Увод в радиоастрономията

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Съдържание

1. Кратка история на радиоастрономията
2. Въведение. Радиотелескопи.
3. Механизми за радиоизлъчване
4. Източници на радиоизлъчване

Литература

- Книга: Aschwanden, M. (2005) https://www.springer.com/gp/book/9783540307655
- Статия: Pick&Vilmer (2008) https://link.springer.com/content/pdf/10.1007%2Fs00159-008-0013-x.pdf
- Статия: Nindos et al. (2008) https://link.springer.com/content/pdf/10.1007%2Fs11207-008-9258-9.pdf
- Лекция: http://astronomy.swinburne.edu.au/sao/downloads/HET608-M03A02.pdf

Ускорение – излъчване – наблюдение

Ускорение на частици (от електрично поле)

- Големи и/или малки по размер токови слоеве и др. (current sheets)
- Ударни вълни (shock waves)
- Взаимодействия между вълни и частици

Излъчване на електромагнитна емисия – от всички ускорени частици

- електрони
- протони

Радиоизлъчване

Наблюдаваните характеристики зависят от:

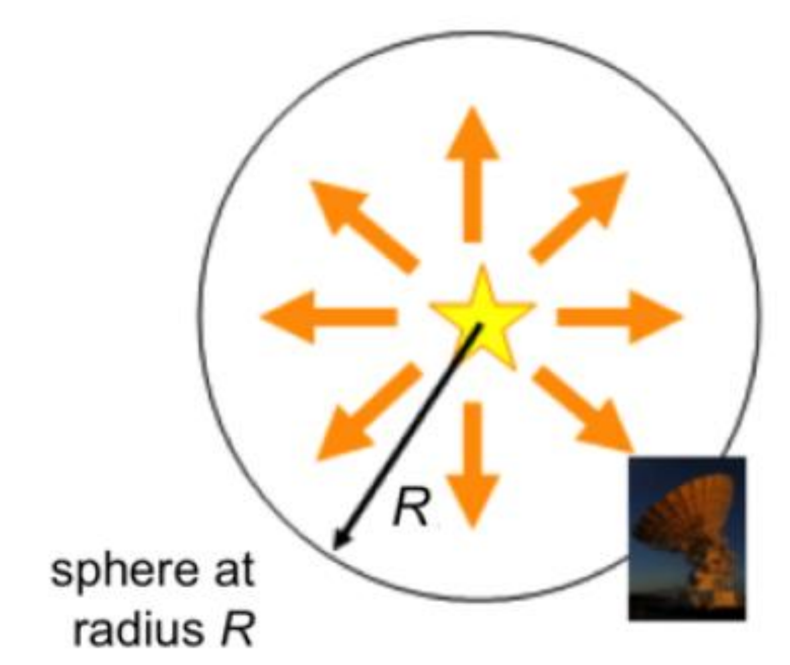
- Вида на излъчването в областта на формиране му (източника)
- Радиативния трансфер
- Ефекти на разпространение – пречупване и поглъщане при наличие на градиенти в плътността в плазмата води до отместване на видимата позиция на емисията, промяна в разпределението на радиояркостта, ъглово и спектрално разширение на областта на емисия

Радиоизлъчване има само от електрони!!!

Радиоемисия

- Поток = лъчение/(площ · честота)

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



интензитет $\mathcal{I}_\nu = k_B T_B \nu^2 / c^2$ brightness temperature T_B

поток $\mathcal{S}_\nu = k_B T_{\text{eff}} \nu^2 / c^2$ effective T_{eff}

При наблюдения от цялото Слънце – потокът се дава в слънчеви единици

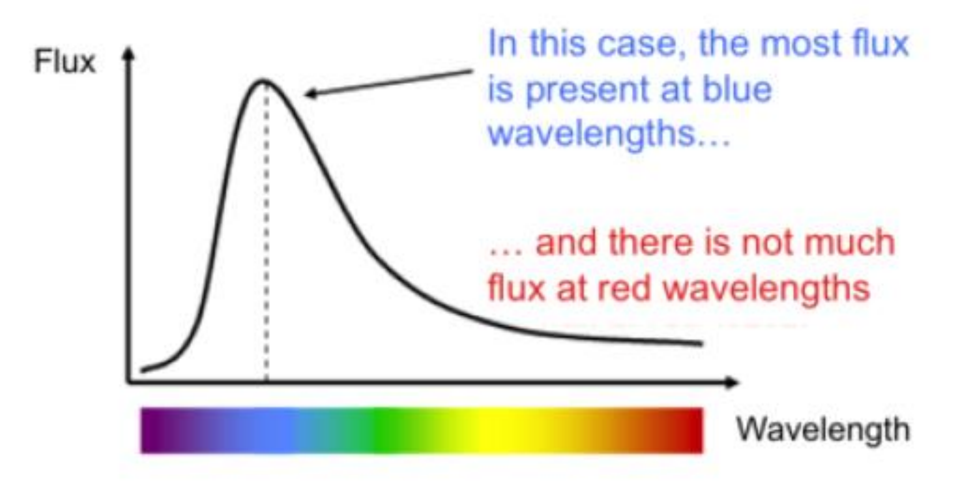
$1 \text{ sfu} = 10^{-19} \text{ ergs cm}^{-2} \text{ sec}^{-1} \text{ Hz}^{-1} = 10^4 \text{ Jansky}$

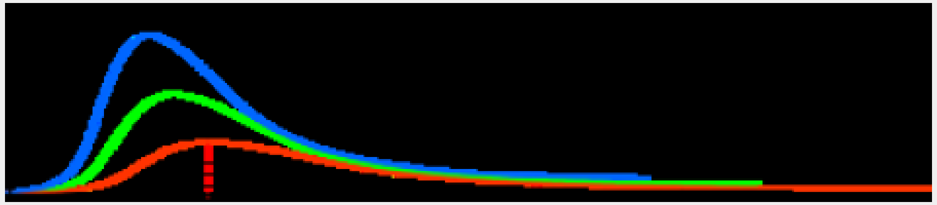
At radio frequencies, $h\nu \ll k_B T$ (the Rayleigh-Jeans regime)

http://astronomy.swinburne.edu.au/sao/downloads/HET608-M03A02.pdf

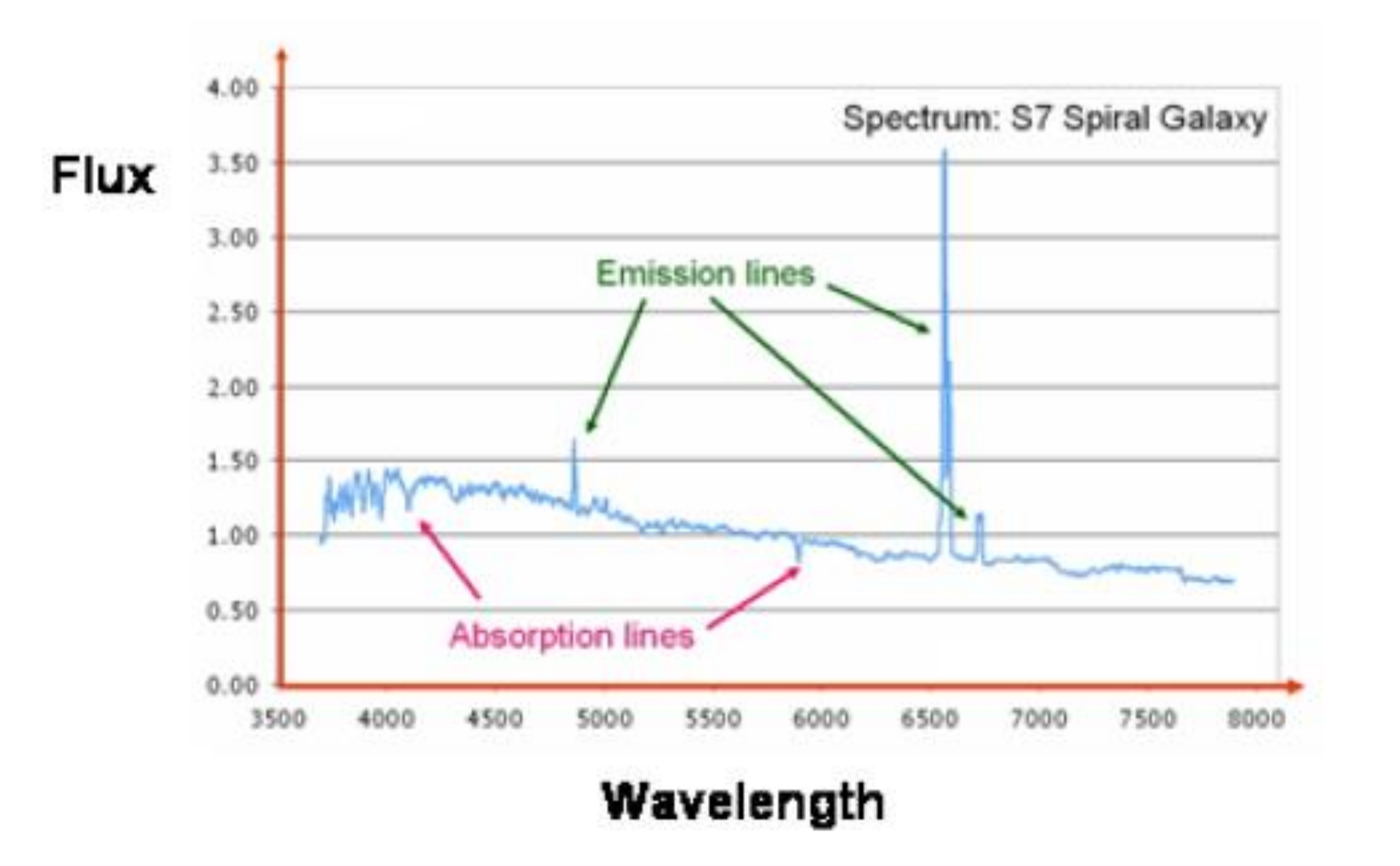
Радиоемисия

- Спектър





Flux (Vertical) vs wavelength (horizontal). The blue line represents hotter stars and the red cooler ones.



