ТЕРАГЕРЦЕВОЕ ИЗЛУЧЕНИЕ СОЛНЦА. ДОСТИЖЕНИЯ И НОВЫЕ ВЫЗОВЫ

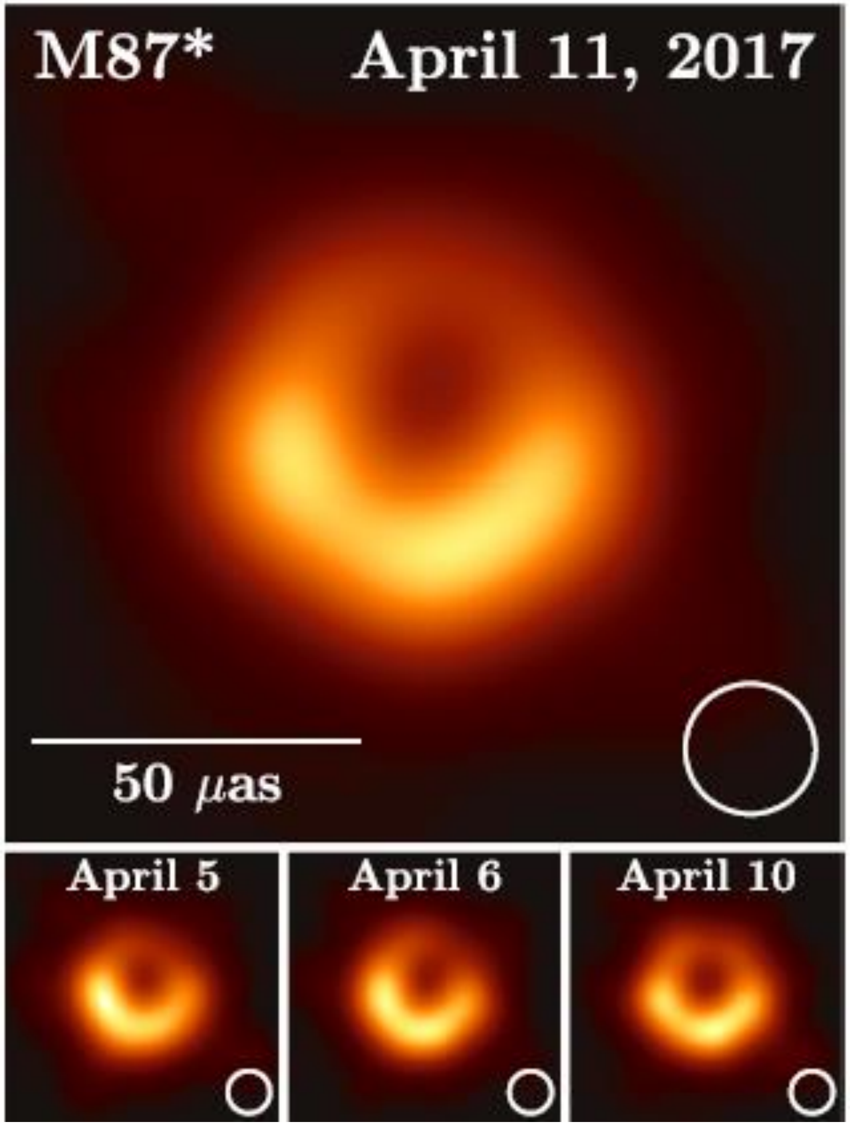
А.В.Степанов

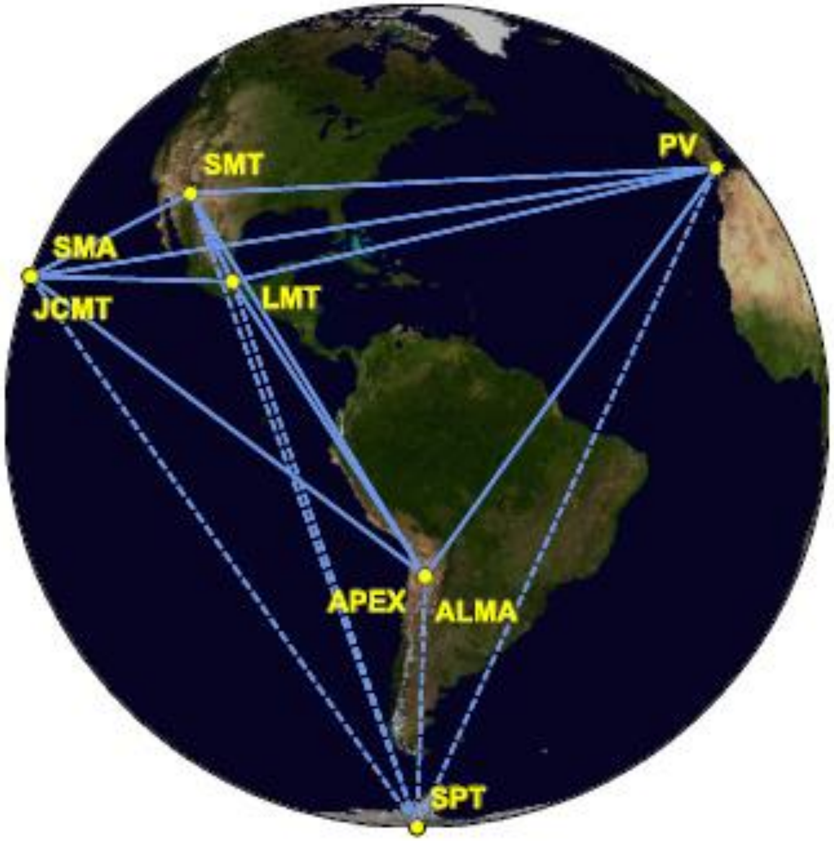
ГАО РАН, ФТИ РАН им. А.Ф.Иоффе

МЕЖДУНАРОДНАЯ БАЙКАЛЬСКАЯ МОЛОДЕЖНАЯ НАУЧНАЯ ШКОЛА ПО ФУНДА МЕНТАЛЬНОЙ ФИЗИКЕ
Иркутск, 16-10 сентября 2019 г.

Event Horizon Telescope $\lambda=1.3$ mm

The Shadow of the Supermassive Black Hole



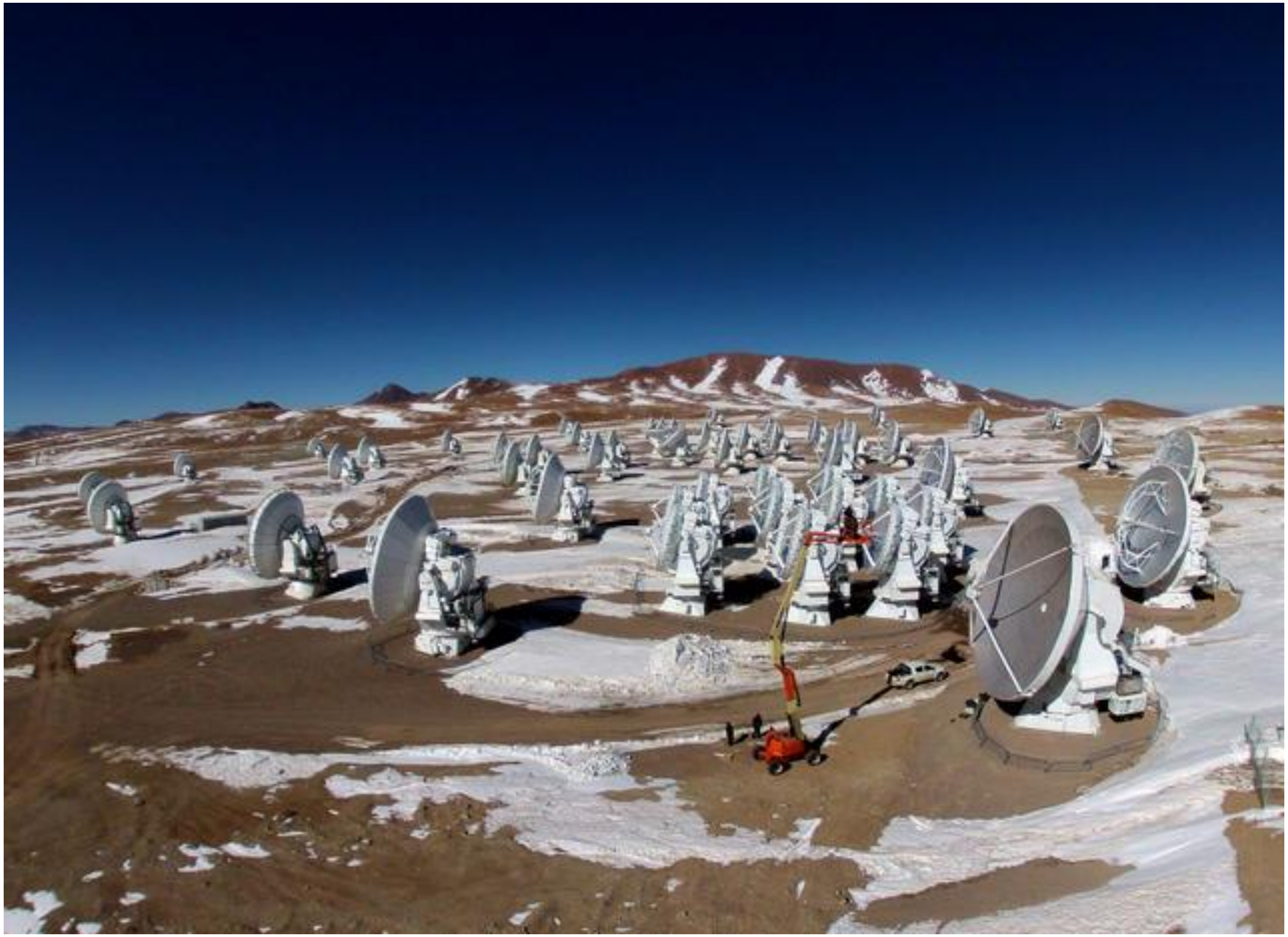


Astrophys. J. Lett. 2019. V.875, L1-17

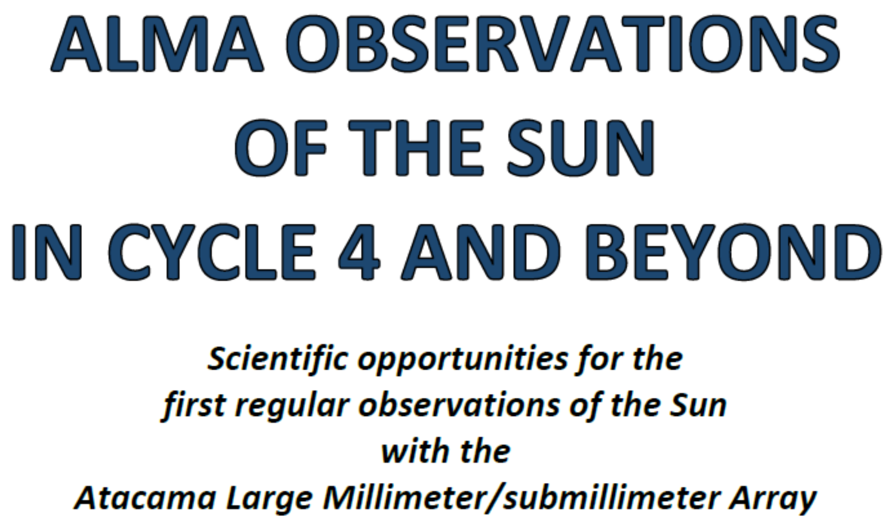
$M = 6.5\times10^{9}\,M_{Sun}$.

ALMA предназначен для изучения процессов, происходивших на протяжении первых сотен миллионов лет после Большого Взрыва, когда формировалось первое поколение звёзд. С его помощью планируется получить новые данные, объясняющие механизмы эволюции Вселенной.

Atacama Large Millimeter Array

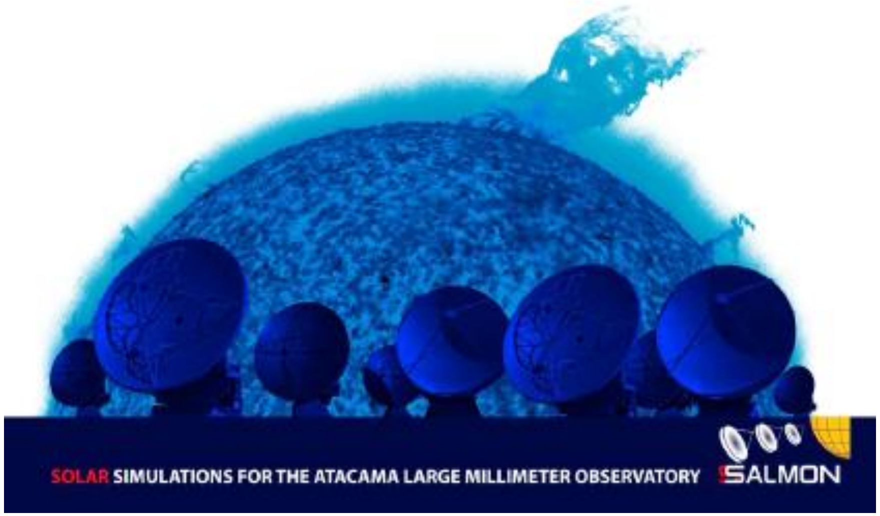


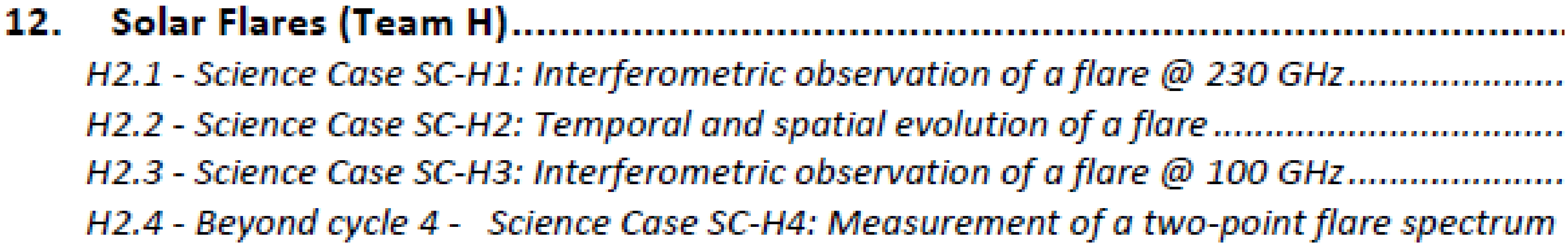
66 антенн:
54 антенны диаметром 12 м и 12 антенн диаметром 7 м.



ALMA OBSERVATIONS OF THE SUN IN CYCLE 4 AND BEYOND

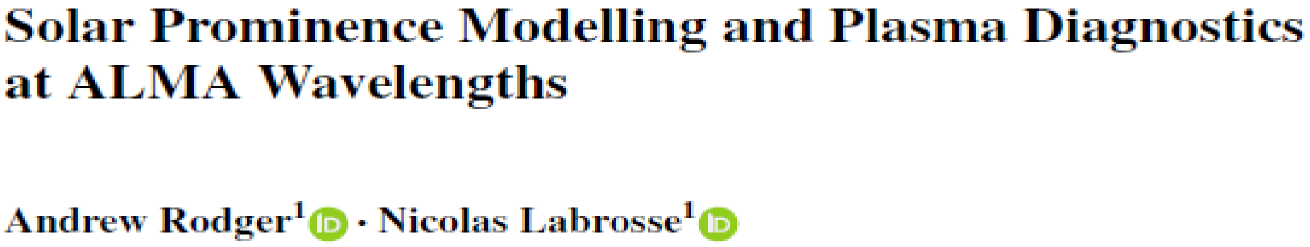
Scientific opportunities for the
first regular observations of the Sun
with the
Atacama Large Millimeter/submillimeter Array





12. Solar Flares (Team H)..
H2.1 - Science Case SC-H1: Interferometric observation of a flare @ 230 GHz....................
H2.2 - Science Case SC-H2: Temporal and spatial evolution of a flare..................................
H2.3 - Science Case SC-H3: Interferometric observation of a flare @ 100 GHz....................
H2.4 - Beyond cycle 4 - Science Case SC-H4: Measurement of a two-point flare spectrum

Probing the Temperature Structure of the Solar Chromosphere with ALMA
by Alissandrakis et al. 2017-08-01 Solar Radio Science Highlights, 100 & 239 GHz.



Solar Prominence Modelling and Plasma Diagnostics at ALMA Wavelengths

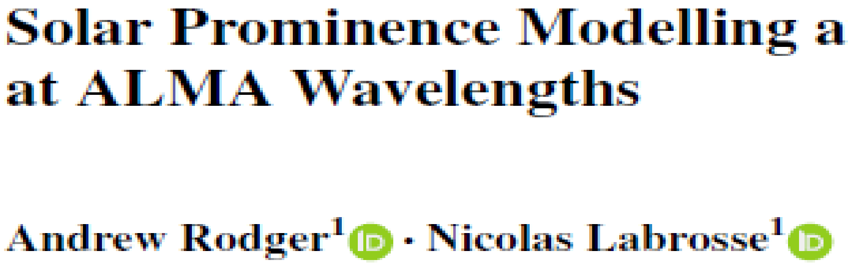
Andrew Rodger[1] · Nicolas Labrosse[1]

- Наиболее яркое достижение терагерцевой астрономии - наблюдения чёрной дыры в Галактике М-87

- ALMA: Изучения процессов, происходивших на протяжении первых сотен миллионов лет после Большого Взрыва, когда формировалось первое поколение звёзд

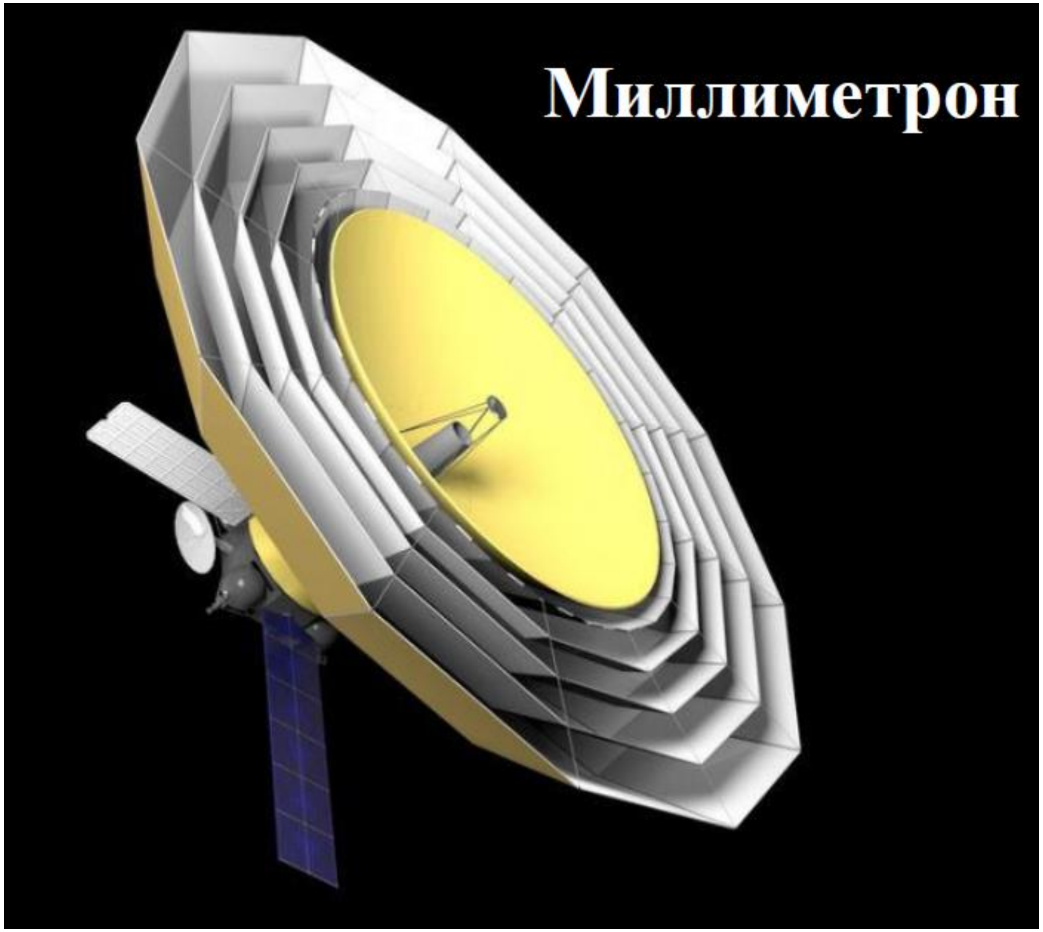
- «Холодная» Вселенная, в основном межзвездные газопылевые облака, области звёздообразования

- Probing the Temperature Structure of the Solar Chromosphere with ALMA by Alissandrakis et al. 2017-08-01 Solar Radio Science Highlights, 100 & 239 THz

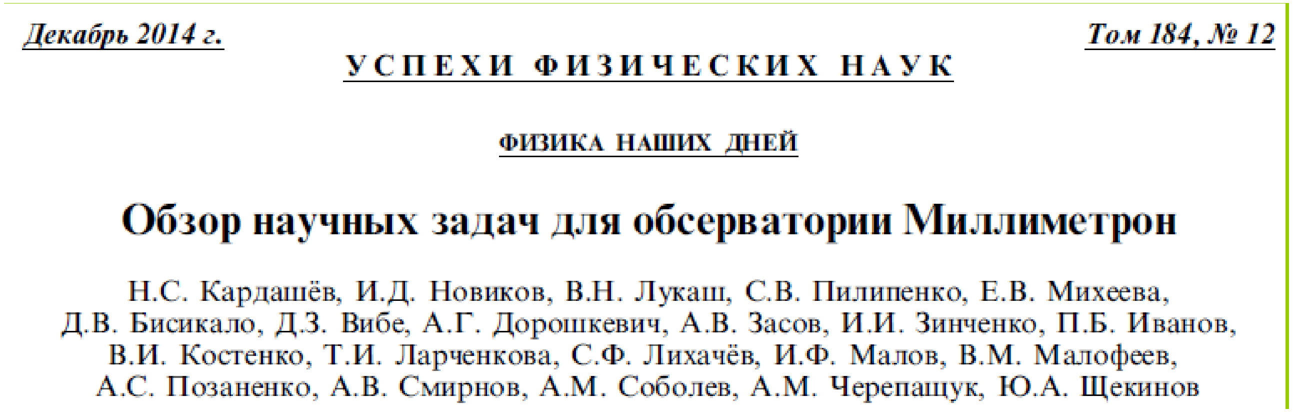


Solar Prominence Modelling and Plasma Diagnostics at ALMA Wavelengths

Andrew Rodger[1] · Nicolas Labrosse[1]



Н.С.Кардашёв (1932-2019)



