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Физика плазмы в Солнечной системе
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Особенности субтерагерцового излучения солнечных вспышек

В.С. Махмутов, Г.А. Базилевская, Ю.И. Стожков, А.А. Квашнин

Физический институт им. П.Н. Лебедева РАН, г. Москва,

В докладе представлены особенности субтерагерцового излучения солнечных вспышек, установленные из данных наземных радионаблюдений в последние 15 лет. Обращено внимание на динамику спектра радиоизлучения в процессе развития солнечной вспышки. Обсуждаются перспективы исследования солнечных вспышечных событий в терагерцовом диапазоне электромагнитного излучения Солнца.

Терагерцовым излучением называется электромагнитное излучение в интервале частот от **0,3 до 10 ТГц, т.е. $0{,}3 \cdot 10^{12} – 10 \cdot 10^{12}$ Гц (длина волны 1 мм – 30 мкм).**

- часть электромагнитного спектра между инфракрасным (ИК) и микроволновым диапазонами, поэтому его часто также называют дальним ИК или субмиллиметровым диапазоном.

- в терагерцовом диапазоне лежат спектры излучения астрономических объектов,

- а также спектры сложных органических молекул (таких как молекулы белков и ДНК,

- некоторых взрывчатых веществ, вредных веществ – загрязнителей атмосферы).

- современные технологии позволяют создавать квантово-размерные объекты, такие как квантовые точки. Энергии возбуждения квантовых точек соответствуют энергии фотонов терагерцового излучения, поэтому с его помощью можно когерентно управлять такими объектами.

- ТГц излучение безвредно для человека, что позволяет применять его для медицинской диагностики, в современных системах безопасности,

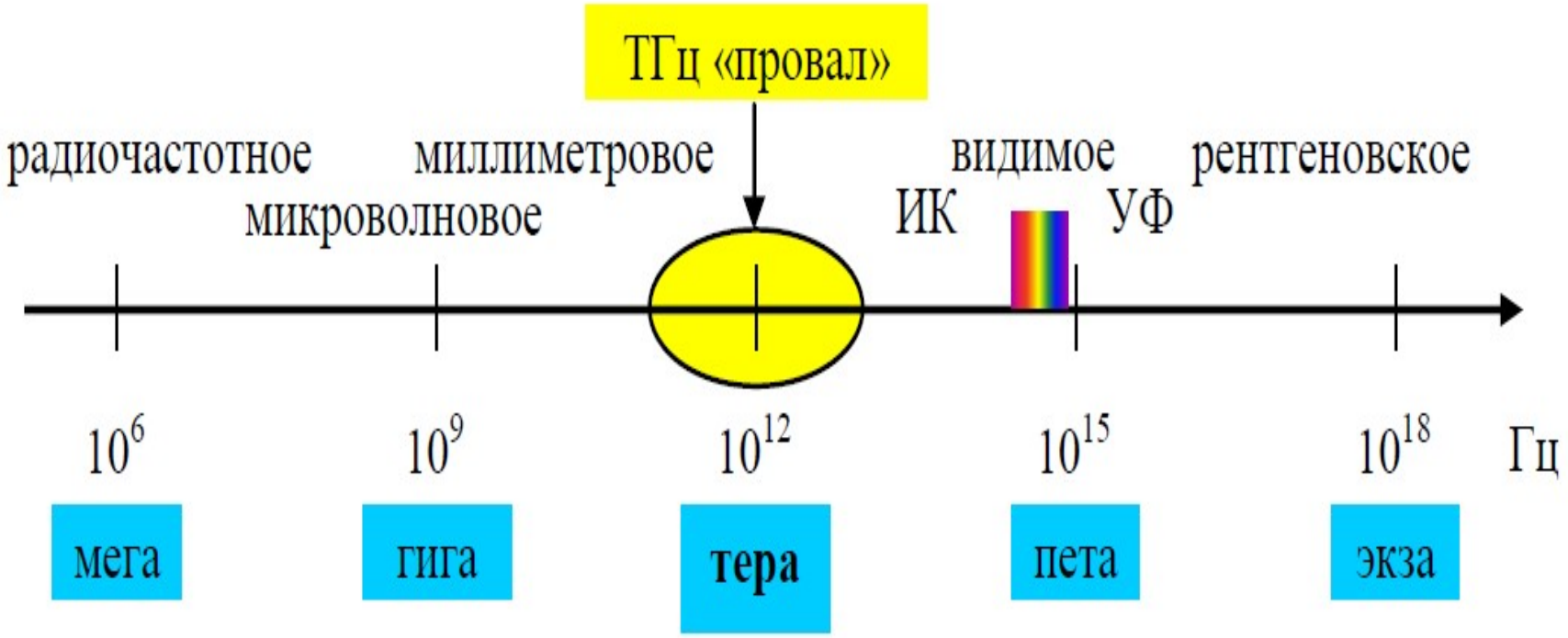


Рис. 1.1. Спектр электромагнитных волн и терагерцовый «провал».