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Механизми

В зависимост от механизма на емисия

- Кохерентни → излъчване на ансамбъла от частици във фаза
- Некохерентни → индивидуално излъчване на всяка от частиците в разпределението

В зависимост от функцията на разпределение на частиците

- Топлинна (thermal) → напр. чернотелно разпределение, емисията зависи само от температурата на излъчвателя (на къси радиовълни)
- Нетоплинна (non-thermal) → не зависи от температурата на излъчвателя (на дълги радиовълни)

Релативистична →

Нестабилна →

В зависимост от вида на спектъра

- Непрекъснат → емитираните фотони имат непрекъснато разпределение по енергии (топлинна и нетоплинна)
- Линеен → емитираните фотони са само на една една дължина в зависимост от квантовите състояния в атома

Видове механизми

В зависимост от вида на радиоспектъра

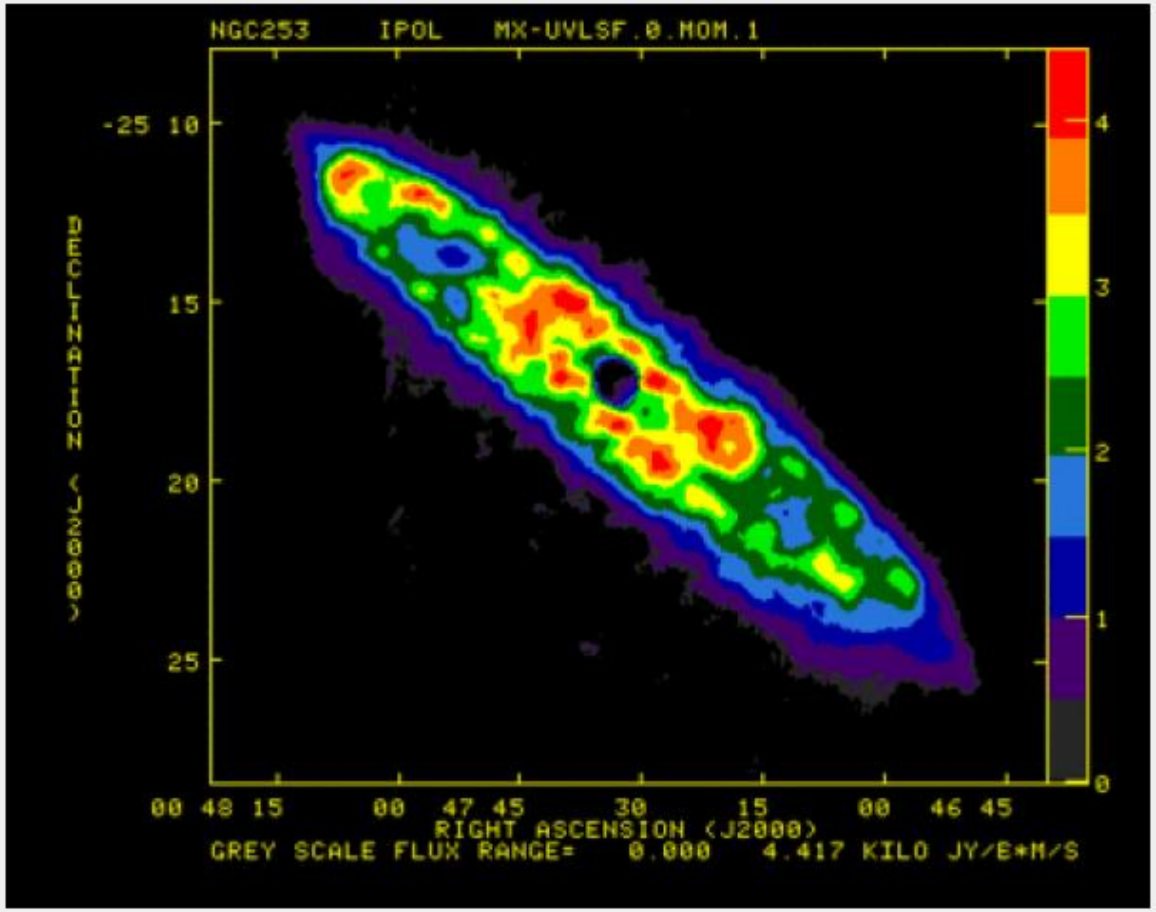
- Непрекъснат – няма информация за интензитета в дадена честота – използват се цветови таблици за означение на големината на радиопотока
- Линеен - 21 cm, излъчване от молекули при промяна на ротационните им състояните

Цветове

Цветовета на радиоизображенията **не са истински**: false-color се използва за означаване на радиоемисия

- По честота (при изображения на много честоти)
- По интензитет (при изображения на една честота, линия)
- И по двете (т.нар. динамичен спектър при наблюдения на Слънчето)

Изображение в 21-cm на спирална галактика NGC253: големите потоци от радиоемисия са означени в червено



Credit: Koribalski, Whiteoak “& Houghton (1995)

http://astronomy.swinburne.edu.au/sao/downloads/HET608-M03A02.pdf

Видове механизми

- Некохерентни → спирачно лъчение, спирално лъчение
- Кохерентни → плазмена емисия, тип циклотронен мазер

Table 15.1: Radio emission mechanisms during solar flares, (gyrofrequences are given in units of angular frequencies, $\omega = 2\pi\nu$) (Aschwanden 2002b).

Emission mechanism	Frequency	Source/Exciter
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(1a) Free-free emission (bremsstrahlung)	$\nu \gtrsim 1$ GHz	Thermal plasma
– Microwave postbursts		Thermal plasma
(1b) Gyroemission	$\omega = s\Omega_e$	
Gyroresonance emission	$(s = 1, 2, 3, 4)$	Thermal electrons
Gyrosynchrotron emission	$(s \approx 10 - 100)$	Mildly relativistic electrons
– Type IV moving		Trapped electrons
– Microwave type IV		Trapped electrons
(2) Coherent radio emission:		
(2a) Plasma emission	$\nu_{pe} = 9000\sqrt{n_e}$	Electron beams
– Type I storms		Langmuir turbulence
– Type II bursts		Beams from shocks
– Type III bursts		Upward propagating beams
– Reverse slope (RS) bursts		Downward propagating beams
– Type J bursts		Beams along closed loops
– Type U bursts		Beams along closed loops
– Type IV continuum		Trapped electrons
– Type V		Slow electron beams
(2b) Electron-cyclotron maser:	$\omega = s\Omega_e/\gamma + k_{\parallel} v_{\parallel}$	Losscones
- Decimetric ms spike bursts		Losscones

Некохерентни: спирачно лъчение

Няма обратна реакция от електроните върху функцията им на разпределение, броя на излъчените фотони е пропорционален на броя на електроните, фотоните нямат асоциация по фаза

- **(1a) Free-free/Bremsstrahlung**: Електронът е отлонява в кулоновото поле на фонов протон

→ когато електроните са част от нетоплинно разпределение емисията на фотони е в рентгеновата област

→ когато електроните имат топлинно разпределение – емисията е в радио диапазона, наблюдава се слаба поляризация (тип x)

→ на честоти над 1 GHz – хромосфера, спокойно Слънце, активни области

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Некохерентни: спирачно лъчение

- (1a) Free-free/Bremsstrahlung

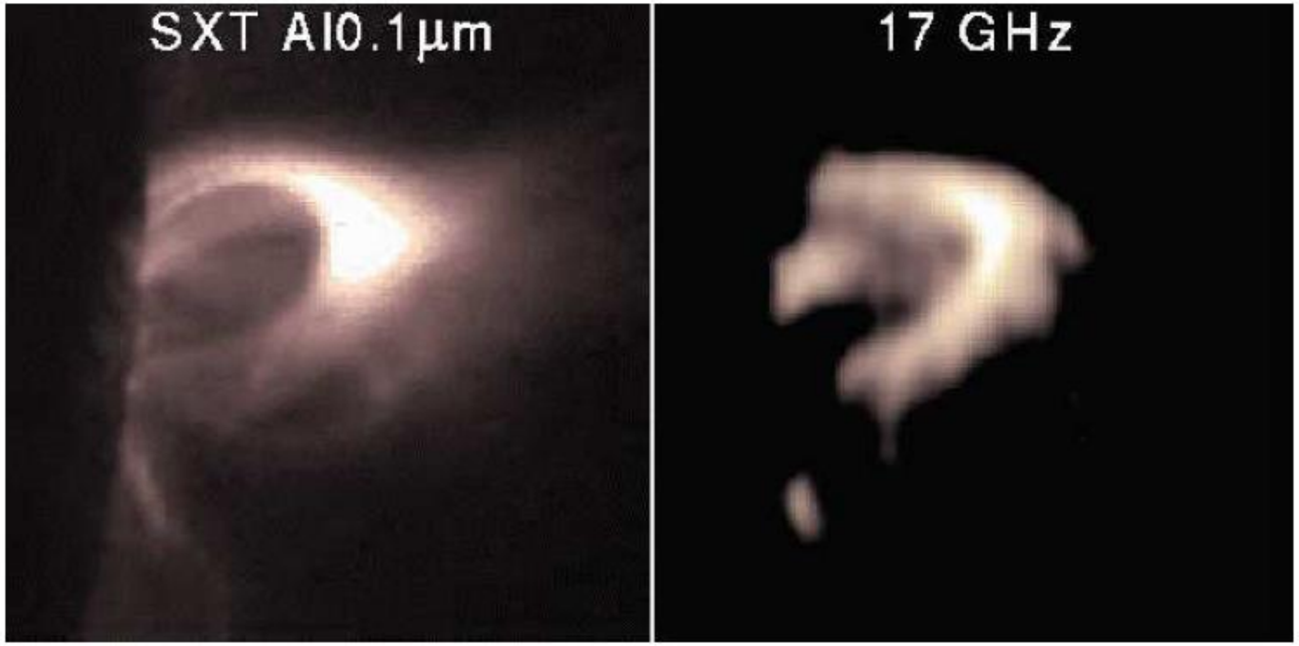

Figure 15.3: Observations of the long-duration flare event of 1993-Mar-16 with the *Nobeyama Radioheliograph* at 17 GHz and *Yohkoh/SXT*. Note the common loop-like structure, although there are little differences due to the different instrumental temperature responses (Hanaoka 1994).