Декабрь 2014 г. *Том 184, № 12*

УСПЕХИ ФИЗИЧЕСКИХ НАУК

ФИЗИКА НАШИХ ДНЕЙ

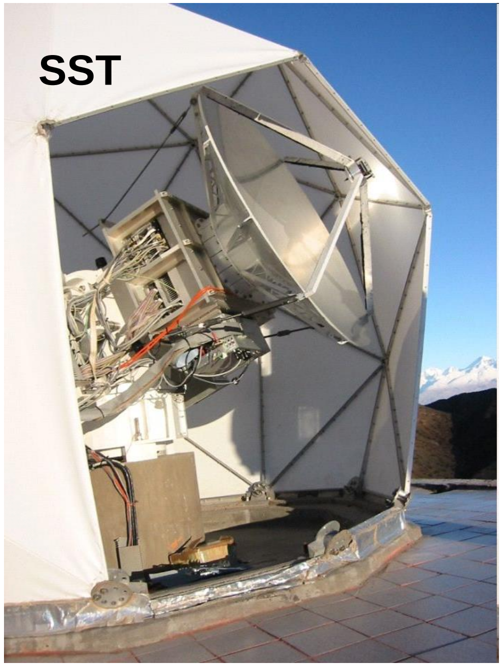
Обзор научных задач для обсерватории Миллиметрон

Н.С. Кардашёв, И.Д. Новиков, В.Н. Лукаш, С.В. Пилипенко, Е.В. Михеева,
Д.В. Бисикало, Д.З. Вибе, А.Г. Дорошкевич, А.В. Засов, И.И. Зинченко, П.Б. Иванов,
В.И. Костенко, Т.И. Ларченкова, С.Ф. Лихачёв, И.Ф. Малов, В.М. Малофеев,
А.С. Позаненко, А.В. Смирнов, А.М. Соболев, А.М. Черепащук, Ю.А. Щекинов

Sub-THz observations:

Clark and Park, 250 GHz (1968)

- KOSMA (Uni Köln, Switzerland) 210–270; 330–365 GHz (Kramer et al. 1998; Kaufmann 1999; Luthi et al. 2004)
- Solar Submillimeter Telescope (SST) (El Leoncito, Argentina Andes) 212 & 405 GHz (Kaufmann et al. 2001)
- RT-7.5 (Dmitrov, Russia) 93 & 140 GHz (Rozanov, 1981; Smirnova et al. 2013)
- 30 THz, El Leoncito, Sao Paulo (Kaufmann, 2013, 2016)
- 3 & 7 THz in Antarctic (Kaufmann, 2016)

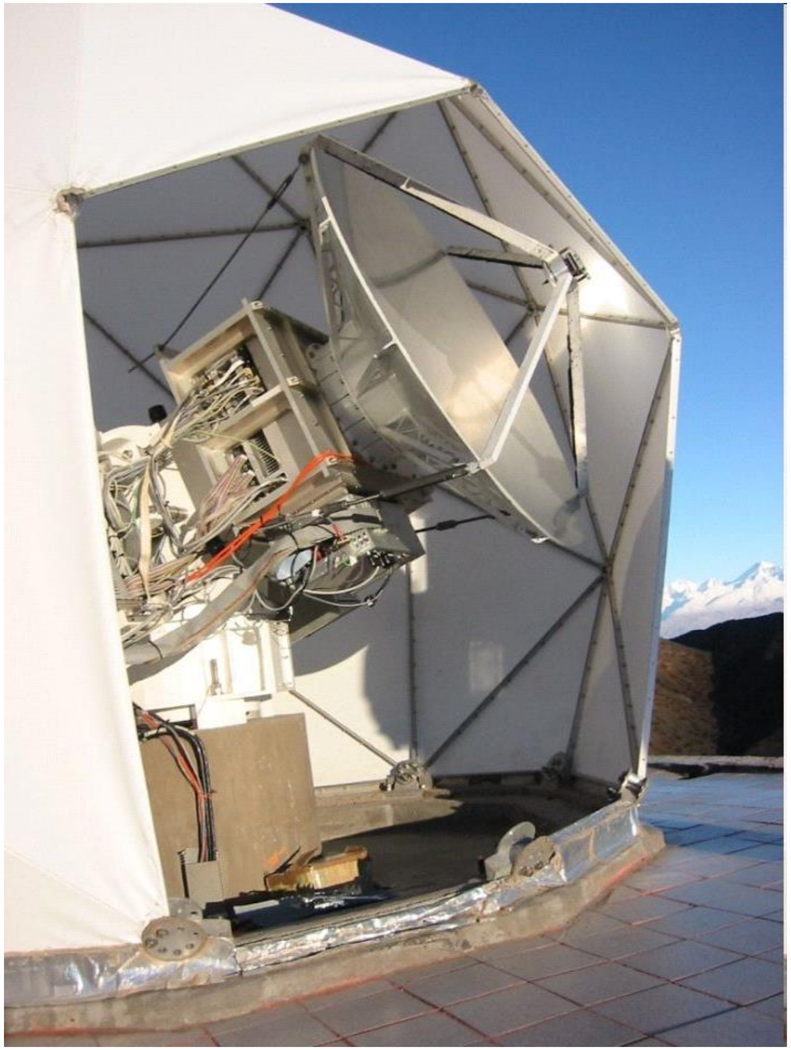


Balloon Born Astronomy in THz (Solar-T)

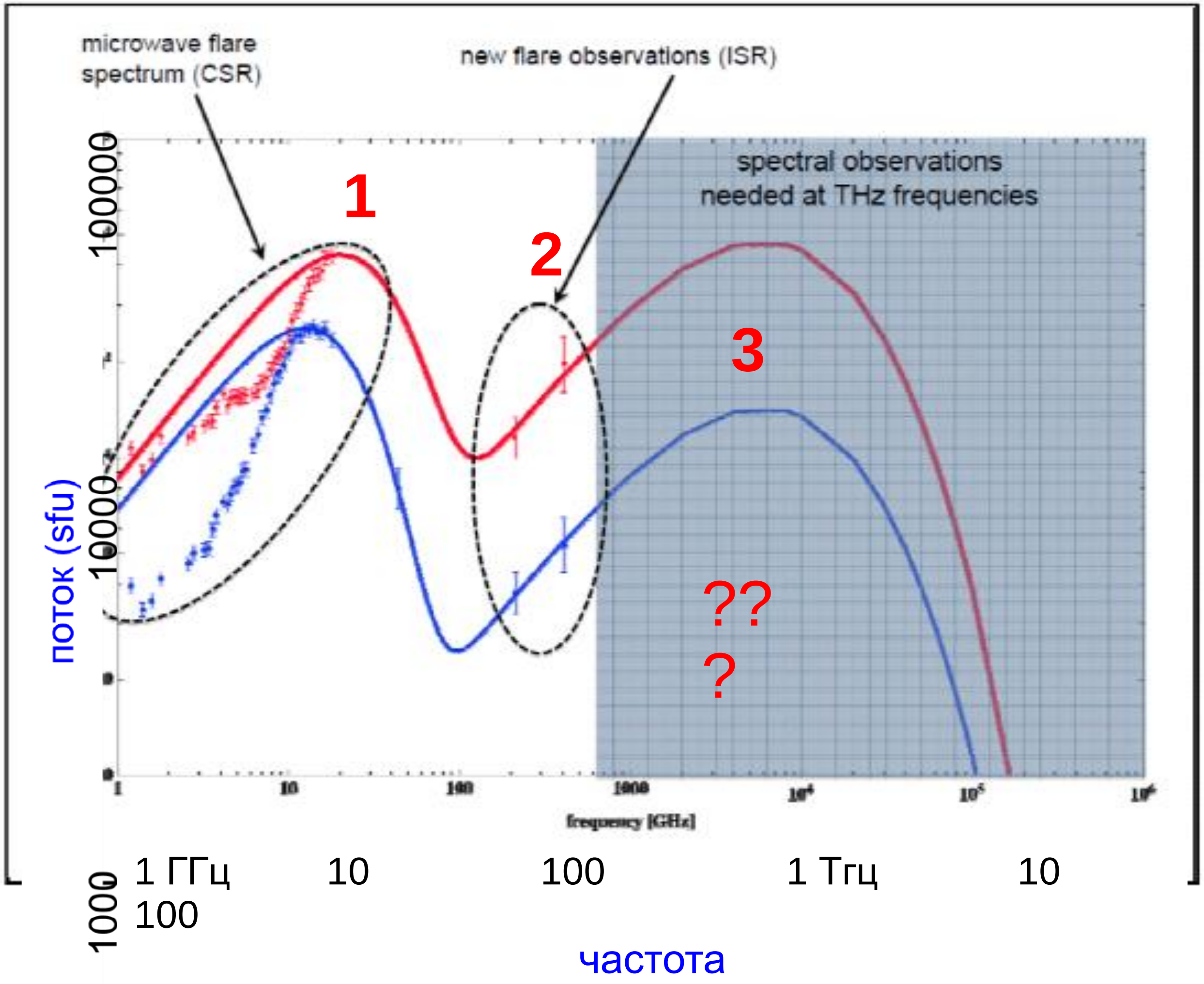
Solar Submillimeter Telescope, 212 & 405 GHz

(Kaufmann et al 2001);
El Leoncito Observatory, Argentina Andes (2550 m)

Pierre Kaufmann
1938-2017



Спектр радиоизлучения солнечных вспышек



1. Известная область микроволнового излучения
2. Новые данные о субмиллиметровом излучении (~ 200 и 400 Ггц; SST)
3. Неисследованная Тгц-область излучения

Motivation

- **Solar Chromospheric Flares**
  A proposal for an ISSI International Team
  Lyndsay Fletcher (Glasgow) and Jana Kasparova (Ondrejov)

- **Solar Flares and the Chromosphere**
  A white paper for the Decadal Survey
  H. S. Hudson, L. Fletcher, R. Turkmani, S. L. Hawley,
  A. F. Kowalski, A. Berlicki, P. Heinzel

- **Giovanelli R.G.** A Theory of Chromospheric Flares, *Nature* (1946)

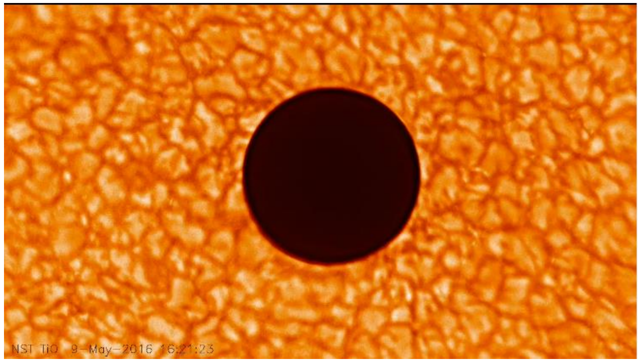
- **Observations** with *New Solar Telescope* of BBSO
  Ji Haisheng, I. Sharykin, A. Kosovichev, I. Zimovets (2012-2016)

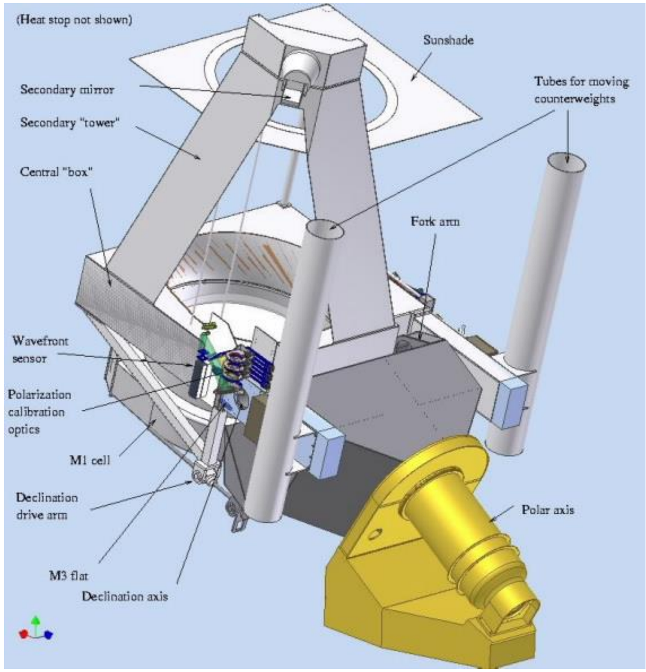
- EWASS-2017 Special Session
  Energy release and radiation in partially ionized plasma of solar and stellar atmospheres

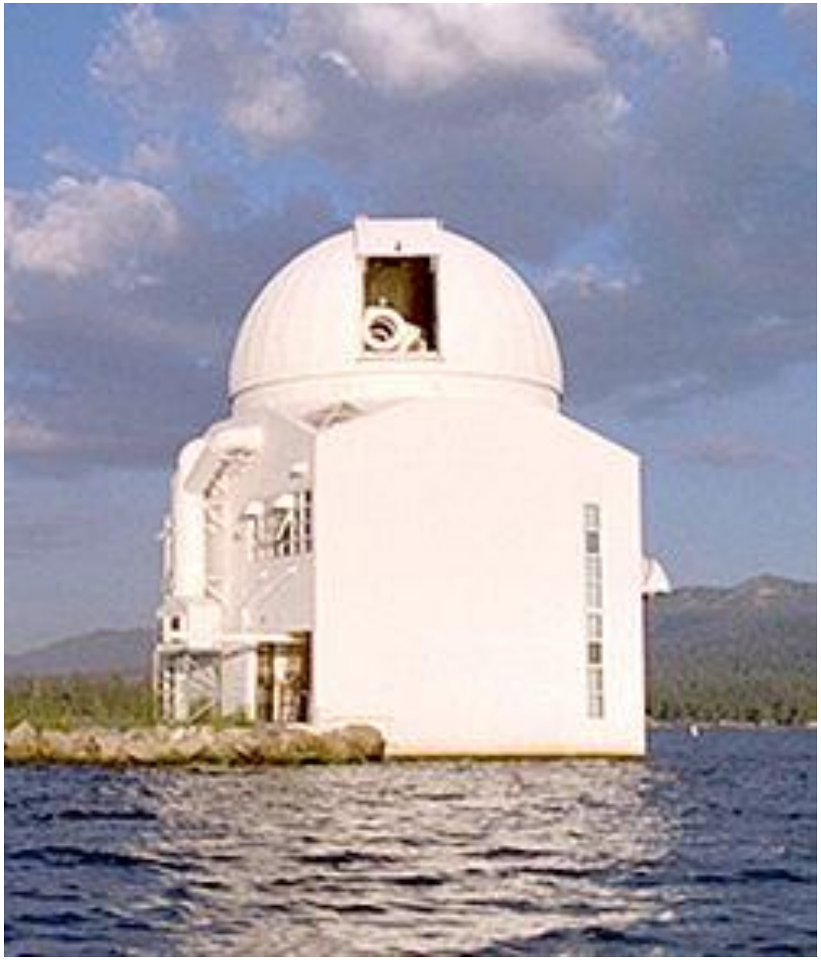
New challenges of solar flare models →

New Solar Telescope of Big Bear Solar Observatory

May 9, 2016: Mercury Transit Observed
by the 1.6 m aperture New Solar Telescope







pixel size ≈ 0.029“, diffraction limit ≈ 0.084"

Ji Haisheng et al. (ApJ 2012): In situ chromosphere heating up to $T \geq 10^6$ K

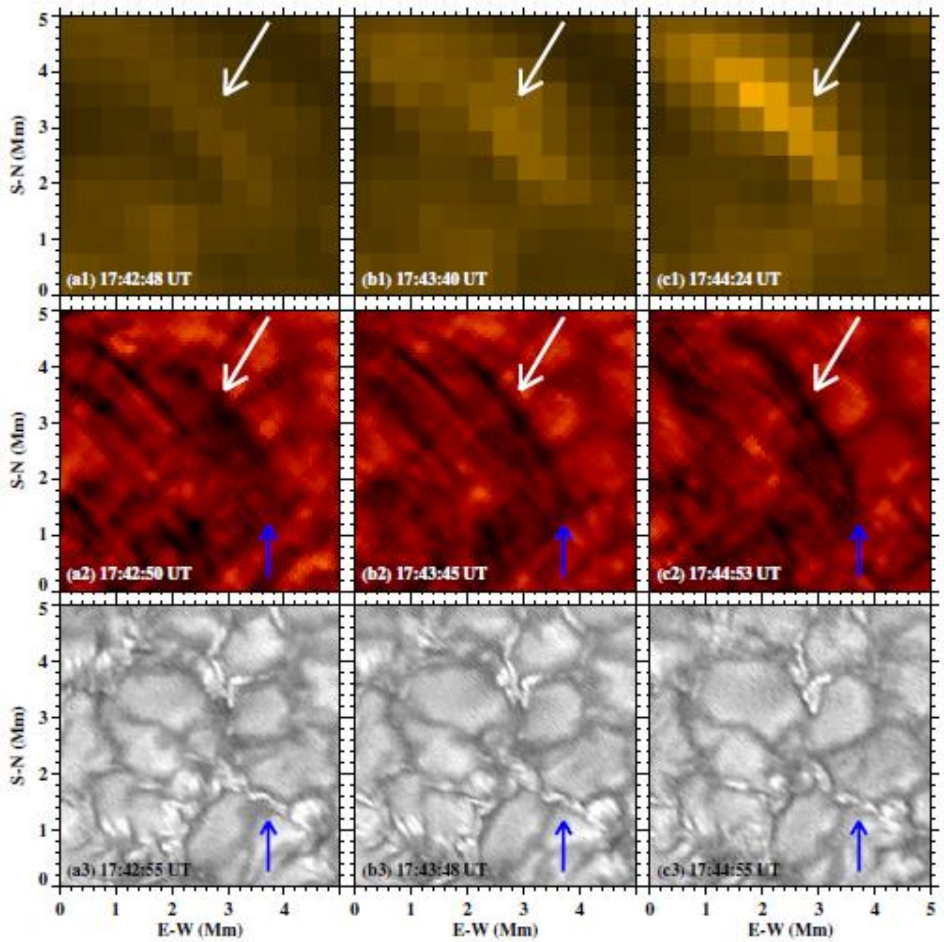
Observations with NST (≤ 100 km resolution) and AIA/*SDO* (~700 km resolution)

Upward injections of hot plasma that excite the ultrafine (≤ 100 km) loops from photosphere to the base of the corona. Energy that heats the corona is channeled through the ultrafine magnetic loops in the form of plasma ejecta.

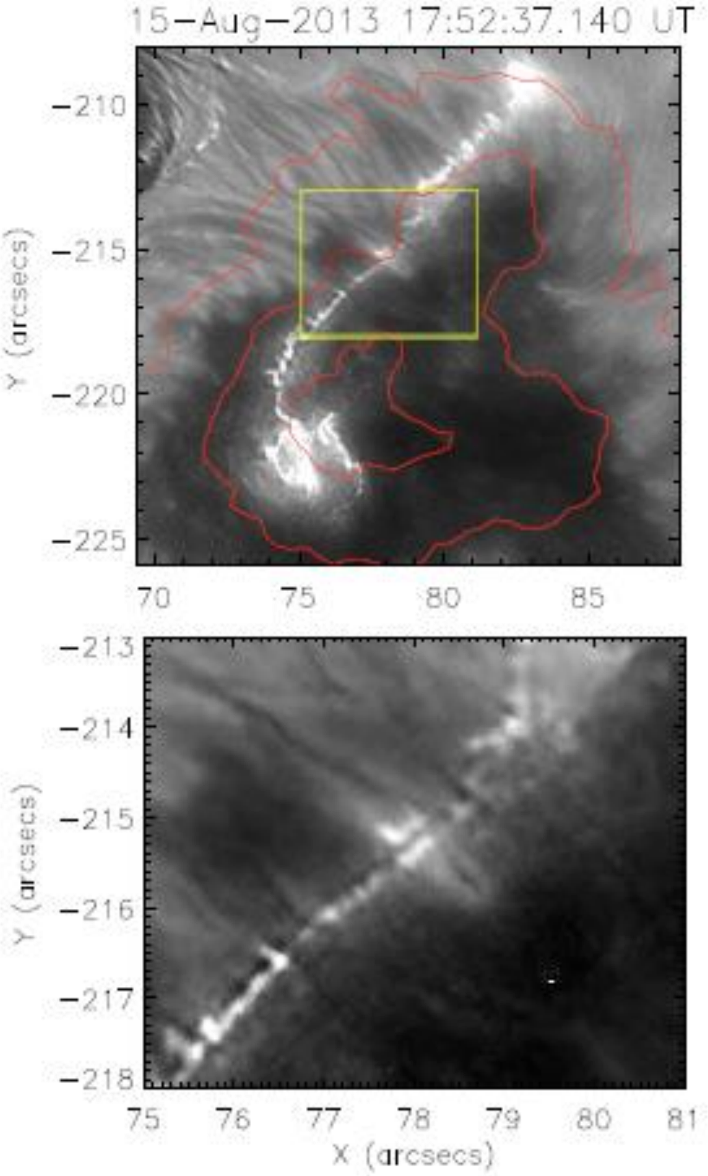
AIA/SDO 171Å images
Atmospheric Imaging Assembly

NST helium I 10830Å

NST TiO 7057Å images



Sharykin & Kosovichev (ApJ 2014): Flare of August 15, 2013 observed with NST, SDO, GOES and FERMI



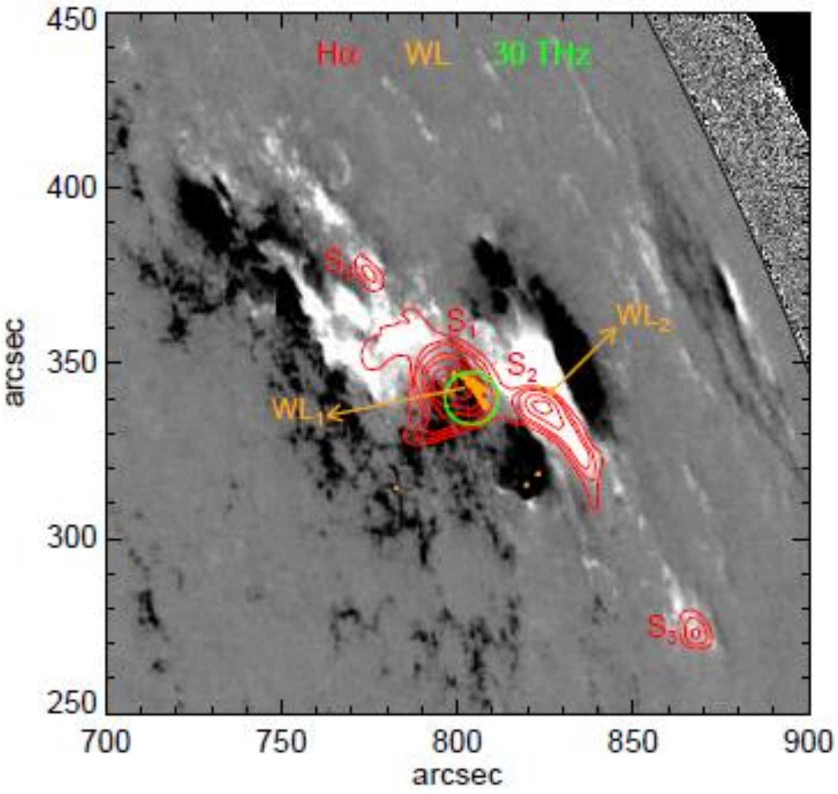
Наблюдения NST BBSO с рекордным разрешением ~ 0,1” выявили ранее неразрешимую тонкую структуру вспышечных лент, состоящую из цепочки ярких ядер размером 70 -100 км. Фотосфера нагревается до $T \approx 10^6$ К некоторым другим механизмом, отличным от thick-target model.