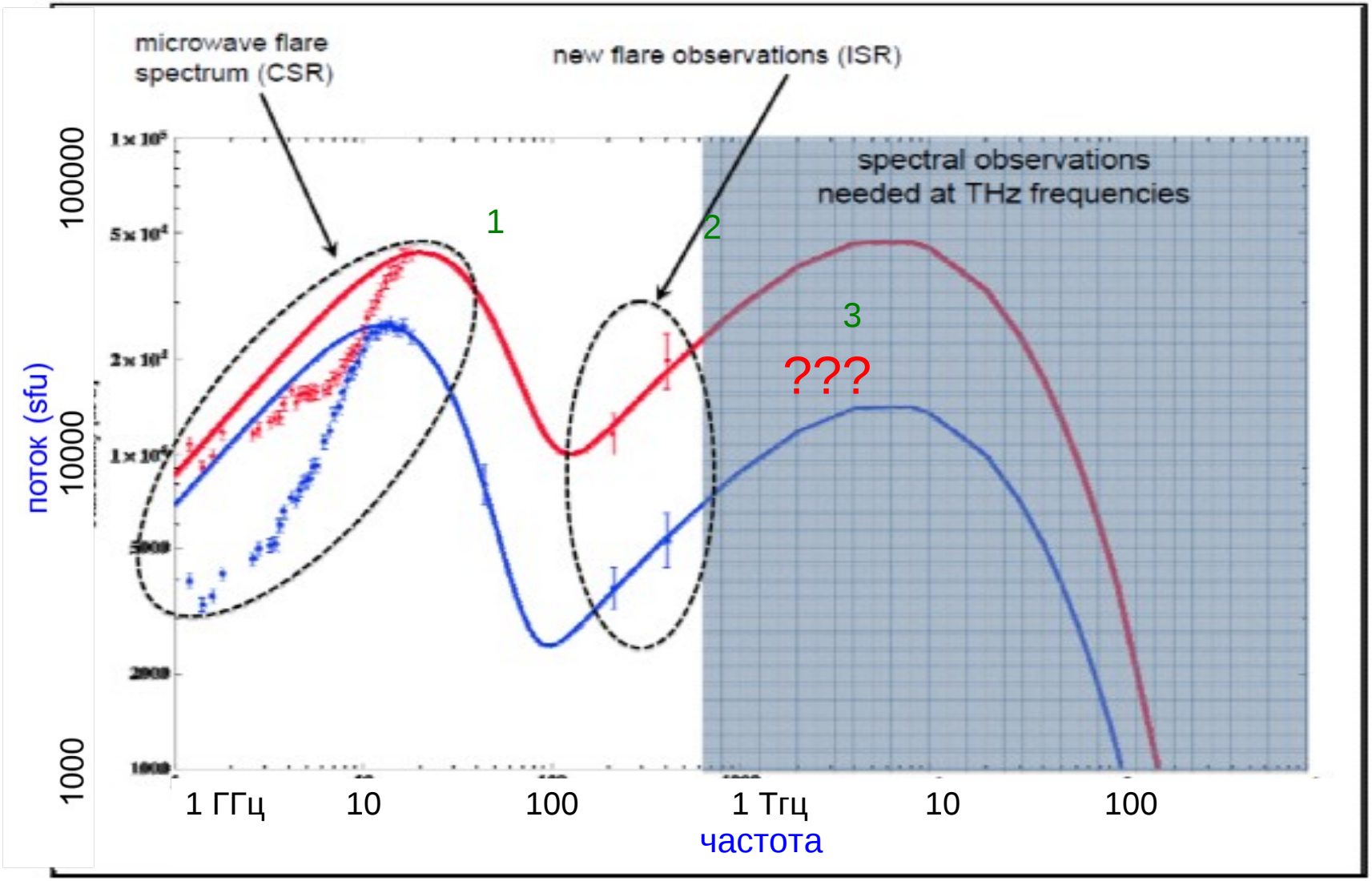
эквивалентная температура излучения частотой 1 ТГц составляет ~ 47,6 К