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От приликата с мекия рентген се предполага, че една и съща плазма създава и двата типа емисия. Радионаблюденията допълват тези от мекия рентрен и ултравиолета и дават количествени оценки за параметрите на нехомогенна плазма.

Некохерентни: спирално лъчение

- **(1b) Gyroemission** – при движение на ускорен електрон в магнитно поле – като всеки електрон излъчва на честота, в зависимост от скоростта си (100 keV–10 MeV)

$$\omega_{\rm ge} = \frac{eB}{m_{\rm e}}$$

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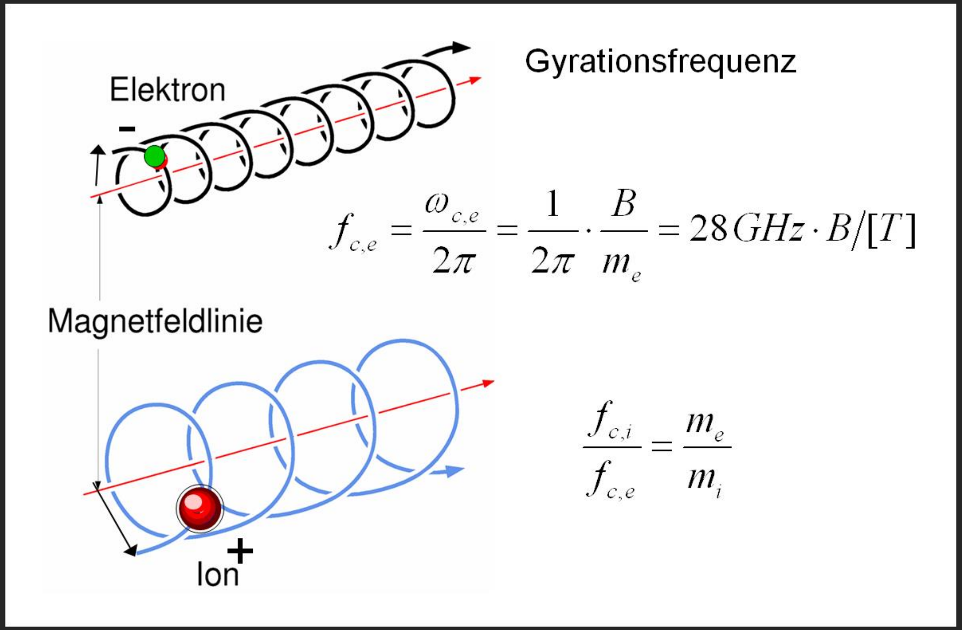
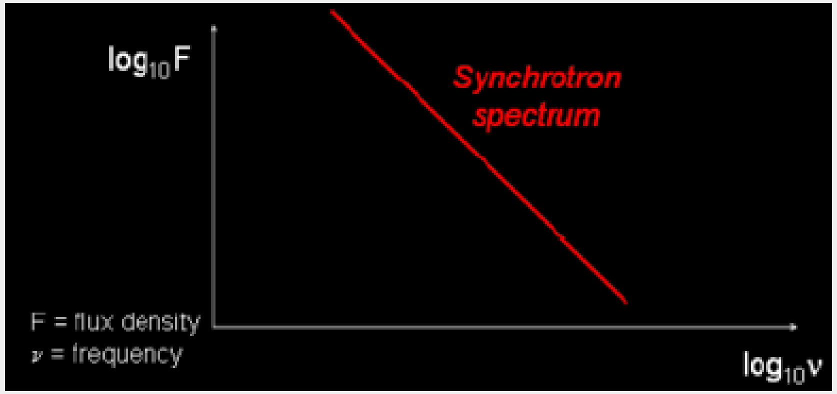
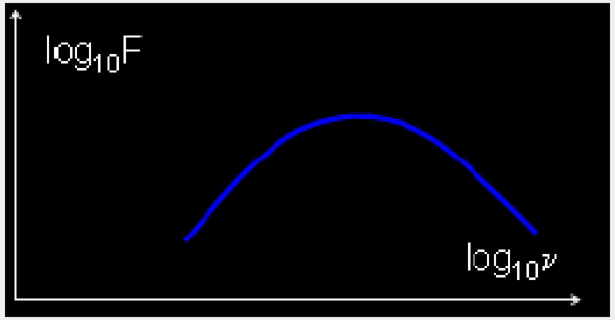


https://de.wikipedia.org/wiki/Datei:Gyrationsfrequenz_de.png



Typical synchrotron spectrum.



Typical thermal spectrum.

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- **(1b) Gyroemission** – получава се непрекъснат спектър като сума от спекрите от всички излъчващи електрони

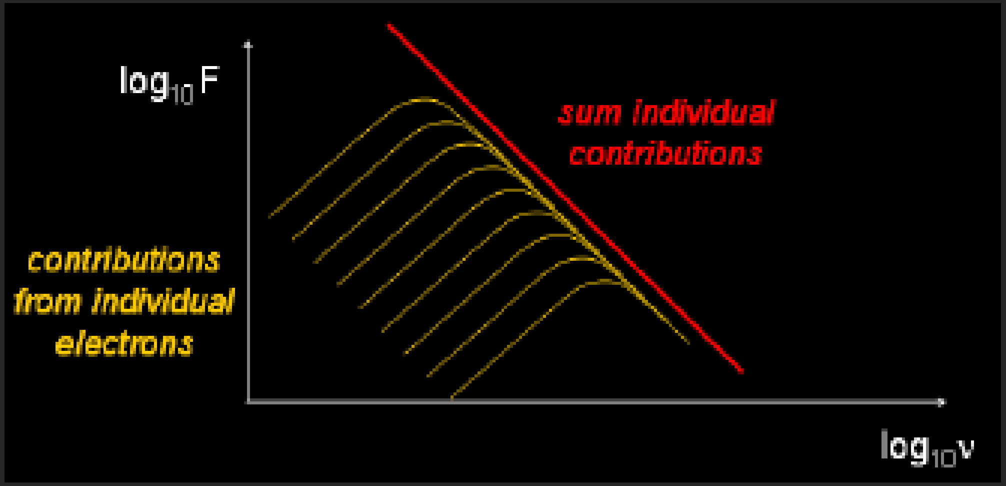
→ излъчване на различни хармоники на циклотронната честота

→ от наклона на спектъра се определя спектралния индекс

→ за диагностика на физичните условия в излъчващата среда

→ за диагностика на магнитното поле и ориентация

$$\nu_{Be}/\gamma = eB/2\pi\gamma m_e c \approx 2.8B/\gamma \text{ MHz, with } B \text{ in Gauss}$$



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Некохерентни: спирално лъчение

- **(1b-1) Резонансно или циклотронно**

→ от електрони с топлинна функция на разпределение (< 10s keV)

→ 1–4 хармоники

→ линеен спектър на емисия от всеки електрон

→ емисия над слънчеви петна (активни области)

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(2b) Electron-cyclotron maser:	$\omega = s\Omega_e/\gamma + k_\parallel v_\parallel$	Losscones
- Decimetric ms spike bursts		Losscones

Некохерентни: спирално лъчение

- **(1b-2) Спирално-синхротронно**

→ от електрони с енергии 10s keV – 10 MeV

→ всеки електрон от разпределението излъчва на хармоники 10–100

→ индивидуалната емисия е силно фокусирана, но топлинното и енергийно разширение на функцията на разпределение води до непрекъснат спектър

→ електрони в конфигурация „магнитна бутилка“

→ емисия в случай на високочестони радио-избухвания

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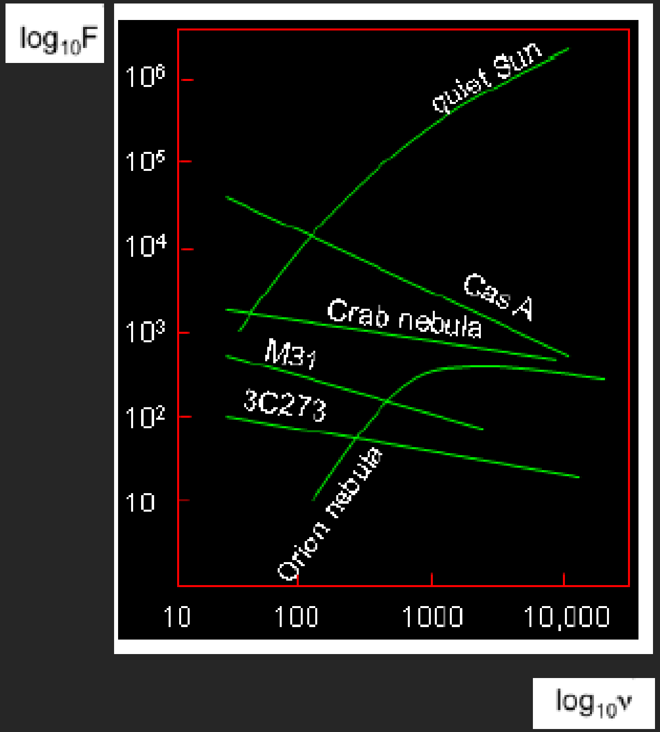
Некохерентни: спирално лъчение

