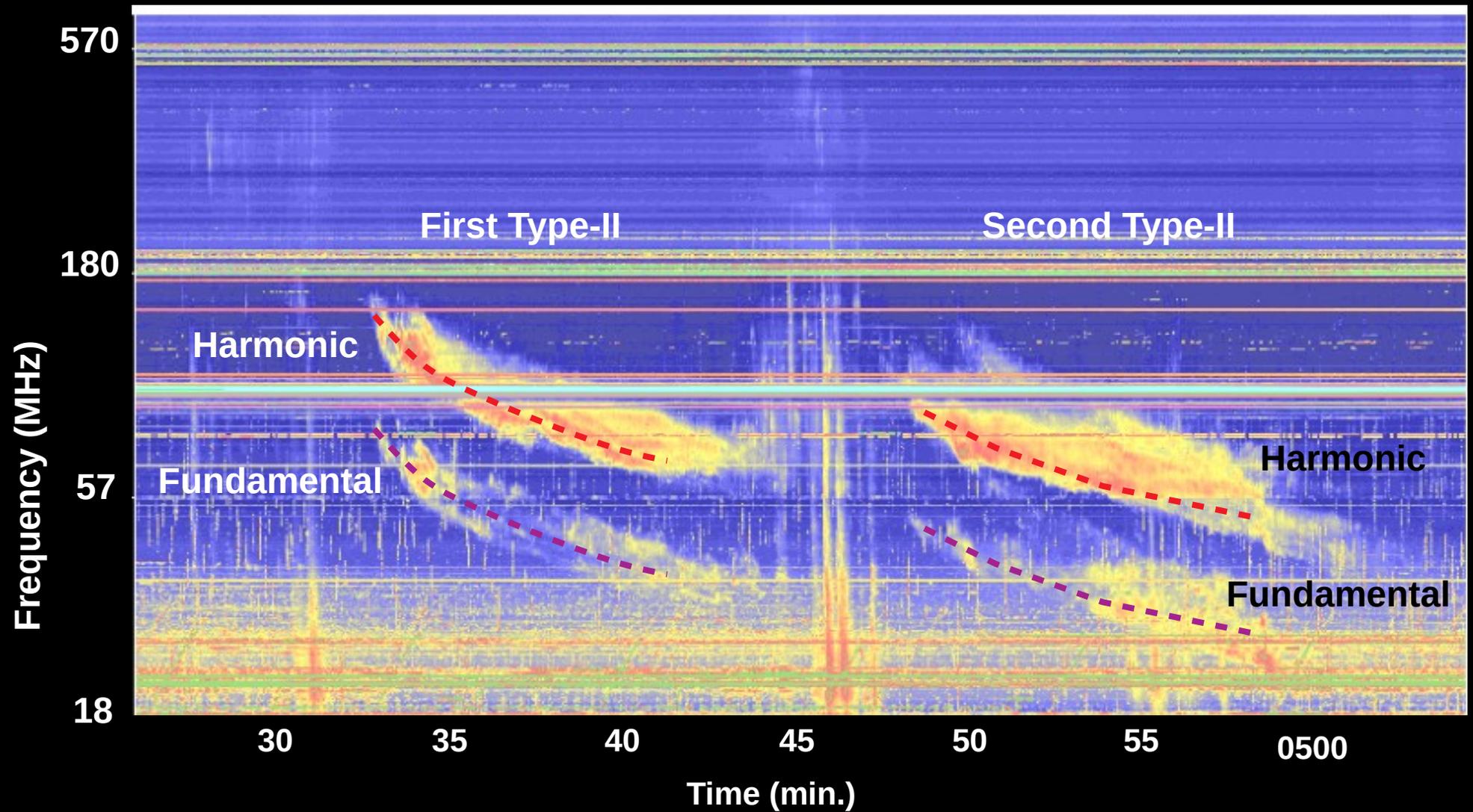
Meter & deca-m λ type-II radio bursts

1. This is a type of burst in which there will be a noticeable delay in the peak of emission as a function of frequency.

2. The high frequency appears first and it is followed by successive emission at lower frequencies with the drift rate of few MHz/s.

3. These are the signatures of coronal shock that are generated by the bulk motion of plasma material from the inner to the outer coronal atmosphere.

4. They generally appear in pairs, called the fundamental and harmonic with the frequency ratio 1:2.

Meter & deca-m λ type-II radio burst variants
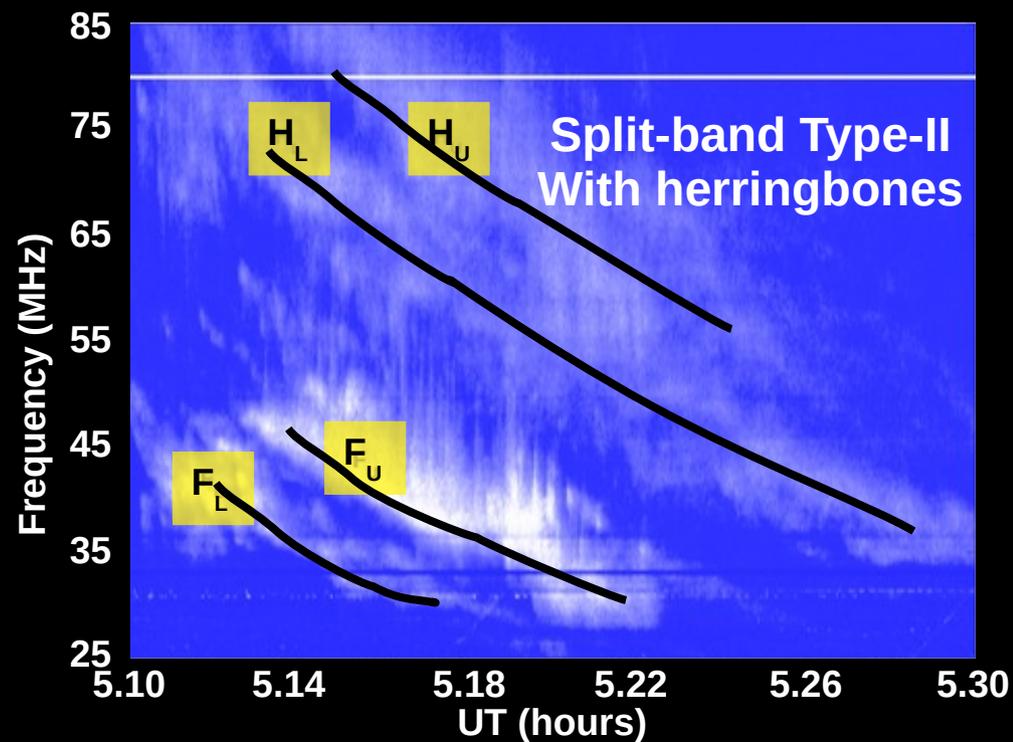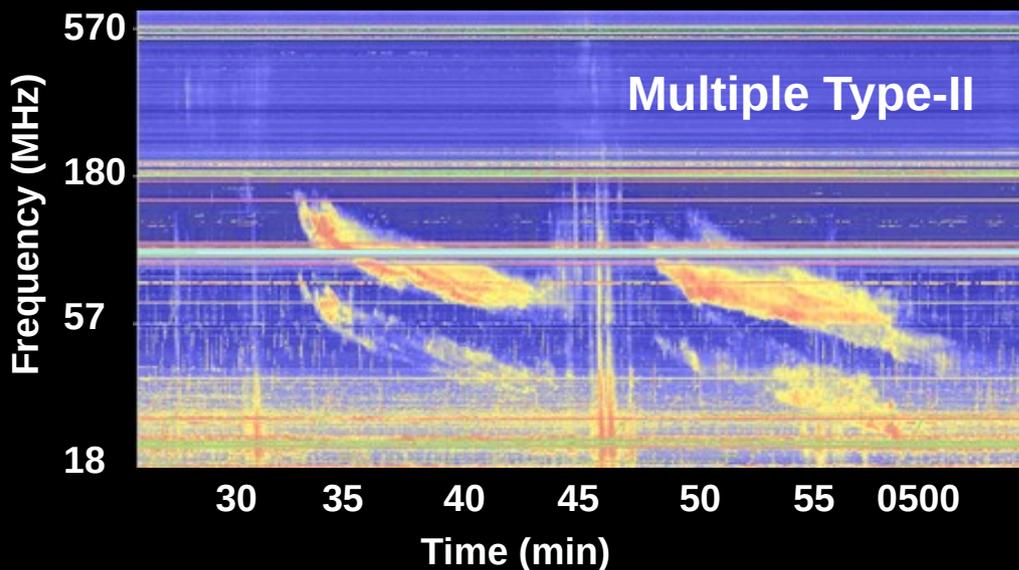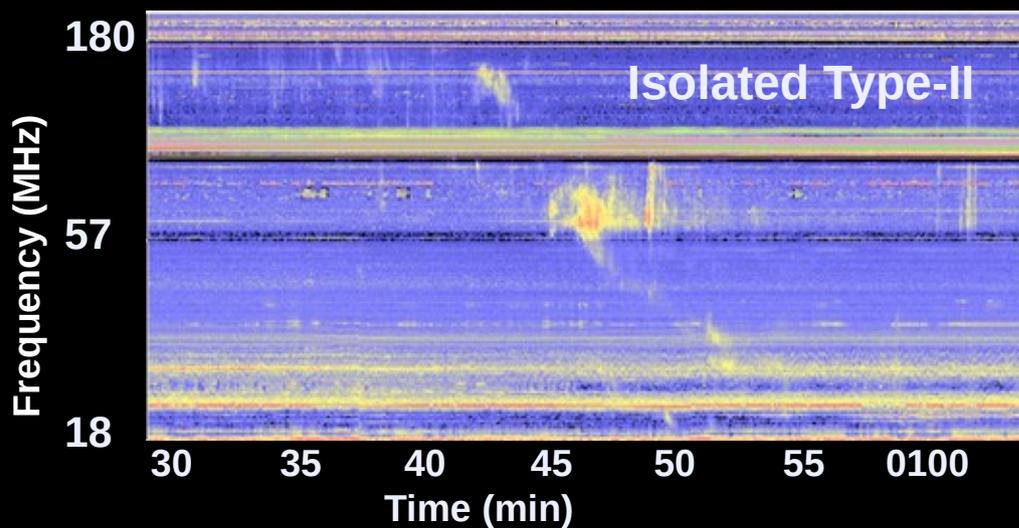
Meter & deca-m λ type-II radio burst drivers
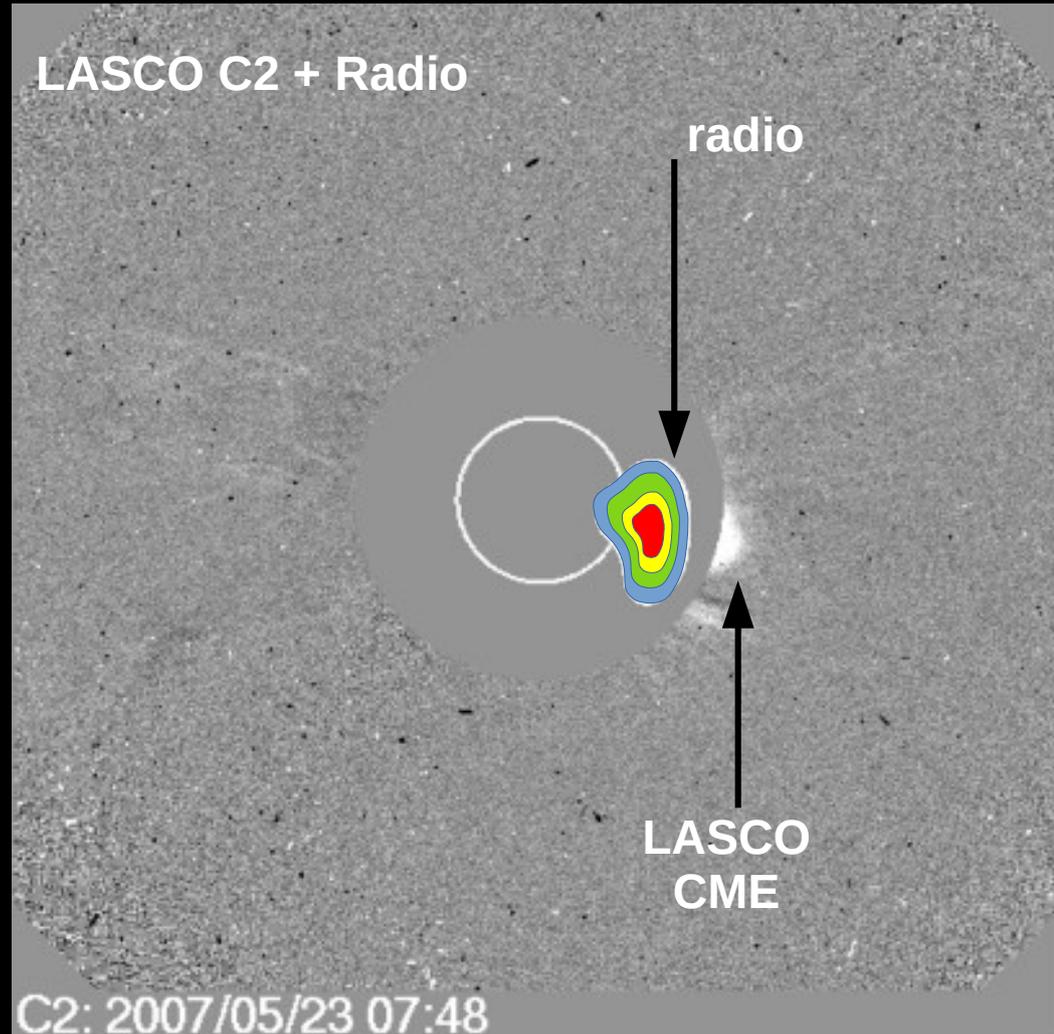
Ramesh et al, APJ, 752, 107 (2012) — **Gopalswamy et al, AIPC, 264, 267 (1992)**

Meter & deca-m λ type-II radio burst drivers

LASCO C2 + Radio

radio

1. The superposition of type-II radio emission and the WL running difference image clearly establishes their association between them.

2. This indicates that the CME is the driver of the type-II radio burst. When a CME travels in a plasma medium with a speed exceeding the local Alfven speed, it creates shocks which in turn triggers a type-II burst.

CME

C2: 2007/05/23 07:48

Ramesh et al, APJ, 752, 107 (2012)   **Gopalswamy et al, AIPC, 264, 267 (1992)**

Meter & deca-m λ type-II : Polarization
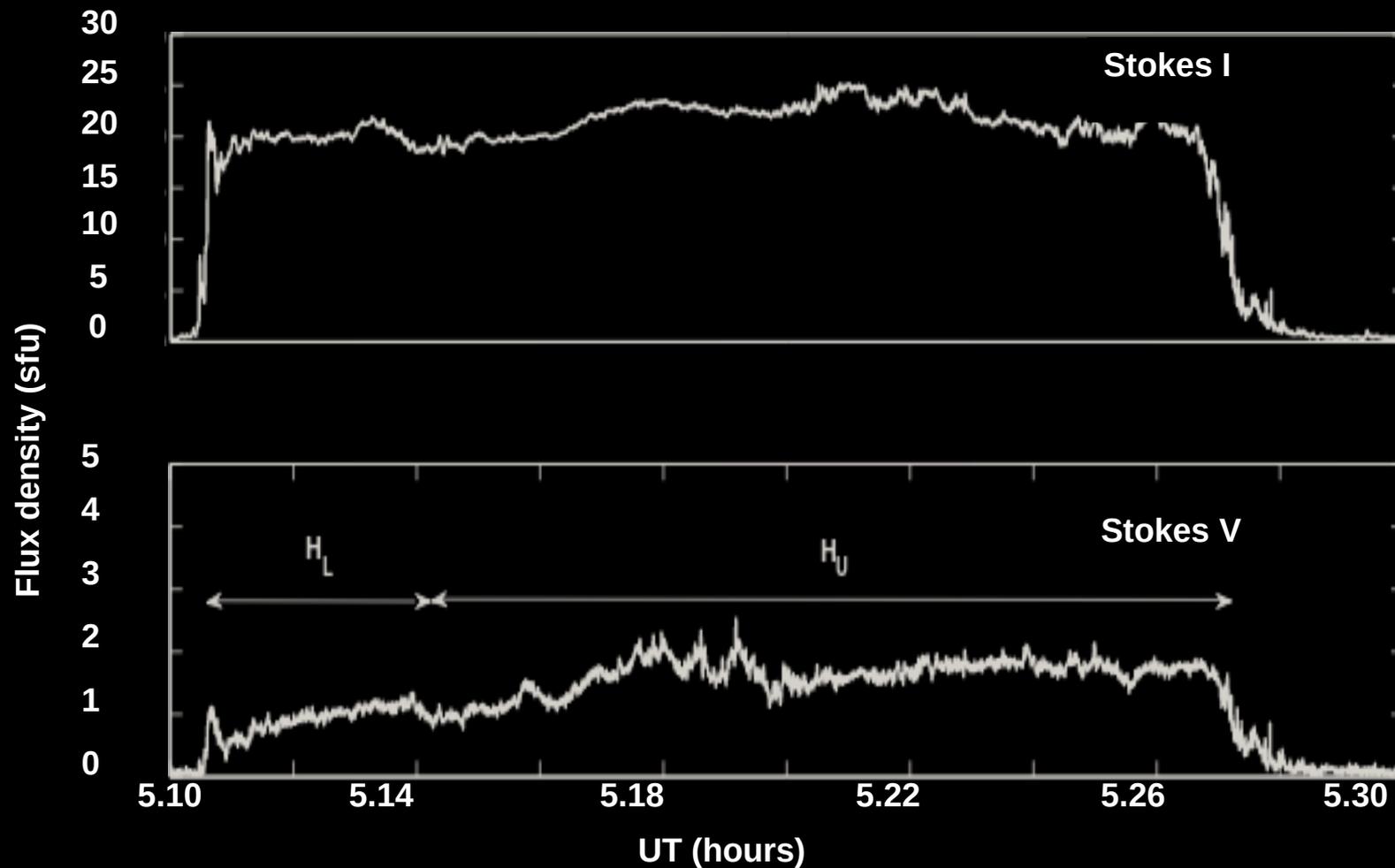
Ramesh et al, ApJ, 752, 107 (2012)