Солнце: T~5800 K, λmax~0.6 μm (ν~ 550 ТГц)

Земля: T~300 K, λmax~10 μm (ν~30 ТГц)

астероиды: T= 10 K, λmax=300 μm (ν= 1 ТГц)

реликт. изл.: T= 2.7 K, λmax~1100 μm (ν~0.27 ТГц)



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

СОЛНЕЧНЫЙ СУБМИЛЛИМЕТРОВЫЙ ТЕЛЕСКОП

(CASLEO, 2550 m, Rc = 9.65 GV)

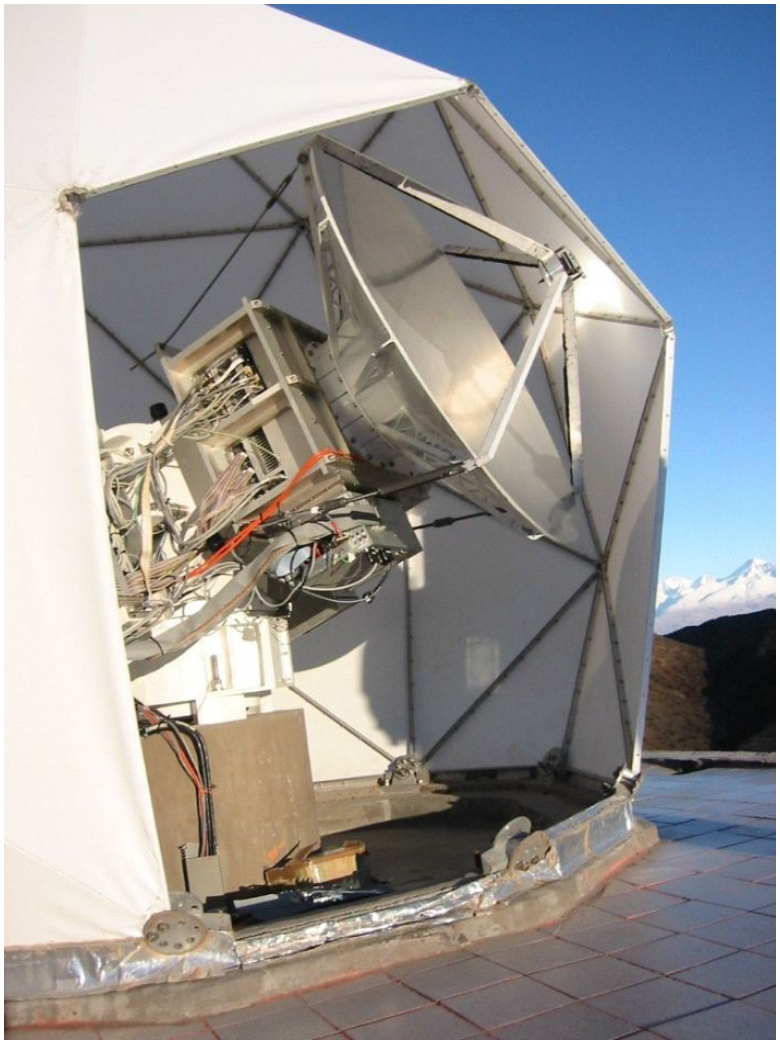
P. Kaufmann, J.-P. Raulin , C.G. Gimenez de Castro, E. Correia, G. Fernandez , A. Marun , R. Godoy.