- **(1b-3) Синхротронно**

→ релативистични енергии, > 10 MeV



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Некохерентни: спирално лъчение

- Този клас лъчение зависи от големината и посоката на магнитното поле, енергията и ориентацията на функцията на разпределение на ускорените електрони, плътността на фоновата плазма и честотата на наблюдение

→ Razin suppression: при емисия в много плътна плазма, на ниски честоти има редуцирана на емисията

→ free-free absorption – по лъча на зрение

→ thermal gyrosynchrotron absorption – от заобикалящата плазма

→ емисия на по-ниски хармоници от теоретичните

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– Type U bursts		Beams along closed loops
– Type IV continuum		Trapped electrons
– Type V		Slow electron beams
(2b) Electron-cyclotron maser:	$\omega = s\Omega_e/\gamma + k_\parallel v_\parallel$	Losscones
- Decimetric ms spike bursts		Losscones

Некохерентни: спирално лъчение

- Резултати от теоретичнен модел
- Наблюдения (mm & cm): Owens Valley Radio Observatory, Radio Solar Telescope Network…
- Източникът е оптически непрозрачен (optically thick) на ниски честоти, размерът му намалява с увеличаване на честотата, спектърът му има добре изразен максимум (между 5 и 10 GHz)
- Наблюденията потвърждават, че емисията от високочестотни радиоизточници е поляризирана (x-mode), докато нискочестотните са предимно без поляризация
- Близки времеви профили с рентгеновата емисия

Bastian et al. (1998)

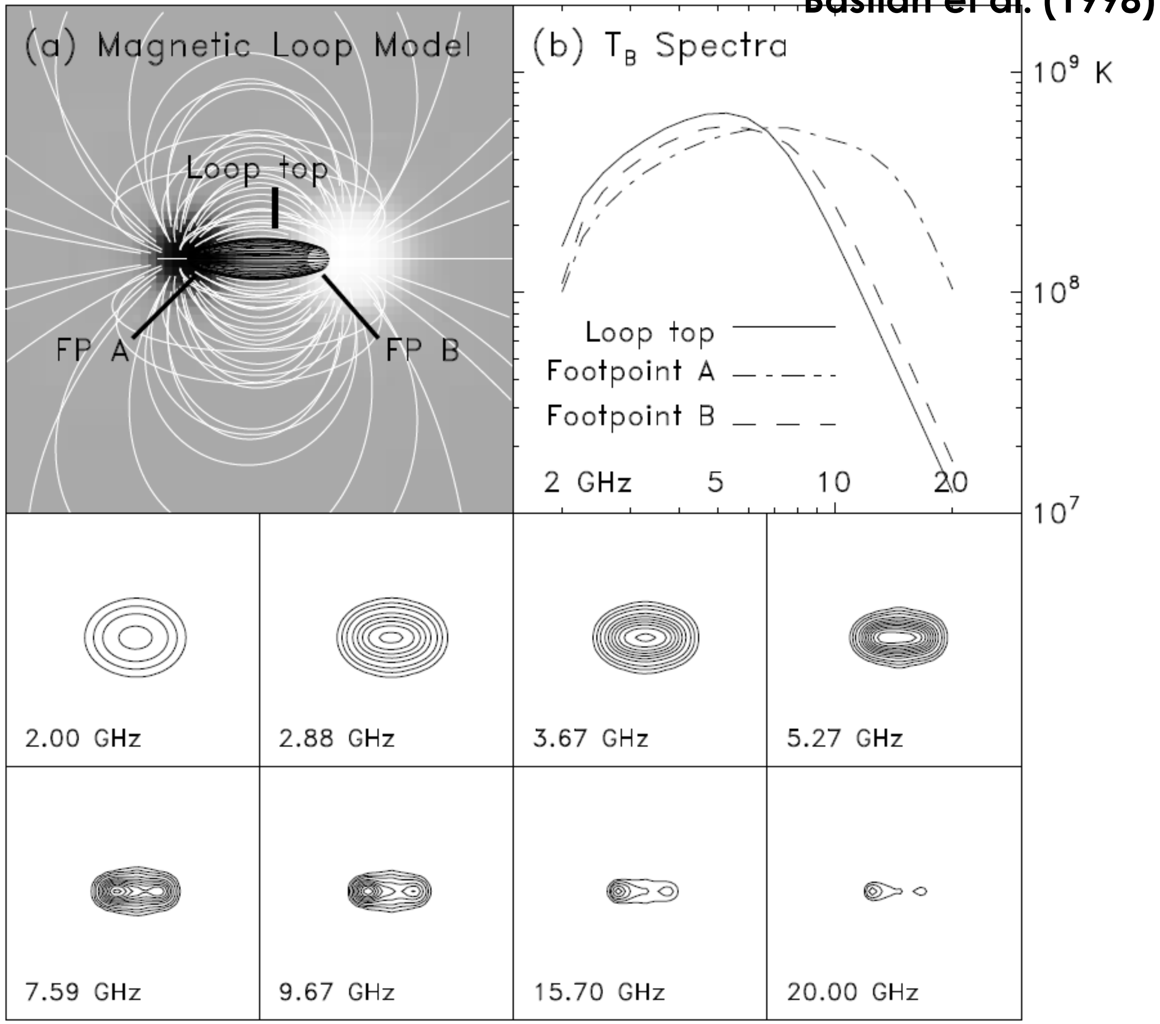

Figure 1 Gyrosynchrotron emission from a model coronal magnetic loop. *Top left*: A representation of the magnetic field lines of force. The *black lines of force* demarcate the full width at half maximum of the electron number density of nonthermal electrons. *Top right*: Brightness temperature spectra of the resulting gyrosynchrotron emission at magnetic footpoints A and B and at the loop top. In the *bottom two rows*, the brightness distribution of the Stokes I parameter are shown for eight frequencies. The *contour levels* are 2%, 5%, 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, and 90% of 6.8×10^8 K. The scale of each of the *lower panels* is half that of the *upper-left panel*.

Некохерентни: спирално лъчение

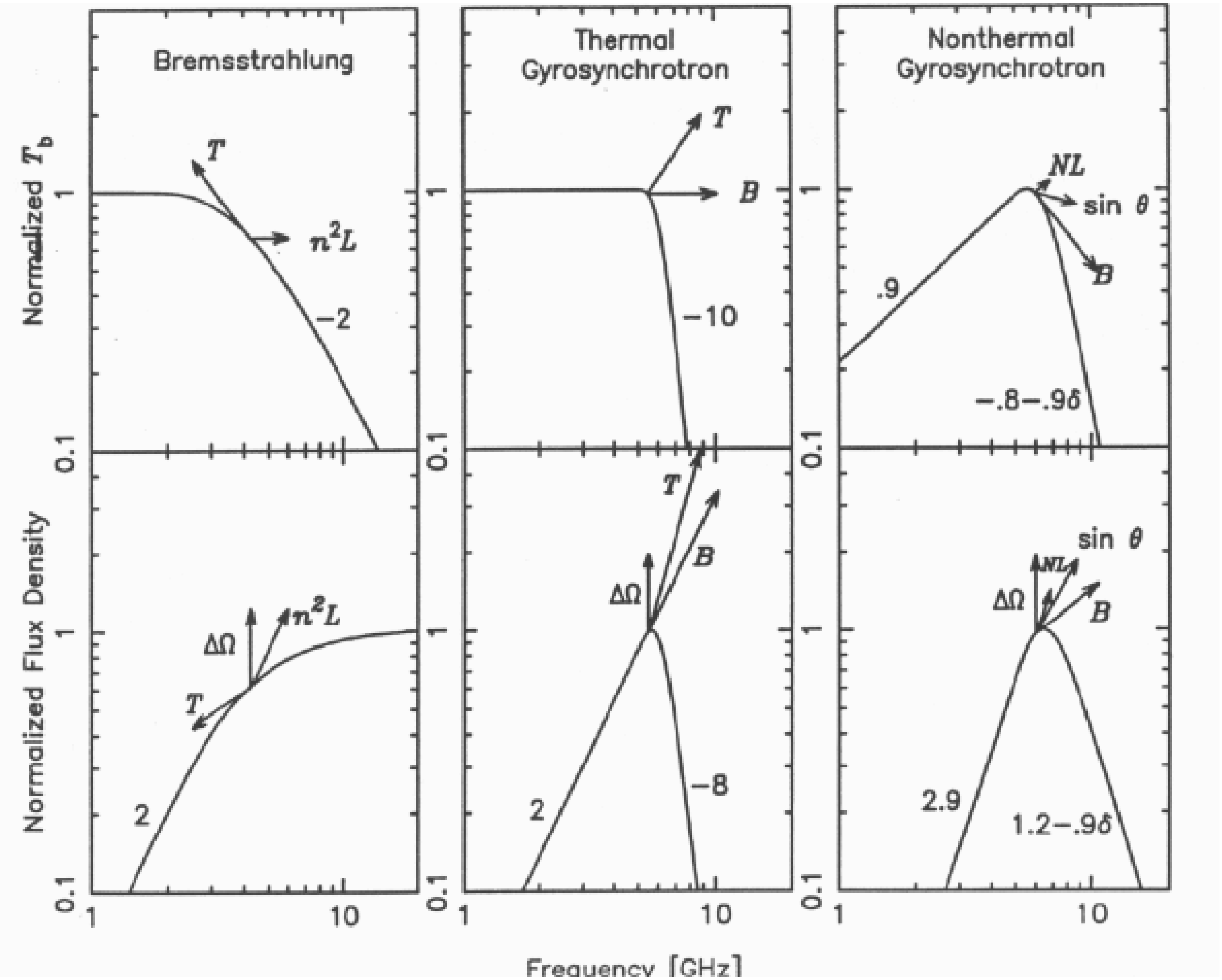

Figure 15.2: Universal frequency spectra of a homogeneous source in radio brightness temperature (top row) and radio flux density (bottom row), for three different emission mechanisms: free-free emission (left), thermal gyrosynchrotron (middle), and nonthermal gyrosynchrotron emission. The arrows represent the magnitude and directions of shift for an increase of parameters by a factor of two (Gary & Hurford 1989).