Meter & deca-m λ type-II : Polarization

1. Type-II burst intensities were found to lie in the range ~ 10^{-21} – 10^{-18} Watt/ m^2 / Hz.

2. Type-II bursts are weakly polarized (~10% at 80 MHz).

Meter & deca-m λ type-III radio bursts
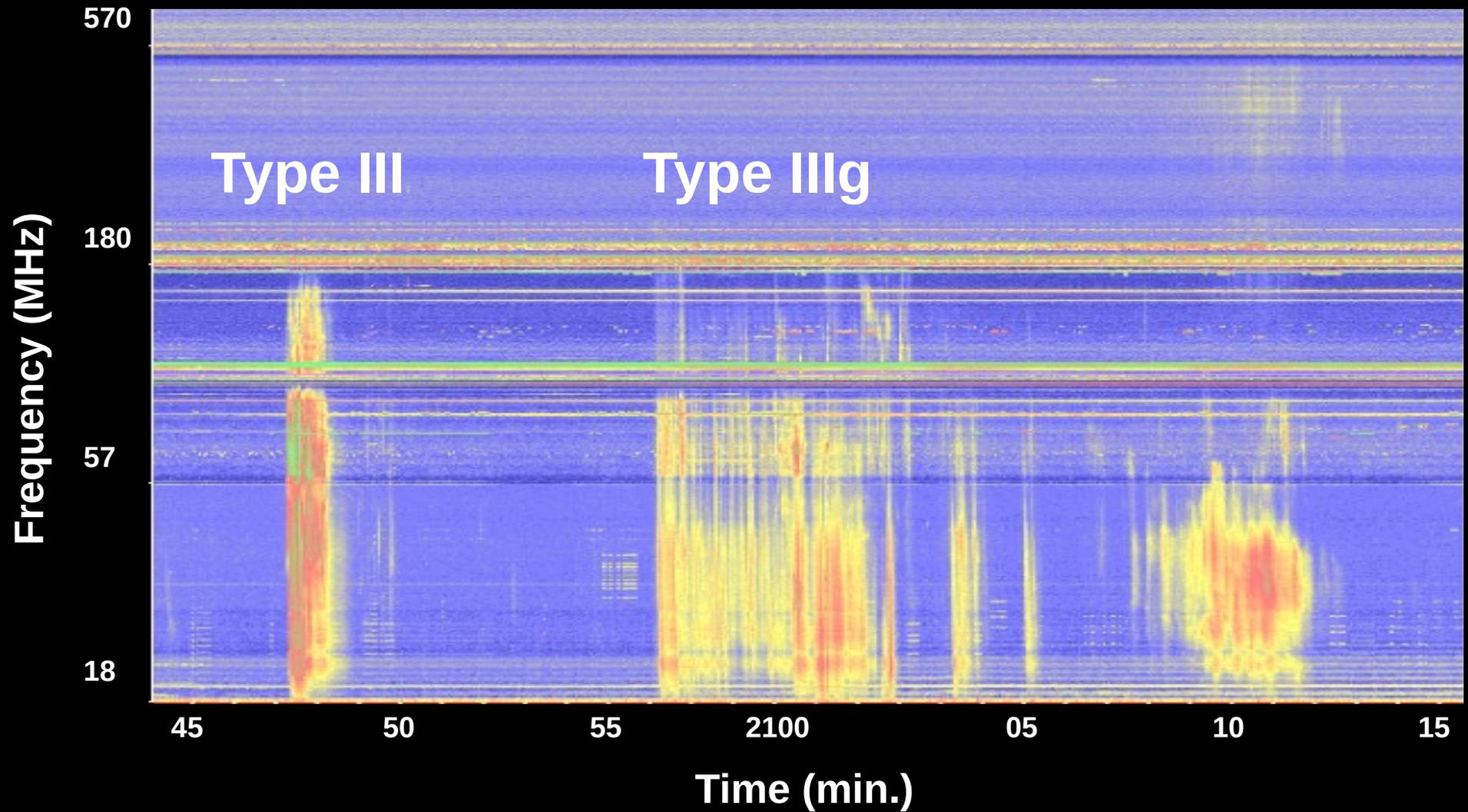
Meter & deca-m λ type-III radio bursts

**1. This type is a fast drifting broad band emission; their average drift rate is ~ 100 MHz/s.**

2. They occur isolated and sometime in groups; they have both fundamental and harmonic components.

3. Their frequency range is ~ GHz - ~ kHz.

4. The high energy electrons released in the aftermath of a flare (X-ray/EUV/H-alpha) travels outward along open magnetic field lines cause type-III.

5. The emission is weakly polarized (<15 %) but occasionally observed to have about 50% (if fundamental)

Meter & deca-m λ type-III : Source regions
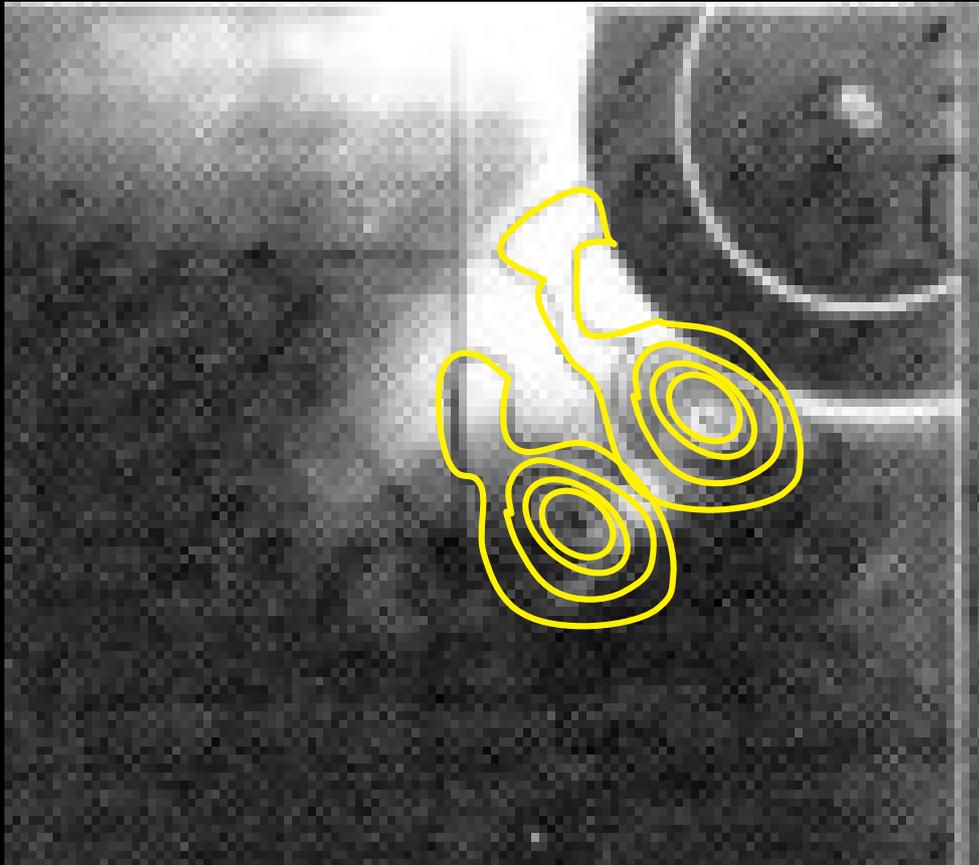
Radio contour on WL
Coronagraph image.

STANFORD MAGNETOGRAM

Solid = +
Dashed = -
N   1856 UT

73.8 MHz

50.0 MHz

38.5 MHz

HOLLOWMAN SUNSPOTS
2230 UT

4680
4681
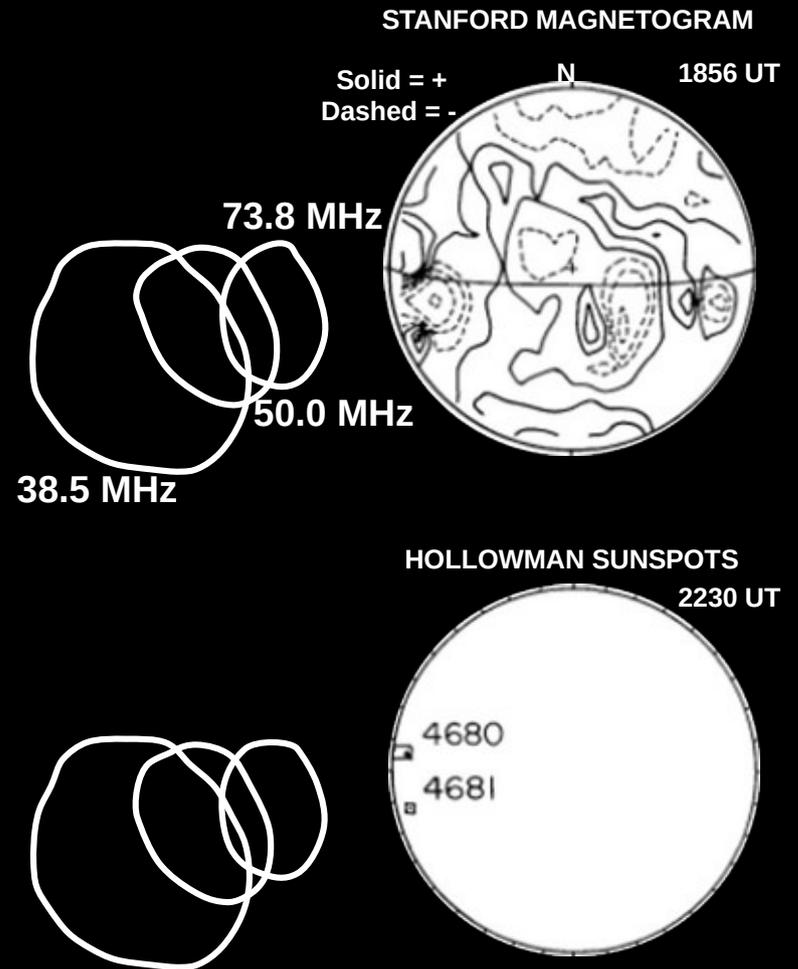
Gopalswamy et al., SoPh, 108, 333 (1987)

Meter & deca-m λ type-III : Source regions

1. Type-III originate from coronal streamers since they have open magnetic field lines on their top.

2. The increasing structure as a function of frequency signifies, the electrons propagate along radial open magnetic field lines.

Gopalswamy et al., SoPh, 108, 333 (1987)

Meter & deca-m λ type-III : Polarization
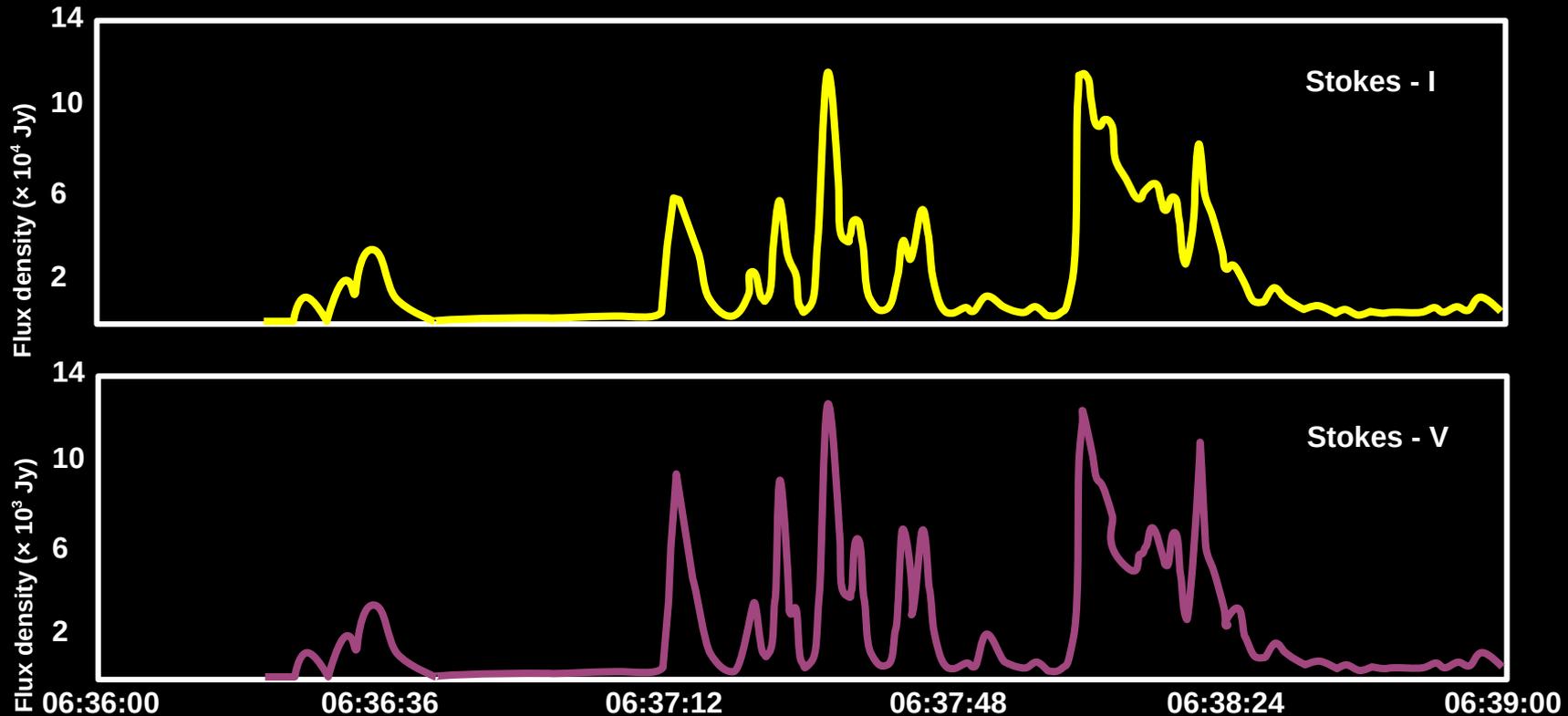
1. **Type-IIIs are weakly polarized < 15 % and occasionally go up to 50 %.**

2. **Linear polarization of type-IIIs are observed for a very low bandwidth of few kHz.**

Sasikumar Raja, ApJ, 775, 38 (2013)　　　　　　　　　　Cohen, ApJ, 130, 221 (1959)

Meter & deca-m λ type-III : Polarization
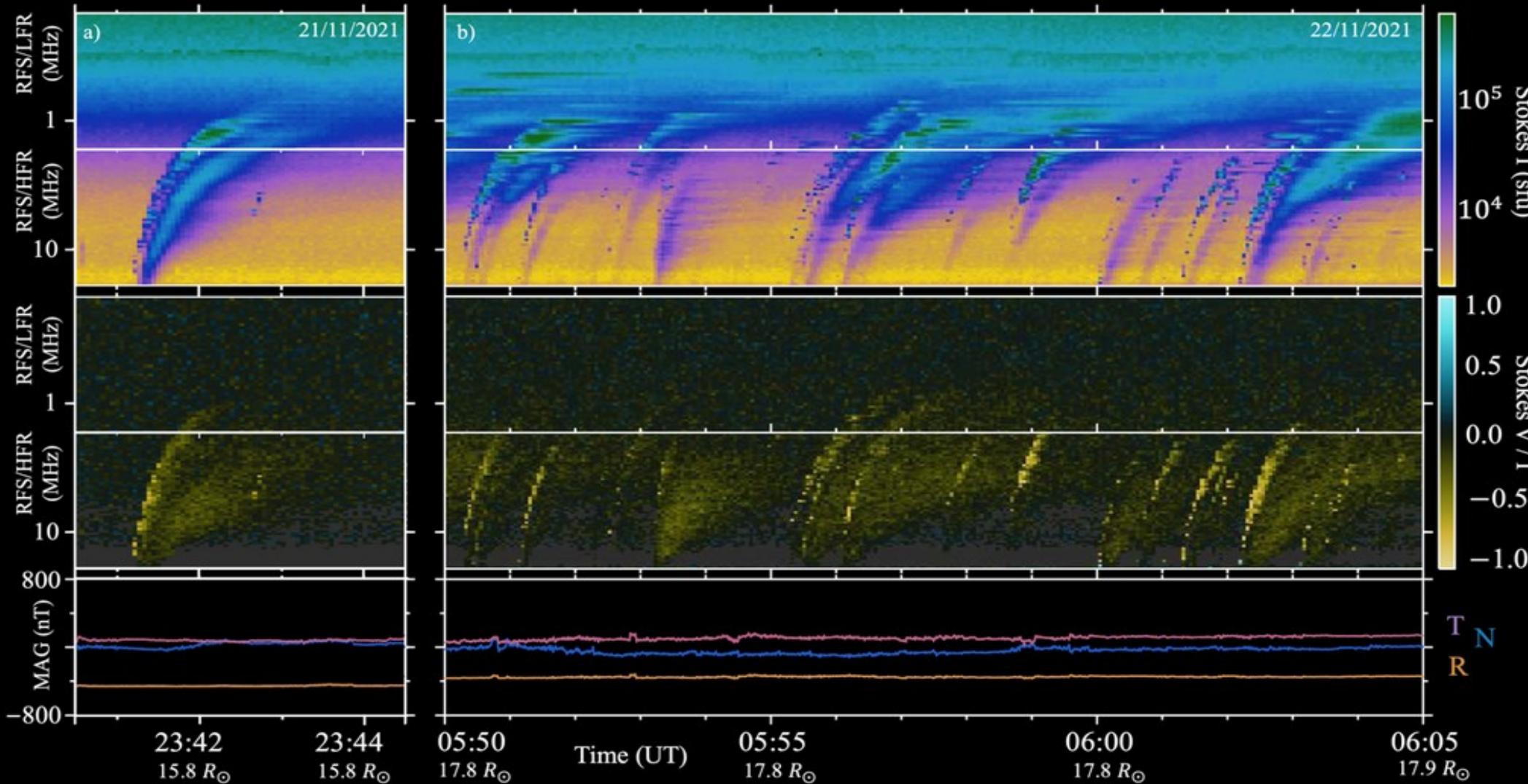
Jebaraj et al., ApJL, 955, 20 (2023)