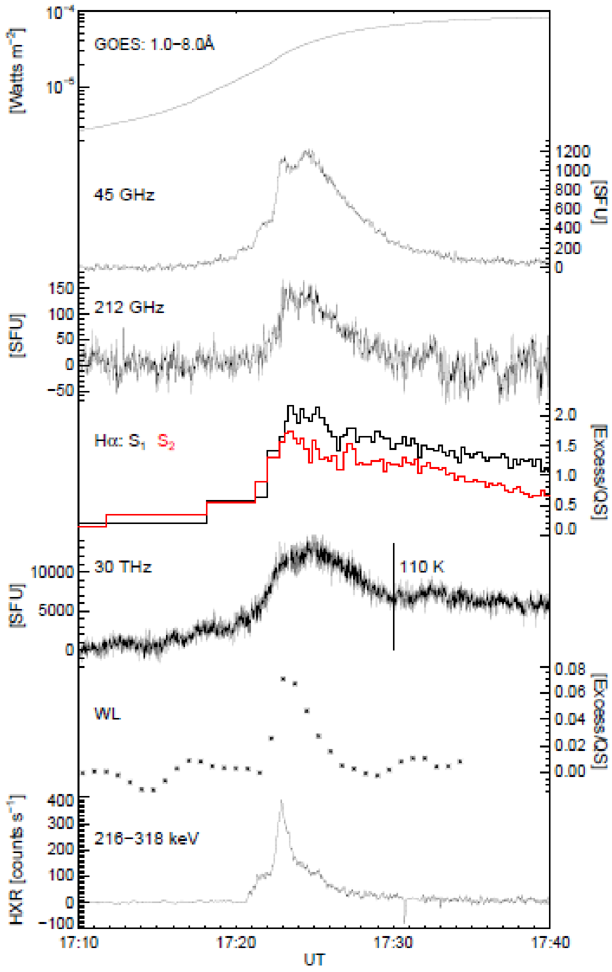
Магнитограммы HMI/*SDO* указывают на электрические токи 5×10^{10} А, пространственно совпадающие с Н*α* лентами

Энерговыделение в лентах наблюдается задолго до жёсткого рентгена и не объясняется вторжением в фотосферу ускоренных в короне частиц. Джоулев нагрев?

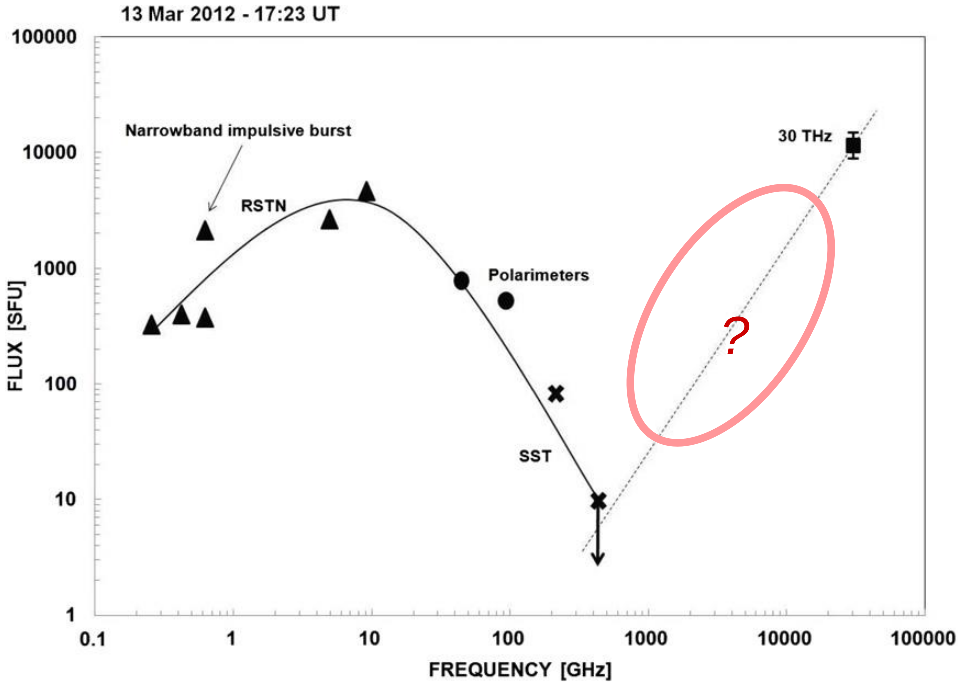
30 THz emission detected during the 2012 March 13 solar flare at 17:20 UT

Trottet et al. Solar Physics (2016)

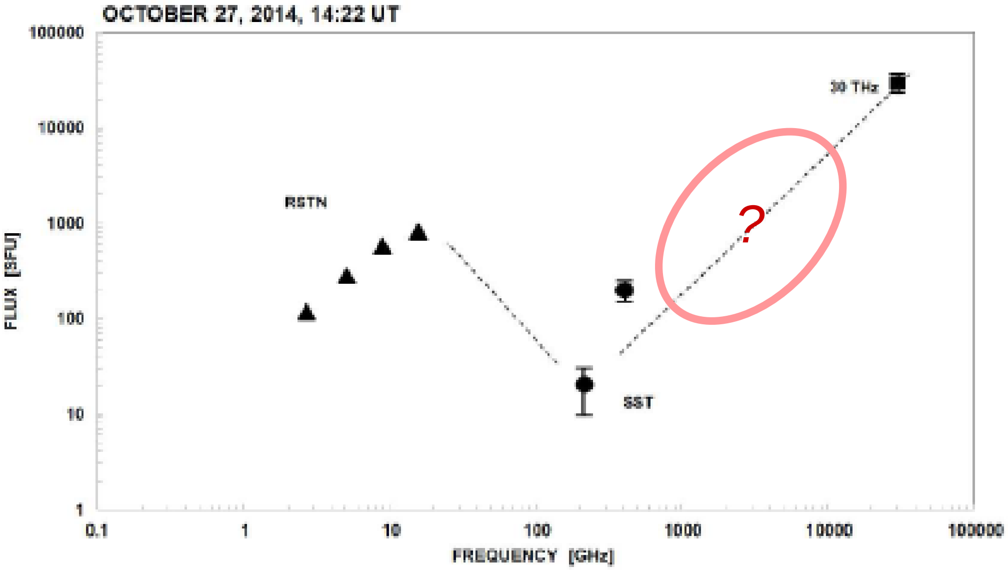




Solar flares up to 30 THz

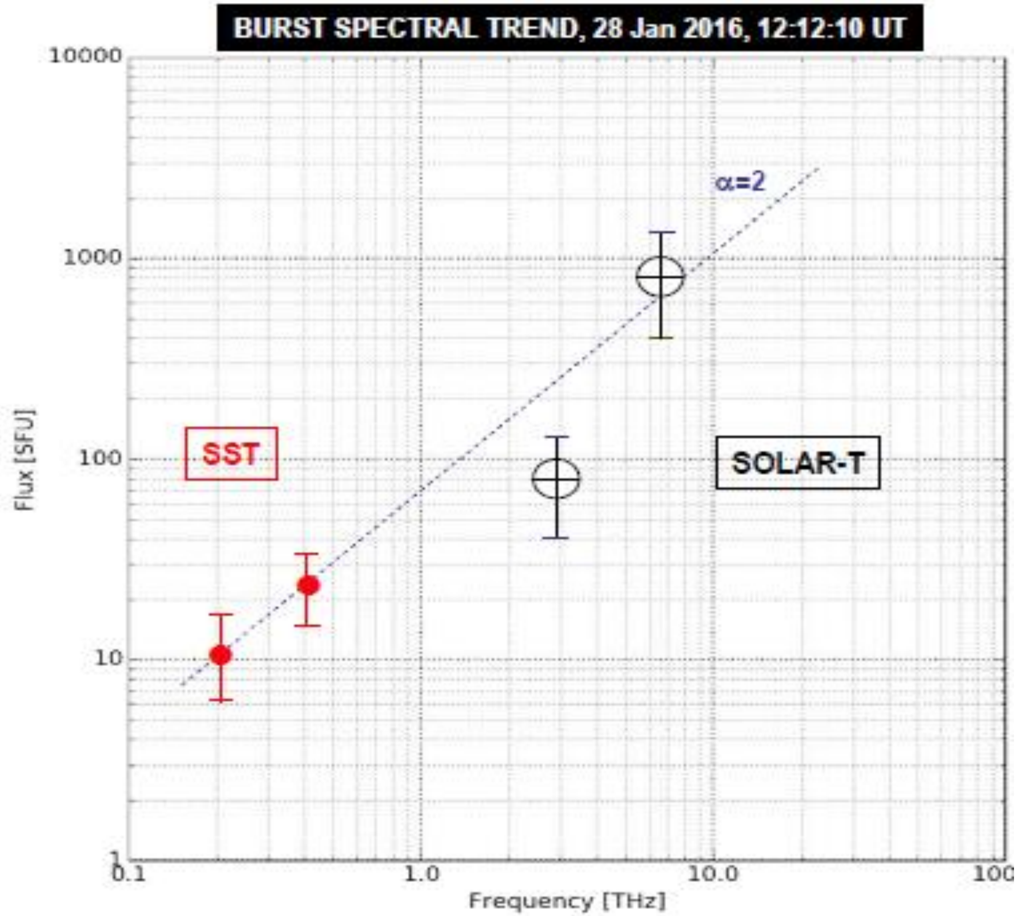


Kaufmann et al ApJ 2013



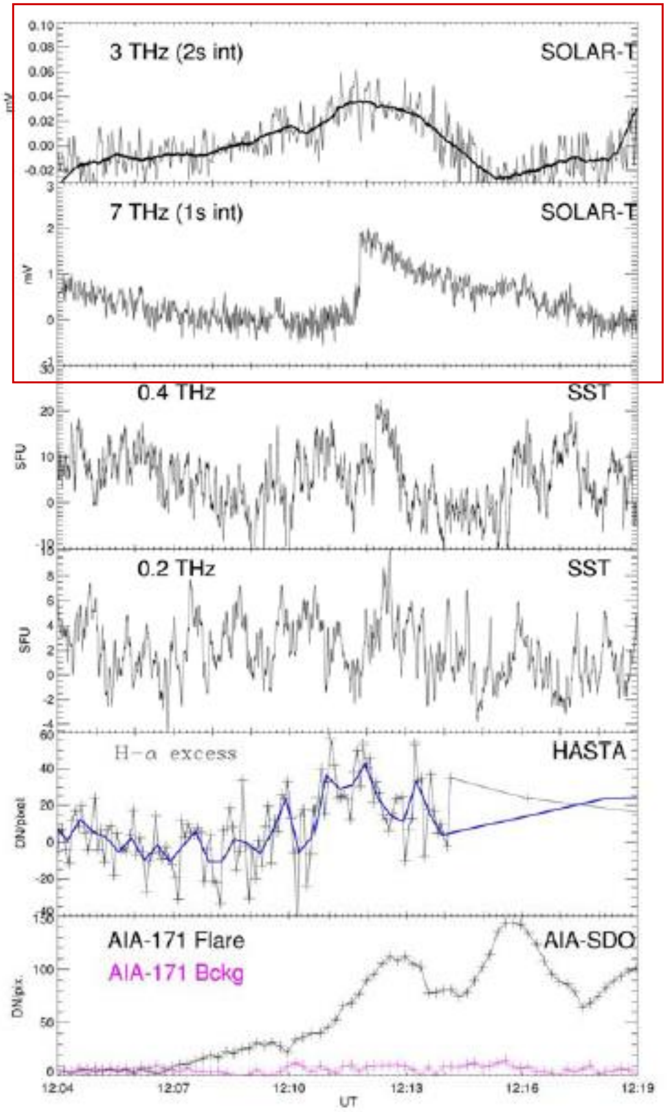
Kaufmann et al JGR 2015

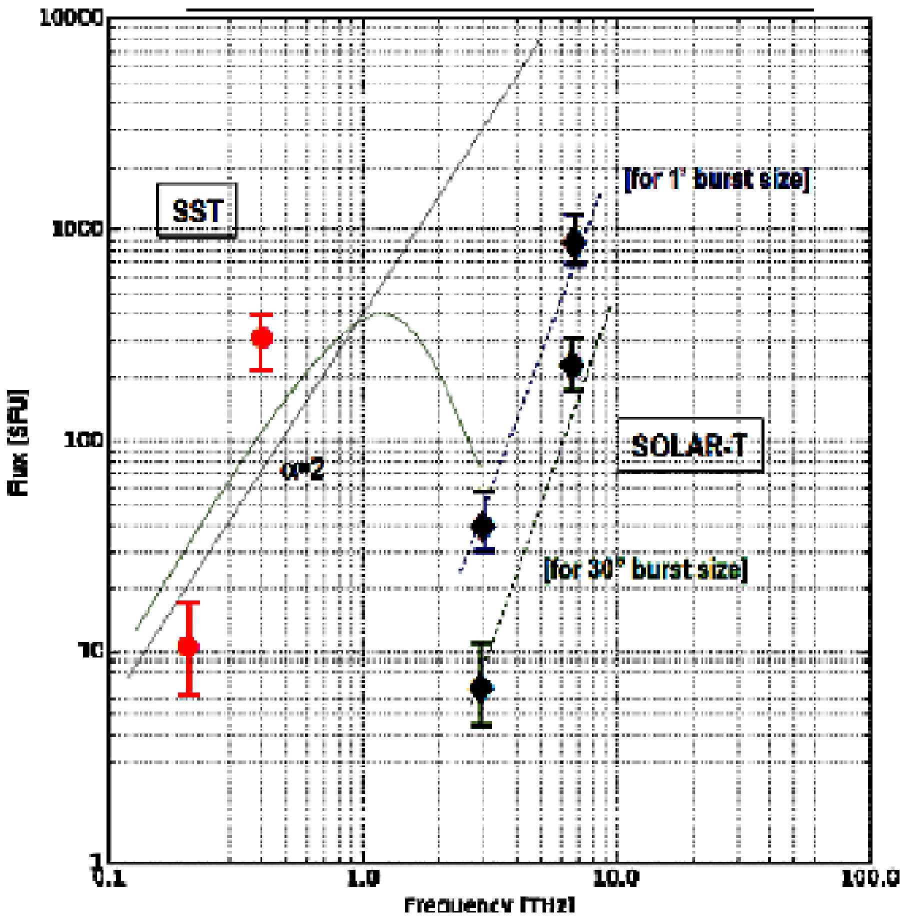
Solar-T flight in Antarctic (U.S. McMurdo base)



THz Solar Observations on Board of a Trans-Antarctic Stratospheric Balloon Flight

January 28, 2016 (Kaufmann et al. IEEE, 2016)



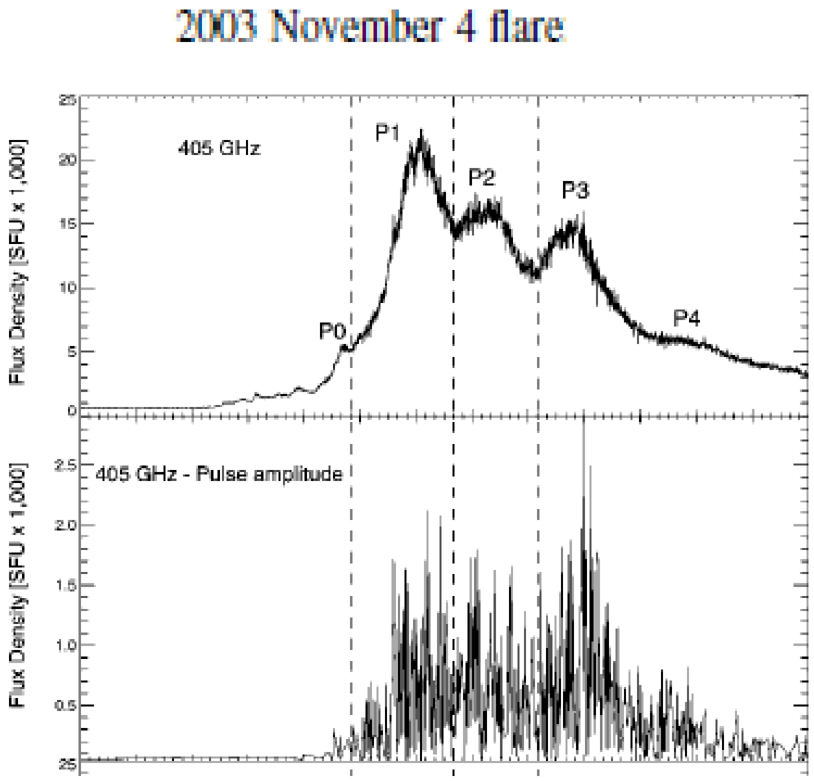


Two main problems:

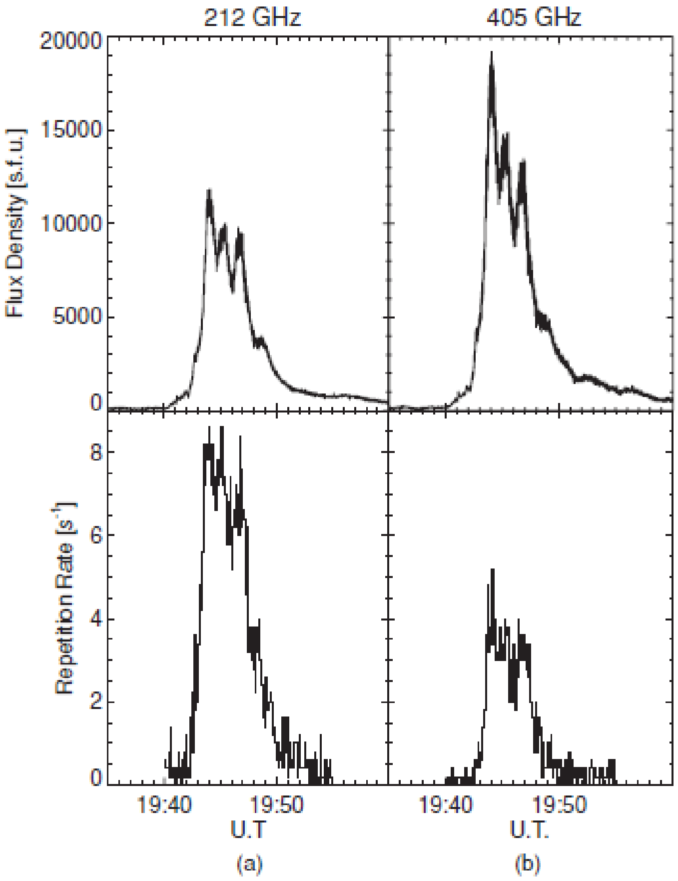
(i) What is the origin of positive slope in the spectra of sub-THz and THz radiation from the Sun

(ii) What is the origin of sub-second and second pulsations with $Q > 10^3$

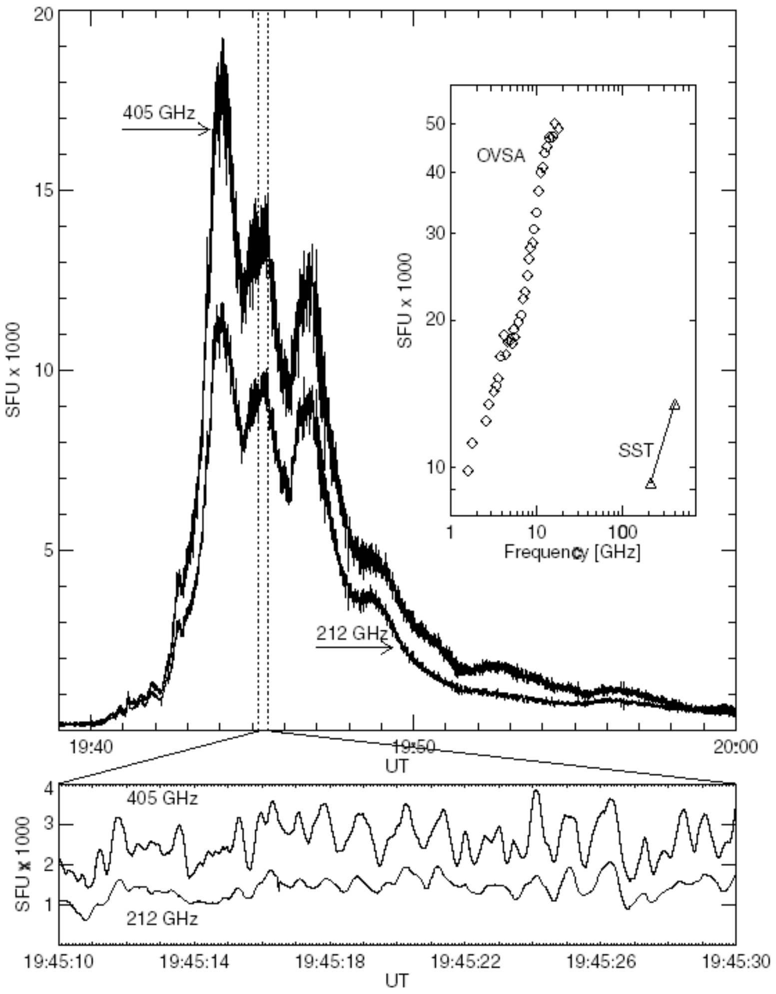
Kaufmann et al. (ApJ 2004, 2009)



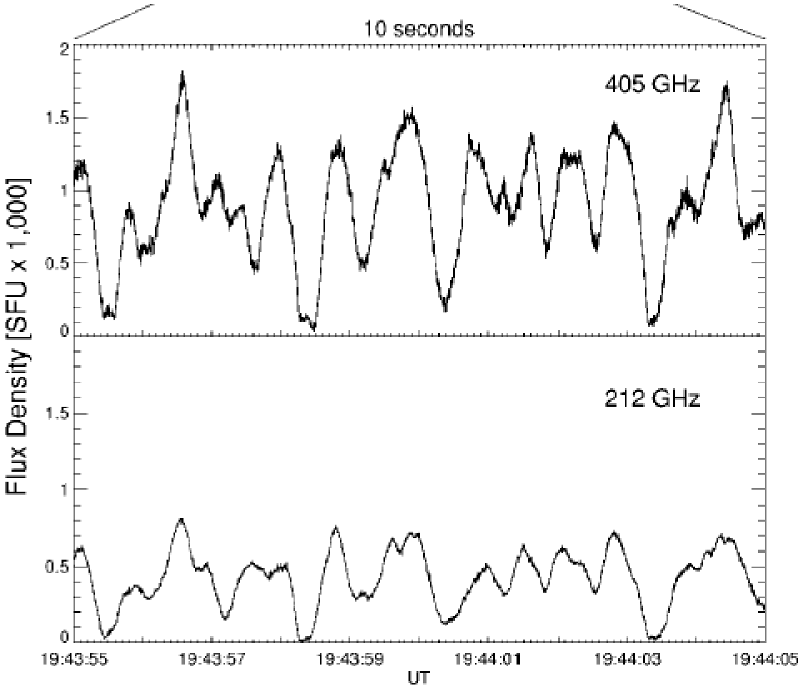
<u>Вызов для астрофизиков:</u> излучение с потоками > 10^4 sfu на 212 and 405 ГГц с развитой пульсирующей структурой. Период пульсаций меняется от 0.2 до 4 с. Амплитуда пульсаций: 5-8% от основного всплеска. Высокая добротность, Q-≥ 10^3.