Кохерентни: плазмена емисия

Електроните се ускоряват във фаза и излъчват фотони, които също са във фаза, радиояркостта е по-голяма от средната енергия на излъчващите електрони

- **(2a)** Плазмена емисия

→ представлява нелинейно превръщане на енергията на излъчващите електрони в плазмени вълни, които на свой ред се превръщат в електромагнитни вълни

→ излъчване на плазмената честота или втора хармоника

→ електронен сноп с нестабилна функция на разпределение

→ за диагностика на електронната плътност близо и вътре в източника и при разпространение на електроните в короната и междупланетната среда

Table 15.1: Radio emission mechanisms during solar flares, (gyrofrequences are given in units of angular frequencies, $\omega = 2\pi\nu$) (Aschwanden 2002b).

Emission mechanism	Frequency	Source/Exciter
(1) Incoherent radio emission:		
(1a) Free-free emission (bremsstrahlung)	$\nu \gtrsim 1$ GHz	Thermal plasma
– Microwave postbursts		Thermal plasma
(1b) Gyroemission	$\omega = s\Omega_e$	
Gyroresonance emission	$(s = 1, 2, 3, 4)$	Thermal electrons
Gyrosynchrotron emission	$(s \approx 10 - 100)$	Mildly relativistic electrons
– Type IV moving		Trapped electrons
– Microwave type IV		Trapped electrons
(2) Coherent radio emission:		
(2a) Plasma emission	$\nu_{pe} = 9000\sqrt{n_e}$	Electron beams
– Type I storms		Langmuir turbulence
– Type II bursts		Beams from shocks
– Type III bursts		Upward propagating beams
– Reverse slope (RS) bursts		Downward propagating beams
– Type J bursts		Beams along closed loops
– Type U bursts		Beams along closed loops
– Type IV continuum		Trapped electrons
– Type V		Slow electron beams
(2b) Electron-cyclotron maser:	$\omega = s\Omega_e/\gamma + k_\parallel v_\parallel$	Losscones
- Decimetric ms spike bursts		Losscones

$$\nu_{pe} = (n_e e^2/\pi m_e)^{1/2} \approx 9000\, n_e^{1/2}\ \mathrm{Hz}$$

$$\omega_{\mathrm{pe}} = \sqrt{\frac{e^2 N_e}{\varepsilon_0 m_e}}$$

$$f_{\mathrm{pe}} = \omega_{\mathrm{pe}}/2\pi \approx 9 \times N_e^{1/2} \qquad \mathrm{m}^{-3}$$

Кохерентни: плазмена емисия

- **(2a)** Плазмена емисия

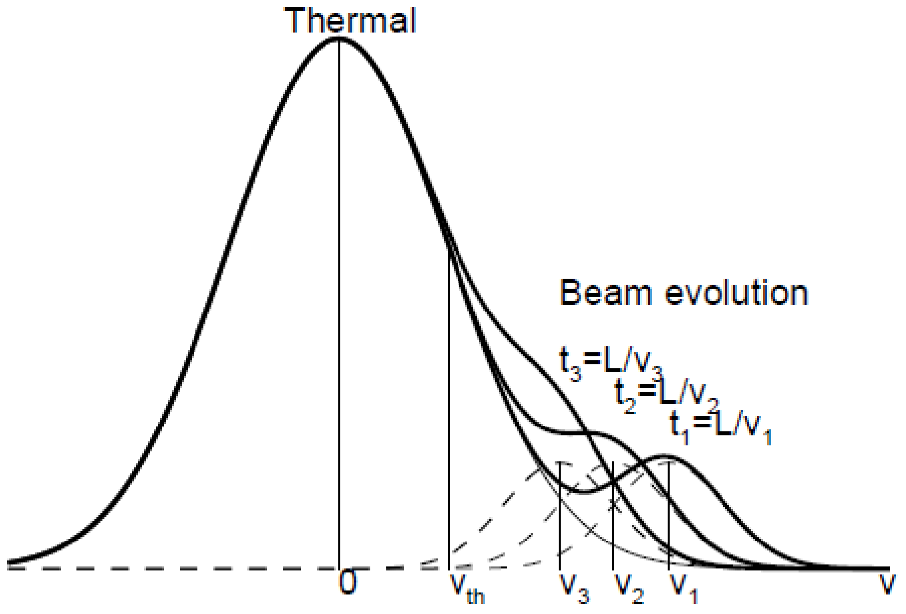

Figure 15.10: The evolution of a beam in the tail of a thermal distribution is shown, starting with the arrival of the fastest electrons at time $t_1 = L/\mathrm{v}_1$, producing a positive slope $\partial f/\partial \mathrm{v} > 0$ and which is unstable. At later times, slower electrons arrive at $t_2 = L/\mathrm{v}_2$ and $t_3 = L/\mathrm{v}_3$, but the slowest ones do not produce a positive slope and are stable (adapted from Lin et al. 1981b).

Table 15.1: Radio emission mechanisms during solar flares, (gyrofrequences are given in units of angular frequencies, $\omega = 2\pi\nu$) (Aschwanden 2002b).

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– Type III bursts		Upward propagating beams
– Reverse slope (RS) bursts		Downward propagating beams
– Type J bursts		Beams along closed loops
– Type U bursts		Beams along closed loops
– Type IV continuum		Trapped electrons
– Type V		Slow electron beams
(2b) Electron-cyclotron maser:	$\omega = s\Omega_e/\gamma + k_\parallel v_\parallel$	Losscones
- Decimetric ms spike bursts		Losscones

1) Поради наличието на дисперсия по скорости, възниква bump-on-tail неустойчивост. Неустойчивостта се развива, когато скоростта на снопа е поне 3 пъти по-голяма от топлинната скорост.

2) Положителния наклон води до резонанс на Ландау, което генерина Лангмюирови вълни.

3) След нелинейно смесване с други Лангмюрови, йонно-акустични или напречни вълни се създава плазмената емисия.

Кохерентни: плазмена емисия

- **(2a)** Плазмена емисия

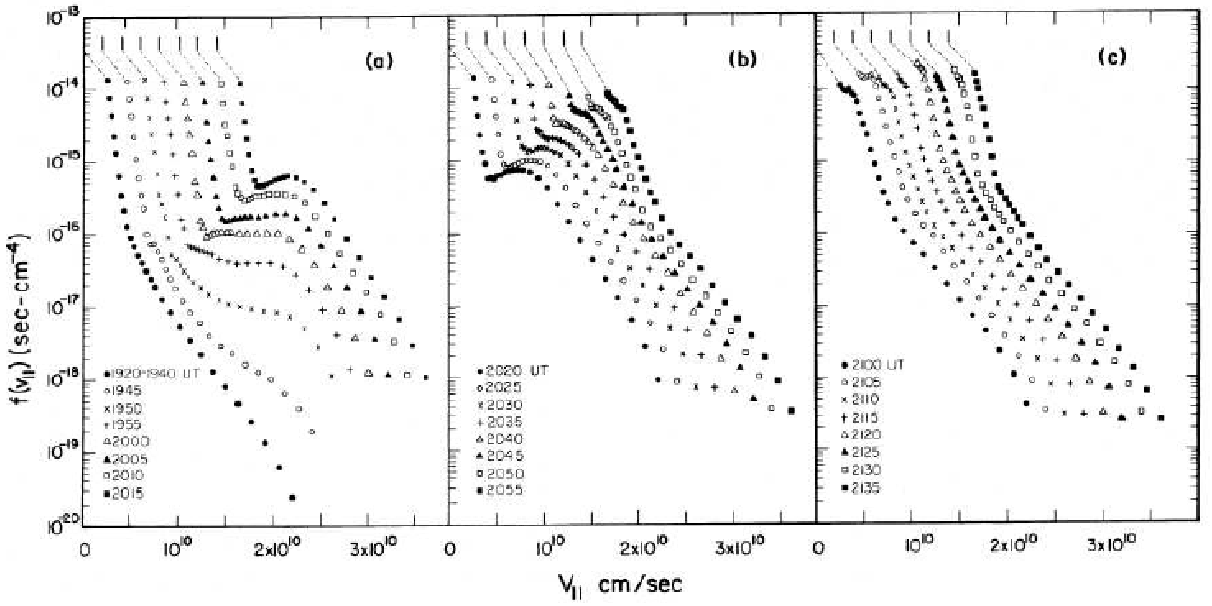

Figure 15.11: *In situ* measurements of the electron beam distribution in interplanetary space by ISEE-3 on 1979-Feb-17. The sequence of 24 distribution functions is taken every 64 s and is displayed incrementally shifted to the right by amounts of $\Delta v = 2 \times 10^9$ cm s^{-1}. Note that a positive slope occurs mainly between 20:00 and 20:30 UT (Lin et al. 1981b).

Table 15.1: Radio emission mechanisms during solar flares, (gyrofrequences are given in units of angular frequencies, $\omega = 2\pi\nu$) (Aschwanden 2002b).