Meter & deca-m λ type-III : Schematic
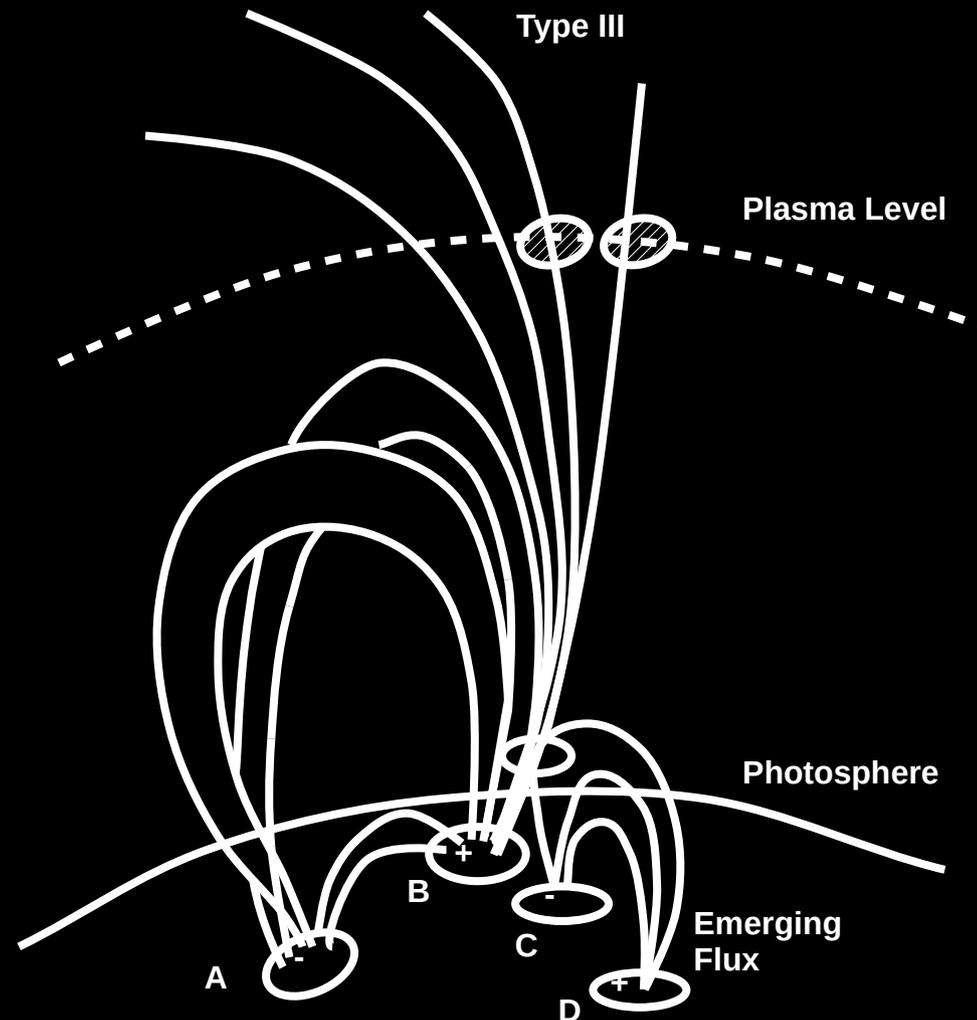
Type III

Plasma Level

Photosphere

B

A

C

D

Emerging Flux

Gopalswamy et al., SoPh, 111, 347 (1987)

Meter & deca-m λ type-IV radio burst

Type IVs or Stationary

Meter & deca-m λ type-IV radio burst

Type IVm or moving
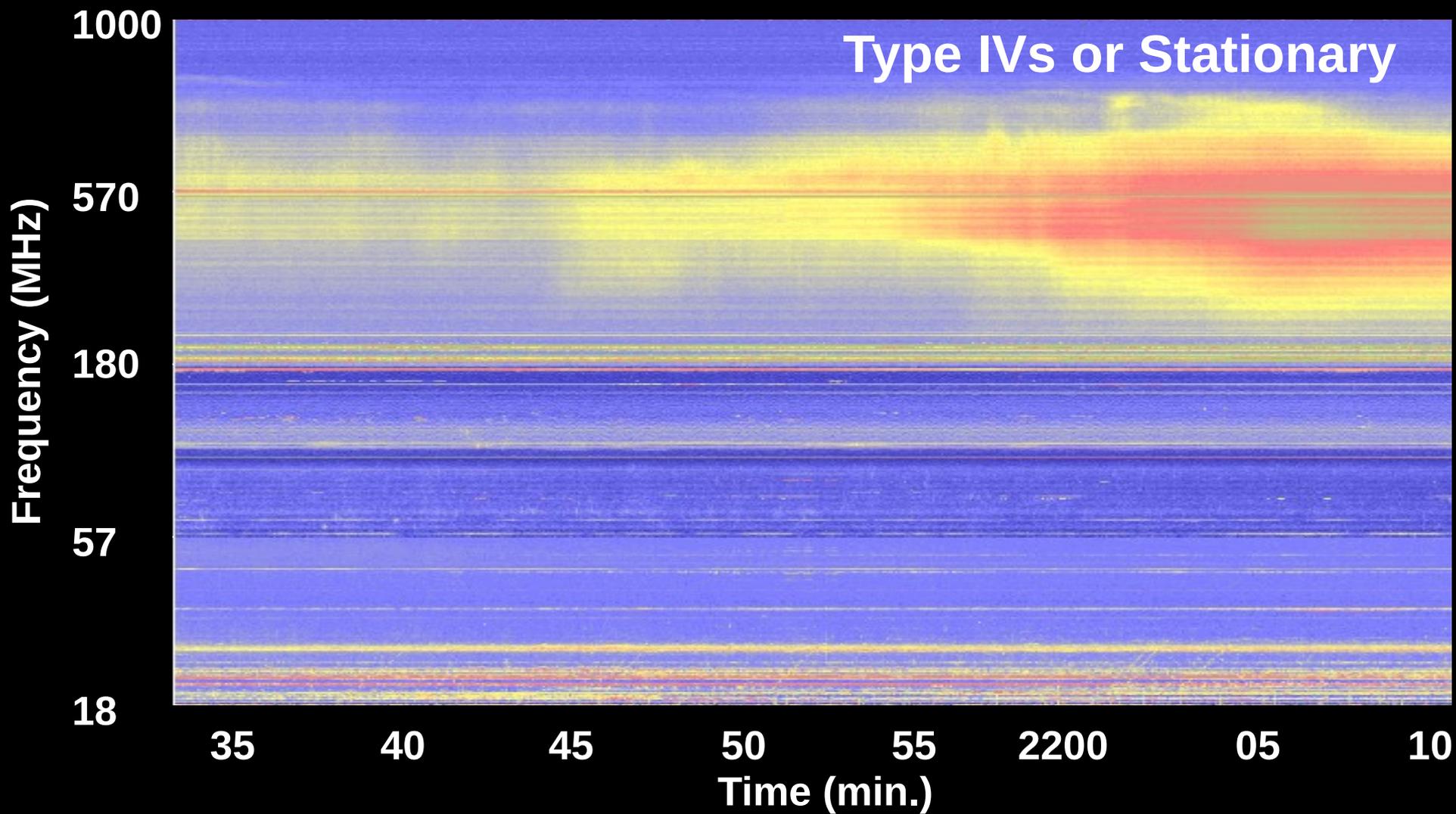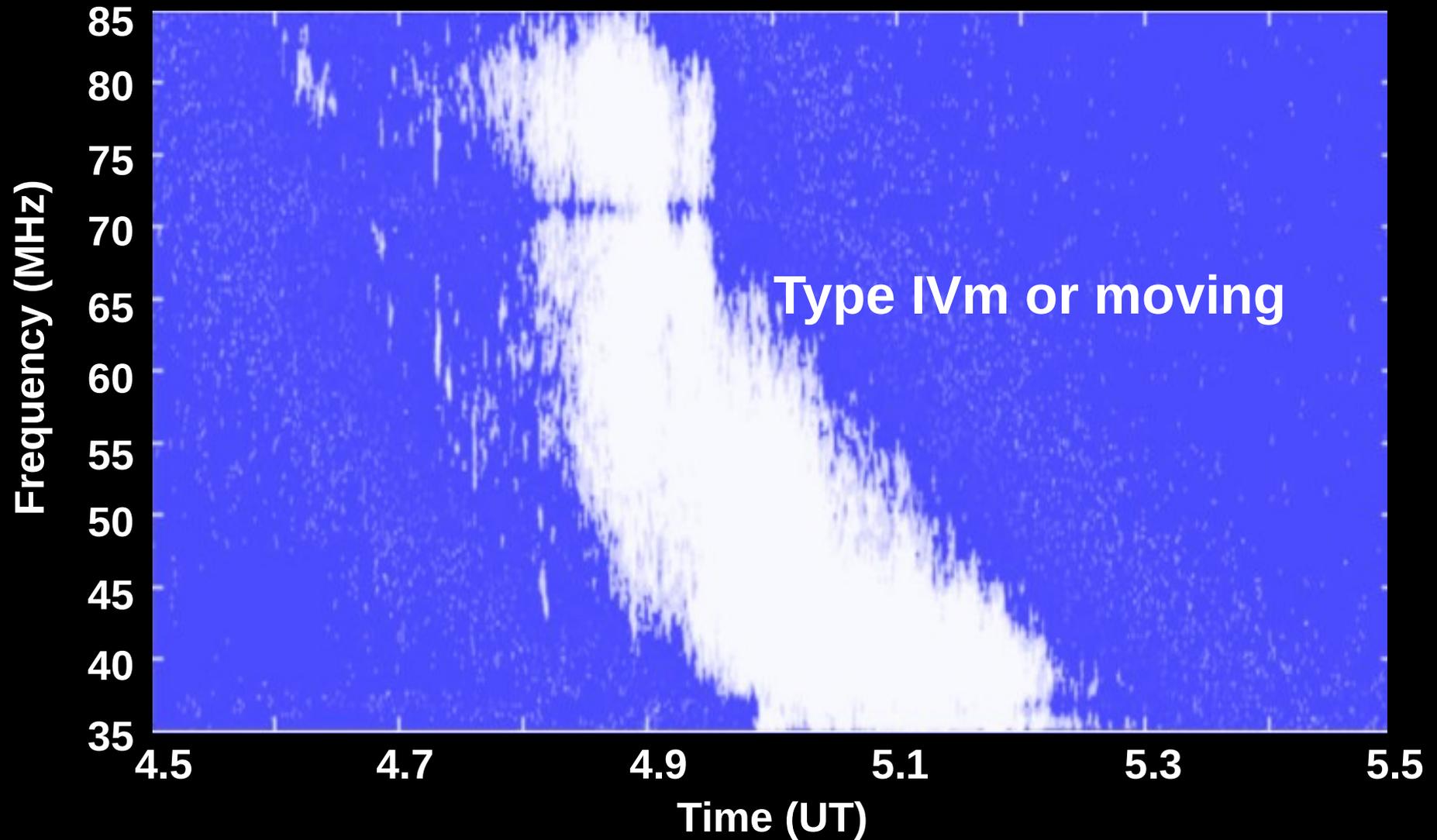
Meter & deca-m λ type-IV radio burst
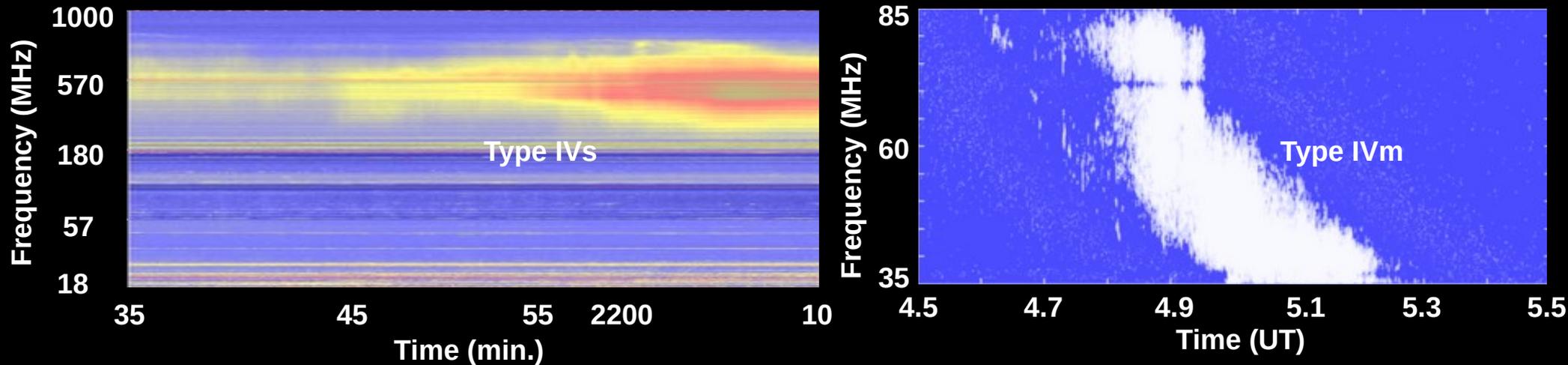
1. These are similar to type-II burst but the bandwidth at an instant is broader than type-II. It lasts up to several tens of minutes to hours.

2. Their size is about 10' (at 170 MHz) and shows a drift of about 6'-8' over 10 minutes. They appear to move faster during the initial phase and gradually reduces as a function of time.

3. The brightness temperature is about $10^{10} - 10^{12}$ K (10^{-19} Watt/ m^2 /Hz). They do not drift further like type-II and type-III.

4. These are weakly circularly polarized (~10 %) and sometimes unpolarized.

Meter & deca-m λ type-IVm : Sources

Type IVm

Frequency (MHz)

Time (UT)

Type-IVs Snapshot

C2: 2012/01/26 05:00   AIA 193: 01/26 05:00
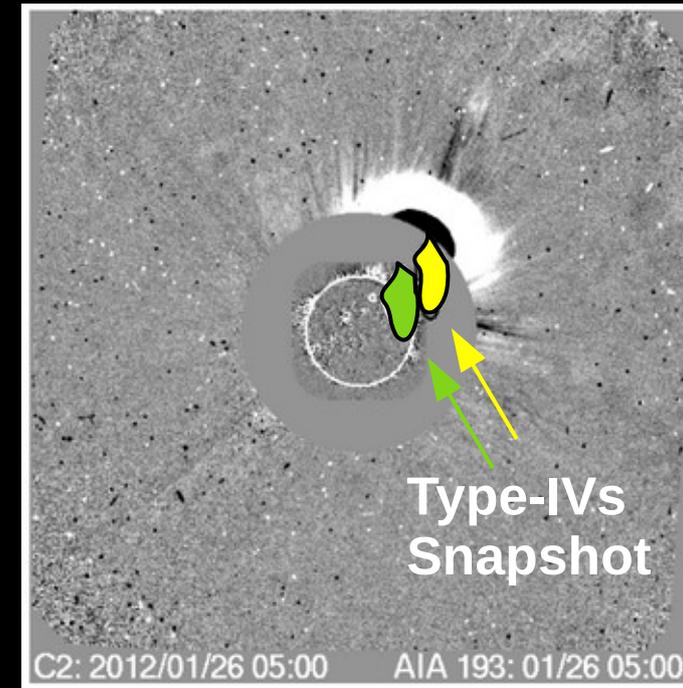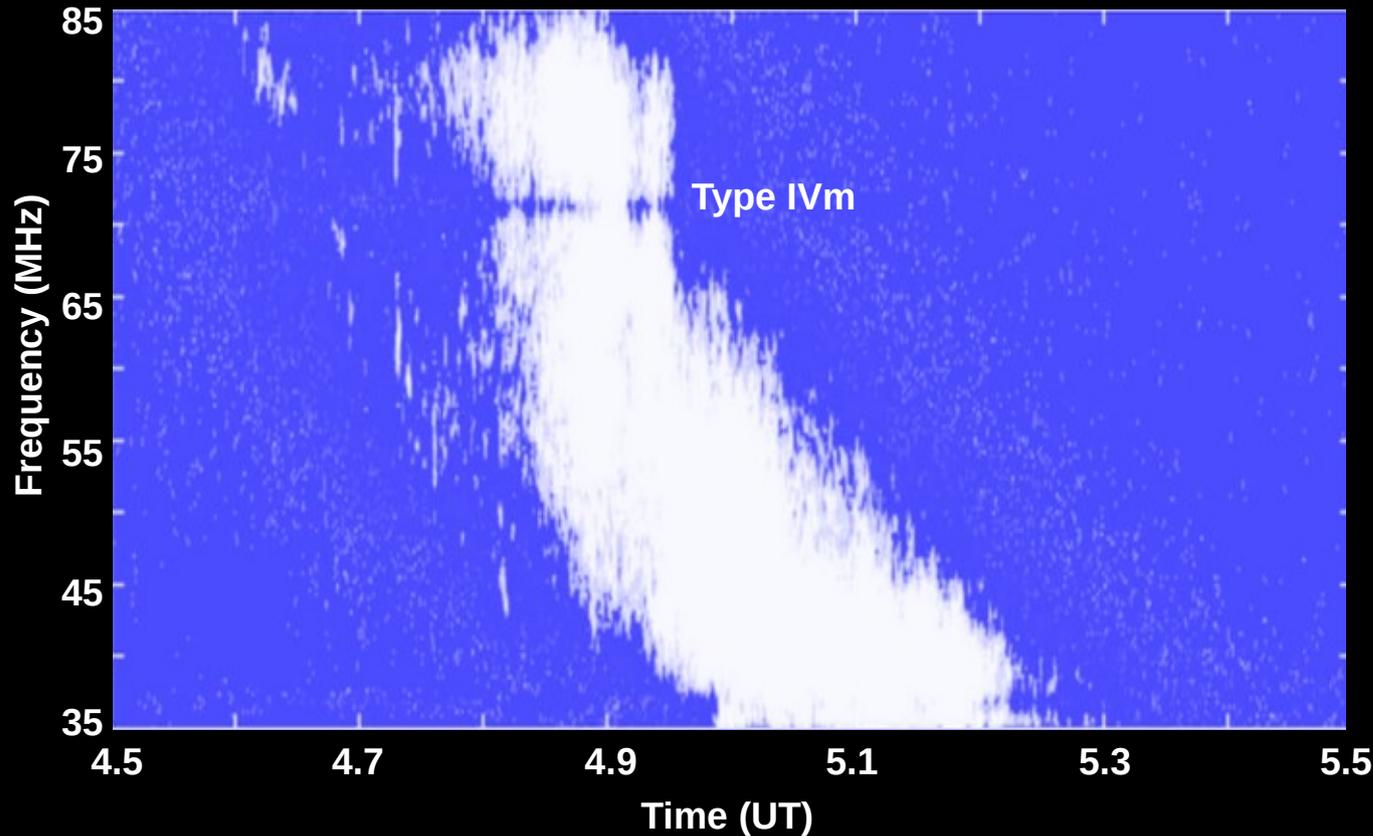
1. Radio spectral and imaging observations show the type-IVm are generally due to plasma emission associated with the flanks / legs of the CMEs. Hence the drift rate is lower than that of the CME leading edge.