CRAAM

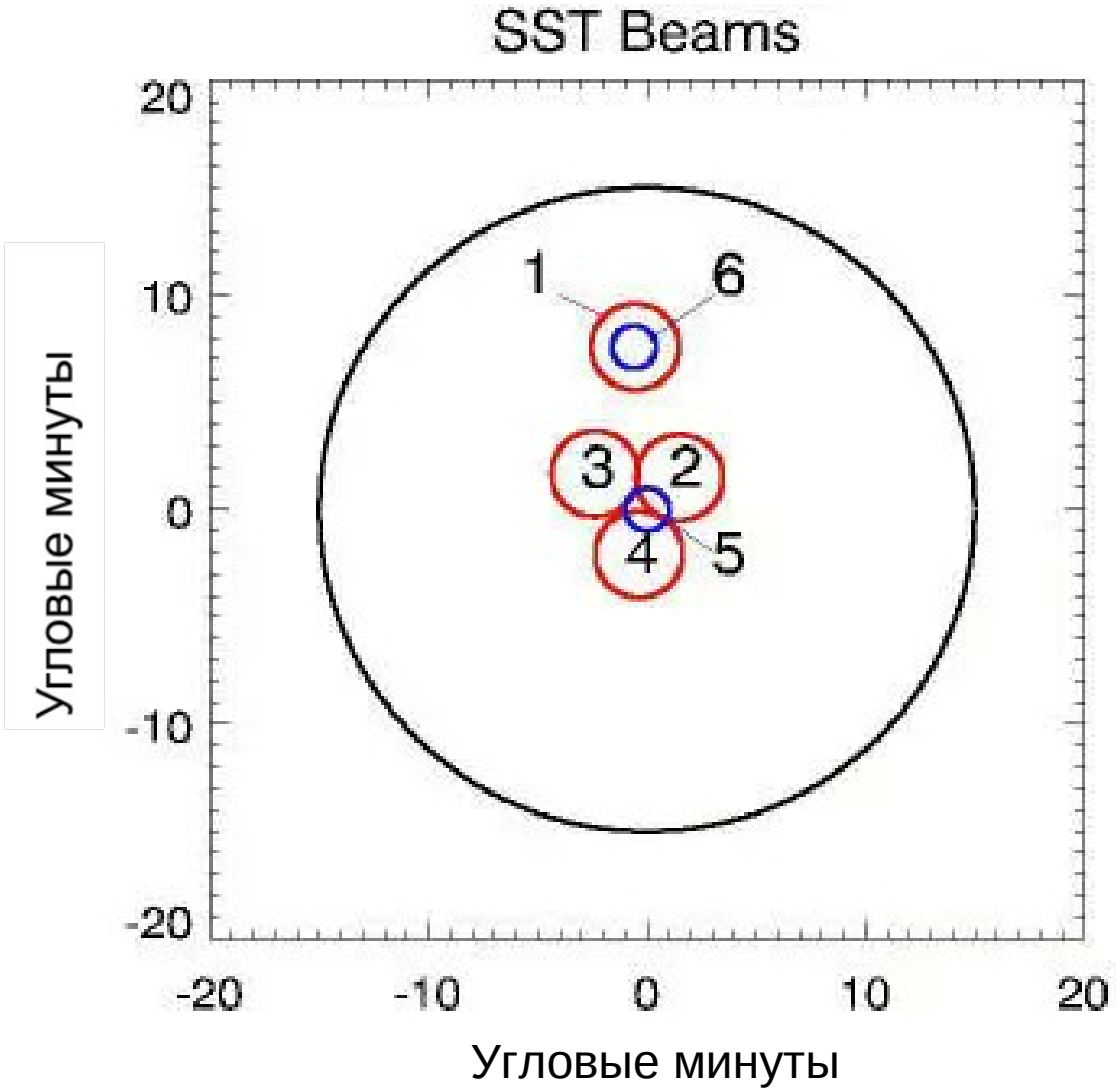
COMPLEJO ASTRONOMICO EL LEONCITO

РОССИЙСКАЯ АКАДЕМИЯ НАУК
Физический институт имени П.Н.Лебедева
Ф И А Н

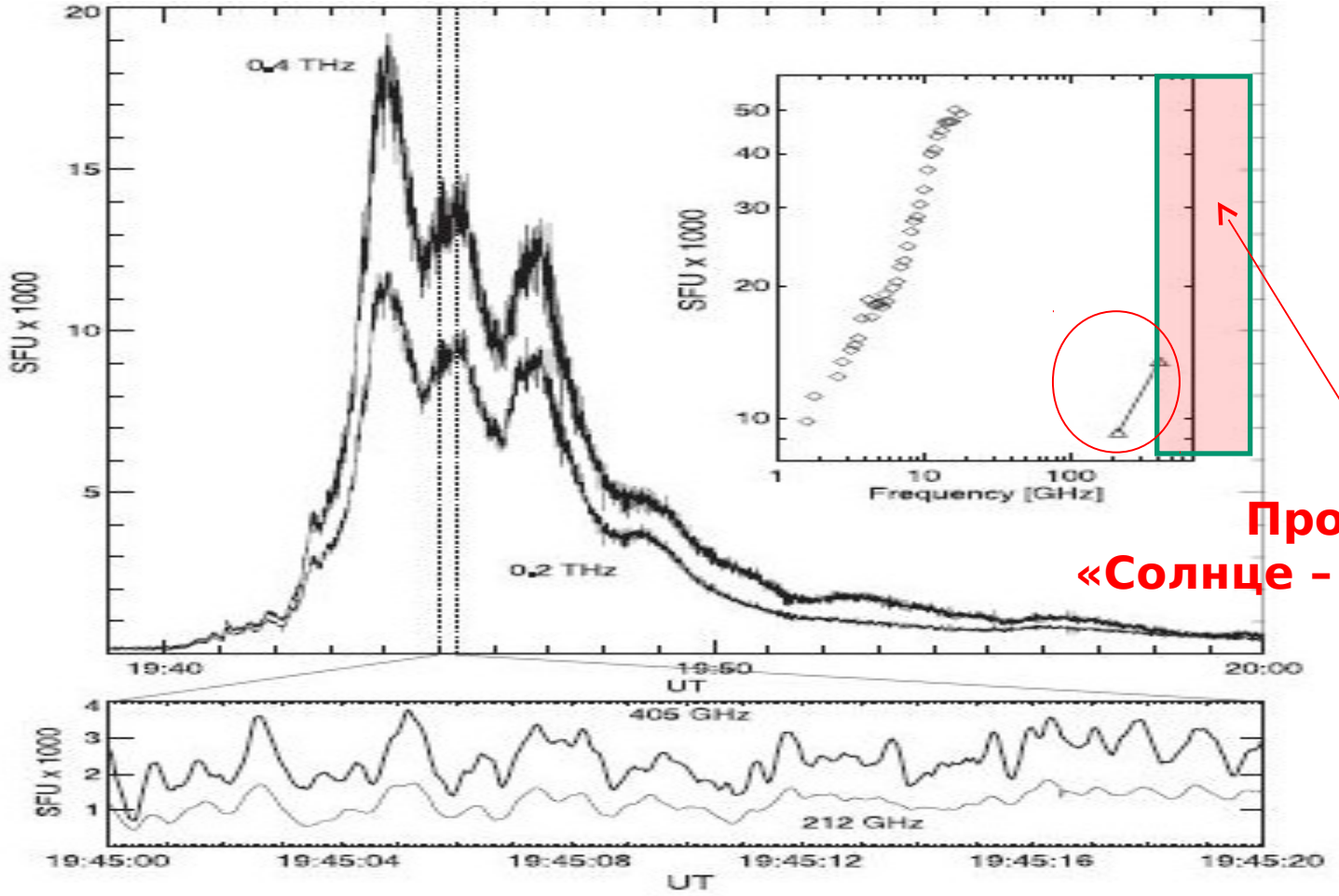
INPE
MINISTÉRIO DA CIÊNCIA E TECNOLOGIA
INSTITUTO NACIONAL DE PESQUISAS ESPACIAIS



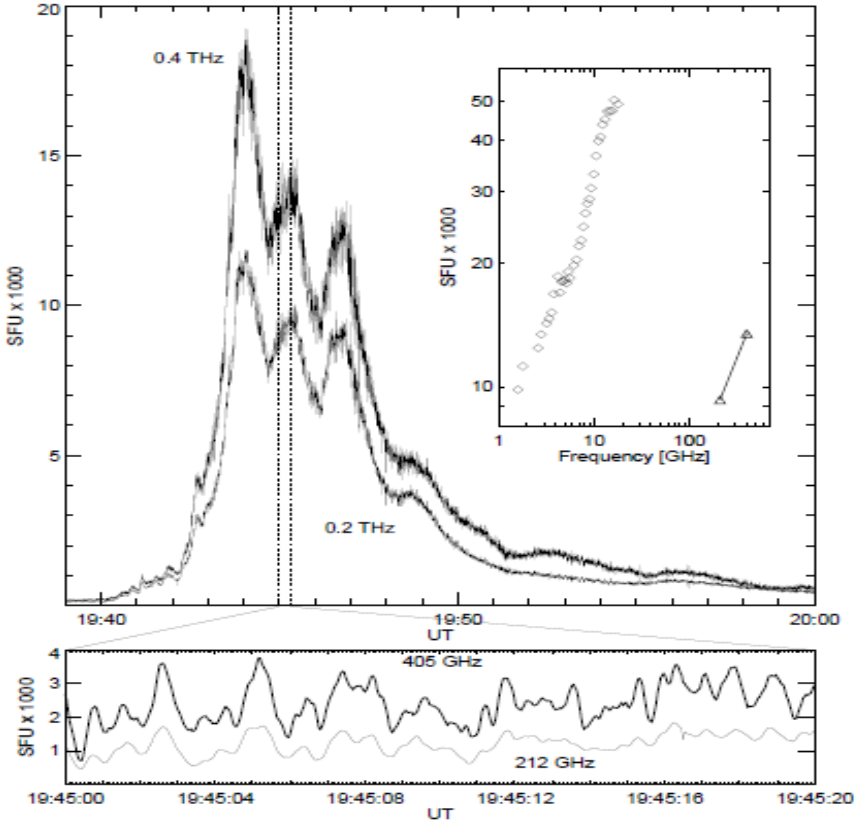
Солнечный субмиллиметровый телескоп (Solar Submillimeter wave Telescope), установленный в астрономическом комплексе Каслео (CASLEO, Аргентина. В фокусе его 1.5- метровой антенны расположены 4 радиометра для измерения потоков излучения на 212 ГГц и 2 радиометра - для приема 405 ГГц излучения.