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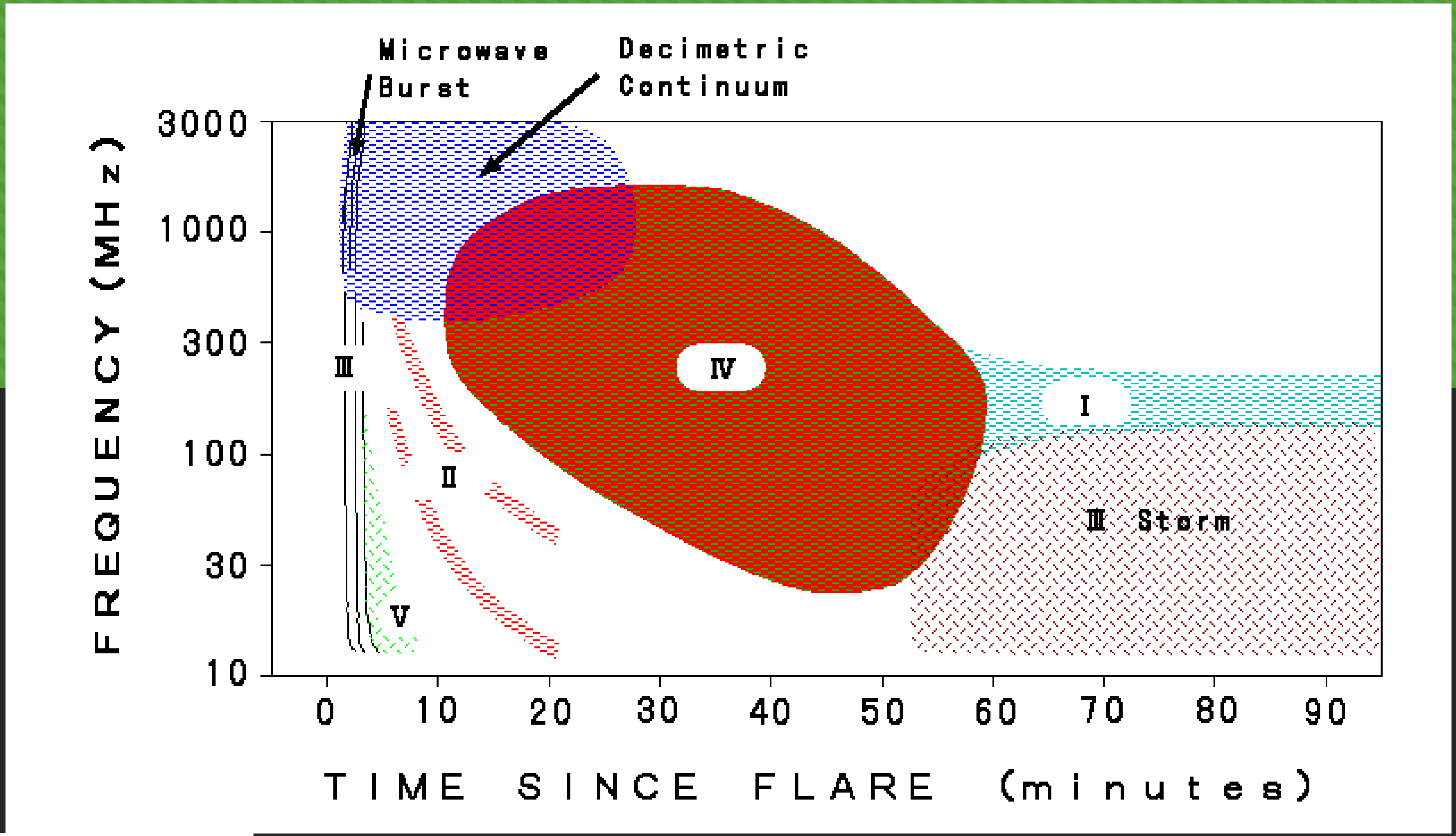
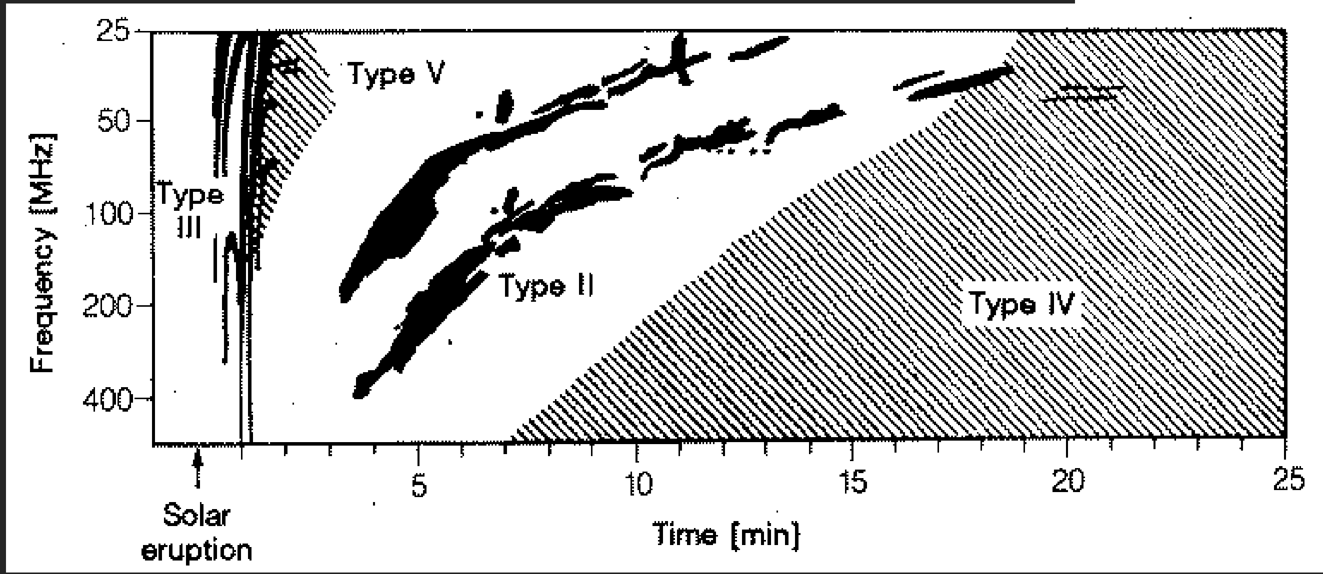
– Type U bursts		Beams along closed loops
– Type IV continuum		Trapped electrons
– Type V		Slow electron beams
(2b) Electron-cyclotron maser:	$\omega = s\Omega_e/\gamma + k_{\|}v_{\|}$	Losscones
- Decimetric ms spike bursts		Losscones

Кохерентни: плазмена емисия

- Тип I → радио бури
- Тип II → ударни вълни
- Тип III → снопове, отворени конфигурации
- Тип IV → затворени конфигурации
- Тип V → следват тип III





https://web.njit.edu/~gary/728/Lecture11.html

[Cliver (2001)](http://astro.u-strasbg.fr/~koppen/RJove/analysis.html)
http://astro.u-strasbg.fr/~koppen/RJove/analysis.html

Кохерентни: плазмена емисия

- Тип I → радио бури
- Тип II → ударни вълни
- Тип III → снопове, отворени конфигурации
- Тип IV → затворени конфигурации
- Тип V → следват тип III