Meter & deca-m λ type-IVs : Sources
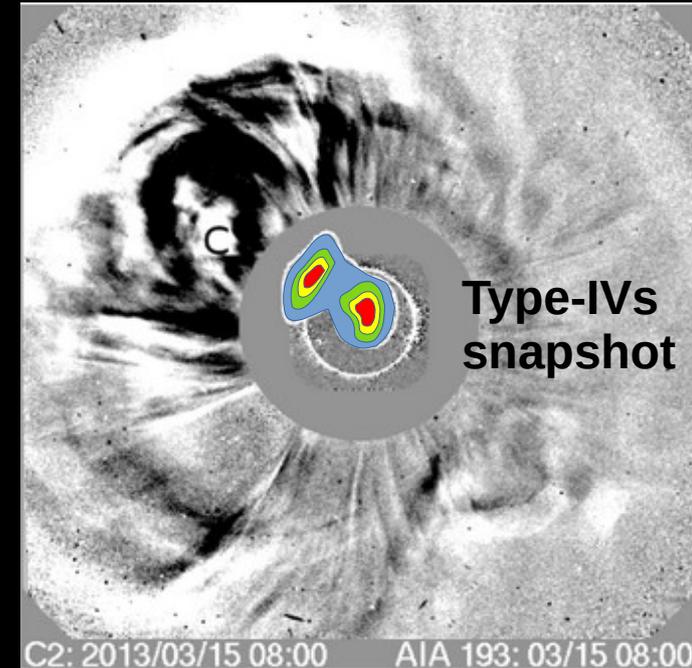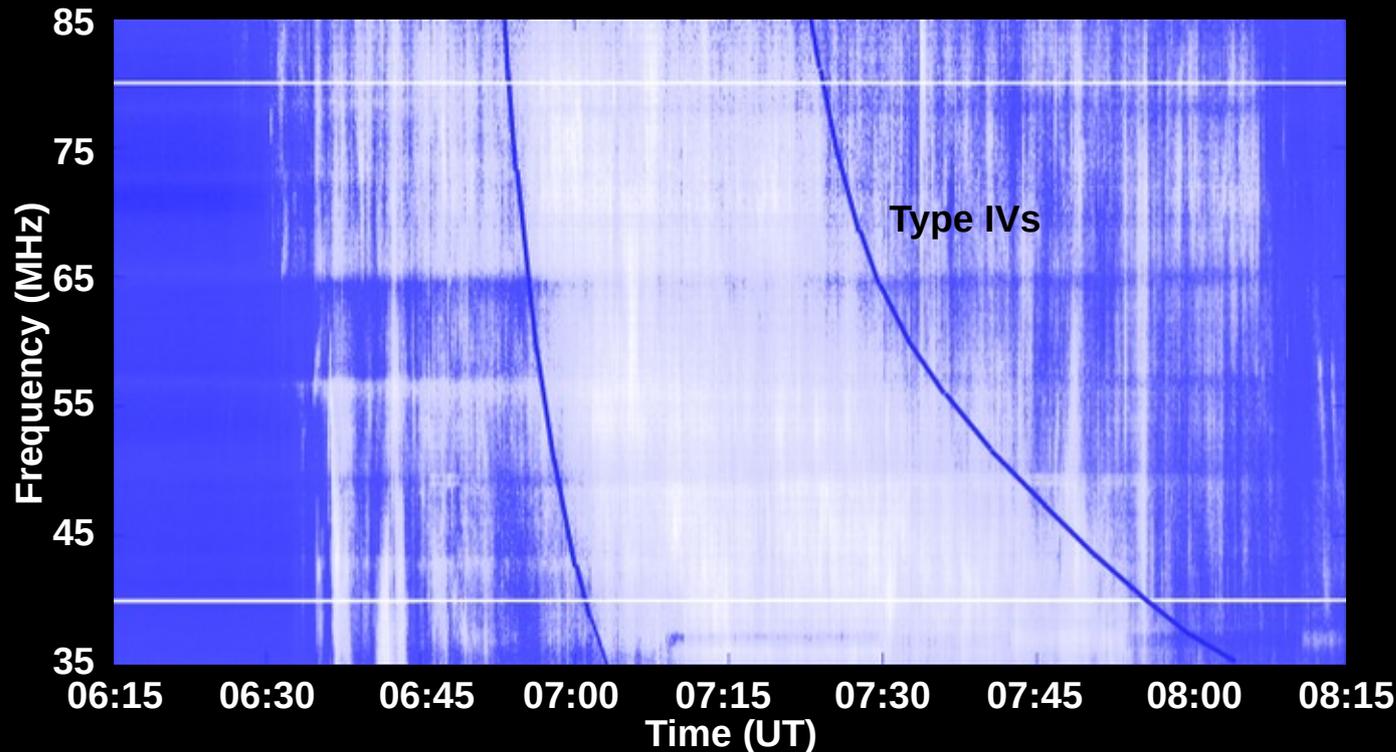
Radio spectral and imaging observations show the type-IVs are generally due to gyro-synchrotron emission associated with the core of the CMEs. Hence the drift rate is lower than that of the CME leading edge / flank.

Meter & deca-m λ type-V radio bursts
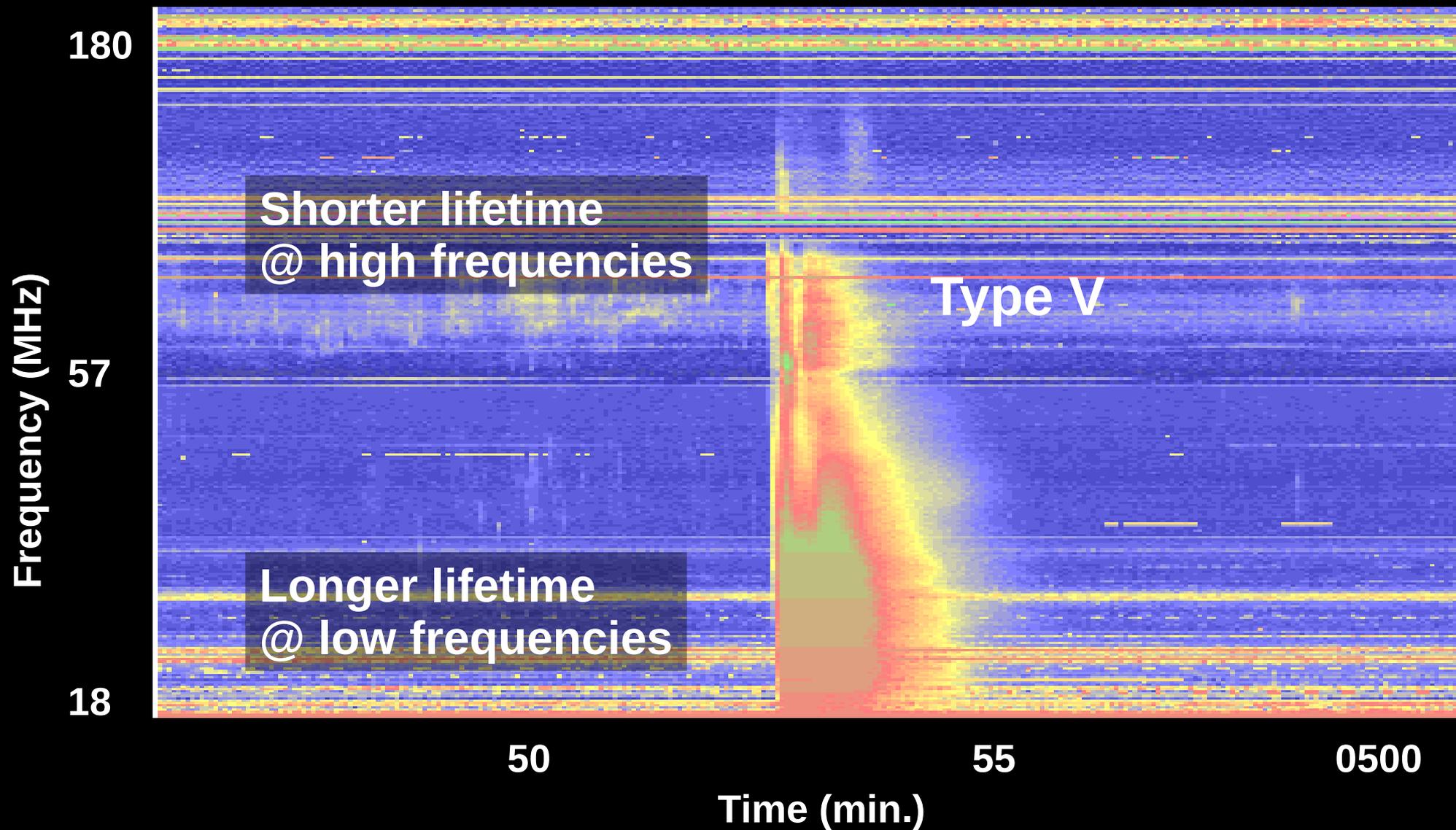
Meter & deca-m λ type-V radio bursts

1. Type-V occur very rarely and they always follow type-III.

2. Their duration as like type III vary as a function of frequency.

3. The emission is due to plasma mechanism like type-III bursts. The electrons that travel along curved magnetic field lines are responsible for type-V bursts.

4. Both type-III and type-V can have the same velocity of propagation, i.e. at 0.3 – 0.5 c.

Meter & deca-m λ type-V : Polarization
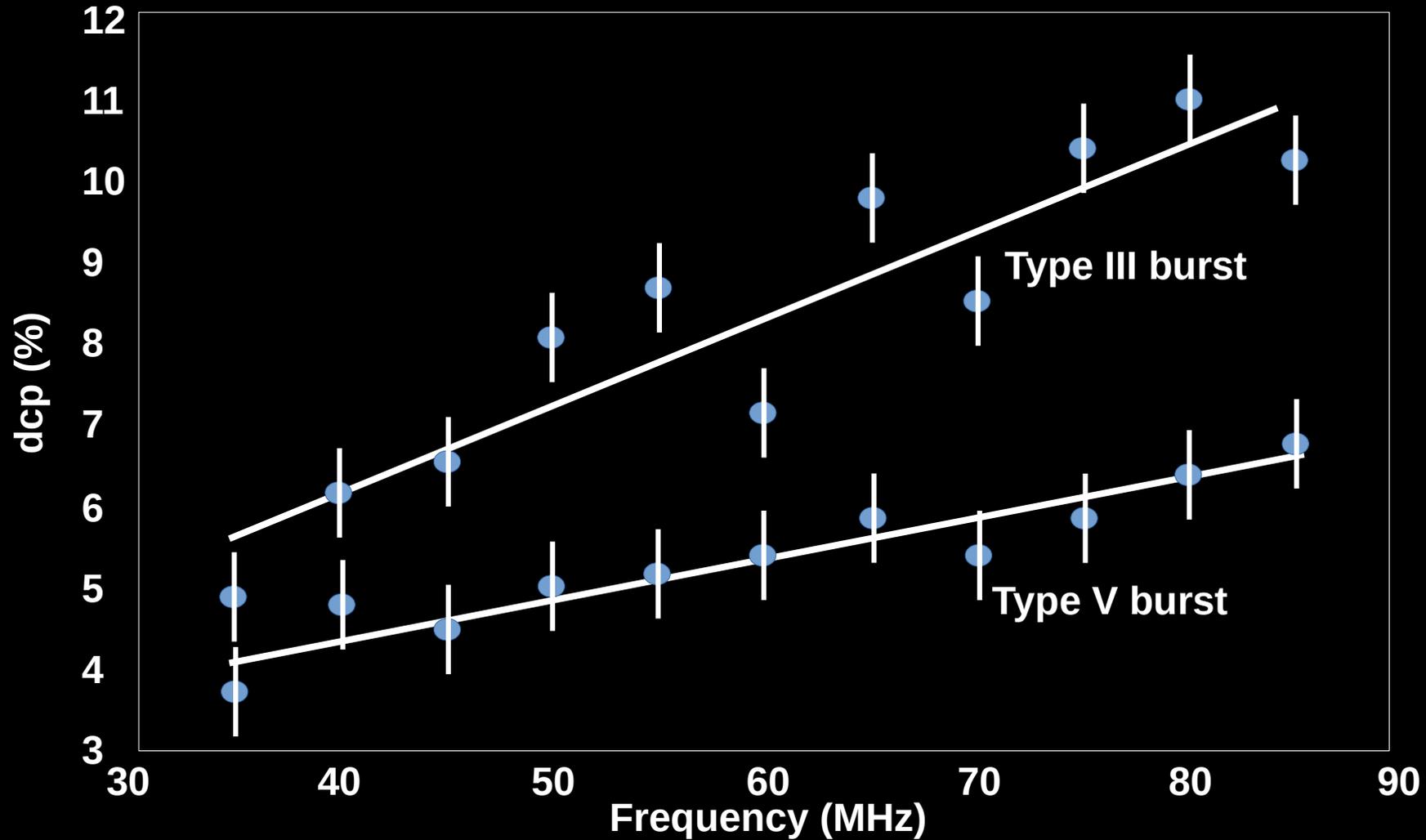
Meter & deca-m λ type-V : Schematic

Gopalswamy et al., SoPh, 111, 347 (1987)

Meter & deca-m λ burst summary

background Coronal plasma

15 MHz

2.4 R ⊙

450 MHz

1.04 R ⊙

Sun

background coronal plasma

Type I

Open mag. Field lines

Type IV

CMEs

Type III

Sun

1.04

Gauribidanur Low Frequency Solar Spectrum -- 2014/01/07

stationary
Type-I Noise storm

Flares
EUV, X-rays

Shock Front
Type II

Type V

Type IV

Type III

CMEs
500-2000 km/s

C/3

Shock front
Type II

~ few 100 km/s

Flares
X-rays

Type V
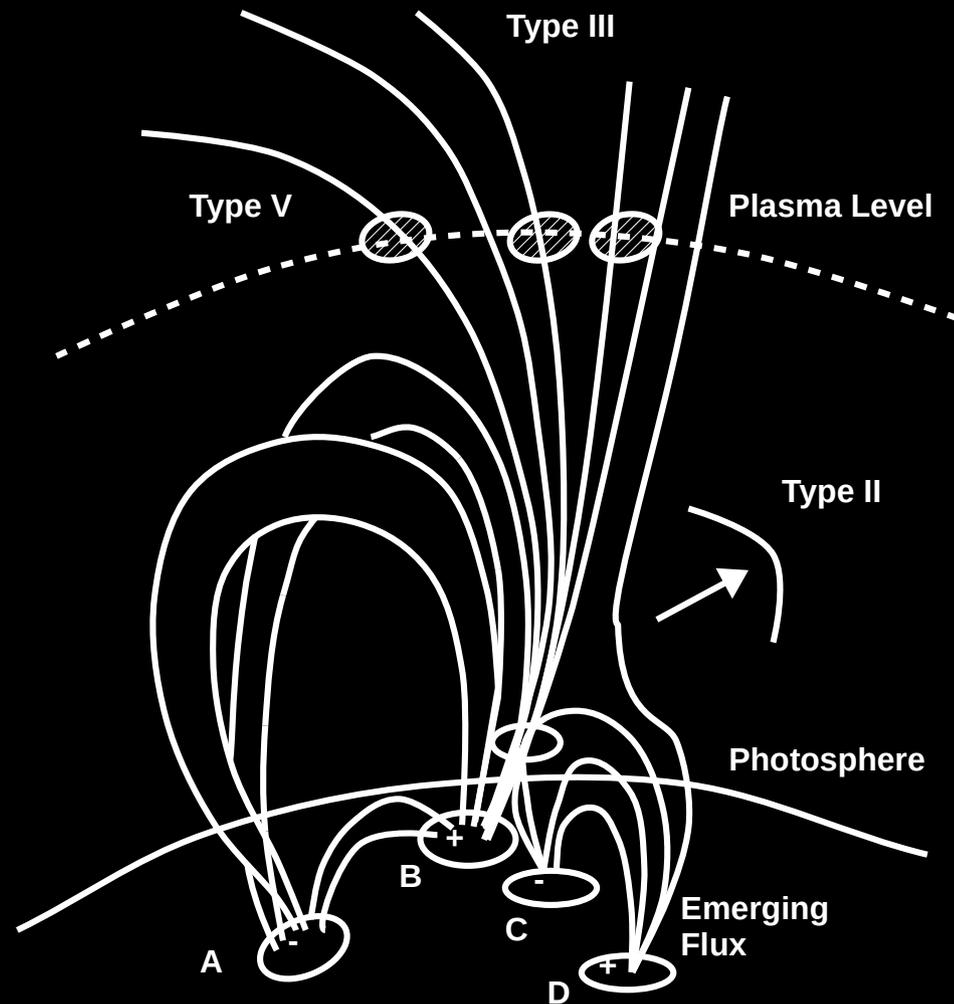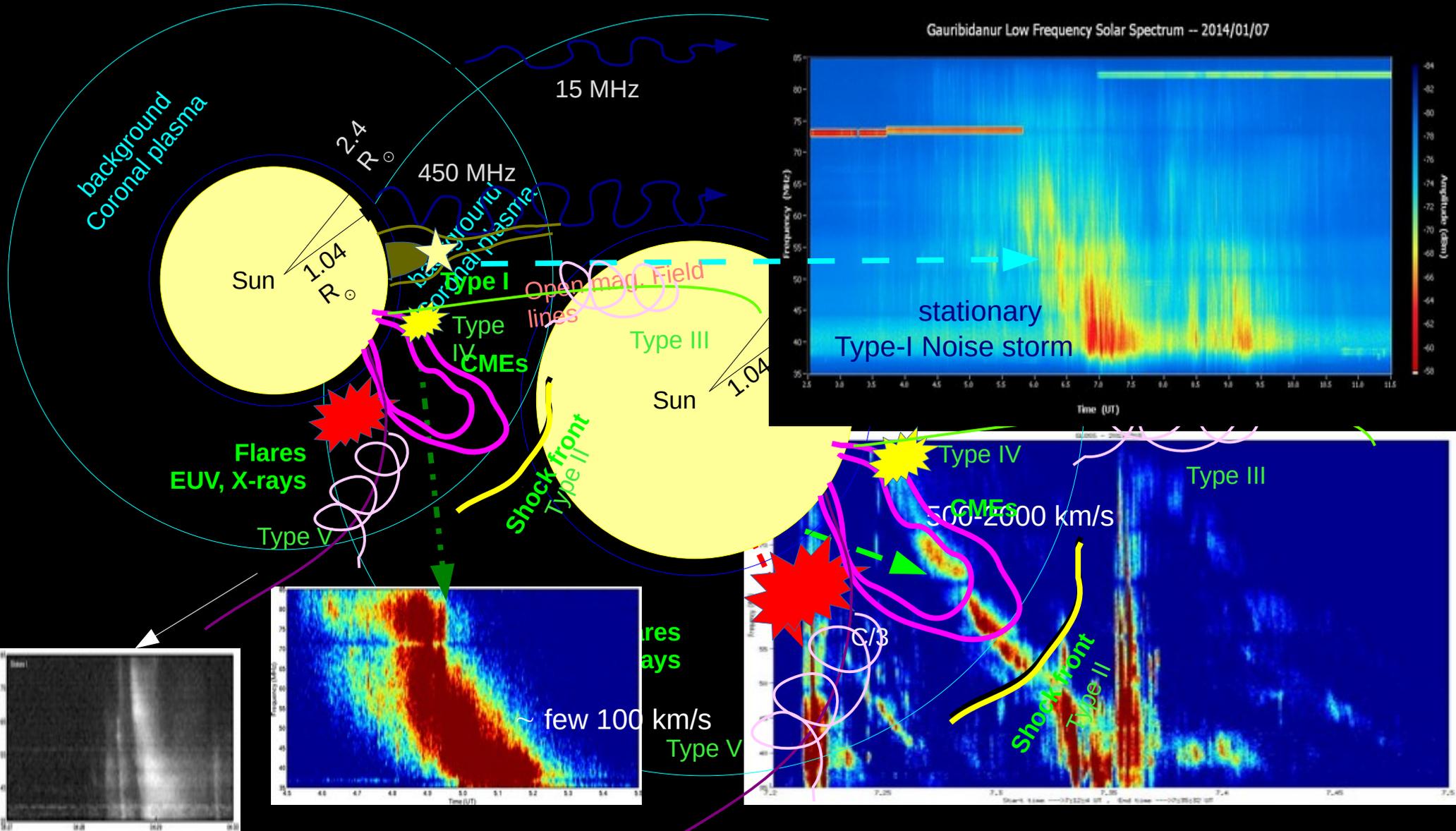
Many more meter-deca-m λ bursts can be discussed further