Загадочная пропорциональность между потоком суб-мм излучения *F* и частотой пульсаций (repetition rate *R* ~ *F*).



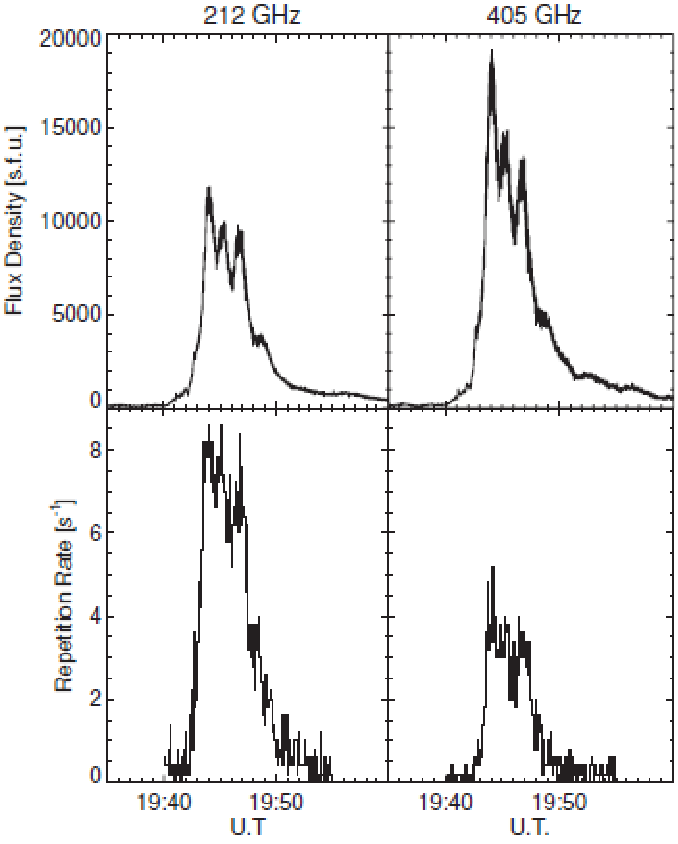
Solar flare on Nov.4, 2003



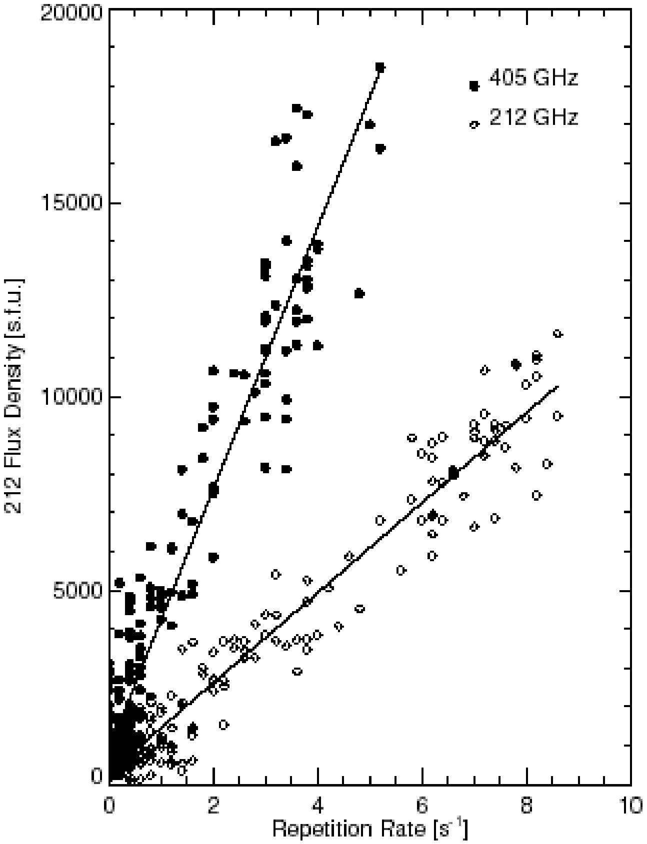
Pulsations with modulation depth 5-8% and periods 0.2-4 s.

Challenge in solar physics: > 10^4 sfu (10^8 Jy) emission at 212 and 405 GHz with pulsations (Kaufmann et al. 2004, 2009).

Zaitsev, Stepanov, Kaufmann (2014): On the origin of pulsations in sub-THz



(a) (b)



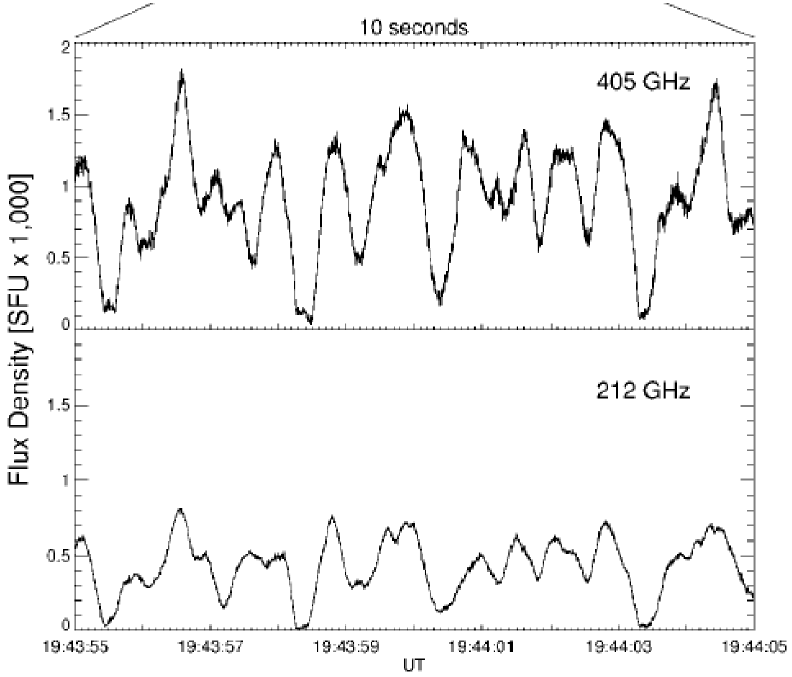
2003 Nov. 4

Puzzling proportionality between pulse repetition rate and mean emission fluxes (Kaufmann et al. 2009)

Two branches $F = kR$, with $k(405) \approx 4k\,(212)$

Модель пульсаций должна объяснить:

- Период P = 0.2-4 с
- Уменьшение P с ростом F
- Высокую добротность $Q \geq 10^3$
- Малую амплитуду пульсаций
- Синхронность пульсаций
  на разных частотах



To know the origin of sub-THz and THz radiation we need:

- Observation data (flux, spectra, fine structure, polarization)
- Plasma parameter in the source (n_0, T, B)
- Source location, configuration, area S, volume V
- Info about energetic electrons (energy, density, spectrum)
- Info about wave propagation conditions, absorption

Sub-THz and THz emission

Thermal: Gradual (time-extended)

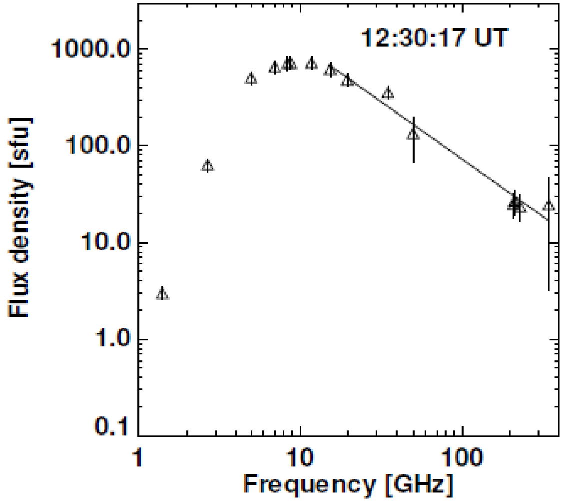
Thermal / Nonthermal: Impulsive

Mechanisms responsible for positive slope in sub-THz and THz domains in impulsive phase remains uncertain.

For gradual phase: thermal bremsstrahlung from the chromosphere and corona.

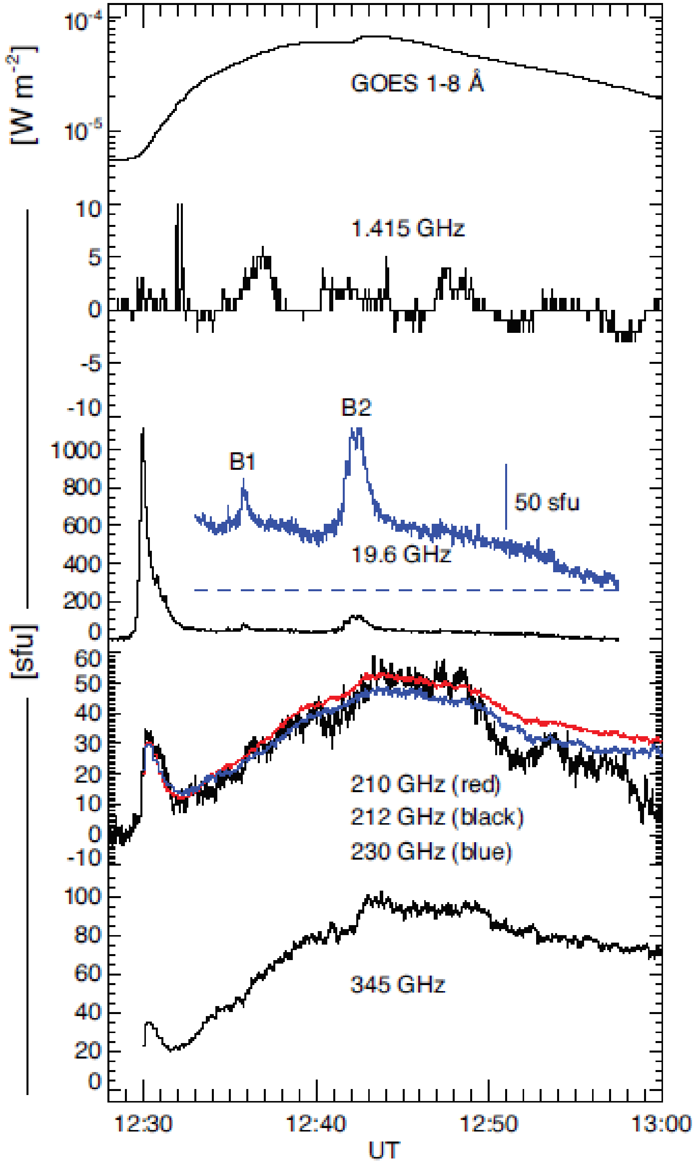
2003 Oct. 27 flare (Trottet et al. Solar Phys. 2011)

Impulsive phase (≤ 3 min): Gyrosynchrotron (τ <1) + Razin effect, B~300 G, n ~ 10^{10} cm^{-3}.



Time-extended phase (10-60 min): < 230 GHz emission is produced in corona by hot and cool materials at 7-16 MK and at 1-3 MK.

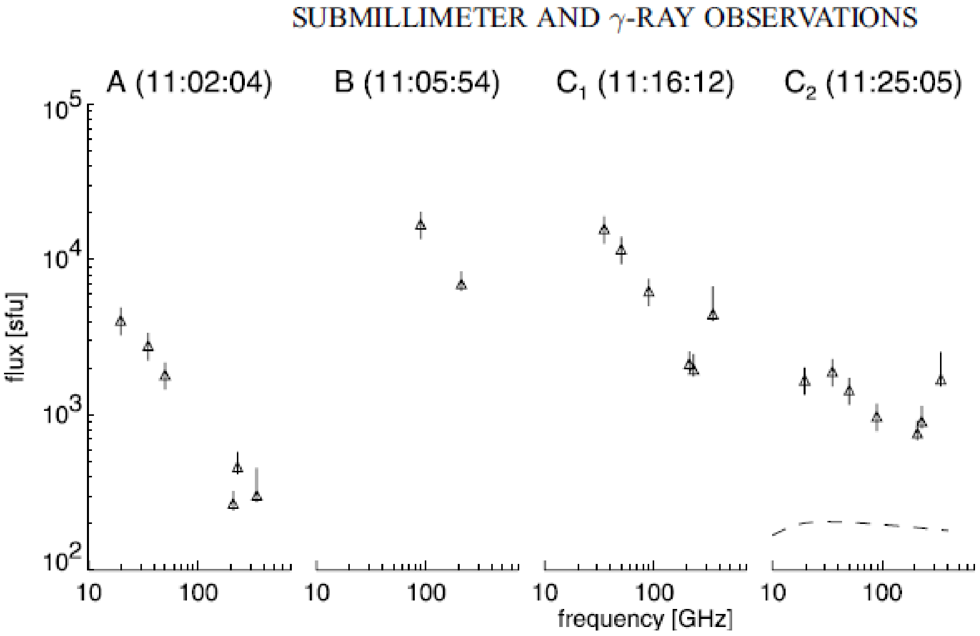
At 345 GHz – optically thick component emitted by the chromosphere with T ~ 10^4 K.

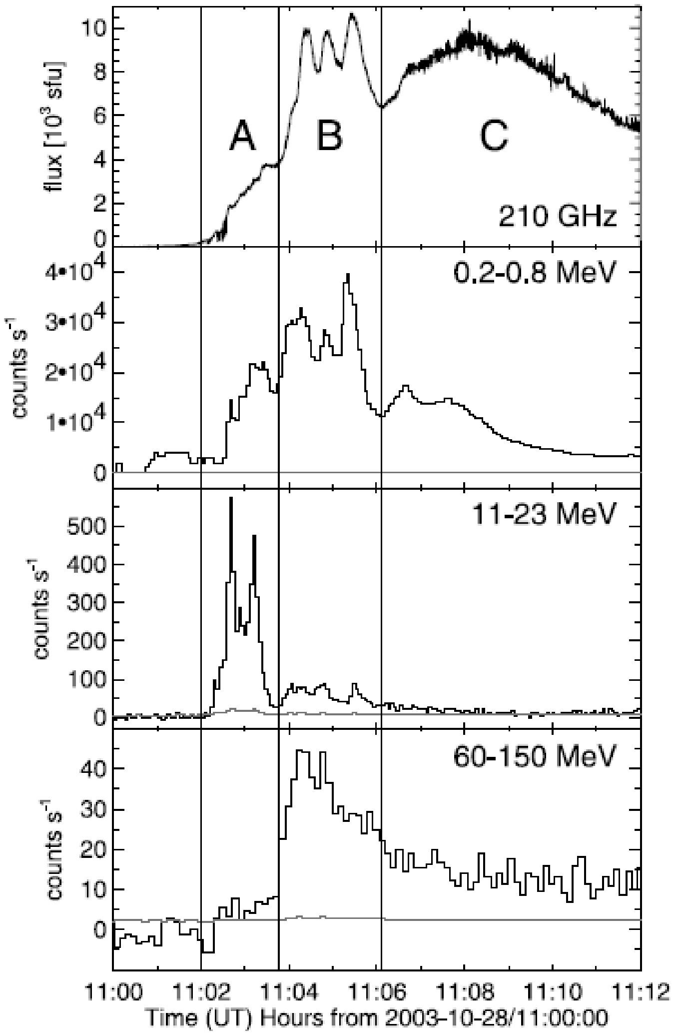


The 2003 October 28 flare (Trotett et al ApJ 2008)

KOSMA (BEMRAK) (210, 230, 345 GHz)
CORONAS-F (HXR/GR)
and RHESSI (HXR/GR)

Synchrotron emission of positrons produced in charged-pion decay ?





Модели суб-ТГц излучения

(i) Синхротронное излучение > 10 МэВ электронов с $B \geq 1000$ Гс (Kaufmann et al. 2009);

(ii) Гиросинхротронное излучение, объясеяющее W-спектр (Melnikov et al. 2011);

(iii) Черенковское излучение в хромосфере $V > c/\sqrt{\varepsilon(\omega)}$ (Fleishman & Kontar 2010). Диэлектрическая проницаемость в хромосфере $\varepsilon(\omega) > 1$.

(iv) Плазменный механизм (Sakai et al 2006; Zaitsev et al 2013):

Плазменная частота электронов 200, 400 ГГц
требует $n = 5\times10^{14}$ и 2×10^{15} $см^{-3}$

Для полной ионизации (из Саха): температура хромосферы $T \geq 10^5$ K.
Источник нагрева – ускоренные электроны.
При $n \sim 10^{15}$ $см^{-3}$, $B \sim 3$ кГ $\omega_p/\omega_B \sim 40 >> 1$, т.е. приближение изотропной плазмы применимо.

Two new mechanisms (Fleishman & Kontar, ApJ 2010)

(i) Diffuse radiation in Langmuir waves. Spectrum peaks at $\omega \sim 2\omega_p \gamma^2$
Looks like *Inverse Compton scattering*: role of low-frequency photons
is played by Langmuir waves, $\alpha \geq 2$.
Long wavelength Langmuir waves $k \ll \omega_p/c$ is the problem.
The origin of short wavelength ($k \sim k^t \sim \omega_p/c$) Langmuir waves ?
The origin of relativistic particles ?

(ii) Cherenkov emission in the chromosphere $V > c/\sqrt{\varepsilon(\omega)}$
dielectric permittivity $\varepsilon(\omega) > 1$ in partially ionized
chromosphere, $\varepsilon(\omega) = 1 - \omega_{pe}^2/\omega^2 + \sum \delta\varepsilon_{nm}$ $\delta\varepsilon_{nm} = ?$

But: Origin of relativistic particles in the chromosphere?
The plasma above sub-THz source absorbs emission.

Krucker et al. Astron Astrophys Rev (2013)

Summary of mechanisms

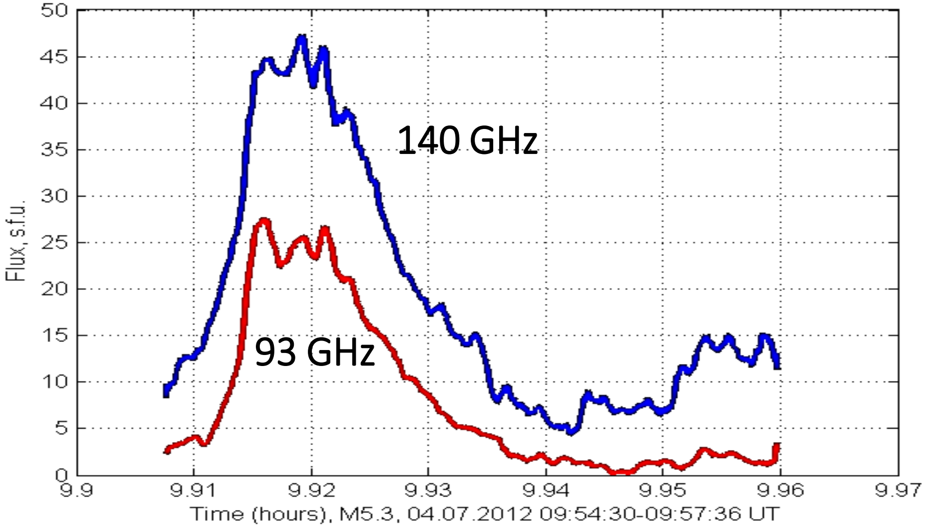
2013

Mechanism	**Arguments for**	**Arguments against**	**Ref.**
Free-free	Known mechanism Can produce $dF_\nu /d\nu > 0$	Extended sources	(1, 3, 11)
Synchrotron (electrons)	Known mechanism Can produce $dF_\nu /d\nu > 0$	Extreme parameters required	(2, 3, 11)
Synchrotron (positrons)	Known mechanism Can produce $dF_\nu /d\nu > 0$ Correlation with γ-rays	Extreme parameters required Not enough positrons?	(2, 3)
Vavilov-Cherenkov	Can produce $dF_\nu /d\nu > 0$ Rapid variations High luminosity	Dielectric properties unknown Relativistic particles required	(4)
Microbunching	Association with GHz	THz from gyrosynchrotron Source of bunching unclear Coronal μwave unclear	(5)
Plasma emission	Correlation with γ-rays High luminosity	Free–free absorption	(6)
Diffusive radiation	Can produce $dF_\nu /d\nu > 0$	Origin of Langmuir waves	(4)
Gyrosynchrotron	Can produce $dF_\nu /d\nu > 0$	Extreme parameters required Thermal HXR not observed	(8)
Synchrotron maser	Can produce $dF_\nu /d\nu > 0$ High luminosity	Extreme parameters required	(9)
Inverse Compton	Association with GHz	Not enough photons	(10)

(1) Bastian et al. (1998); (2) Silva et al. (2007); (3) Trottet et al. (2008); (4) Fleishman & Kontar (2010); (5) Kaufmann & Raulin (2006); (6) Sakai & Nagasugi (2007a); (7) –; (8) –; (9) –; (10) This paper; (11) Kaufmann et al. (2009b)

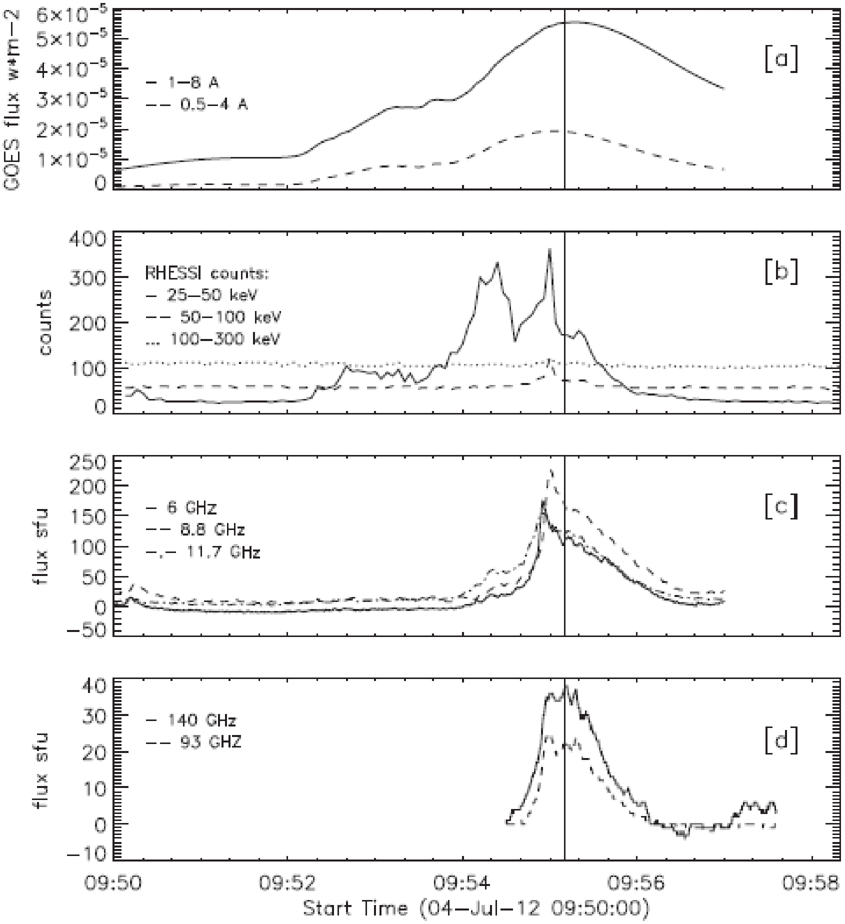
Increasing spectra at 93 and 140 GHz observed with RT-7.5 m of the Bauman Technical University

4-Jul-2012 flare

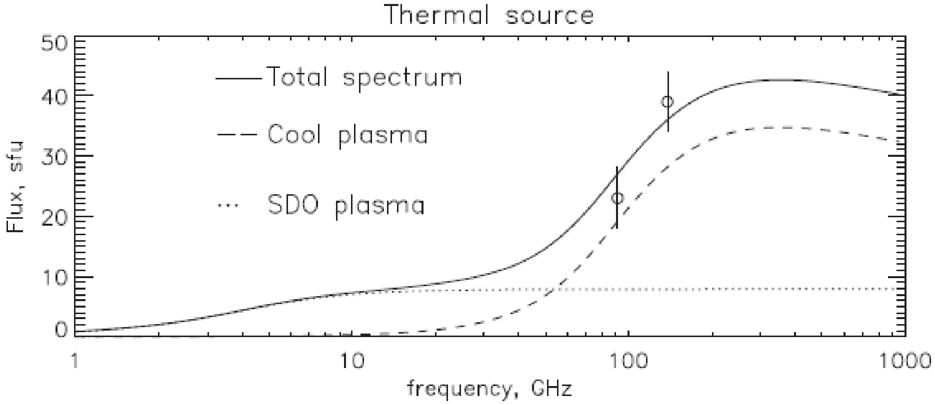


Tsap et al. (Adv.Sp.Sci. 2016): Flare of July 4, 2012

The non-thermal gyrosynchrotron mechanism is responsible for mcw emission near 10 GHz .
Mm spectral characteristics are likely to be produced by thermal free-free emission from the plasma of upper chromosphere and transition region with T ≈ 0.1 MK, n ≈ 10^{11} cm^{-3}. The source area S ≈ 4×10^{18} cm^2.



$$F_{total} = \frac{2k_B\nu^2}{c^2R^2}\left(T_{b1}(\nu)S_1 + T_{b2}(\nu)S_2\right).$$



SDO coronal plasma with T = $10^{5.7}$ - $10^{7.3}$ K

$S_1 = S_2$ - why?