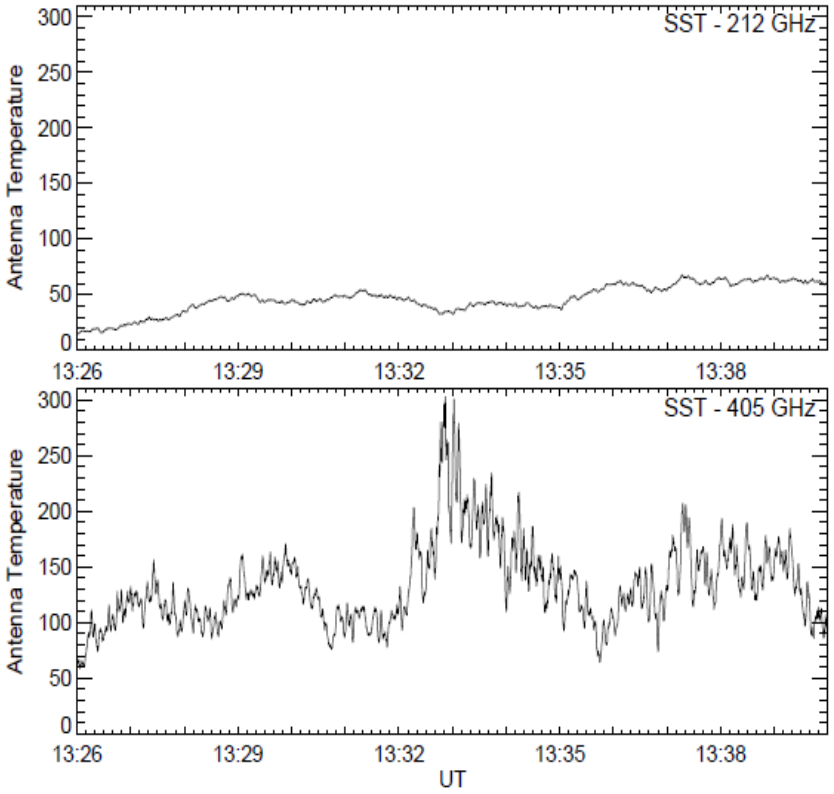
Проекция радиометров солнечного субмиллиметрового телескопа (SST) на солнечном диске: радиометры 1-4 для приема 212 ГГц волн, а радиометры 5,6 — для измерения 405 ГГц излучения.