Limited it due to time constraint

Hecto-m & km λ / IP radio bursts

c) WIND/WAVES: 2015/07/01 14:48

IP Type-II

IP Type-III
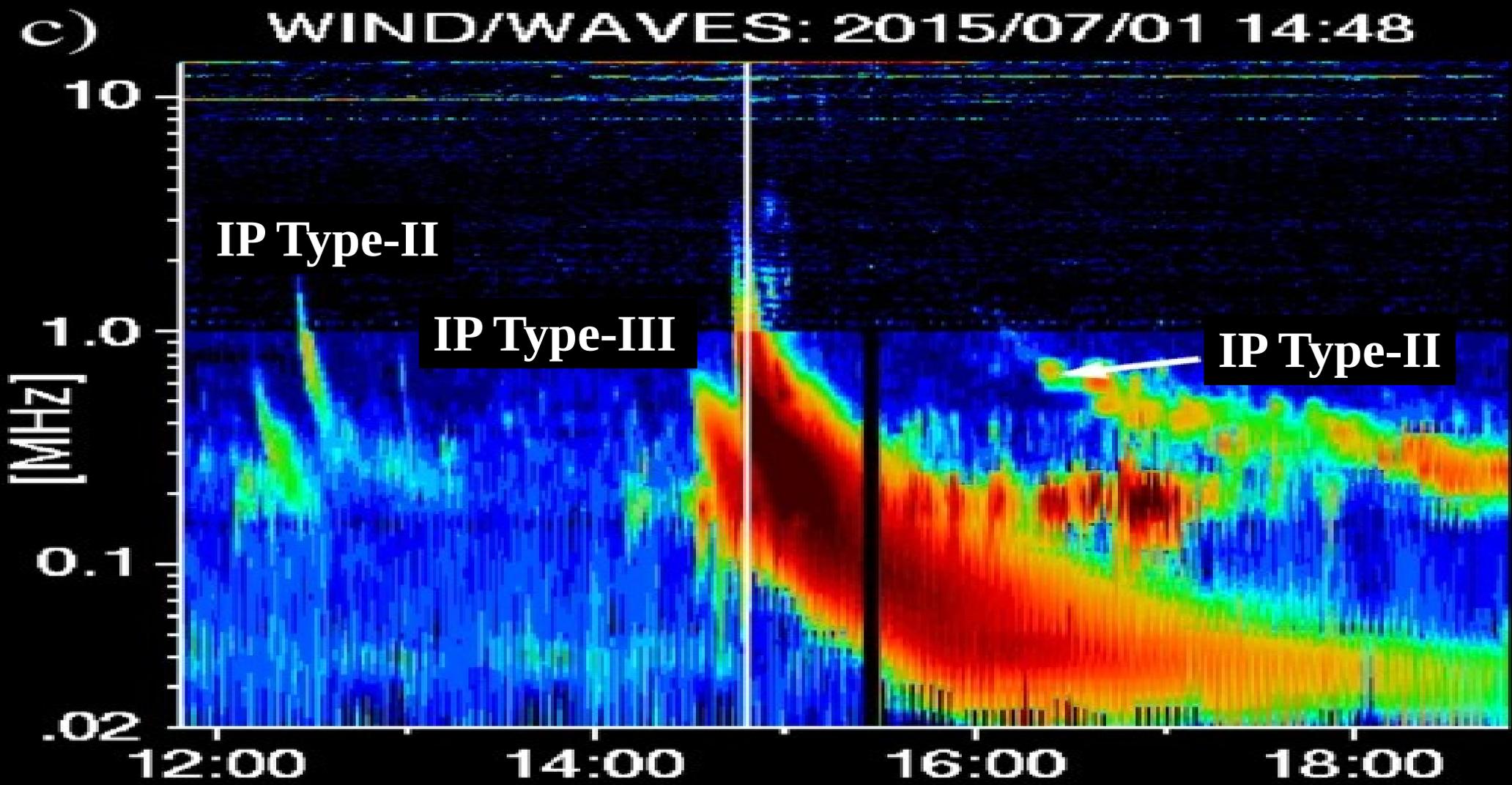
IP Type-II

Pohjolainen et al. SoPh, 296, 81 (2021)

Hecto-m & km λ / IP radio bursts

1. Interplanetary type-III bursts are similar to meter-deca meter type-III. When they reach the Earth's atmosphere they live longer.

2. Unless the spectra are continuous in the deca-meter to hecto-meter domain, it would be difficult to identify IP type-III bursts.

3. IP type-II bursts are driven by shocks that are generated by Interplanetary CMEs (ICMEs).

Since CMEs and flares are also transients, can they be observed in radio ??

Yes… Radio Imaging of transients

1

CME associated Radio signatures

Coronal Mass Ejection (CME)

A discrete brightening observed in the field of view of a white-light coronagraph.

It always moves outward from the Sun into the heliosphere over a time-scale of several hours to ~ days.

Webb, D. et al., LRSP, 9, 3 (2012)

Frontal Structure

CME

Core

Occulter

Width

CPA

Cavity

Photosphere

Helmet Streamer
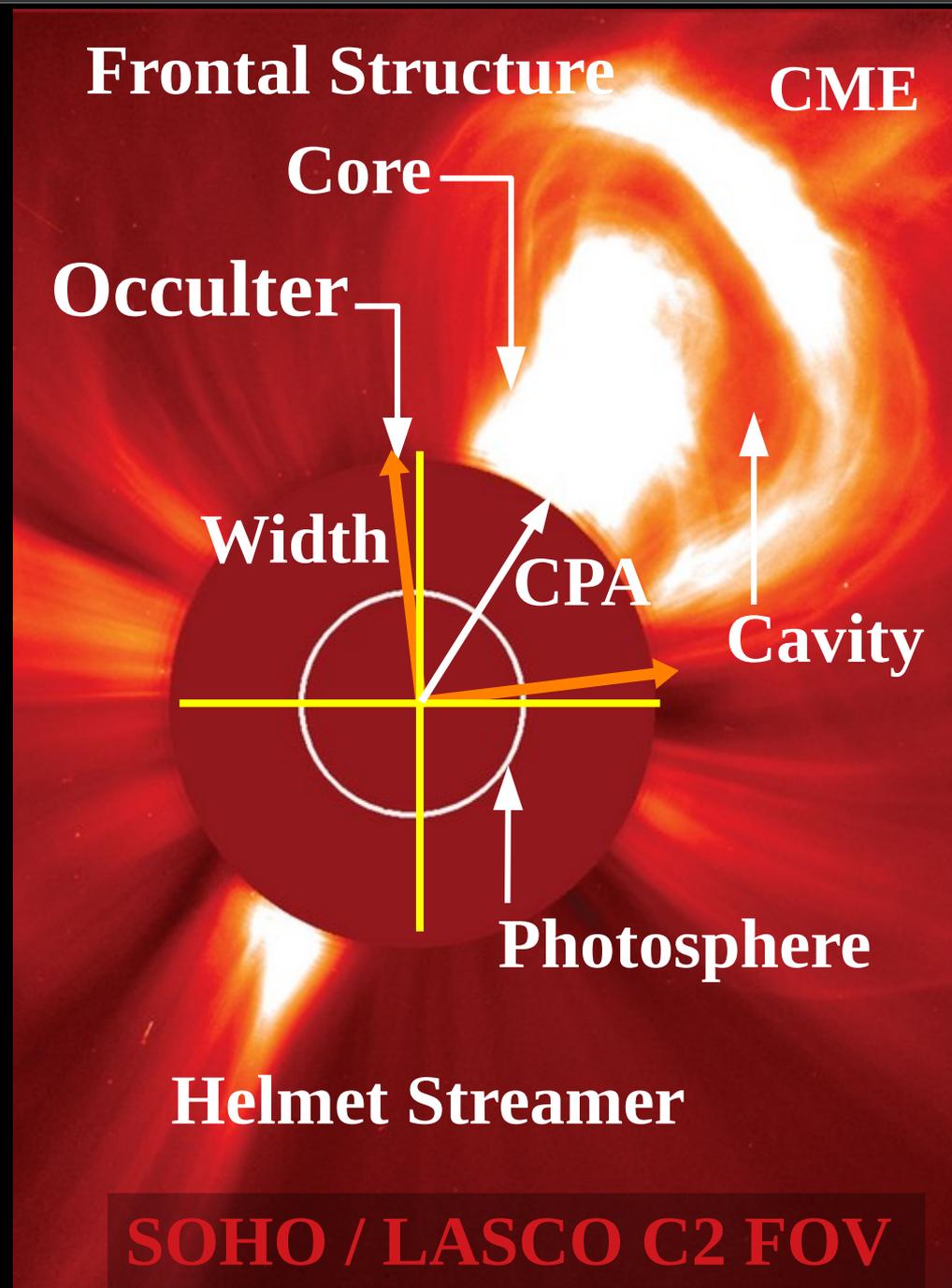
SOHO / LASCO C2 FOV

Coronal Mass Ejection (CME)

It is a large scale plasma entrained on an expanding magnetic field (flux rope).

One can identify the CME features clearly from the running difference images and its propagation from the time-lapse movies.

Webb, D. et al., LRSP, 9, 3 (2012)

RUNNING DIFF. IMAGE

CME

EUV Image

C2: 2015/11/04 02:24   AIA 193: 11/04 02:24

Can CMEs be observed in Radio ??

Two Possibilities :

CME → Thermal ✓

CME → Non-thermal

CME → Mass + Sky-plane Speed

Radio Observation Summary

Radio Telescope : GRAPH
Nov. 24, 2000 – 04:55 UT
f = 109 MHz
$\Omega_{res} = 7' \times 11'$
$T_b = 4.2 \times 10^6$ K ←
T_b (interval) $= 0.5 \times 10^6$ K ←
Dynamic Range : ≈ 20 dB
Red : Maximum Temperature   **Violet : Minimum Temperature**

GAURIBIDANUR RADIOHELIOGRAM – 109 MHz

2000/11/24 – 04:55 UT

N
W

$T_p = 4.2 \times 10^6$ K

ARC MIN (x-axis: -60, -40, -20, 0, 20, 40, 60)
ARC MIN (y-axis: -60, -40, -20, 0, 20, 40, 60)
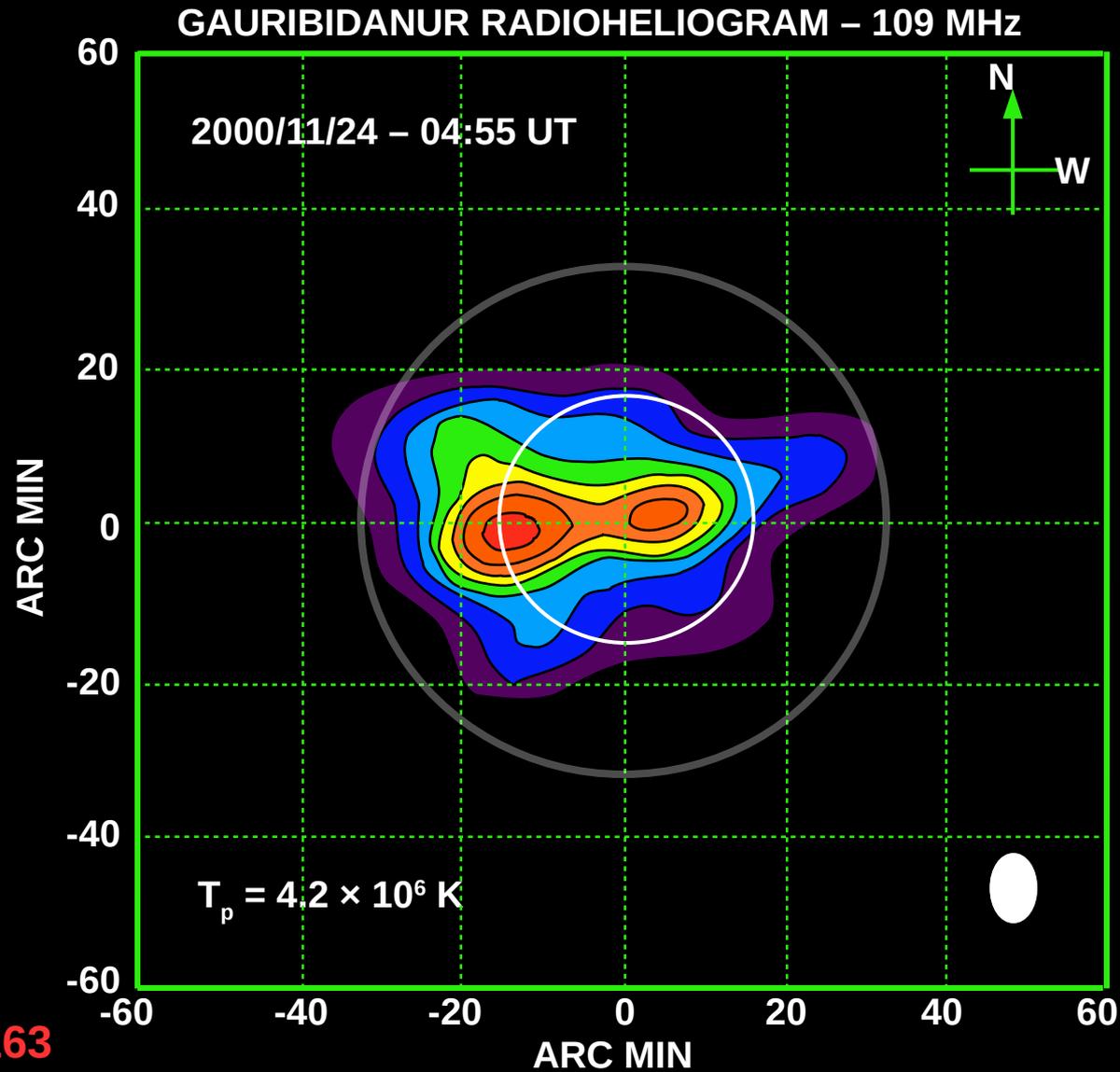
Ramesh, R. et al. ApJL, 2003, 591, 2, 163

CME → Mass + Sky-plane Speed

Radio Observation Summary

Radio Telescope : GRAPH

Nov. 24, 2000 – 05:05 UT

f = 109 MHz

Ω_{res} = 7' × 11'

T_b = 6.1 × 10^6 K ←⋯

T_b (interval) = 0.6 × 10^6 K ←⋯

Dynamic Range : ≈ 20 dB

Red : Maximum Temperature
Violet : Minimum Temperature

Ramesh, R. et al. ApJL, 2003, 591, 2, 163

GAURIBIDANUR RADIOHELIOGRAM – 109 MHz

2000/11/24 – 05:05 UT

N
W

T_p = 6.1 × 10^6 K

ARC MIN

ARC MIN

CME → Mass + Sky-plane Speed

Radio Observation Summary

Radio Telescope : GRAPH

Nov. 24, 2000 – 05:15 UT

f = 109 MHz

Ω_{res} = 7' × 11'

T_b = 6.1 × 10^6 K ←⋯

T_b (interval) = 0.6 × 10^6 K ←⋯

Dynamic Range : ≈ 20 dB

Red : Maximum Temperature
Violet : Minimum Temperature

Ramesh, R. et al. ApJL, 2003, 591, 2, 163

GAURIBIDANUR RADIOHELIOGRAM – 109 MHz

2000/11/24 – 05:15 UT

N
W

T_p = 6.1 × 10^6 K

ARC MIN

ARC MIN

CME → Mass + Sky-plane Speed

Radio Observation Summary

Radio Telescope : GRAPH

Nov. 24, 2000 – 05:25 UT

f = 109 MHz

$\Omega_{res} = 7' \times 11'$

$T_b = 5.6 \times 10^6$ K ←⋯

T_b (interval) $= 0.5 \times 10^6$ K ←⋯

Dynamic Range : ≈ 20 dB

Red : Maximum Temperature
Violet : Minimum Temperature

Ramesh, R. et al. ApJL, 2003, 591, 2, 163

GAURIBIDANUR RADIOHELIOGRAM – 109 MHz

2000/11/24 – 05:25 UT

$T_p = 5.6 \times 10^6$ K

CME → Mass + Sky-plane Speed

LASCO C2

RDI

Ramesh, R. et al. ApJL, 2003, 591, 2, 163

GAURIBIDANUR RADIOHELIOGRAM – 109 MHz

2000/11/24 – 05:25 UT

N

W

$T_p = 5.6 \times 10^6$ K

ARC MIN

ARC MIN

CME → Mass + Sky-plane Speed

GAURIBIDANUR RADIOHELIOGRAM – 109 MHz

Radio Analysis Summary

GRAPH DIFF IMAGE

Nov. 24, 2000
05:25 – 04:55 UT

f = 109 MHz

Difference Images were made
@ t = 5:05, 5:15, 5:25 UT

$v_1 = (r_2 - r_1)/(t_2 - t_1)$
$v_2 = (r_3 - r_2)/(t_2 - t_1)$
$a = (V_2 - V_1)/(t_{m2} - t_{m1})$

Ramesh, R. et al. ApJL, 2003, 591, 2, 163

2000/11/24 : 05:25 UT - 04:55 UT

N

W

r_3

05:25 UT

r_2

05:15 UT

r_1

05:05 UT

RUN. DIFF. IMAGE

ARC MIN

ARC MIN

CME → Mass + Sky-plane Speed

Radio Analysis Summary					
Time (UT)	P.A. (deg)	T_{CME} (K)	N_e (cm^{-3})	Mass (g)	Speed (km/s)
04:55					
05:05	282	3.3×10^5	12.4×10^7	2.7×10^{16}	
05:15	308	2.8×10^5	4.5×10^7	3.8×10^{16}	1087±73
05:25	318	1.9×10^5	2.8×10^7	4.4×10^{16}	1185±73
				Acceleration	157±120 m/s^2

Ramesh, R. et al. ApJL, 2003, 591, 2, 163

**Radio data can be used to estimate
the mass & speed of CMEs
in the sky plane
similar to WL coronagraph data**

Since CMEs travel in 3D space, do the 2D image data help to infer whether a CME would reach the Earth or not ??