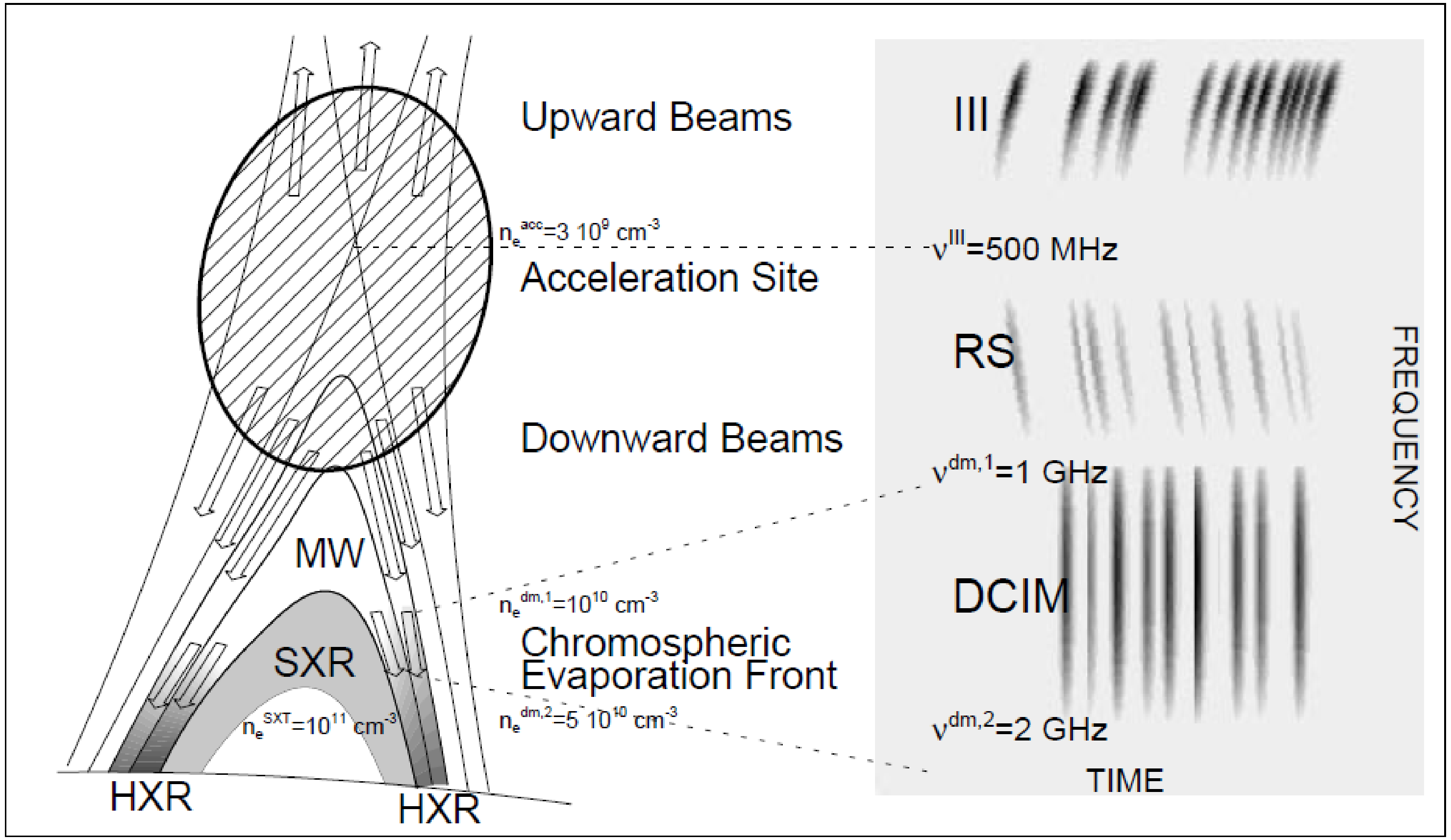
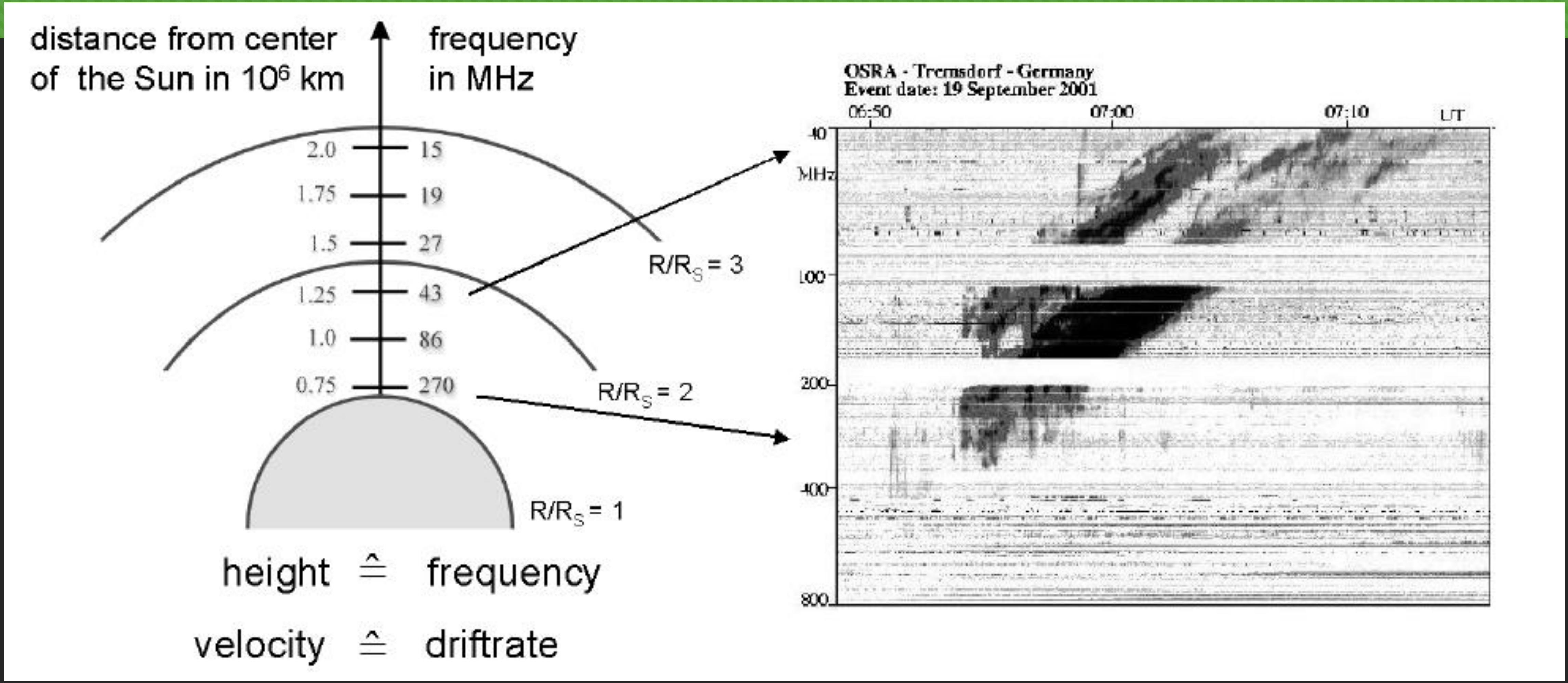


Figure 9 Cartoon of a flare model suggesting a global view of acceleration and evaporation processes in the context of density measurements by coherent radio bursts and SXR emission. The *panel* on the *right* illustrates a radio spectrogram (dynamic spectrum) with bursts indicated schematically. The acceleration site is located in a low-density cusp from where electron beams are accelerated in upward (m-λ type III and type U bursts) and downward (reverse-slope or RS type IIIdm bursts) directions. Downward-precipitating beams that intercept the chromospheric evaporation front may show as decimetric bursts (DCIM) with almost infinite drift rate in the 1- to 2-GHz range. The chromospheric upflow fills SXR-bright loops with subsequently wider footpoint separation while the reconnection point rises higher. (From Aschwanden & Benz 1997.)

Слънчева корона



Warmuth & Mann (2005)

Кохерентни: тип циклотронен мазер

- (2b) Мазер

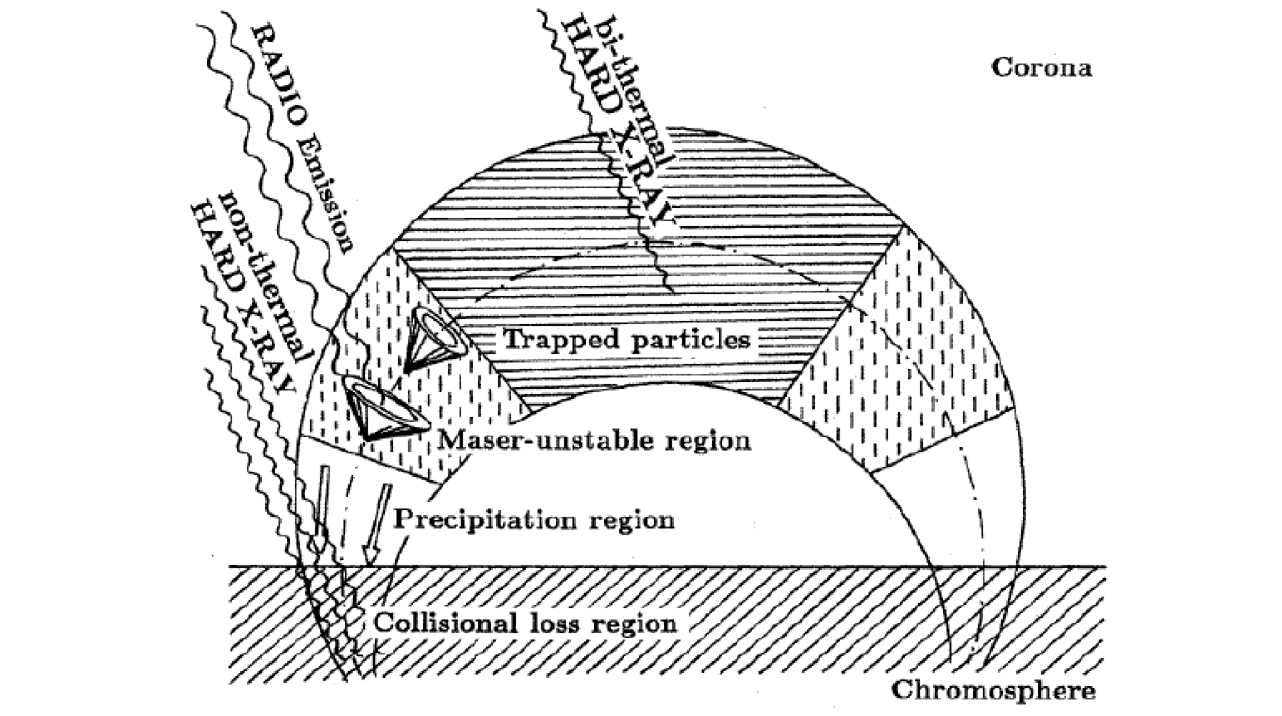


Figure 15.23: Spatial configuration of losscone-driven radio emission in the context of a flare loop with a magnetic trap (Aschwanden et al. 1990).