Tsap et al. Sol. Phys. 293:50 (2018)

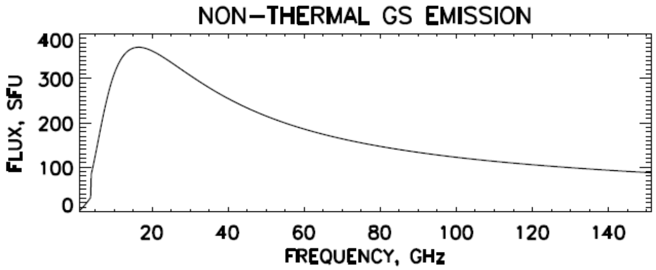
Millimeter and X-Ray Emission from the 5 July 2012 Flare

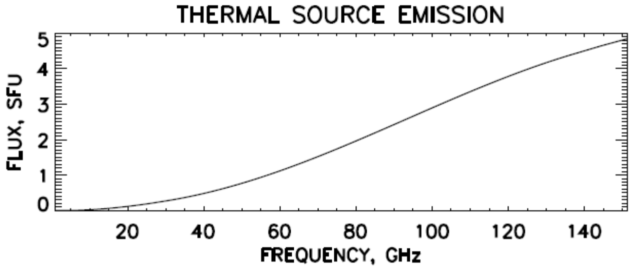
Increasing mm-spectrum between 93 and 140 GHz observed with RT-7.5 of the Bauman Technical University.

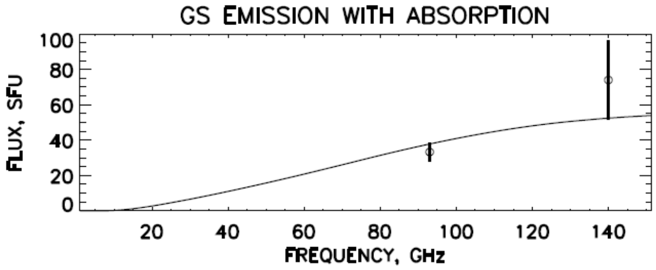
Hybrid model

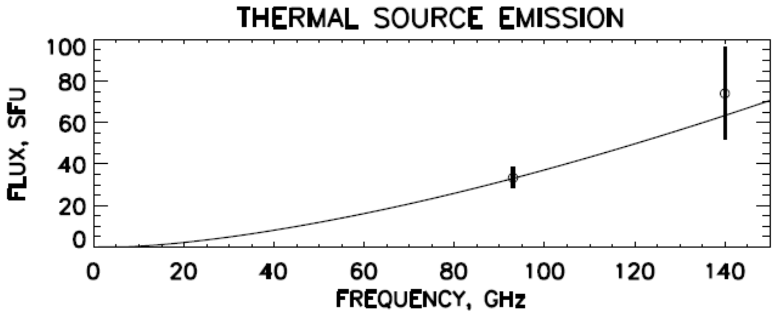
(i) Gyrosynchrotron emission of ~300 keV electrons in the chromosphere

(ii) Free-free emission ($\tau > 1$) from a source with $S \sim 3\times10^{18}$ cm^2 , $T \approx 0.1$ MK, $n_0 \approx 4.5\times10^{11}$ cm^{-3} .


NON−THERMAL GS EMISSION


THERMAL SOURCE EMISSION

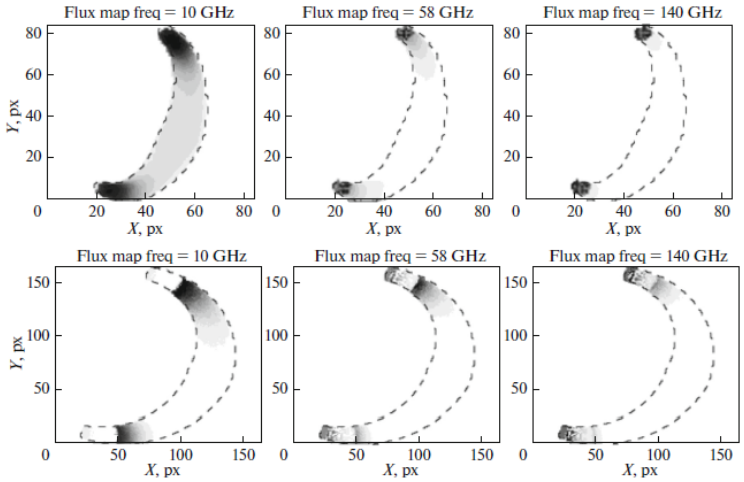

GS EMISSION WITH ABSORPTION

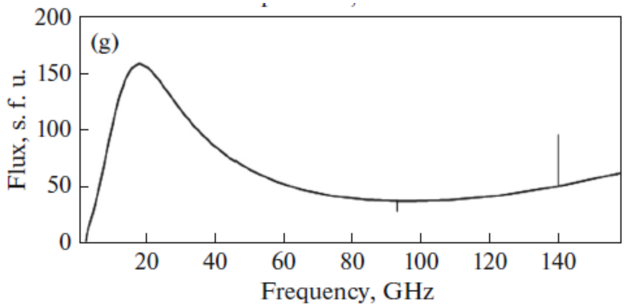

THERMAL SOURCE EMISSION

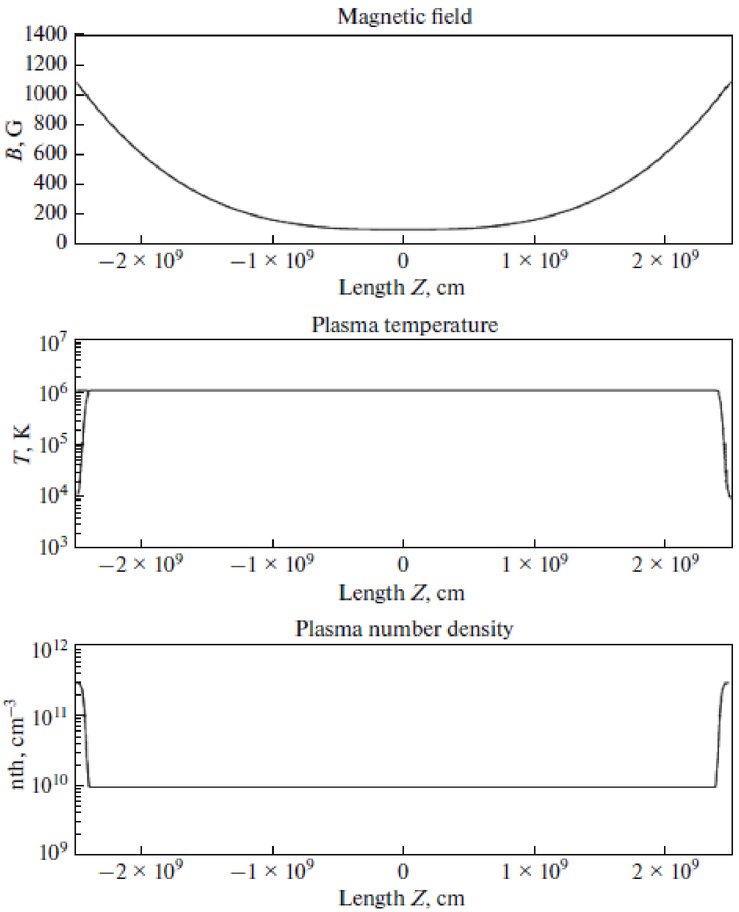
Morgachev et al. Geomag & Aeron. 57, 2017: **Solar Flare of July 5, 2012**

GYROSYNCHROTRON: NT electrons can be responsible for both cm bell-shaped emission spectrum generated in the coronal part of the loop and for the increasing mm spectrum generated in the chromosphere. An important feature of the model is the setting of the flare loop inclination from the vertical at least 20°.

$n_0 \approx 10^{10}$ cm^{-3}, B ≈ 1000 G, and 0.1–10 MeV electrons with n ≈ 10^6 cm^{-3} and spectral index δ = 2-4.



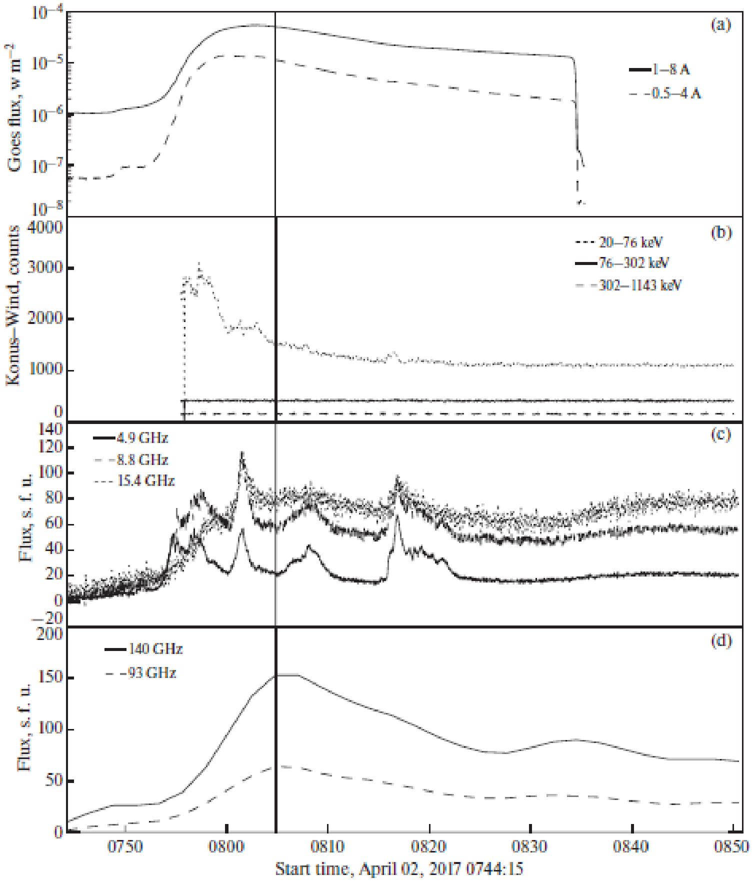




Morgachev et al. Geomag & Aeron. 58, 2018: **Solar Flare of April 2, 2017**

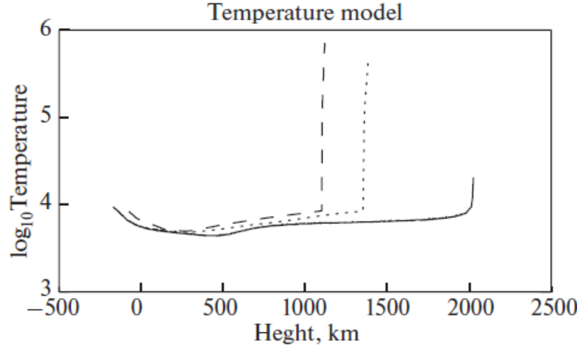
Flux density of mm-radiation increases with frequency throughout the entire burst.

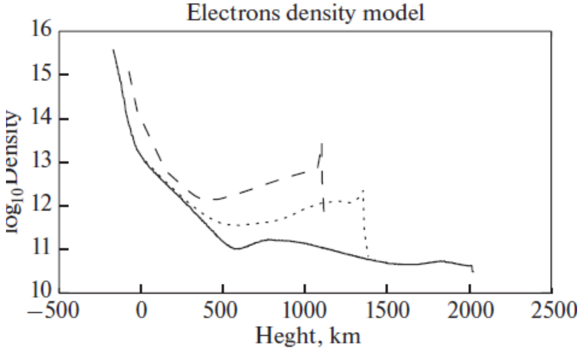
Similarity of mm and SXR light curves suggests the thermal origin of mm-emission.

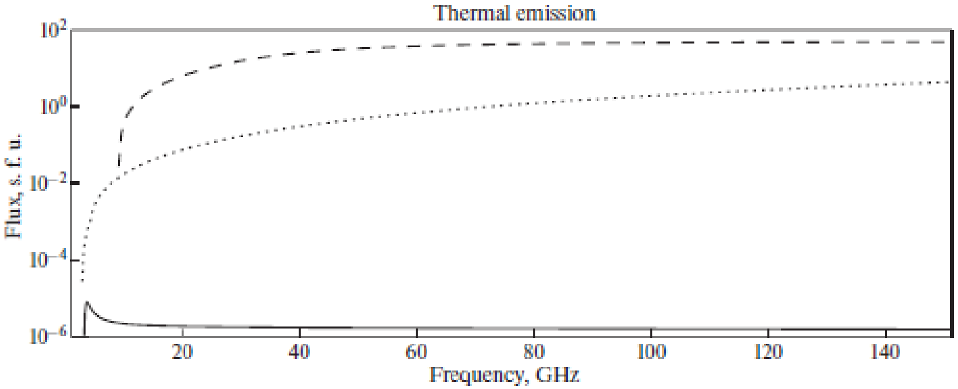


Atmosphere model (Machado et al. 1980) yields mm fluxes by several factors lower than the observed one

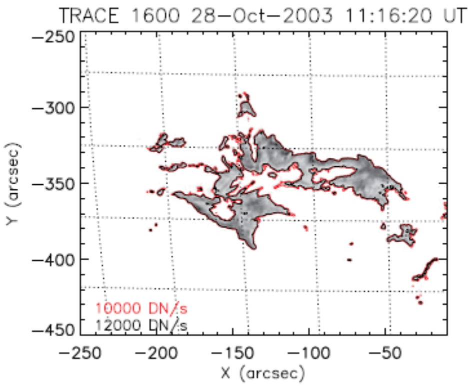
$S_{mm} = S_{SXR}$?







Kontar, Motorina et al. A&A 620, A95 (2018) **Frequency rising sub-THz emission from solar flare ribbons**



Events must meet the following criteria:

(i) Fluxes at sub-THz frequencies (200-400 GHz) > 10 sfu

(ii) UV images at the 1600 Å band

List of flares with a rising spectrum of sub-THz emission.

Solar flare (GOES class)	Sub-THz (UT)	δ	F. density (sfu)	UV(UT)	$A_{\rm UV}$ (arcsec²,
SOL2000-03-22T18:48 (X1.1)[a]	18:50:00	$1.27^{+0.63}_{-0.63}$	500	18:50:00	412 ± 51
SOL2001-04-12T10:28 (X2.0)[b]	10:17:54	$1.09^{+0.96}_{-1.07}$	810†	10:16:11	816 ± 189
SOL2003-10-27T12:43 (M6.7)[c]	12:32:30	$1.68^{+0.48}_{-0.49}$	86†	12:32:36	490 ± 143
SOL2003-10-28T11:10 (X17)[d]	11:16:12	$2.0^{+0.8}_{-0.53}$	4500†	11:16:20	3590 ± 506
SOL2003-11-02T17:25 (X8.3)[e]	17:19:30	$3.41^{+2.92}_{-1.79}$	50 000	17:35:38	1268 ± 349
SOL2003-11-04T19:50 (X28)[f]	19:44:00	$0.71^{+0.23}_{-0.24}$	18 000	19:43:11	1969 ± 390
SOL2006-12-06T18:47 (X6.5)[g]	18:43:51	$0.98^{+0.68}_{-0.93}$	6800	18:43:53	2785 ± 182
SOL2012-10-22T18:51 (M5.0)[h]	18:48:30	$1.42^{+0.48}_{-0.49}$	50	18:49:52	148 ± 56
SOL2012-07-04T09:55 (M5.3)[i‡]	09:55:30	$1.29^{+0.6}_{-0.63}$	39‡	09:57:04	142 ± 91
SOL2012-07-05T11:44 (M6.1)[j‡]	11:44:24	$1.33^{+0.6}_{-0.63}$	26‡	11:41:52	126 ± 51
SOL2013-02-17T15:50 (M1.9)[h]	15:46:25	$1.42^{+0.28}_{-0.28}$	200	15:47:52	67 ± 27
SOL2014-10-27T14:47 (X2.0)[h]	14:22:50	$1.07^{+0.31}_{-0.31}$	60	14:18:40	133 ± 53
SOL2014-11-05T19:44 (M2.9)[h]	19:53:40	$0.63^{+0.4}_{-0.38}$	30	19:53:52	15.6 ± 15.4
SOL2014-11-07T17:26 (X1.6)[h]	17:25:30	$0.52^{+0.29}_{-0.29}$	70	17:25:28	202 ± 99

$$F = \frac{2\nu^2 k_{\rm B} T}{c^2}\frac{\textcircled{A}}{R^2}$$?

δ = log(F_{405}/ F_{212})/ log(405/212),

List of flares with a decreasing spectrum of sub-THz emission.

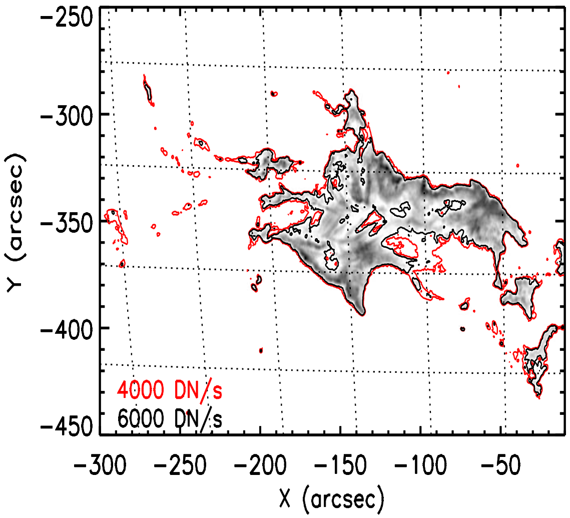
Solar flare (GOES class)	Sub-THz (UT)	δ	F. density (sfu)	UV(UT)	$A_{\rm UV}$(arcsec²)
SOL2012-01-27T18:37 (X1.7)[a]	18:26:00	$-1.46^{+0.44}_{-0.46}$	140	18:25:53	522 ± 163
SOL2012-03-13T17:41 (M7.9)[a]	17:23:10	$-1.07^{+0.54}_{-0.64}$	100	17:19:05	86 ± 44
SOL2014-10-22T14:28 (X1.6)[a]	14:06:50	$-0.28^{+0.35}_{-0.36}$	100	14:07:28	299 ± 96

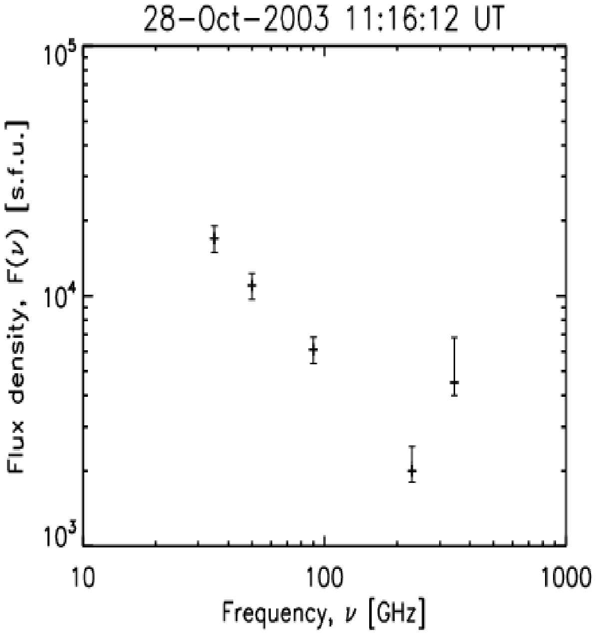
UV observations of flare ribbons

- Hard X-rays producing non-thermal electrons in flares deposit most of their energy in the chromosphere leading to bright emission from the chromosphere/transition region
- UV images show flare ribbon emission from the transition region and chromosphere