CME Modeling

1 **Epi-polar geometry & tie-Pointing technique**

2 **Forward modeling & Reverse reconstruction**

3 **Polarization ratio technique**

4 **GCS modeling**

2D WL, EUV, etc. observations → 3D reconstruction

CME Modeling

2D Radio observations → 3D reconstruction

Ray-Tracing technique

CME → True Mass

C2 1998/06/02 10:29:34

GAURIBIDANUR RADIOHELIOGRAM – 109 MHz

1998/06/02 : 07:30 UT

REPRODUCED
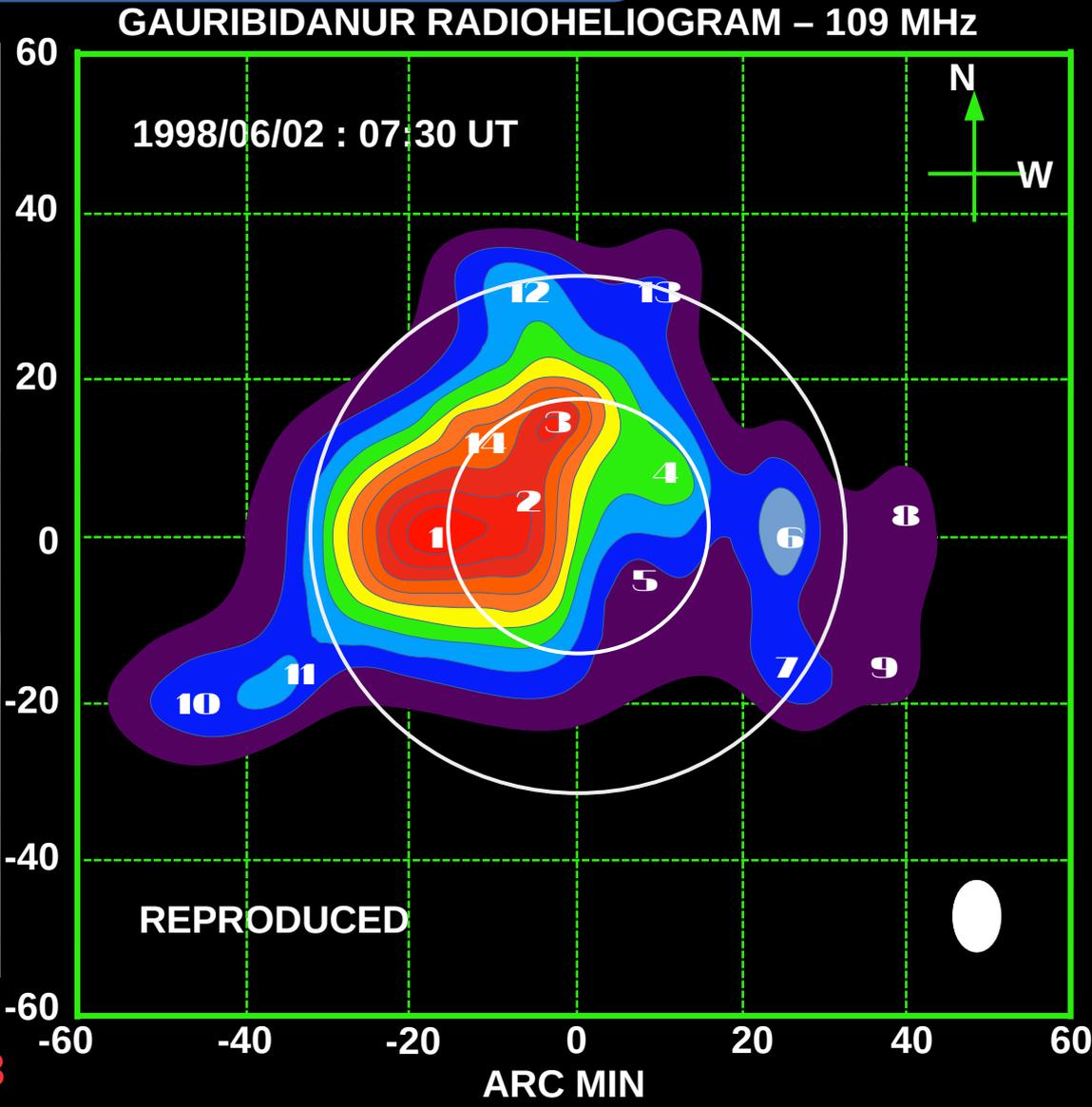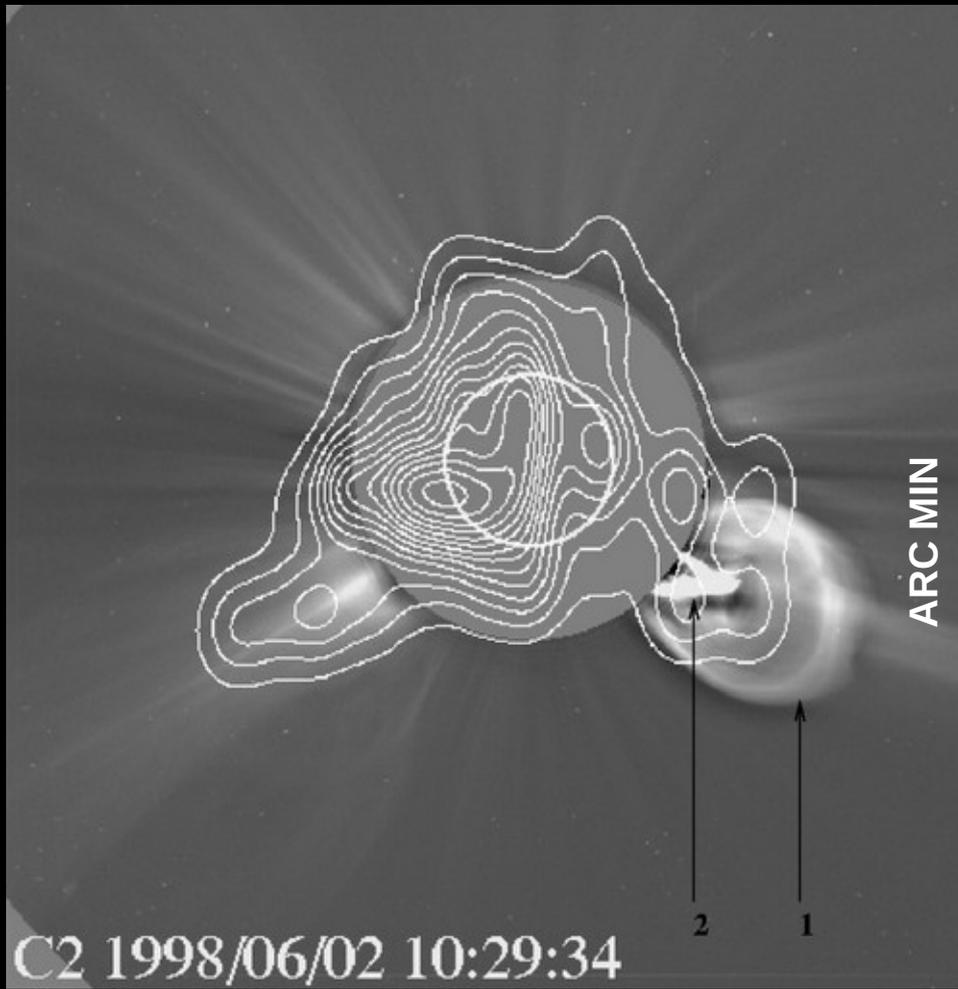
Kathiravan, C. et al. ApJL, 2002, 567, 1, 93

CME → True Mass

Radio Analysis Summary			
Source	Location (Sol. Rad.)	Size (Sol. Rad.)	Density factor
S6	1.50, 1.70, -0.06	0.2,0.22,0.64	10
S7	1.70. 1.72, -1.22	0.22, 0.29, 0.29	17
S8	1.70, 2.48. -0.03	0.26, 0.29, 0.50	20
S9	1.70, 2.44. -1.22	0.22, 0.29, 0.50	20
	Average Density	2.65×10^7 cm^{-3}	
	Total Mass	2.02×10^{15} g	< LASCO (1/4)

Kathiravan, C. et al. ApJL, 2002, 567, 1, 93

Radio reconstruction method can be used to estimate the true mass of CMEs similar to other techniques

Since CME related Structures are identified, Can they be used to find the true / 3D Speed ??

CME → True Speed

Radio Observation Summary

Rad. Tele. : GRAPH

Jan. 21, 1998 – 05:01 UT

f = 109 MHz

$\Omega_{res} = 7' \times 11'$

$T_b = 1.2 \times 10^6$ K ←⋯

T_b (interval) $= 0.1 \times 10^6$ K ←⋯

Dynamic Range : ≈ 20 dB

Red : Maximum Temperature
Violet : Minimum Temperature

Kathiravan, C. et al. ApJ, 2004, 610, 1, 532

GAURIBIDANUR RADIOHELIOGRAM – 109 MHz

1998/01/21 : 05:01 UT

N

W

ARC MIN

OBSERVED

ARC MIN

CME → True Speed

Radio Observation Summary

Radio Telescope : GRAPH

Jan. 21, 1998 – 06:01 UT

f = 109 MHz

Ω_{res} = 7' × 11'

T_b = 1.0 × 10⁶ K ←···

T_b (interval) = 0.1 × 10⁶ K ←···

Dynamic Range : ≈ 20 dB

Red : Maximum Temperature
Violet : Minimum Temperature

Kathiravan, C. et al. ApJ, 2004, 610, 1, 532

GAURIBIDANUR RADIOHELIOGRAM – 109 MHz

1998/01/21 : 06:01 UT

N
W

OBSERVED

CME → True Speed

LASCO C2

GAURIBIDANUR RADIOHELIOGRAM – 109 MHz

1998/01/21 : 06:01 – 05:01 UT

OCCULTER

Photosphere

CME

DIFF IMAGE $T_b = 1 \times 10^5$ K°

1998/01/21 07:32

RDI

Kathiravan, C. et al. ApJ, 2004, 610, 1, 532

CME → True Speed

Radio Analysis Summary

V_{los} = 318 km/s

V_{pos} = 485 km/s

V_{tot} = 580 km/s

Mass = 6.4×10^{15} g

$M_{CME} = M_8 + ... + M_{13}$

$\vec{R}_{CME} = \dfrac{1}{M_{CME}} (M_8 \vec{r}_8 + ... + M_{13} \vec{r}_{13})$

$\vec{R}_{CME} = 1.16 \vec{x} + 0.52 \vec{y} - 1.54 \vec{z}$

$\vec{R}_{H\alpha} = 0.51 \vec{x} - 0.18 \vec{y} - 0.84 \vec{z}$

where

M_{CME} ➔ Mass of radio CME

$\vec{R}_{CME}$ ➔ Position vector of CME centroid

$\vec{R}_{H\alpha}$ ➔ Position vector of solar filament (DSF)
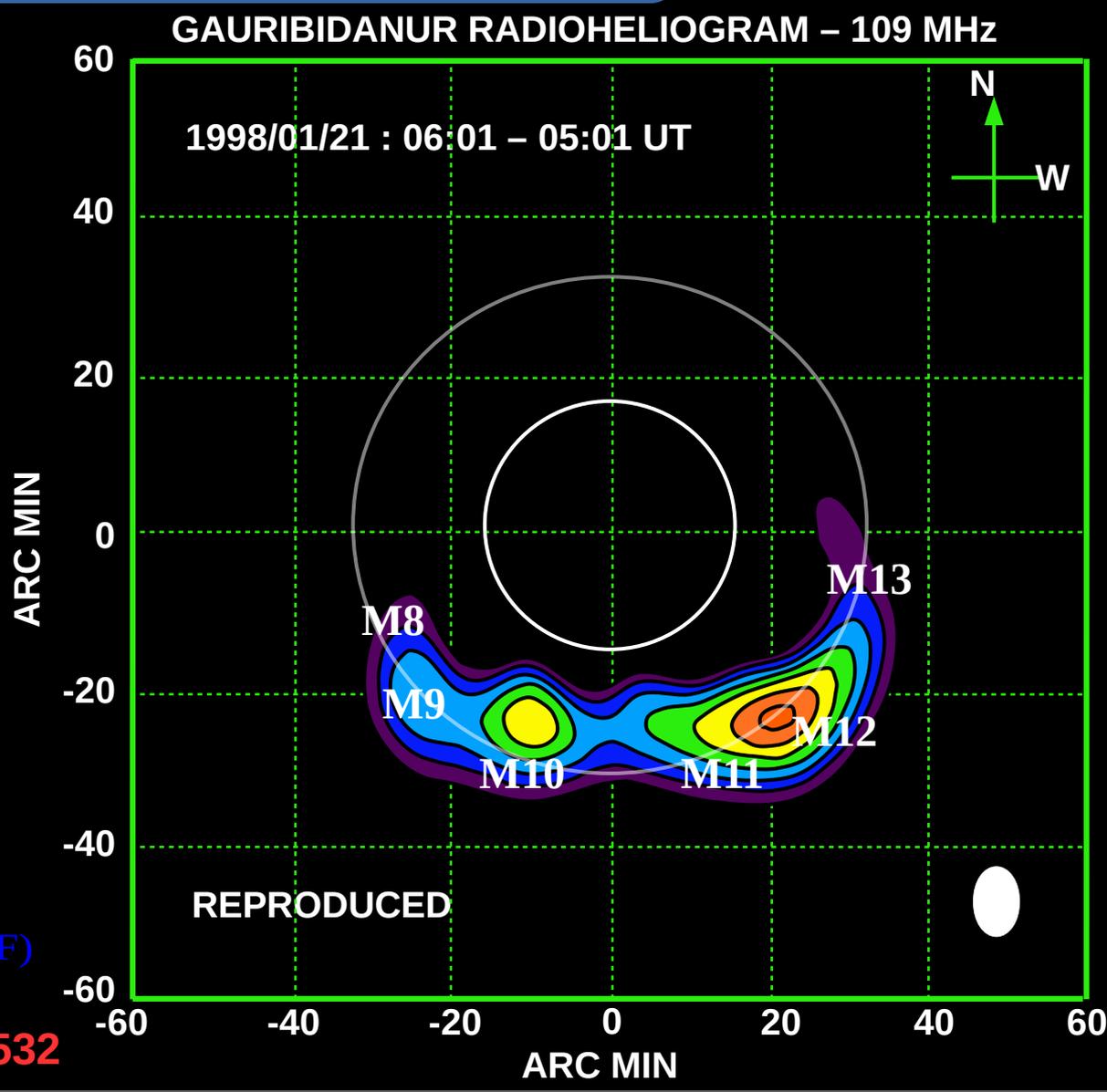
Kathiravan, C. et al. ApJ, 2004, 610, 1, 532

GAURIBIDANUR RADIOHELIOGRAM – 109 MHz

1998/01/21 : 06:01 – 05:01 UT

N

W

M13

M8

M9

M12

M10   M11

ARC MIN

ARC MIN

Radio reconstruction method can be used to estimate the true speed (3D) of CMEs similar to other techniques

Can we say anything about CME precursor using the disk info ??

CME → Pre-eruption Signature

Before CME onset   **After CME onset**
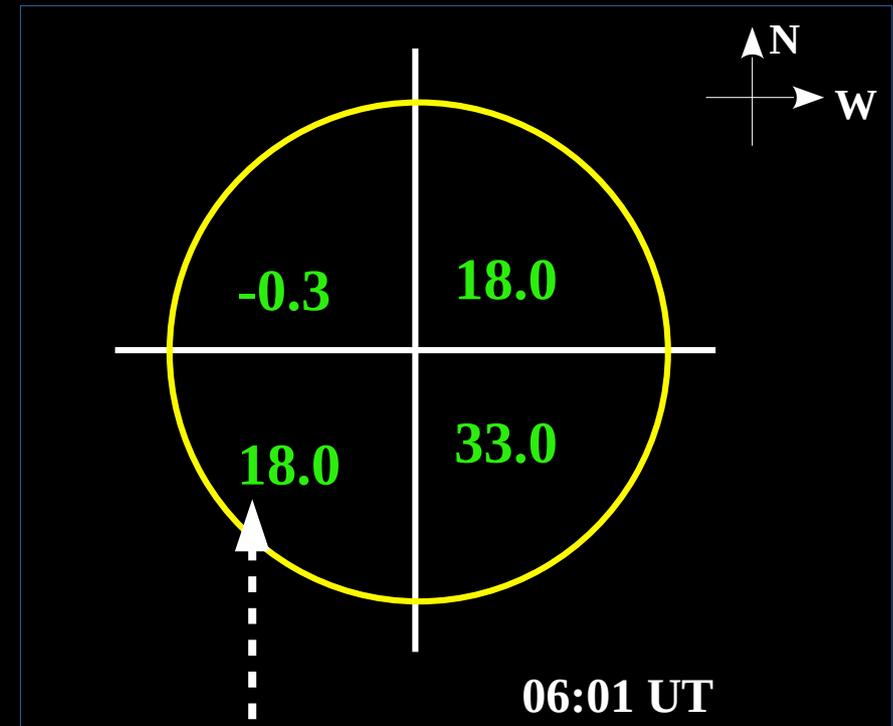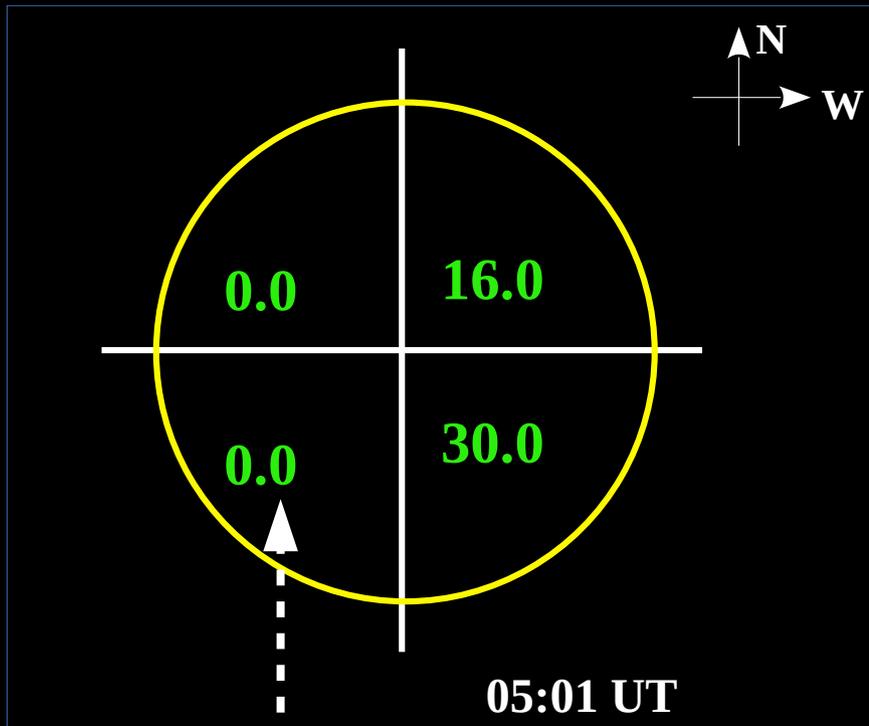
Γ_{SE} = 18

Mass Injection Rate = 8.8×10^{15} gm/hr
CME mass = 6.5×10^{15} g

Kathiravan, C. et al., ApJL, 2005, 627, 1, 77

Two Possibilities :

$$\text{CME} \rightarrow \text{Thermal}$$
$$\text{CME} \rightarrow \text{Non-thermal} \checkmark$$