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– Type U bursts		Beams along closed loops
– Type IV continuum		Trapped electrons
– Type V		Slow electron beams
(2b) Electron-cyclotron maser:	$\omega = s\Omega_e/\gamma + k_\parallel v_\parallel$	Losscones
- Decimetric ms spike bursts		Losscones

→ при движение на електрони в магнитни арки (захващане в магнитна бутилка и депозиране в хромосферата)

→ за диагностика на физични условия при емисия на фини радиоструктури (краткотрайни, тесни честотни диапазони и голям интензитет на емисията)

Видове механизми

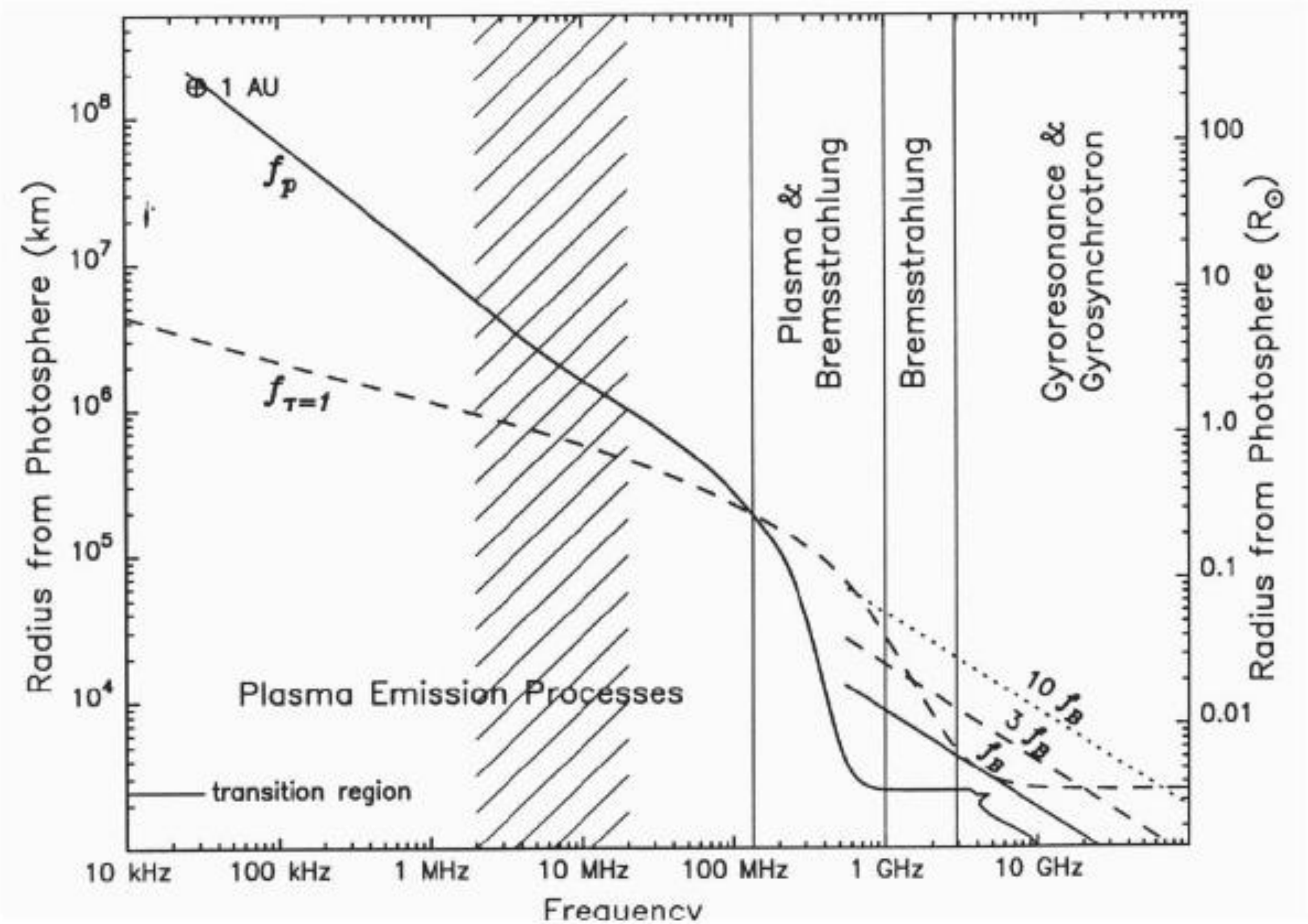


Figure 15.1: Characteristic frequencies for radio emission in the solar corona and heliosphere. The plasma frequency (solid line) and the frequency where the free-free opacity is unity (dashed line) are shown as distance from the photosphere versus frequency. The regimes of dominant plasma emission, bremsstrahlung emission, and gyroresonance or gyrosynchrotron emission are marked as a function of frequency (Gary & Hurford 1989).

Механизми

В зависимост от функцията на разпределение $f(\mathbf{v}_{||},\mathbf{v}_{\perp})$

- Топлинно или изотропно супратермално → при некохертно излъчване
- Нетоплинно, анизотропно →

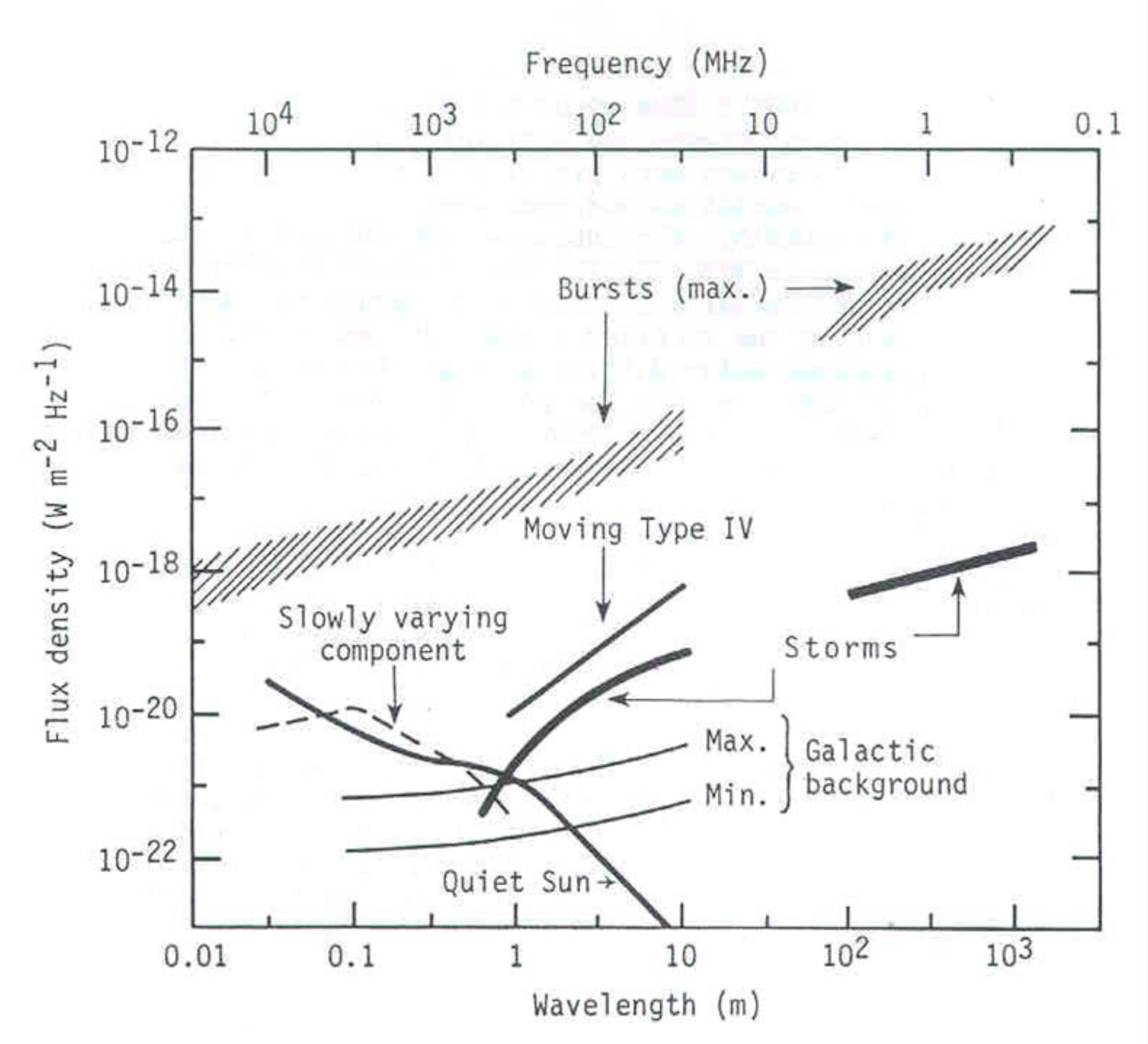
$\partial f/\partial v_{||} > 0$ дисперсия по скорости – разпределение тип beam: плазмена емисия

$\partial f/\partial v_{\perp} > 0$ магнитна бутилка – тип losscone: емисия тип електронно-циклотронен мазер

Честотно разпределение

- mm/300 GHz → e^- > 1 MeV (диагностика за едни от най-енергетичните електрони ускорени при активни процеси в слънчевата конона)
- cm/30 GHz → e^- ~ 100s keV (за диагностика на физичните условия по време на избухванията, изображения и спектроскопични методи)
- dm/3 GHz → radio burst types
- m/300 MHz → radio burst types
- dam/30 MHz → radio burst types
- hm/0.3 MHz → radio burst types
- km/300 kHz → radio burst types

Видове спектри



https://web.njit.edu/~gary/728/Lecture10.html

Основни зависимости

Planck function

$$B_\lambda(T) = \frac{2hc^2/\lambda^5}{e^{hc/\lambda kT} - 1} \text{ (wavelength form)}$$

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

The ***intensity***, or ***surface brightness***

$$I = \int I(\nu)d\nu \text{ (units: J m}^{-2}\text{ s}^{-1}\text{ sr}^{-1}\text{).}$$

get the ***flux*** F:

$$F = \int I\, d\Omega \quad \text{(units: J m}^{-2}\text{ s}^{-1}\text{, or W m}^{-2}\text{)}$$

flux density

$$S = \int I(\nu)\, d\Omega \quad \text{(units: W m}^{-2}\text{ Hz}^{-1}\text{)}$$

1 Jansky (Jy) = 10^{-26} W m^{-2} Hz^{-1}

1 Solar Flux Unit (sfu) = 10^{-22} W m^{-2} Hz^{-1} = 10000 Jy

blackbodies, which are by definition optically thick and in thermal equilibrium.

if a source is not optically thick

its emission will appear weaker (lower intensity) than if it were

brightness temperature

$$T = B_\nu(T)c^2/2k\nu^2$$

The brightness temperature is the same as the true temperature only for an optically thick blackbody.

flux density measured by a radio telescope becomes

$$S = \int 2kT_b\nu^2/c^2\, d\Omega = 2k\nu^2/c^2 \int T_b\, d\Omega$$

effective temperature

$$T_{eff} = E/k$$

non-thermal sources

The field of view is also called the ***beam***.

https://web.njit.edu/~gary/728/Lecture1.html