- We calculated UV flare ribbon areas at the sub-THz emission peak

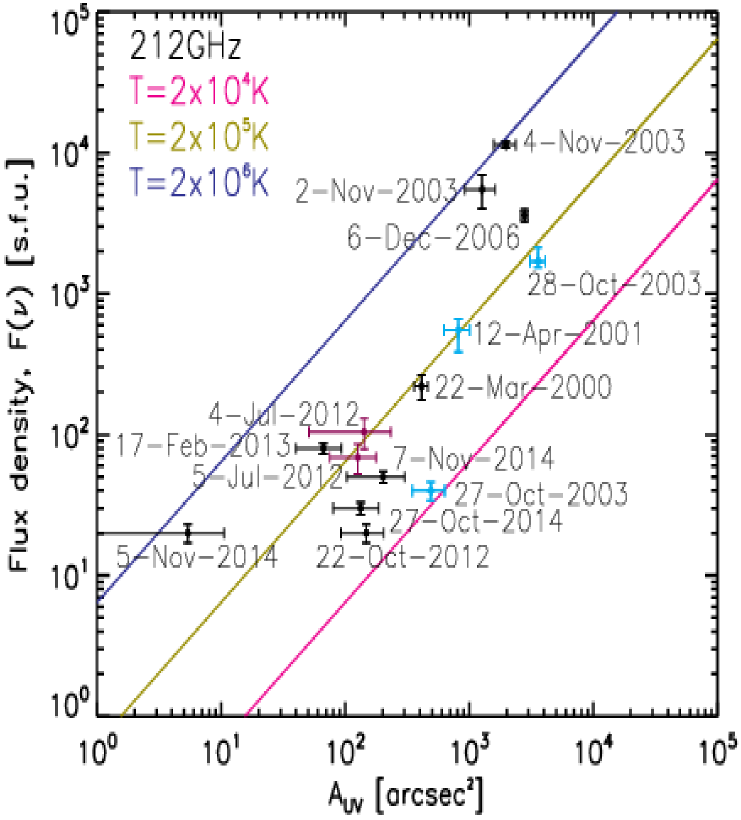
- **And found a correlation between UV areas & sub-THz fluxes**

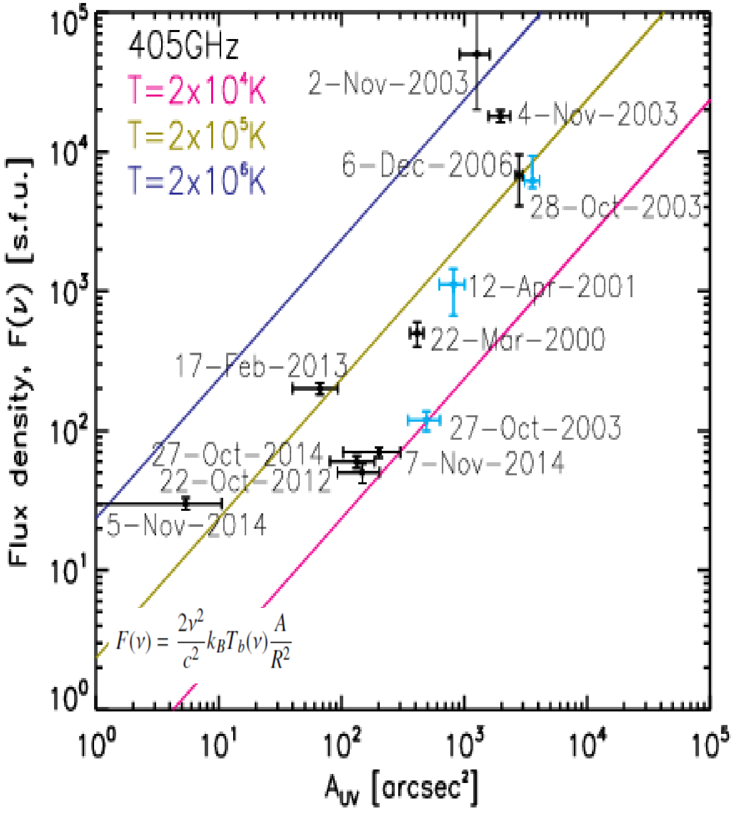




(Kontar et al., 2018)

UV flare ribbon areas and sub-THz flux





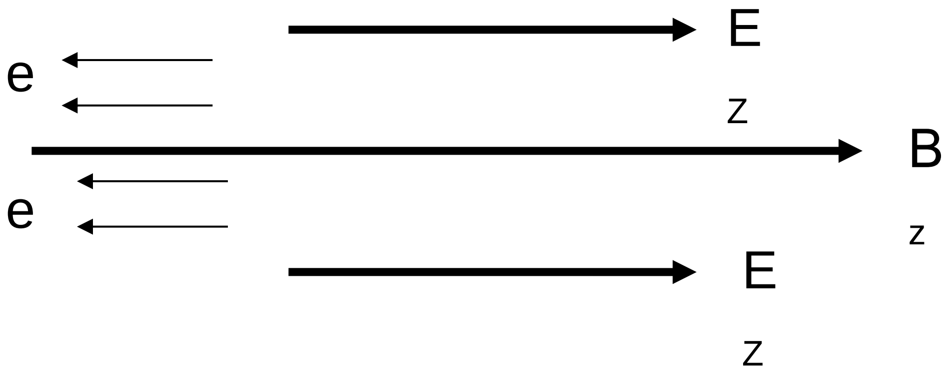
All radio fluxes at 200-400 GHz frequency range can be explained by the radiation of an optically thick source with a plasma temperature between 2×10^4 K and 2×10^6 K, which characterizes the chromosphere and transition region

Most of mechanisms require accelerated particles:

- Gyrosynchrotron
- Synchrotron (electrons and positrons)
- Vavilov-Cherenkov
- Plasma emission
- Microbunching
- Diffusive radiation
- Inverse Compton

What is the acceleration domain of energetic electrons, in the corona or in the chromosphere (*in situ)*?

The most effective electron acceleration - in DC electric field



Acceleration rate (Knoepfel & Spong, 1979):

$$\dot{n}_s = 0.35 n \nu_{ei} V_a x^{3/8} \exp\left(-\sqrt{2x} - x/4\right)$$

$$x = E_D / E_Z$$

Dreicer field $E_D = 6\times10^{-8} (n_e / T)\ V / cm$

x < 1: bulk of electrons are in ‘run away’ mode

Three ways:

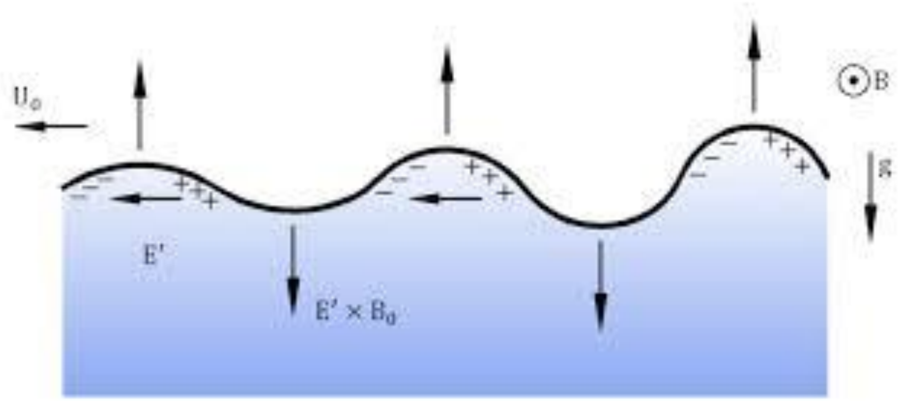
(i) Acceleration in the corona

(ii) Magnetic reconnection in partially-ionized chromosphere plasma

(iii) R-T instability; *in situ* acceleration by electric fields

Magnetic Rayleigh-Taylor instability

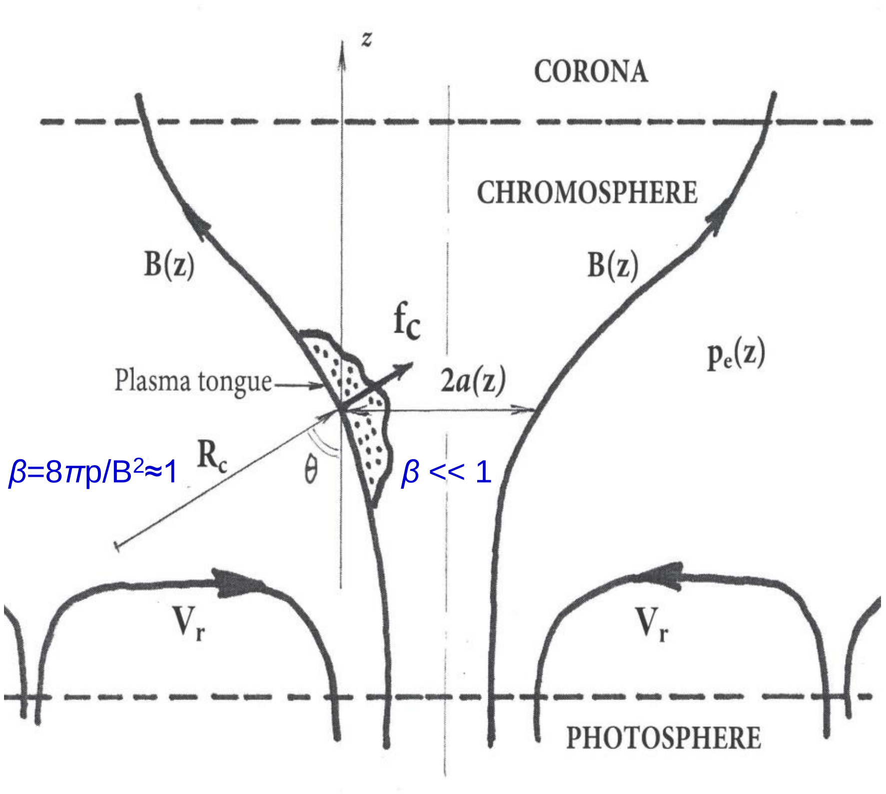
(great role in astrophysics)



Kruskal & Schwarzschild (1954)
Chandrasekhar (1981)

Rayleigh-Taylor instability in the foot of current-carrying magnetic loop (ballooning mode)

Zaitsev & Stepanov (Solar Phys. 2015)



R-T instability condition:

$$\frac{nT}{2(n+n_a)T_e} + \frac{8\Lambda V_r^2(t)}{a^2 g} > 1$$

$$\Lambda = \frac{k_B T_e(z)}{m_i g}$$

$$\vec{f}_c = \frac{2nk_B T}{R_c^2}\vec{R}_c$$

$$B_z(r,t)\ ,\quad \mathrm{B}_\varphi(r,t) \longrightarrow I_z(z,t)$$

Pre-heating of the R-T instability domain to $T \approx 10^4$ K by the electric current in a loop is needed.

Chromosphere pre-heating for ballooning instability

Modified Saha formula:

$$\frac{(n+n_a)x^2}{1-x} = 7.2\times10^{18}T^{0.5}\exp\left(-6.583-\frac{1.185\times10^5}{T}\right)$$

$$x = n/(n+n_a)$$

Temperature to which the chromosphere should be heated for ballooning instability *($n > n_a$)*

.

Chromosphere density

$$n_{tot} = n + n_a = 10^{16}, 10^{15}, 10^{14}\ cm^{-3}$$

Temperature should be as high as

$$T \approx 2\times10^4 K,\ 1.5\times10^4 K,\ 1.2\times10^4 K$$

Current dissipation is provided by Cowling conductivity related to electron-atom collisions

$$q_J = \frac{n m_i \nu'_{ia} V_r^2 (1+x)}{(1-x)^2}$$

(Sen & White,1972)

The radiation losses

$$q_r = (1.397\times10^{-8}T)^{6.15}(n+n_a)n$$

From $q_j > q_r$ we obtain the lower boundary for the rate of photosphere convection that provides R-T instability:

$$V_r \geq 3.5\times10^4 cm/s$$

Induced electric field in a current-carrying loop

Before R-T instability: $B_{z0}(r) = const, \quad B_{\varphi\mathbf{0}}(r) = B_{\varphi\mathbf{0}} r/a$

Penetration of chromosphere plasma into a loop with velocity $V_r(r,t) = -V_r(t) r/a$

From Eqs $\dfrac{\partial \vec{B}}{\partial t} = rot(\vec{V} \times \vec{B})$ and $rot\vec{E} = -\dfrac{1}{c}\dfrac{\partial \vec{B}}{\partial t}$ $\Rightarrow$ $\vec{E} = -(1/c)[\vec{V} \times \vec{B}]$

No acceleration in instability domain!

For the time $\tau \approx l/V_A \approx$ 5-10 s a disturbance dealing with $B_\varphi(r,t)$ is running away from instability domain with $V \approx V_A$.

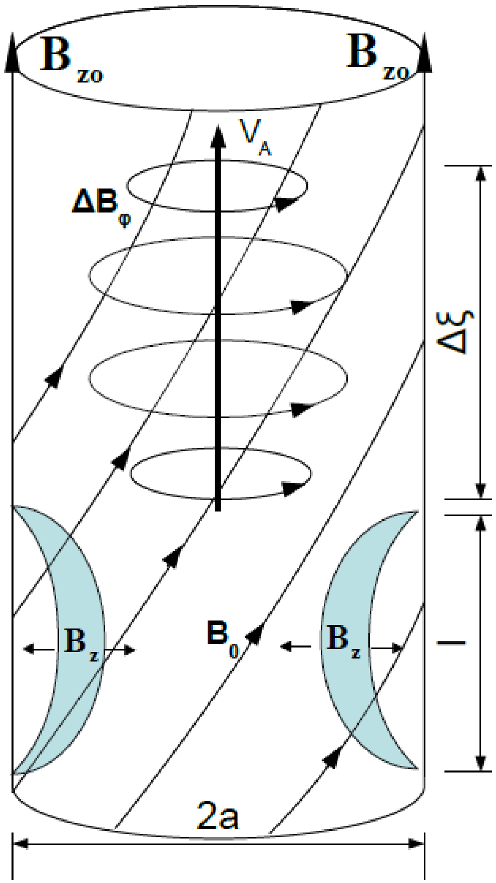
(a) Weak current $p >> B_\varphi^2/8\pi$. Pulse propagation as linear Alfven wave with no E_z

$$\boxed{\frac{\partial^2 B_\varphi}{\partial t^2} - \frac{B_{0z}^2}{4\pi\rho}\frac{\partial^2 B_\varphi}{\partial z^2} = 0} \qquad \frac{\partial E_z}{\partial r} = 0$$

Zaitsev, Stepanov, Kronshtadtov (Solar Phys. 2016)

(b) Strong current, $p << B_\varphi^2/8\pi$

Magnetic field disturbances are not compensated by gas pressure gradient



Induced non-linear electric field component E_z appears:

$$\frac{\partial E_z}{\partial r} = -\frac{1}{c}\frac{B_\varphi^2}{4\pi\rho V_A^2}\frac{\partial B_\varphi}{\partial t}$$

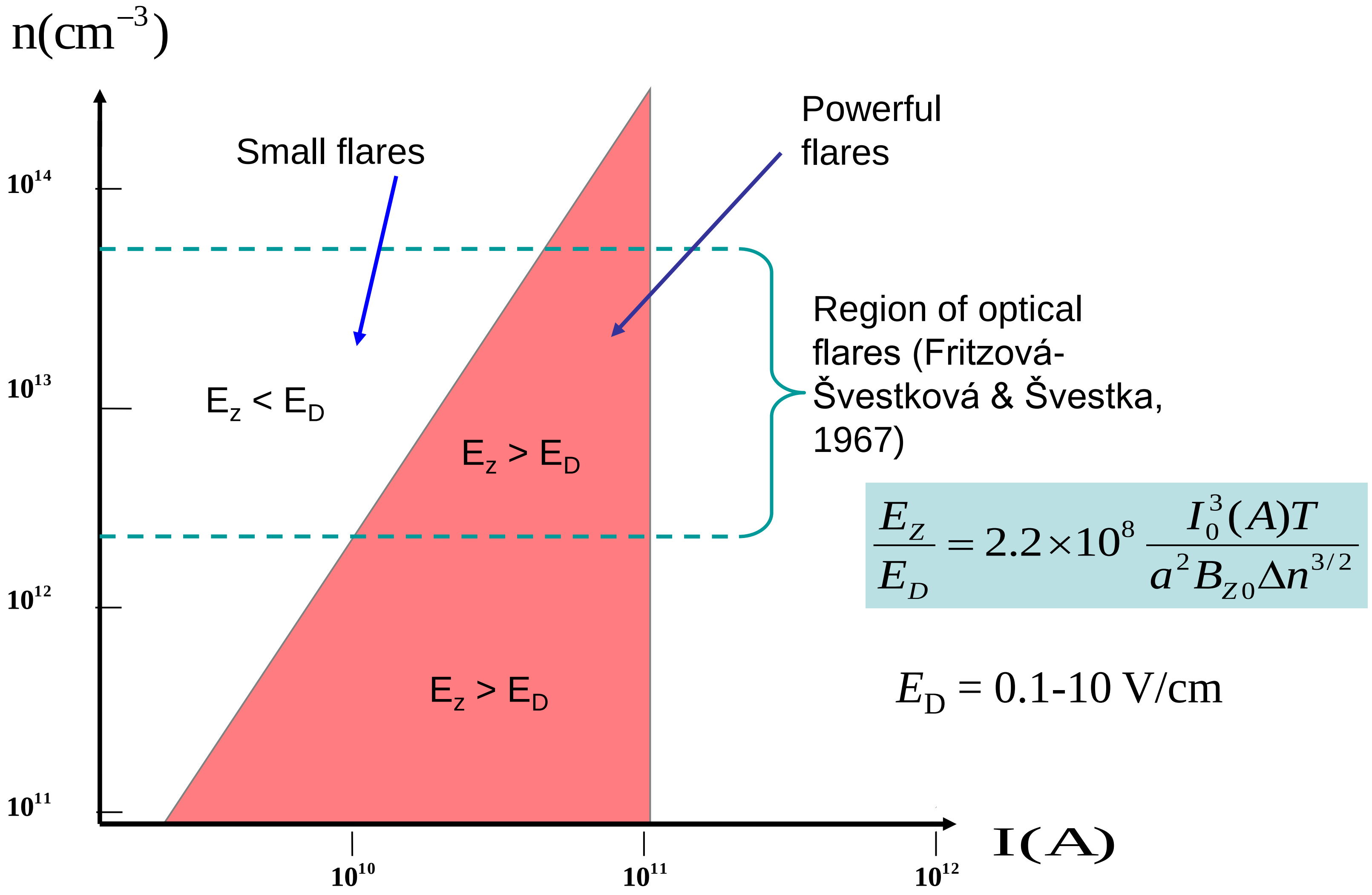
Electric field grows with increasing electric current and for $B_\varphi^{\max} \approx \sqrt{4\pi\rho} V_A$ reaches the value

$$\frac{\partial E_{zm}}{\partial r} \approx -\frac{1}{c}\frac{\partial B_\varphi}{\partial t}$$

$$B_\varphi = 2rI_0(z - V_A t)/ca^2 \Longrightarrow E_{zm} = \frac{2I_0^2 V_A}{c^4 a^2 B_{z0}^2}\frac{\partial I_0}{\partial \xi}, \quad \xi = z - V_A t$$

“Splitting” of the components

A pulse of magnetic field tension $B_\varphi^2/8\pi$ escapes from R-T instability in the form of non-linear Alfvén wave. Pulse of magnetic field pressure $B_z^2/8\pi$ remains in the R-T instability domain, and excites sausage oscillations.



Region of optical flares (Fritzová-Švestková & Švestka, 1967)

$$\frac{E_Z}{E_D} = 2.2\times10^8 \, \frac{I_0^3(A)T}{a^2 B_{Z0} \Delta n^{3/2}}$$

$E_D = 0.1\text{-}10$ V/cm

Plasma density vs electric current for loop radius $a = 10^7$ cm, $B_{z0} = 2$ kG, $T = 2\times10^4$ K, R-T instability scale $\Delta = 5\times10^7$ cm. The regions of super-Dreicer electric fields - in red.

Plasma sub-THz radiation – excitation of plasma waves and conversion into electromagnetic waves:

- regular conversion (Sakai, Nagasugi et al. A&A 2006);
- Rayleigh & Compton scattering (Zheleznyakov & Ginzburg 1964)

Plasma sub-THz radiation: Preliminary considerations

Plasma frequency at 200 и 400 GHz means n = 5×10^{14} and 2×10^{15} см$^{-3}$. One can find such high density in the solar chromosphere.

For full ionization: chromosphere temperature should be $T \geq 10^{5}$ K.

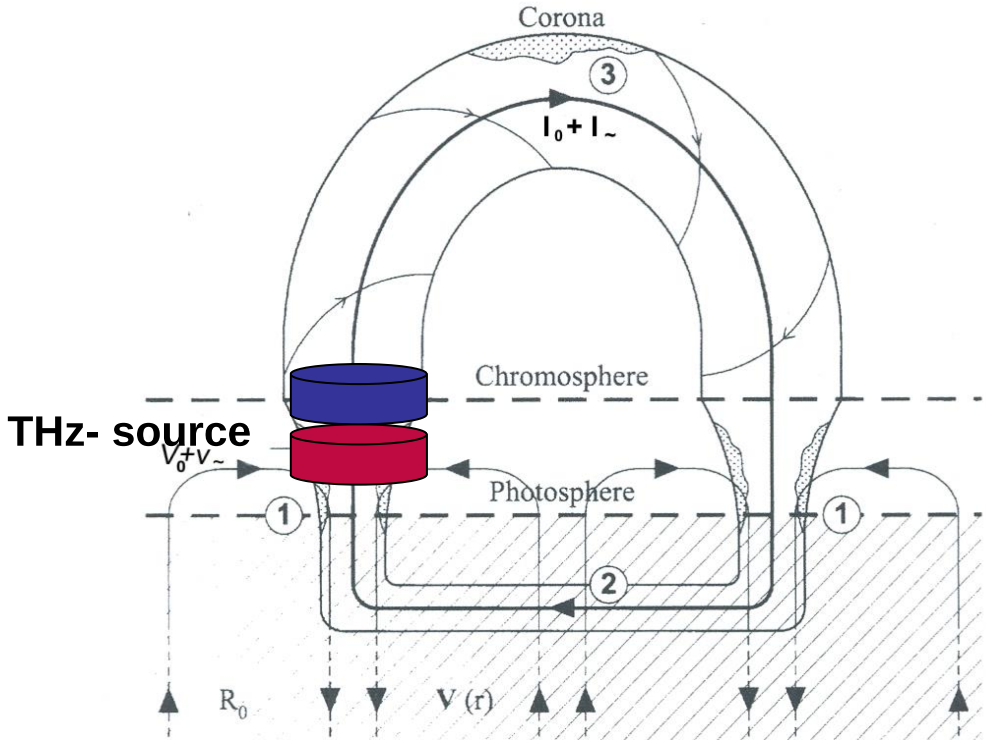
A source of heating – accelerated electrons
$n_0 \sim 10^{14}$ -10^{15} cm^{-3}, B ~ 3 kG.
Isotropic plasma approach is true, $\omega_p / \omega_c \sim 40 >> 1$.

Plasma radiation at sub-THz

Zaitsev, Stepanov, Melnikov (Astr. Lett. 2013); Zaitsev, Stepanov, Kaufmann (Sol. Phys.2014)

FLARING LOOP

$$T_b = \frac{a}{\mu}\left[1-\exp\left(-\tau_n-\tau_c\right)\right]\exp\left(-\tau_{ext}\right)+T_{ext}\left[1-\exp\left(-\tau_{ext}\right)\right]$$



“Transparency” conditions for chromosphere:

- Large currents in flaring loops ~10^{11} A

- Ballooning instability, which induced electron acceleration in the chromosphere, plasma heating and plasma wave turbulence generation.