CME → Non-thermal Type-II radio bursts

Flare location, t_0

Radioheliogram Type-II location, t_2

Occulter

Bg. Corona

Radio : type-II Dynamic spectrum

Frequency

Time

VELC FOV

CME onset location, t_1

CME location (acceleration), t_1 - t_3

CME first C2 appearance, t_4

Coronagraph FOV : CME LE (h-t plot)

Height

Time
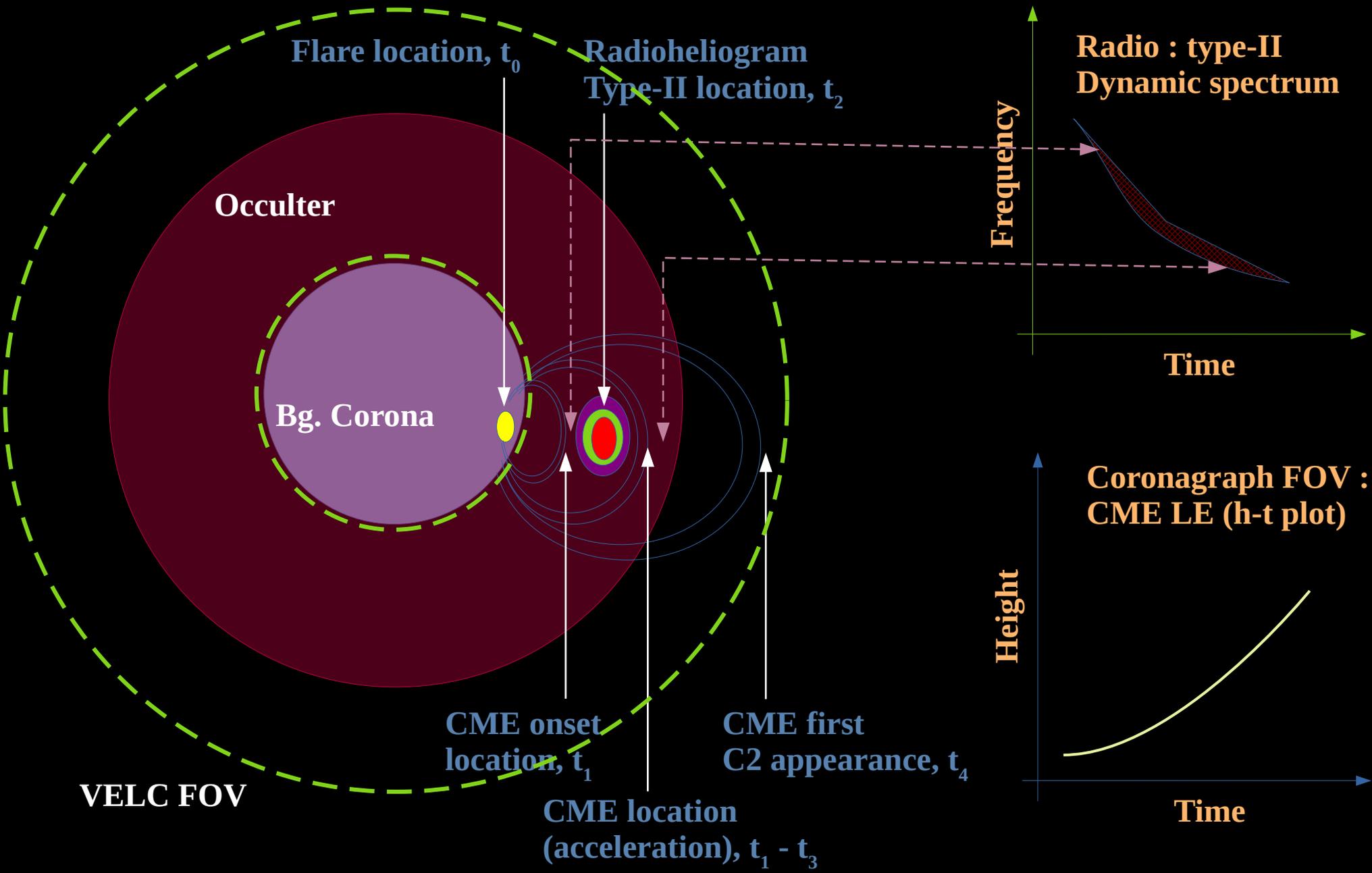
CME → Coronal type-II burst
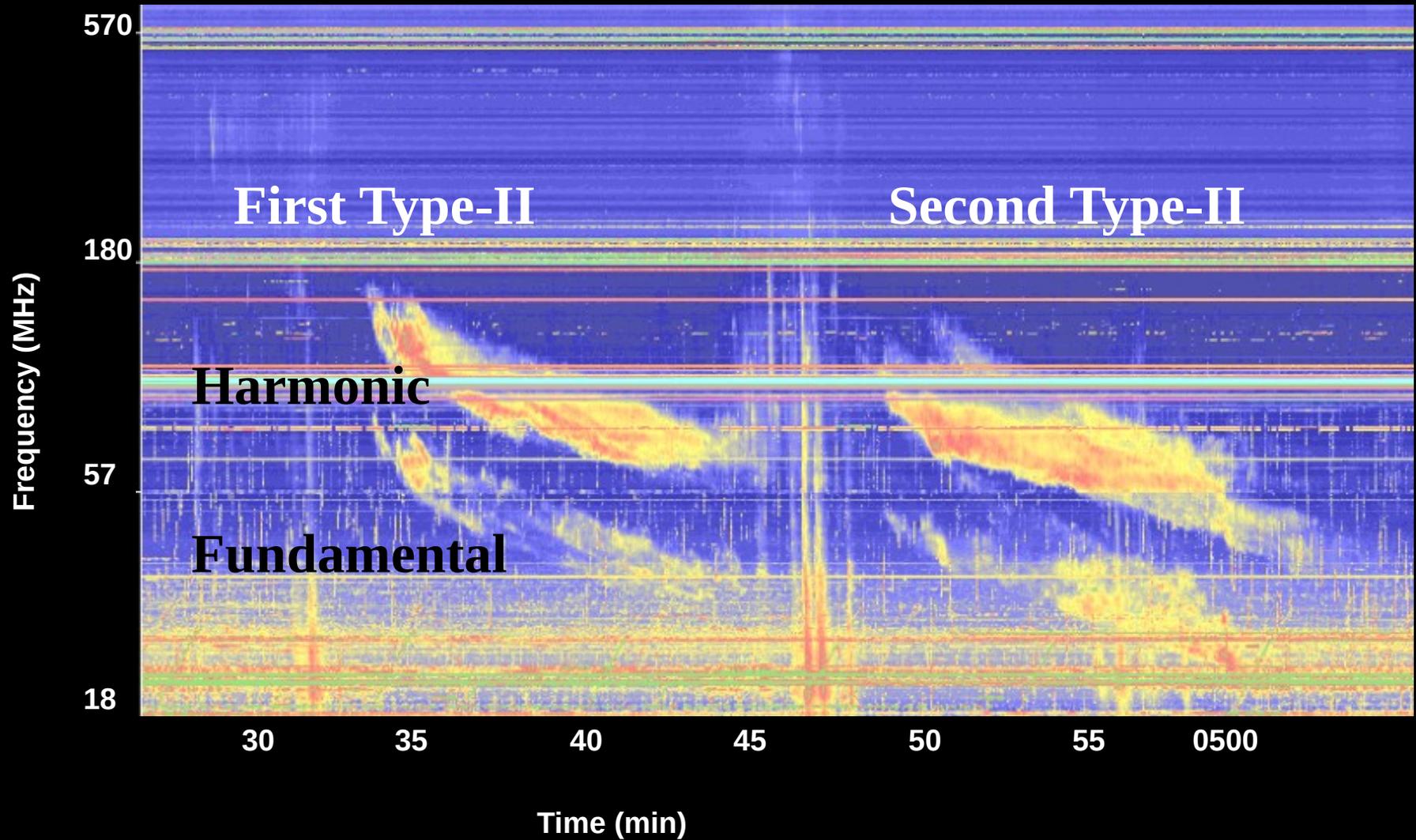
CME → Coronal type-II burst

Type-II burst :

1. A slow drifting non-thermal continuum emission.
2. T_b ~ 10^7 - 10^9 K.
3. The drift rate is lower (~MHz/s) than type-III.
4. They generally appear in pairs (Fundamental & Harmonic)
5. These are the signatures of coronal shock that are generated by the bulk motion of plasma material (associated with CMEs) from the inner to the outer coronal atmosphere.

Can't the CMEs be observed beyond 15 MHz ??

Yet another Radio technique – IPS Obs.

CME / ICME IPS Observations

FOV : 250 R$_\odot$

SUN

Bg. Radio Objects

Interplanetary Scintillation
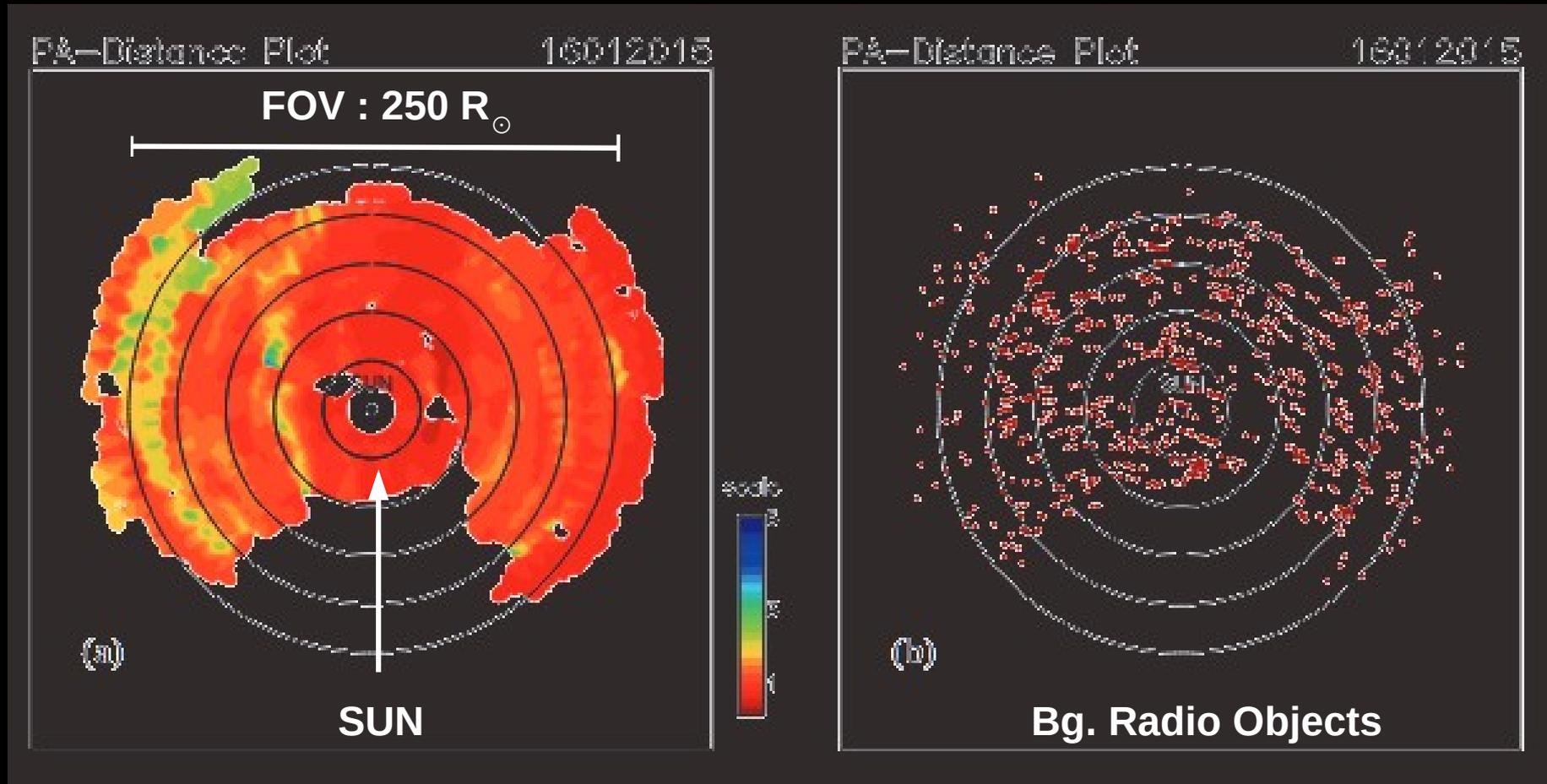
Ooty Wide Field Array (OWFA)

Manoharan, P. K. et al., JApA, 38, 16 (2017)

1

Flare associated Radio signatures

Standard FLARE model

Radio (cm-λ) & Soft X-ray emission

10.7 GHz / 2.8 cm

Radio blips
(microwave)

SXR 1-8Å & 0.5-4Å

X-ray Continuum +
Line emission
(He-like Iron ions)
1.8 Å
~ tens of keV

Fuerst et al., A&A, 107, 1, 178 (1982)

Radio (cm-λ) & Soft X-ray emission

10.7 GHz / 2.8 cm

SXR 1-8Å & 0.5-4Å
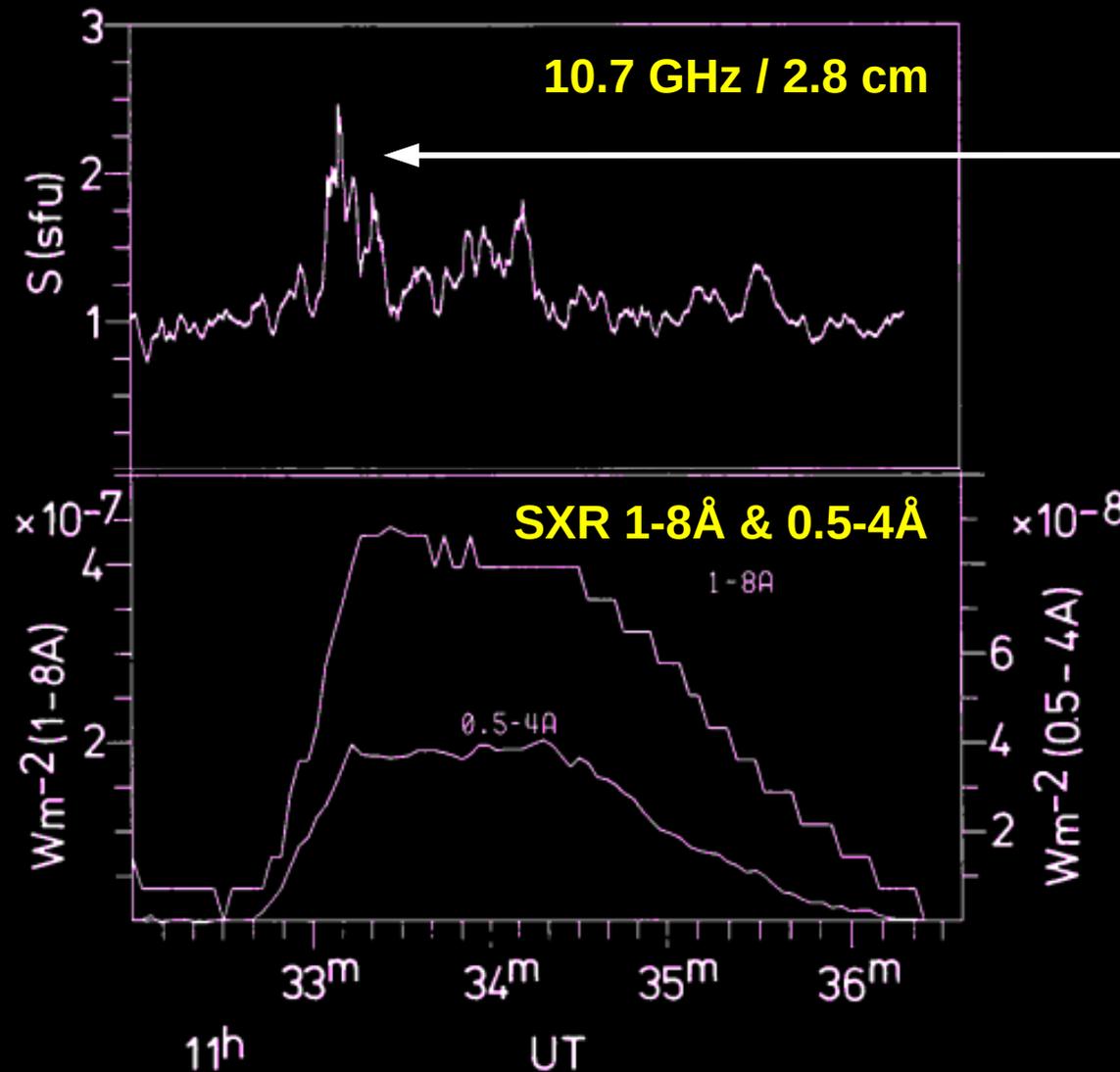
Radio blips
(microwave)

X-ray Continuum +
Line emission
(He-like Iron ions)
1.8 Å
~ tens of keV

Fuerst et al., A&A, 107, 1, 178 (1982)

Radio (cm-λ) & Soft X-ray emission

Radio blips:

1. Predominantly occur in the rise phase of SXR flares.

2. Are due to non-thermal (10^7 K) radiation from fast electrons. SXR emission is due to thermal flare plasma at a similar temperature.

3. Sources are located at flux emerging sites.
Radio blips and SXR flares are indicators of energy dissipation by fast electrons.

Fuerst et al., A&A, 107, 1, 178 (1982)

Radio (cm-λ) & X-ray (S&H) emission

(a) 01:45:33 UT

beam

Yohkoh SXT (greyscale)
17 GHz (white contours)

17 GHz / 1.7 cm

(b)

L → 13.9-22.7 keV
M1 → 22.7-32.7 keV

Yohkoh SXT (greyscale)
HXT L (white contours)
HXT M1 (blank contours)
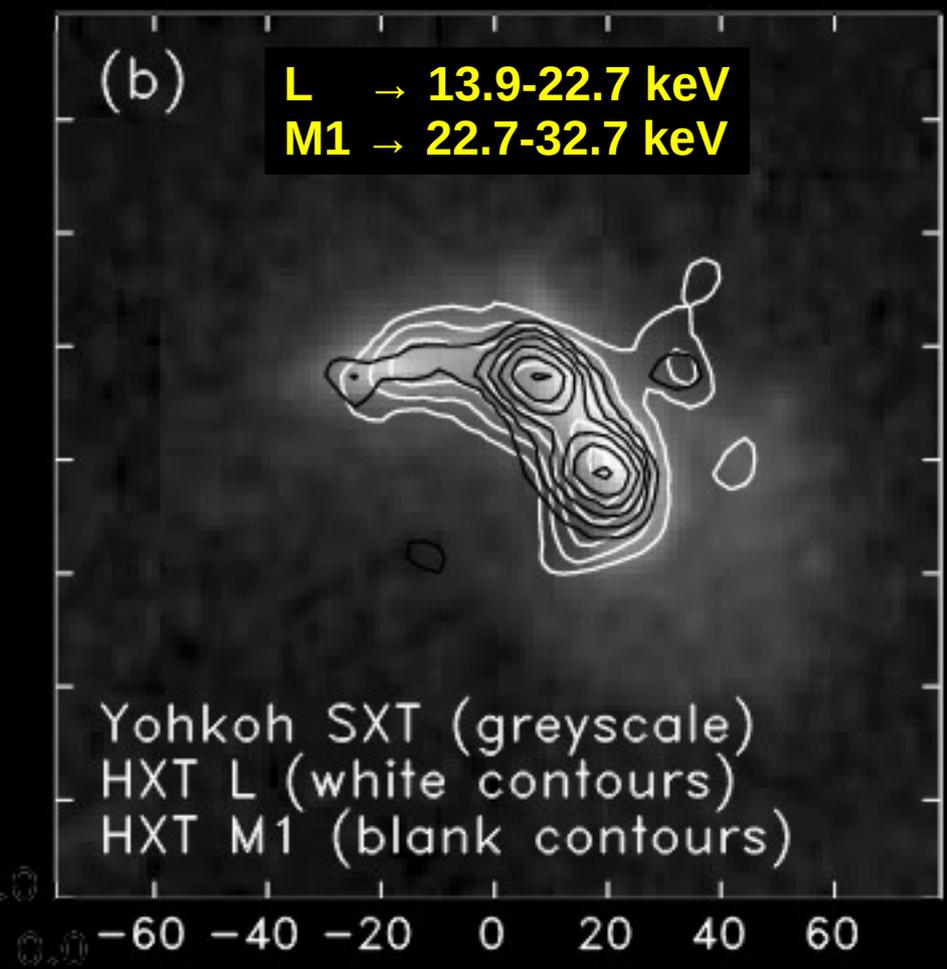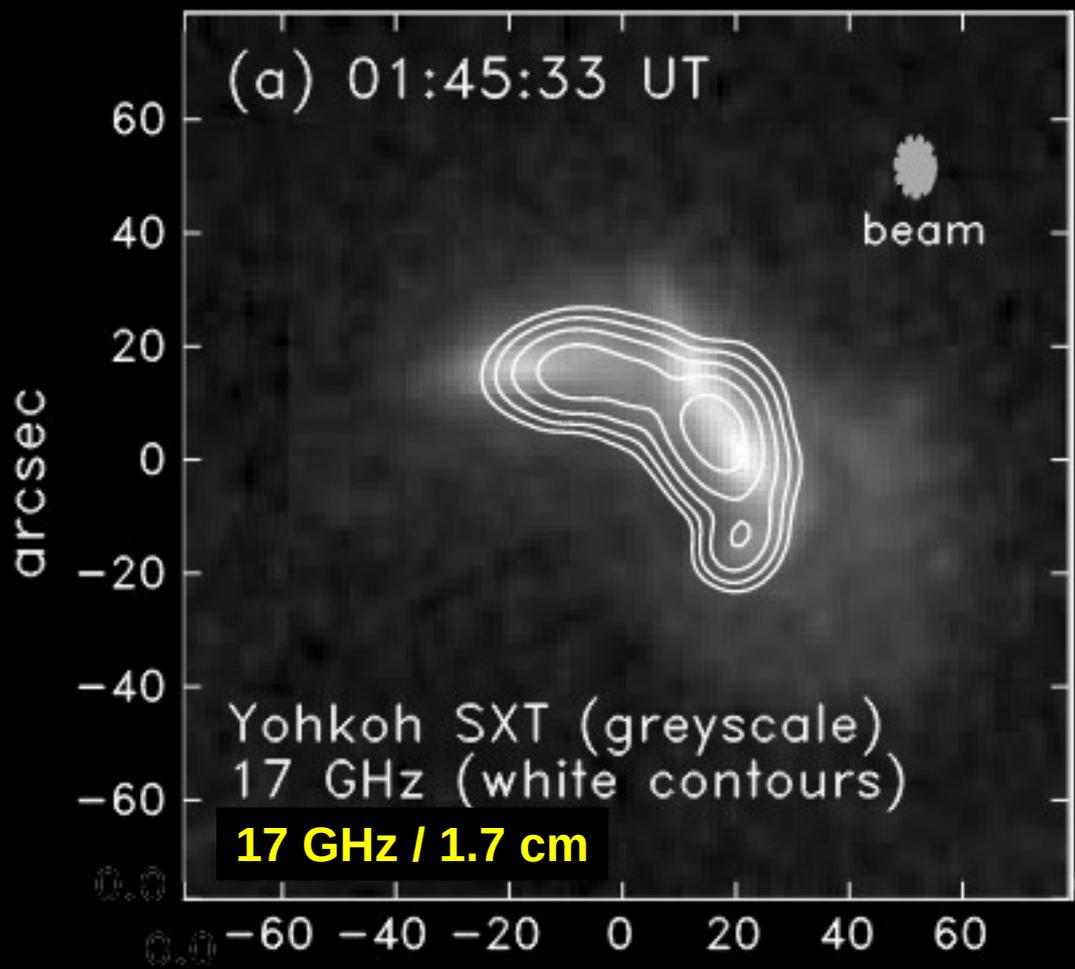
Takakura et al., PASJ, 46, 653 (1994)

Radio (cm-λ) & X-ray (S&H) emission

HXR & Radio overlay:

1. The emissions are almost co-spatial.
2. The emissions involve the foot-points of a complex / system of magnetic loops that fan out across an AR.
3. HXR are due to e⁻ accelerated to very high energies (~MeV) at flare onset which then hit atoms at inner dense layers and produce bremsstrahlung continuum.
4. Same e⁻ are responsible for high freq. radio emission.

Takakura et al., PASJ, 46, 653 (1994)

Radio obs. + Other λs
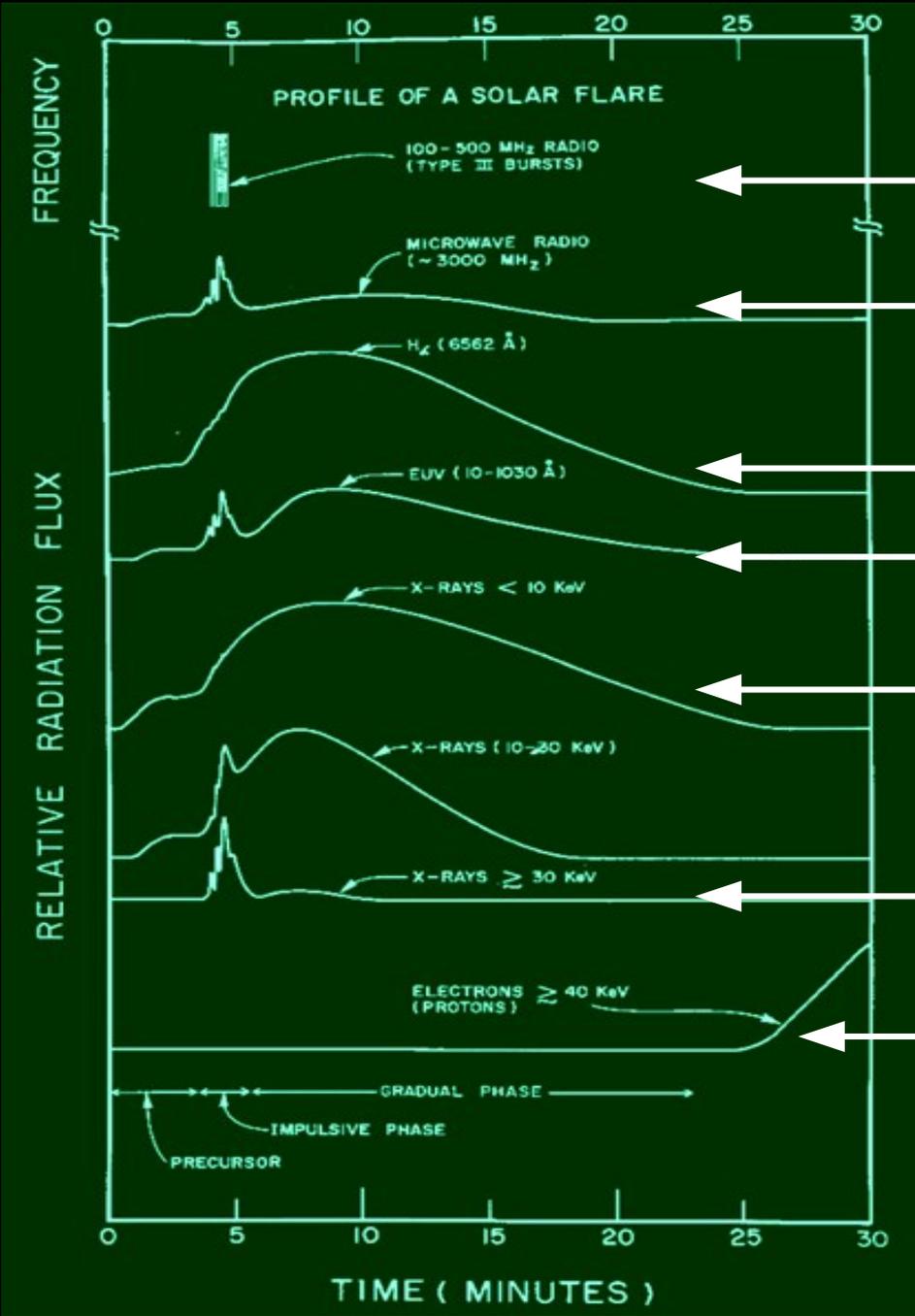
Radio – m λs

Radio – dcm λs

Hα
EUV

SXR

HXR

Electrons & Protons

Shibata, K. et al, LRSP, 8, 6 (2011)

Type-III bursts & Space Weather

← **X-ray flare**

← **cm-λ band**

← **meter-λ band**

      Regular type-III

← **deca meter-λ band**

← **hecto meter-λ band**

     IP type-III or type-III (*l*)

← **kilo meter-λ band**

Cane et al. JGR, 107, A10, 1315 (2002)
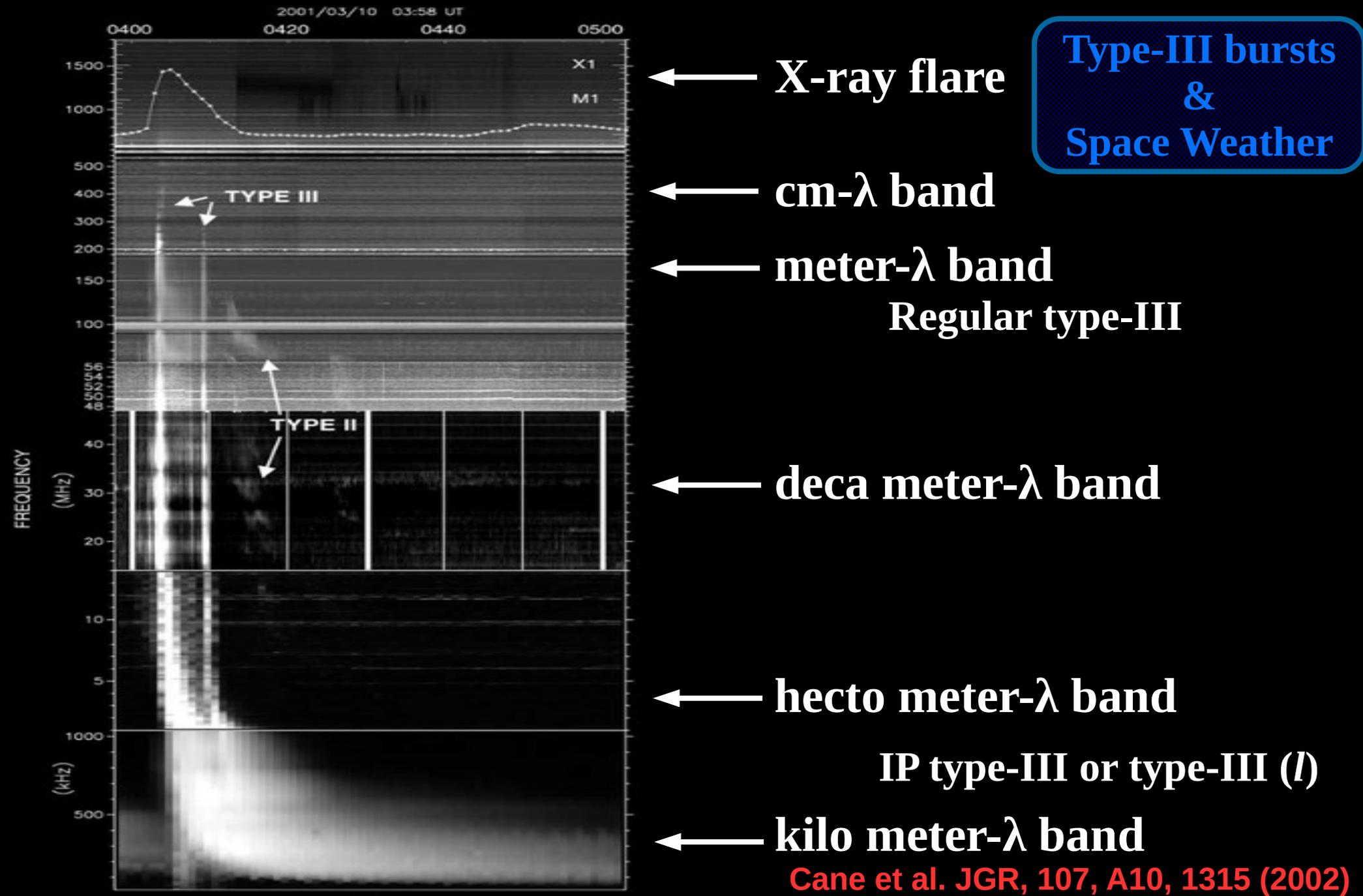
Sun - Earth Connection

Transient activities of outer solar atmosphere

i. **Flares**
ii. **Mass expulsions (CMEs)**
iii. **Particles …..**

Systematic around the clock

Solar　from the Earth
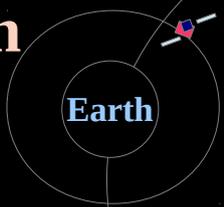
Earth

Space climate

Harsh Sudden Unpredictable
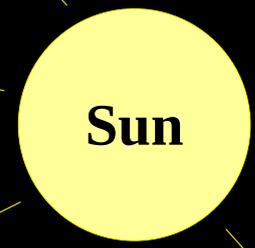
Space-borne instruments operation

Sun

Interplanetary medium

Solar Particle entry
– onset of Geo-magnetic Storms, Aurora,
…... formation of Ring Current above equator

Earth – Geospace

Open magnetic field lines

90000 km

Atmosphere

10000 km

Ionsphere

300 km

Earth

Atmosphere Exosphere

Closed magnetic field lines
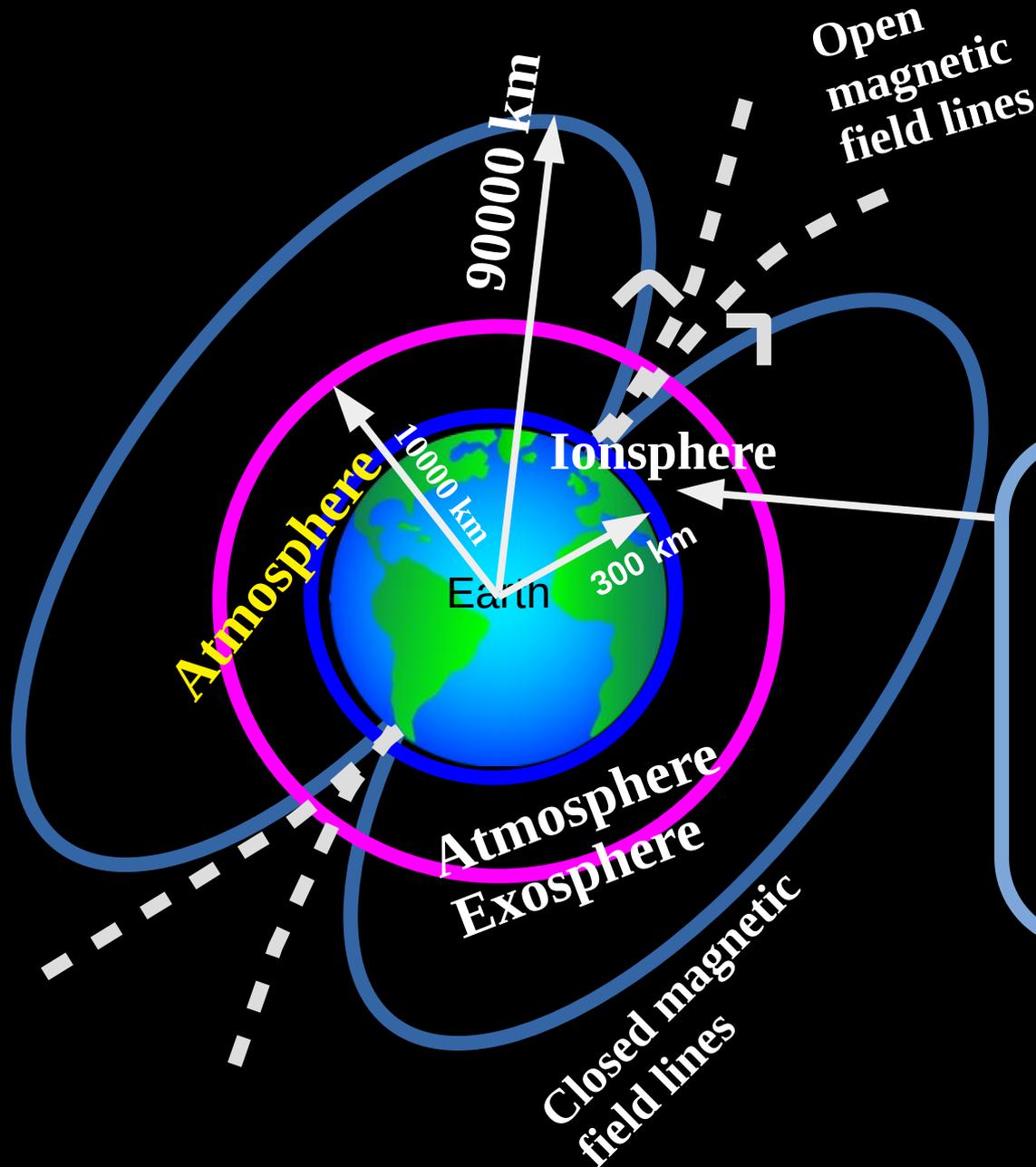
Place of

Communication satellites
Remote sensing satellites
Military surveillance satellites
International space station

Thank you ALL

Organizers
(SU-UZB, COSPAR, ISWI, SCOSTEP, e-CALLISTO)
Participants

IIA & GBR observatory staff