Even for B = 2000 G $\omega_p / \omega_{ce} \approx 40 \gg 1$.
So, isotropic plasma approximation is true.

Chromospere above THz source (blue) is heated by evaporated plasma from THz source (red).
Heat conduction is less important.

Requirements to the source:

$$n \approx 5\times10^{14}\,cm^{-3}, \quad T \approx 3\times10^{6} \div 10^{7}\,K,$$

$$n_s \geq 10^{9}\,cm^{-3}, \;\; \varepsilon_s \approx 500 \div 1000\,keV$$

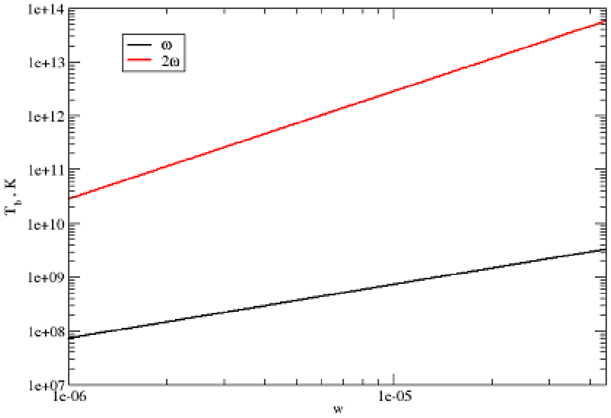
$$\frac{n_s}{n}\omega_p > \nu_{ei}$$

$$\frac{n_s}{n} > 10^{-6}$$

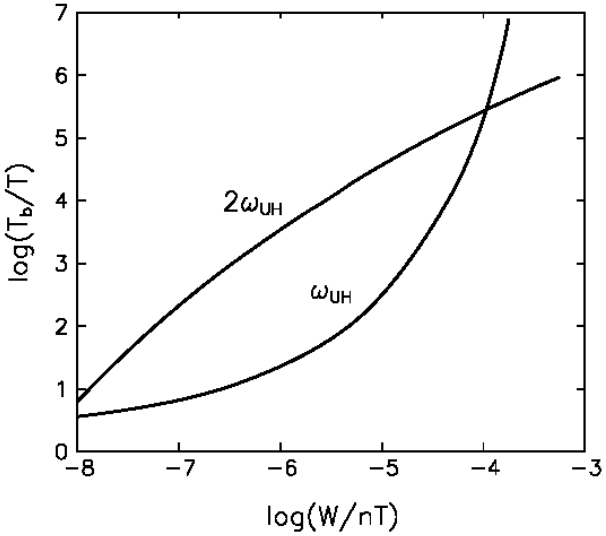
Conversion $l \to t$: Radiation at the fundamental ($\omega = \omega_p$) and harmonic $\omega = 2\omega_p = (4\pi)\times 200$ GHz

Solar plasma radiation:

at sub-THz



at MHz-GHz



Maser-effect $\mu < 0$:

$$\frac{T_{b1}}{T} = 3\frac{m_i}{m_e}\left[\exp(\tau_{n1}) - 1\right] \approx 6\times10^{3}\exp\left(1.5\times10^{7}w\right)$$

$T_{b2} \sim (nT)w^2$ $w = W_p l/nT$

"Transparency" at plasma turbulence level $w \geq 10^{-4}$

Dulk(1985): The free-free optical thickness of 2 ω_p plasma radiation with the same frequency as ωp is lower by a factor of 16.

Plasma radiation in sub-THz range: Scenario

- Disturbance of electric current in flare loop due to ballooning instability.
  Electric field generation

$$E_z = -\frac{|V_r| l_1 I_0}{c^2 r_1 l} \approx (1 \div 5) \times 10^{-2} \ V/cm$$

- Electron acceleration by induced E-field.

$$\varepsilon_s \approx E_z l_1 \approx 500 - 1000\, keV$$

- Generation of plasma waves by beam instability

$$n_s = \frac{q_s}{\varepsilon_s} \frac{l_1}{c} \approx 2 \times 10^{-20} n^2 \approx 5 \times 10^9 \ cm^{-3}$$

- Conversion of plasma waves into electromagnetic ones ($l \longrightarrow t$)

Particle free-flight length:

$$\lambda_{ee} \approx \lambda_{ei} \approx \lambda_{ii} \approx \frac{\varepsilon_s^2}{2\pi n e^4 \Lambda} \approx 5 \times 10^7 \, cm$$

- Heating of chromosphere plasma by accelerated electrons

$$\lambda \leq l_1$$

- Accelerated particles don't leave the source

- Heating rate by fast particles

$$q_s \approx \varepsilon_s 0{,}35 n \nu_{ei} \left(\frac{E_D}{E_z} \right)^{3/8} \exp\left(-\sqrt{\frac{2E_D}{E_z}} - \frac{E_D}{4E_z} \right) \qquad E_D = \frac{6 \times 10^{-8} n}{T} \frac{V}{cm}$$

UV emission from hot loop foot-points

UV emision in the range $\nu_1 < \nu < \nu_2$ (Shklovsky, 1965):

$$\mathfrak{I} = 1.55\times10^{-52}\left(\frac{10^6}{T}\right)^{1/2}\left[e^{\frac{-h(\nu_1-\nu_0)}{k_BT}} - e^{\frac{-h(\nu_2-\nu_0)}{k_BT}} + \frac{k_BT}{2h\nu_0}\left(e^{\frac{-h\nu_1}{k_BT}} - e^{\frac{-h\nu_2}{k_BT}}\right)\right]EM$$

$EM = \iint n^2 dl\, dS \approx n^2 V$, $\nu_0 = 3.28\times10^{15}$ Hz

For $V = (1\text{-}5)\times10^{21}$ cm^3 in the range 225 Å < λ <900 Å,
$\mathfrak{I}$ ≈ (0.05-0.25) erg cm^{-2} s^{-1} for T = 10^6 К
and ≈ (0.08-0.4) erg cm^{-2} s^{-1} for T = 10^7 К.

Bruzek & Durrant (1977): max $\mathfrak{I}$ in flares 10^{-2}-10^1 erg cm^{-2} s^{-1}

2019

Mechanism	Arguments for	Arguments against	New arguments for
Free-free	Known mechanism Can produce $dF_\nu/d\nu > 0$	Extended sources	Yes, extended sources Light curves ≈ SHR
Synchrotron (electrons)	Known mechanism Can produce $dF_\nu/d\nu > 0$	Extreme parameters required	
Synchrotron (positrons)	Known mechanism Can produce $dF_\nu/d\nu > 0$ Correlation with γ-rays	Extreme parameters required Not enough positrons?	
Vavilov-Cherenkov	Can produce $dF_\nu/d\nu > 0$ Rapid variations High luminosity	Dielectric properties unknown Relativistic particles required	
Microbunching	Association with GHz	THz from gyrosynchrotron Source of bunching unclear Coronal μwave unclear	
Plasma emission	Correlation with γ-rays High luminosity Can produce $dF_\nu/d\nu > 0$	High B > 2000 G Source size?	Chromosphere transparency
Diffusive radiation	Can produce $dF_\nu/d\nu > 0$	Origin of Langmuir waves	
Gyrosynchrotron	Can produce $dF_\nu/d\nu > 0$	Extreme parameters required Thermal HXR not observed	Gyrosynchrotron + Free-free
Synchrotron maser	Can produce $dF_\nu/d\nu > 0$ High luminosity	Extreme parameters required	
Inverse Compton	Association with GHz	Not enough photons	

To the pulsation origin

(i) Thermal approach: Radiation losses lead to effective cooling (Kontar et al. A&A 620, A95, 2018)

Cox & Tucker (1969);
Bian et al. (2016):

$$\Delta t_{\mathrm{rad}} = 3\frac{k_{\mathrm{B}} T}{n_{\mathrm{e}} \Lambda}$$

But what are drivers for pulsations?

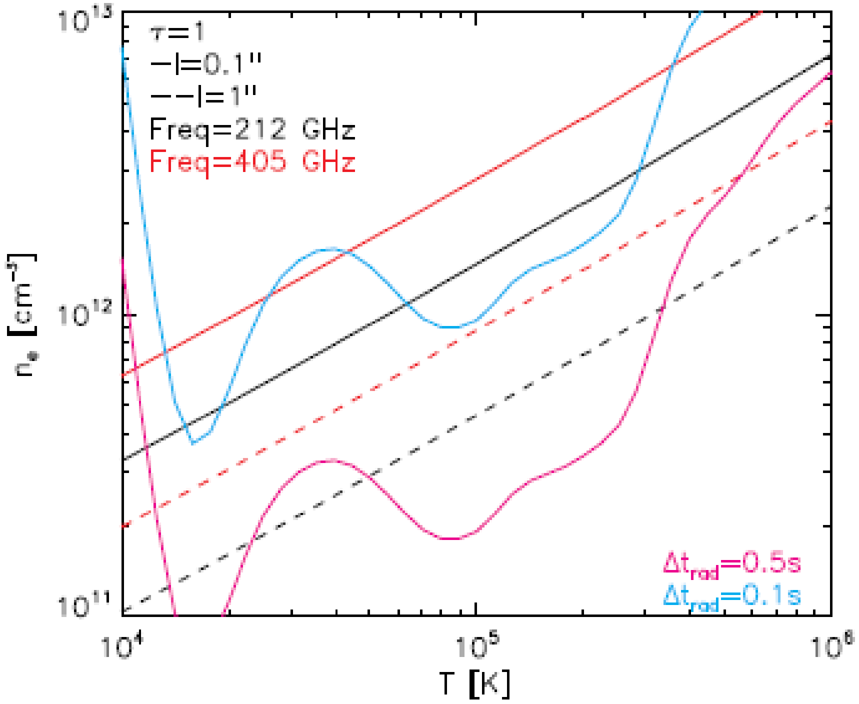


Fig. 3. Electron number density n_e vs. temperature for $T = 10^4 - 10^6$ K, $\tau = 1$, and a geometrical depth of $l = 0.1''$ (solid lines) and $l = 1''$ (dashed lines) for $\nu = 212$ (*black*) and 405 GHz (*red*). The pink and blue lines indicate n_e for the radiative loss times of $\Delta t_{\mathrm{rad}} = 0.5, 0.1$ s, respectively.

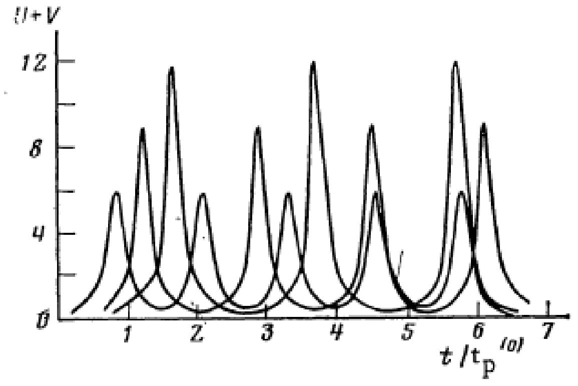
Существующие механизмы пульсаций

Уравнение Ло́тки — Вольте́рры (Zaitsev 1971) – не подходит: $P \approx (\gamma\nu)^{-1/2}$ ~ мс

Сейчас не удается отобразить рисунок.

$$\frac{dw}{dt} = \gamma w - \xi w w^*$$

$$\frac{dw^*}{dt} = \xi w w^* - \nu w^*$$



БМЗ-колебания (Qin et al 1996) не объясняют $R(F)$, кроме того $Q \ll 10^2$ из-за потерь на излучение при $n \sim 10^{15}$ cm^{-3}. Увеличение R с ростом F требует $\beta > 1$.

$$P_{ÂÌÇ} \approx \frac{r}{\sqrt{c_A{}^2 + c_s{}^2}} \approx 0.1-1\tilde{n} \qquad c_s{}^2 = \frac{2\gamma k_B T}{M} > c_A{}^2 = \frac{B^2}{4\pi n M}, \beta > 1? \qquad \nu_r \propto n^2 \Phi(T)$$

Медленная МЗ-мода: период растёт со временем.

Изгибная мода: $P = l/c_A \geq 10$ с.

Вспышечная арка как RLC-контур

Для малых возмущений тока уравнение осциллятора (Khodachenko et al. 2009):

$$\frac{L}{c}\frac{\partial^2 \tilde{I}}{\partial t^2} + \left[R(I) - \frac{|V_r|\, l_1}{r\, c^2}\right]\frac{\partial \tilde{I}}{\partial t} + \frac{\tilde{I}}{C(I)} = 0$$

$$\tilde{I} << I$$

Возбуждение при

$$\boxed{R(I) < |V_r|\, l_1/(rc^2)}$$

$$R \approx 4\frac{I^2 l_1 \alpha^2}{c^4 n m_i \nu_{ia} \pi r^4} \qquad L \approx 4 l_2 \left(\ln\frac{8 l_2}{\pi r_2} - \frac{7}{4}\right) \qquad C \approx \frac{c^4 n m_i S^2}{2\pi l_2 I^2} = \varepsilon_A \frac{S}{l_2}, \quad \varepsilon_A = \frac{c^2}{c_A^2}$$

Частота осцилляций $\nu_r = \omega_0/2\pi$ определяется I_0 и параметрами корональной части арки

$$\omega_0 = \frac{c}{\sqrt{LC(I_0)}} \approx \frac{1}{(2\pi)^{1/2}\sqrt{\Lambda}}\,\frac{I_0}{c r_2^2 \sqrt{n_2 m_i}}$$

$$\Lambda = \ln\frac{4 l_2}{\pi r_2} - \frac{7}{4}$$

При $\nu_r = 8$ s^{-1} в максимуме вспышки до $\nu_r = 0.2$ s^{-1} в фазе затухания ток уменьшается от $I_0 = 2\times10^{12}$ A до $I_0 = 4\times10^{10}$ A .

Alfven & Carlqvist, Solar Phys. 1967

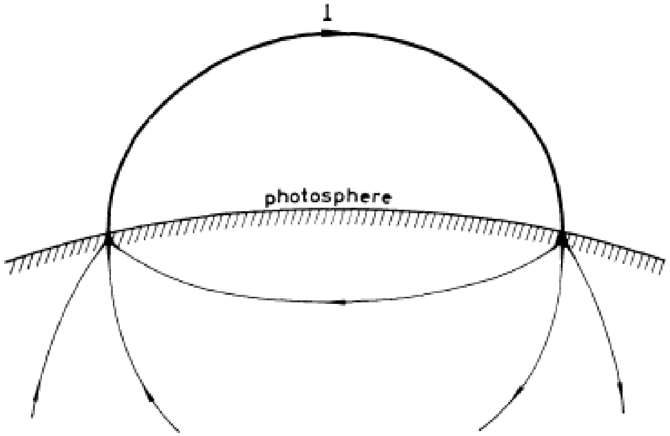


Fig. 4. General pattern of electric currents in the solar atmosphere. The current exists in narrow channels passing through the solar atmosphere and is closed in the photosphere or in deeper layers.

current $I = 10^{11}$ amps

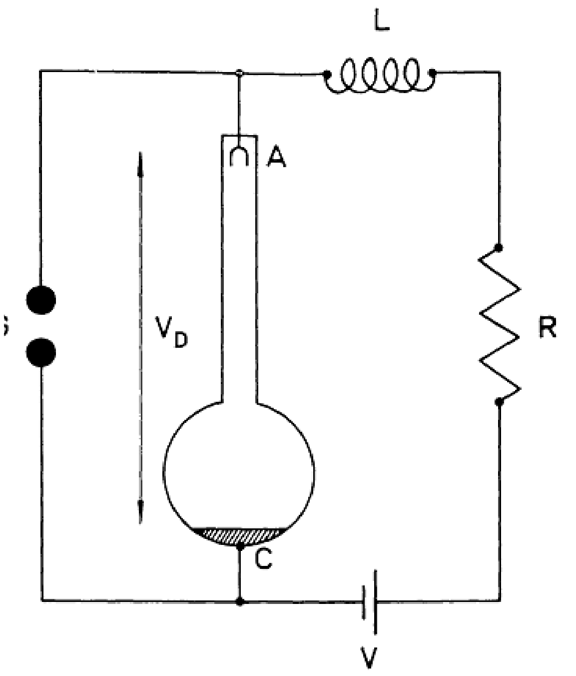
inductance $L = 10\ H$

time constant $\tau = 10^3$ sec

voltage drop over the interruption $V = L\, dI/dt \approx LI/\tau = 10^9$ volts

magnetic energy of the circuit $W = \frac{1}{2} LI^2 = 0.5 \cdot 10^{23}$ joules $= 0.5 \cdot 10^{30}$ ergs

CURRENTS IN THE SOLAR ATMOSPHERE, AND SOLAR FLARES



Electric circuit approach for flaring energy release:

Stenflo (1969); Sen & White (1972); Spicer (1977); Kan, Akasofu, Lee (1982); Ionson (1982); Zaitsev & Stepanov (1991); Stepanov & Tsap (1993); Melrose (1995); Wheatland & Melrose (1995); Zaitsev et al (2000)

RLC-модель пульсаций в суб-ТГц диапазоне

Модифицированные А-колебания: $v_{RLC} = V_{A\varphi}/r$ – это RLC-колебания с **k** почти перпендикулярном магнитному полю ***B*** ($\cos\theta = B\varphi/Bz << 1$).

Триггер вспышки: – проникающие в хромосферные основания арки «языки» плазмы вследствие неустойчивости баллонной моды.

Определим добротность $Q = R^{-1}(L/C)^{1/2}$

$L \approx 10l = 10^{10}$ см $= 10$ Гн; $C = (c^2/V_A{}^2)S/l \approx 10^{11}$ см $= 0.1$ Ф.

Период $P = \sqrt{LC} \approx 1$ с. Средний эл. ток во вспышке $I \approx 3\times10^{11}$ А.

Из мощности вспышки: $R_{\rm eff} = W/I^{2} = (10^{19}\text{-}\ 10^{20})/10^{23} = 10^{-4}\ \text{-}\ 10^{-3}$ Ом

Пороговое R:

$$R_{eff} \approx |V_r|\, l_1 / c^2 r_1 \approx (1-5)\times10^{-3}\,\Omega \quad ,$$

Сопротивление Каулинга в хромосфере: $R_{xp} \approx 10^{-3}$ Ом, т.е. $\mathbf{Q \approx 10^4 >> 1}$

Вспышечная арка как RLC-контур

Для малых возмущений тока уравнение осциллятора (Khodachenko et al. 2009):

Возбуждение при

$$\frac{L}{c}\frac{\partial^2 \tilde{I}}{\partial t^2} + \left[R(I) - \frac{|V_r|\, l_1}{r\, c^2}\right]\frac{\partial \tilde{I}}{\partial t} + \frac{\tilde{I}}{C(I)} = 0$$

$$\tilde{I} << I$$

$$\boxed{R(I) < |V_r|\, l_1 / (r c^2)}$$

$$R \approx 4\frac{I^2 l_1 \alpha^2}{c^4 n m_i \nu_{ia} \pi r^4} \qquad L \approx 4 l_2\left(\ln\frac{8 l_2}{\pi r_2} - \frac{7}{4}\right) \qquad C \approx \frac{c^4 n m_i S^2}{2\pi l_2 I^2} = \varepsilon_A \frac{S}{l_2}, \quad \varepsilon_A = \frac{c^2}{c_A^2}$$

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$$\omega_0 = \frac{c}{\sqrt{LC(I_0)}} \approx \frac{\mathbf{1}}{(\mathbf{2}\pi)^{1/2}\sqrt{\Lambda}}\;\frac{I_0}{c r_2^2\sqrt{n_2 m_i}}$$

$$\Lambda = \ln\frac{4 l_2}{\pi r_2} - \frac{7}{4}$$

При $\nu_r = 8\ \mathrm{s}^{-1}$ в максимуме вспышки до $\nu_r = 0.2\ \mathrm{s}^{-1}$ в фазе затухания ток уменьшается от $I_0 = 2\times10^{12}$ A до $I_0 = 4\times10^{10}$ A .

Амплитуда пульсаций: Решение нелинейного уравнения для возмущений электрического тока (метод Ван дер Поля)

$$\frac{1}{c^2}L\frac{d^2y}{dt^2}+\left[R(I_0)-\frac{|V_r|l_1}{c^2r_1}\right]\frac{dy}{dt}+\frac{1}{C(I_0)}y=0 \quad\Longrightarrow\quad \frac{d^2y}{d\tau^2}-\varepsilon(\delta-2y-y^2)\frac{dy}{d\tau}+\left(1+\frac{3}{2}y+\frac{1}{2}y^2\right)y=0$$

Малый параметр: $\varepsilon = 1/Q \ll 1 \qquad y=(I-I_0)/I_0 \qquad \tau=\omega_0 t$

$$\delta=\frac{|V_r|\,l_1}{c^2r_1R(I_0)}-1 \qquad y=A(\tau)e^{i\tau}+A^*(\tau)e^{-i\tau} \qquad A(\tau)=\frac{1}{2}a(\tau)e^{i\varphi(\tau)}$$

Решение для амплитуды осцилляций:

$$a(\tau)=\frac{2\sqrt{\delta}}{\left[1+\left(\frac{4\delta-a_0^2}{a_0^2}\right)\exp(-\varepsilon\delta\omega_0 t)\right]^{1/2}}$$

Установившееся значение: $a_\infty=2\sqrt{\delta}=(5\div 8)\times 10^{-2}$

$$y=\frac{I(t)-I_0}{I_0}=2\sqrt{\delta}\cos\left[\omega_0\left(1-\frac{3\sqrt{2}}{8}\delta^{3/2}\right)t\right]$$

Модуляция суб-ТГц излучения обязана модуляции эл. тока → модуляция ускоренных частиц → модуляция уровня плазменной турбулентности.

Хромосферный источник излучения компактный, но осцилляции тока - во всей корональной арке.

Условие синхронизма пульсаций

Альфвеновское время $\tau_A = l / c_A$ должно быть меньше периода осцилляций $\sim 1/\nu_{RLC}$ (lamped circuit),

т.е. $B_\varphi / B_z < 2\sqrt{\zeta}(r/l) \approx 10\ r/l$,

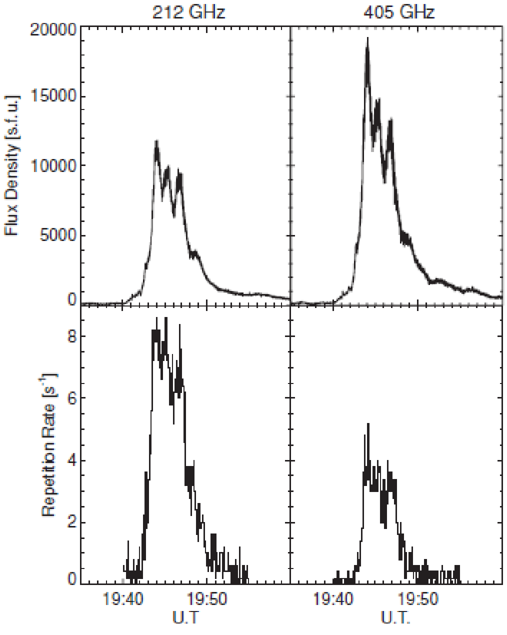
Это выполняется для вспышечных арок с $l/r \sim 10$ и $B_\varphi/B_z < 1$.

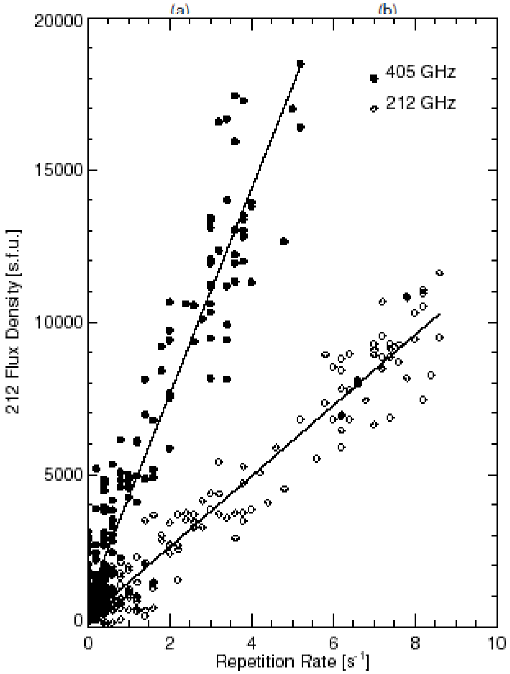
Пропорциональность между потоком излучения и частотой пульсаций можно объяснить откликом на дискретное ускорение электронов в источнике – хромосфере Солнца.

Малые вариации электрического тока вызывают вариации B_{φ}, которые, в свою очередь, приводят к появлению электрического поля вдоль оси вспышечной петли.

Это электрическое поле является причиной дополнительного ускорения электронов и инжекции таких электронов в область излучения. В результате появляются сравнительно небольшие (5-10%) дополнительные импульсы излучения.

С ростом электрического тока растет поток излучения на суб-ТГц и одновременно частота пульсаций. Сложный спектр пульсаций связан с «мгногопетлевой» структурой вспышки.





Плазменный механизм излучения на суб-ТГц объясняет зависимости *F*(*R*)

$$T_{b1} = \frac{a_1}{\mu_{c1}} \propto w \propto n_1\varepsilon_e,$$

$$T_{b2} = \frac{a_2}{\mu_{c2}} \propto w^2 \propto (n_1\varepsilon_e)^2$$

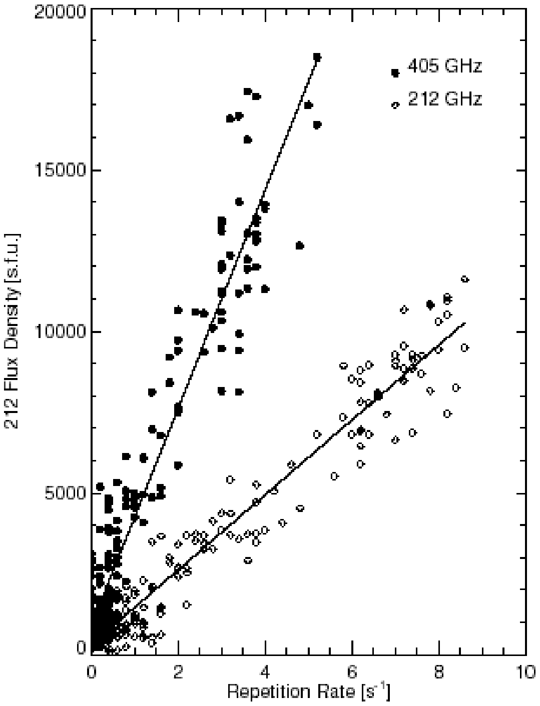
$$T_{b1} \propto I(t),$$

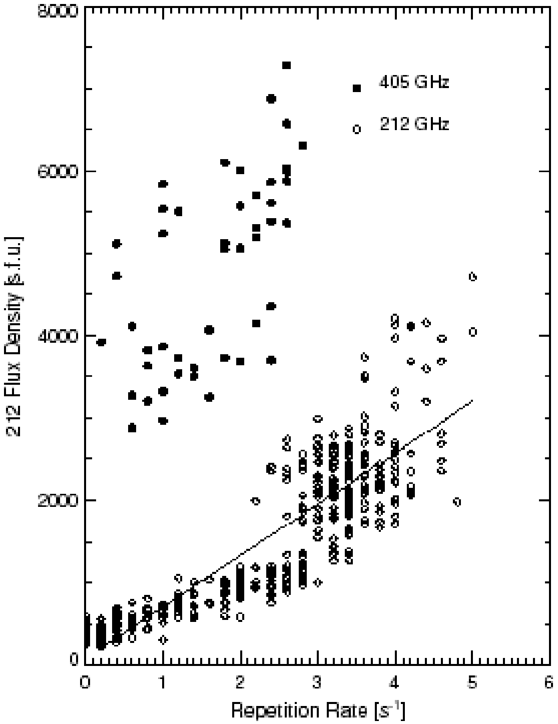
$$\omega_0 \sim I$$

$$T_{b2} \propto I^2(t)$$

$$T_{b1} \propto \omega_0(t),$$

$$T_{b2} \propto \omega_0^2(t)$$





Две «ветви» с *F* = *kR*, с *k*(405 ГГц) ≈ 4*k* (212 ГГц) объясняются связью

$$F_{sfu} \propto T_b \nu^2 S$$

Однако в событии 6 12. 2006 зависимость квадратичная, *F*~R^2.

Пульсации. Выводы

LRC-модель пульсаций, связывающая модуляцию суб-ТГц излучения с собственными колебаниями электрического контура – вспышечной арки, объясняет следующие особенности пульсаций:

(i) Частоту пульсаций (repetition rate) $R = 0.2\text{-}8\ s^{-1}$,
(ii) Высокую добротность пульсаций, $Q > 10^3$,
(iii) Малую амплитуду пульсаций, 5-10%,
(iv) Синхронность пульсаций на разных частотах,
(v) Зависимости $F \sim R$ и $F \sim R^2$, которые свидетельствует в пользу плазменного механизма излучения.

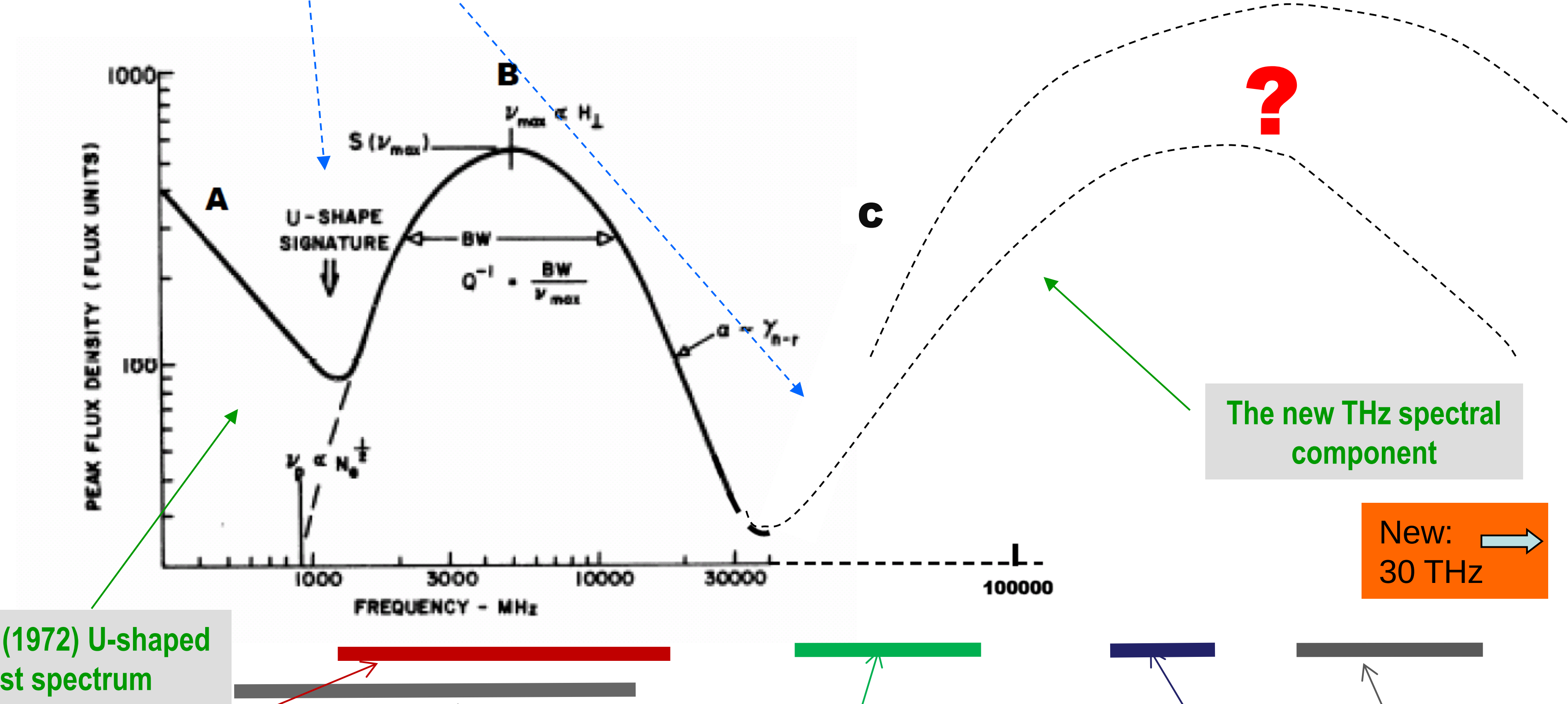
Для понимания физики энерговыделения в хромосфере («хромосферных» вспышек) необходимы многоволновые наблюдения. Важная роль принадлежит исследованию терагерцового излучения (Солнечная часть проекта ALMA).

Radio broadband W-shaped burst spectrum spectral coverage

Smearing mechanisms ?

A: plasma waves
B: gyrosynchrotron
C: ? not known

SOLAR-T



The new THz spectral component

New: ⇨
30 THz

Castelli (1972) U-shaped burst spectrum

1-18 GHz, every 0.2 GHz, Owens Valley Solar Array

0.245-15.4 GHz, 8 frequencies, USAF RSTN

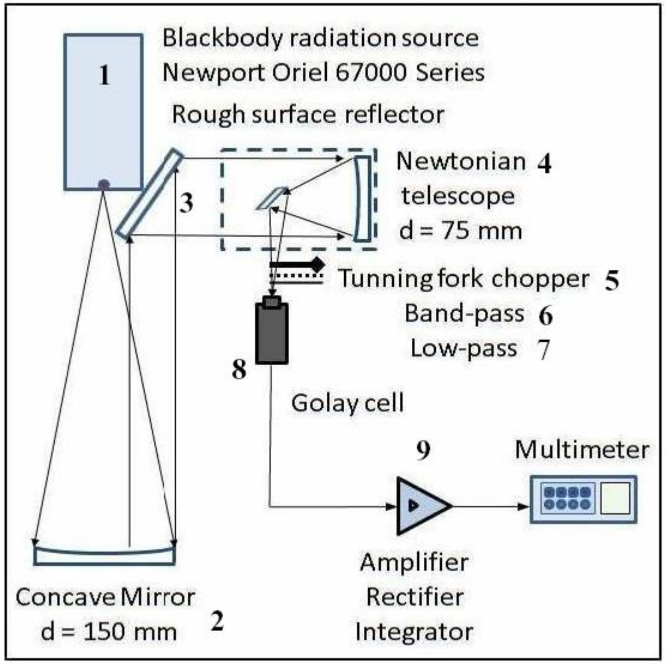
45 & 90 GHz, El Leoncito Patrol Polarimeters 2011

0.2 & 0.4THz, SST, El Leoncito

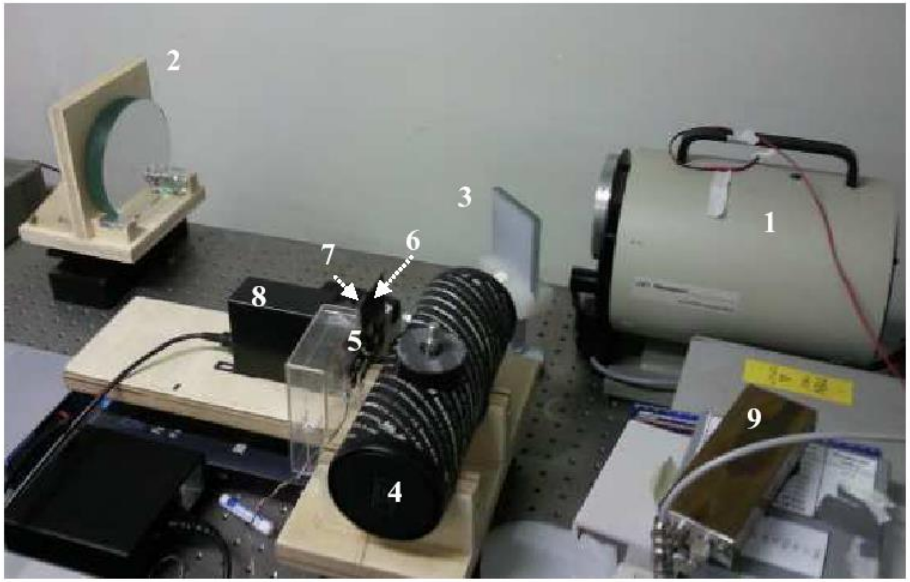
3 & 7 THz Solar-T Balloon

Bauman Inst. 90, 140 GHz

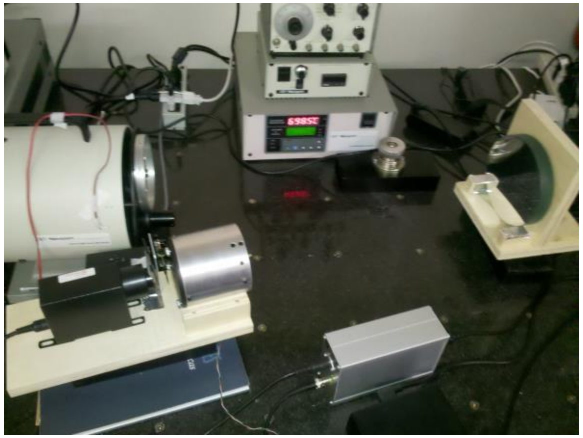
SOLAR-T DOUBLE THz RADIOMETER PROTOTYPES

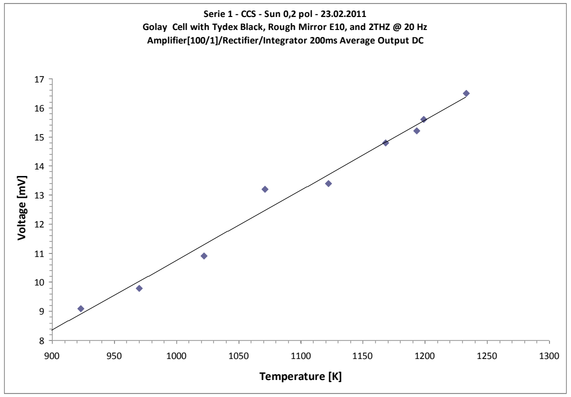


(a)

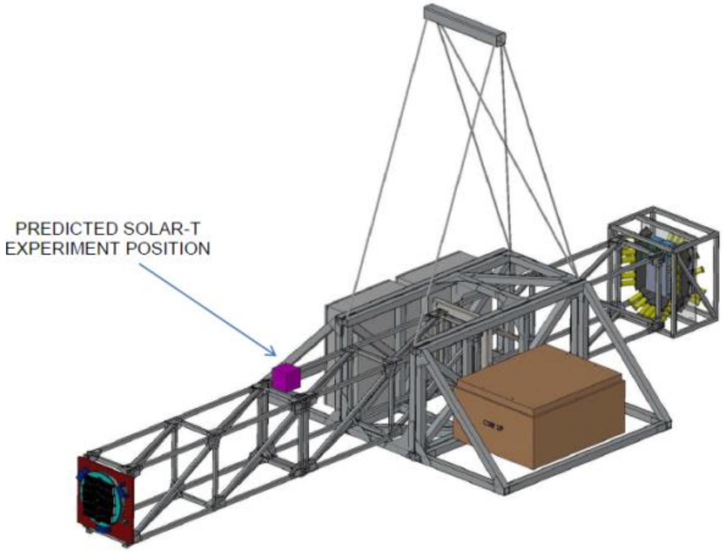


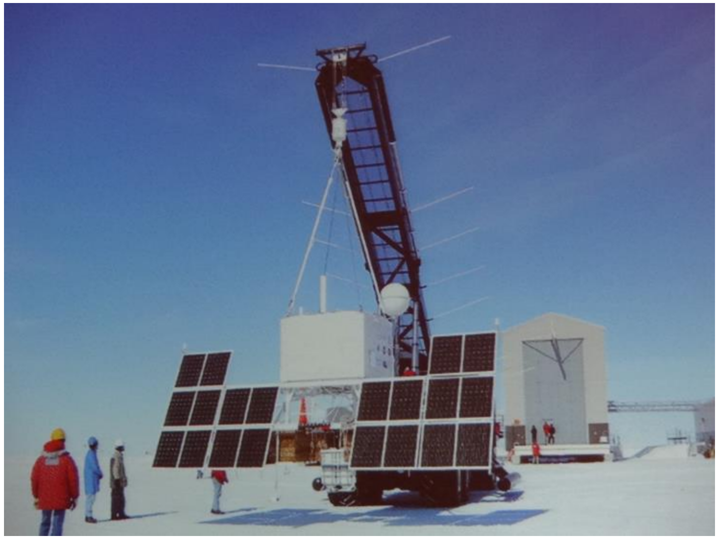
(b)

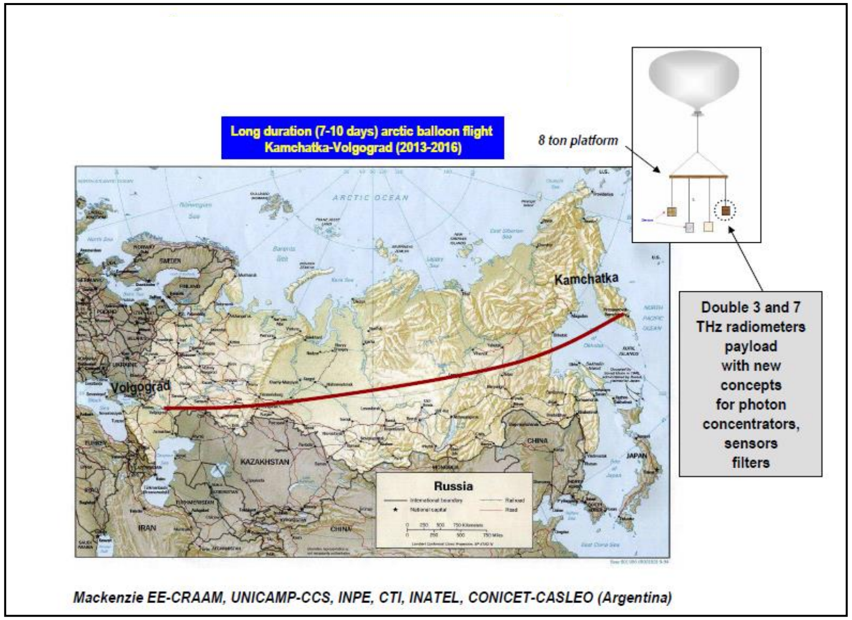




STRATOSPHERIC BALLOON MISSIONS TO CARRY SOLAR-T SOLAR PHOTOMETERS





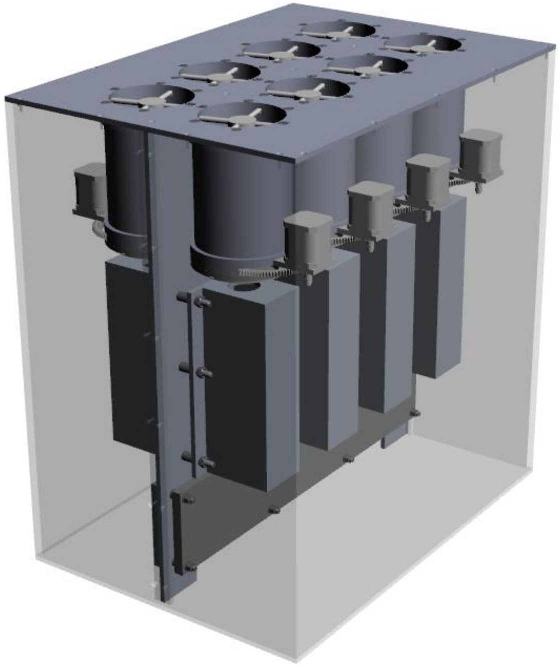


Planned: long duration balloon flight
Lebedev Physical Institute, Moscow, Russia

Макет НА «Солнце-Терагерц» для МКС

ФИАН – МАИ

На первом этапе создан приёмно-детектирующий тракт и изготовлен макет одного канала регистрации ТГц излучения в диапазоне 0,4-10ТГц



Барокамера с помещённым внутрь макетом НА

Conclusion

No consensus about mechanism of sub-THz and THz emission in impulsive phase of solar flares up to now .
New observations directed to the spectral information in sub-THz and THz bands are needed. The main contribution - from observations at sub-THz (93,140, 220, 350, 400 GHz, and 1-30 THz radiation from flares.

Plasma mechanism of sub-THz radiation is realized at the electric currents $\sim 10^{11}$ A in the flare loops due to ballooning mode instability leading to the particle accelerated in the chromosphere, heating of the plasma and the excitation of plasma turbulence. But for $\beta < 1$ $B > 2$kG.

Thermal plasma ($T \sim 10^4 – 10^6$ K) of the chromosphere/transition region with $\tau > 1$ can be responsible for sub-THz radiation with positive slope. The model provides a temperature diagnostic of the flaring chromosphere and transition region.

Spatial resolution is very important!

C. De Jager: “Flares are different”

Новые вызовы:

- Недостатки «стандартной» модели
- «Солнцетрясения»
- Предвестники вспышек

Старая, но нерешённая проблема количества ускоренных частиц (Hoyng, Brown & Van Beek, Solar Phys 1976)

Ji Haisheng et al (2012), Sharykin & Kosovichev (2014):

in situ heating of loop footpoints up to coronal temperatures without precipitating coronal beams.

Simoes, Graham, Fletcher (2015):

beam heating alone isn’t sufficient to heat ribbon plasma at 10 MT even low-energy cutoff = 8 keV.

Что предлагается:

- Важная роль фотосферы и хромосферы
- Важная роль электрических токов и индуцированных электрических полей
- Развитие идеи Альфвена: Вспышка – эквивалентный электрический контур
- Роль неустойчивости Рэлея-Тейлора
- Перспективы ТГц исследований активного Солнца

Спасибо