Первый случай обнаружения: мощная солнечная вспышка, зарегистрированная в субтерагерцовом диапазоне 4 ноября 2003 г. Показан временной профиль потока радиоизлучения на частотах 0.2 и 0.4 ТГц. Нижняя панель показывает 20 секундные данные в увеличенном масштабе. На врезке дан частотный спектр вспышки, где виден хорошо изученный микроволновой спектр (<100 ГГц) и новая компонента в

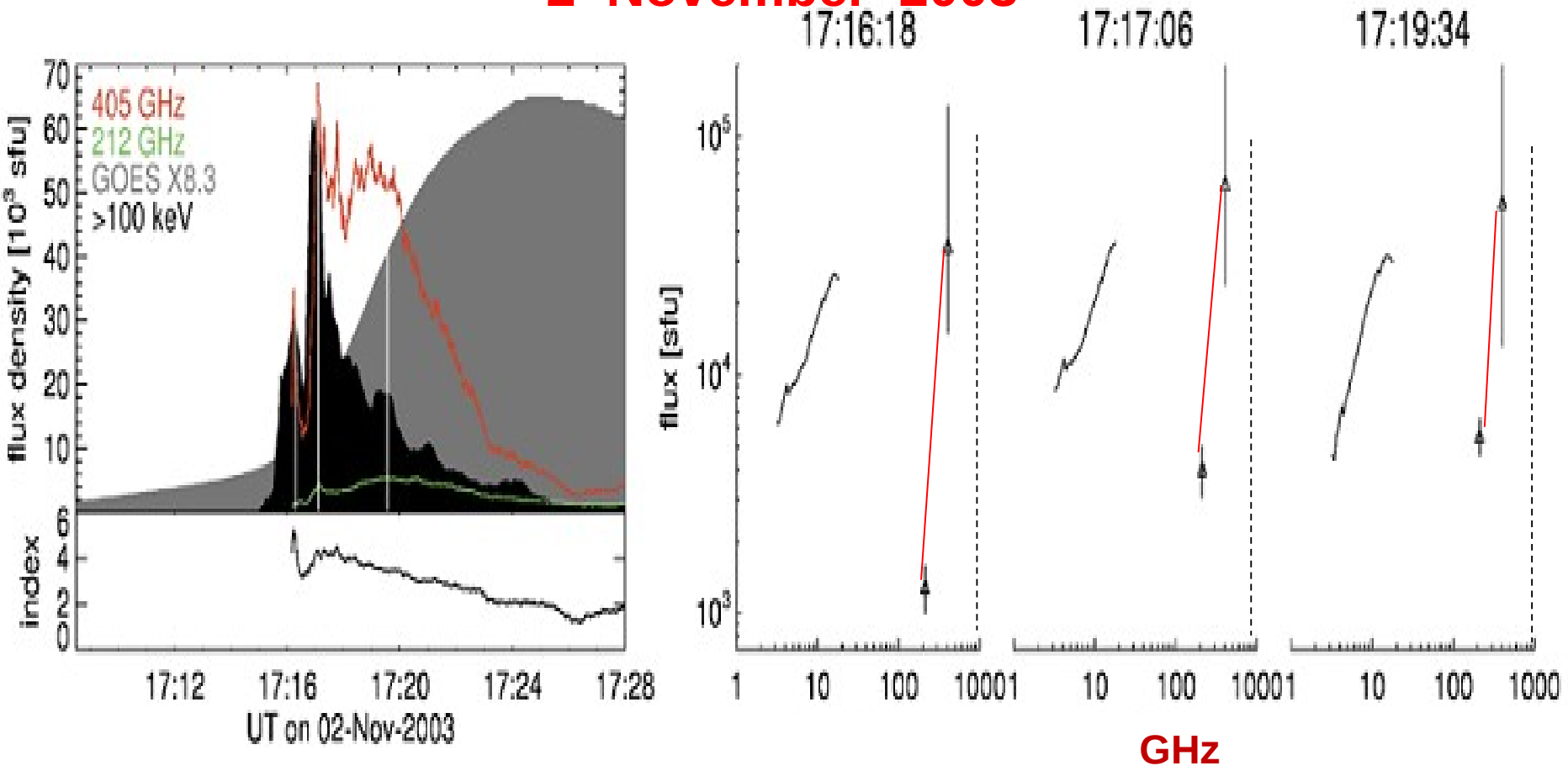


The largest sub-THz solar burst observed by the SST telescope [1] that occurred on November 4, 2003 showing the time profiles at 0.2 and 0.4 THz. The bottom panel shows a 20 s zoom of the first peak of the event, exhibiting intense subsecond time structures. The inner panel shows the "double spectral" features, with the well known microwaves and the new THz component [2,3].



One of the smallest solar burst recorded on February 8, 2010, showing complex time structures observed at 0.4 THz only. Intensity is given in equivalent antenna excess noise temperature, with a peak of about 150 K at 0.4 THz and less than 10 K at 0.2 K, corresponding to 100 and 4 solar flux units, respectively [6].

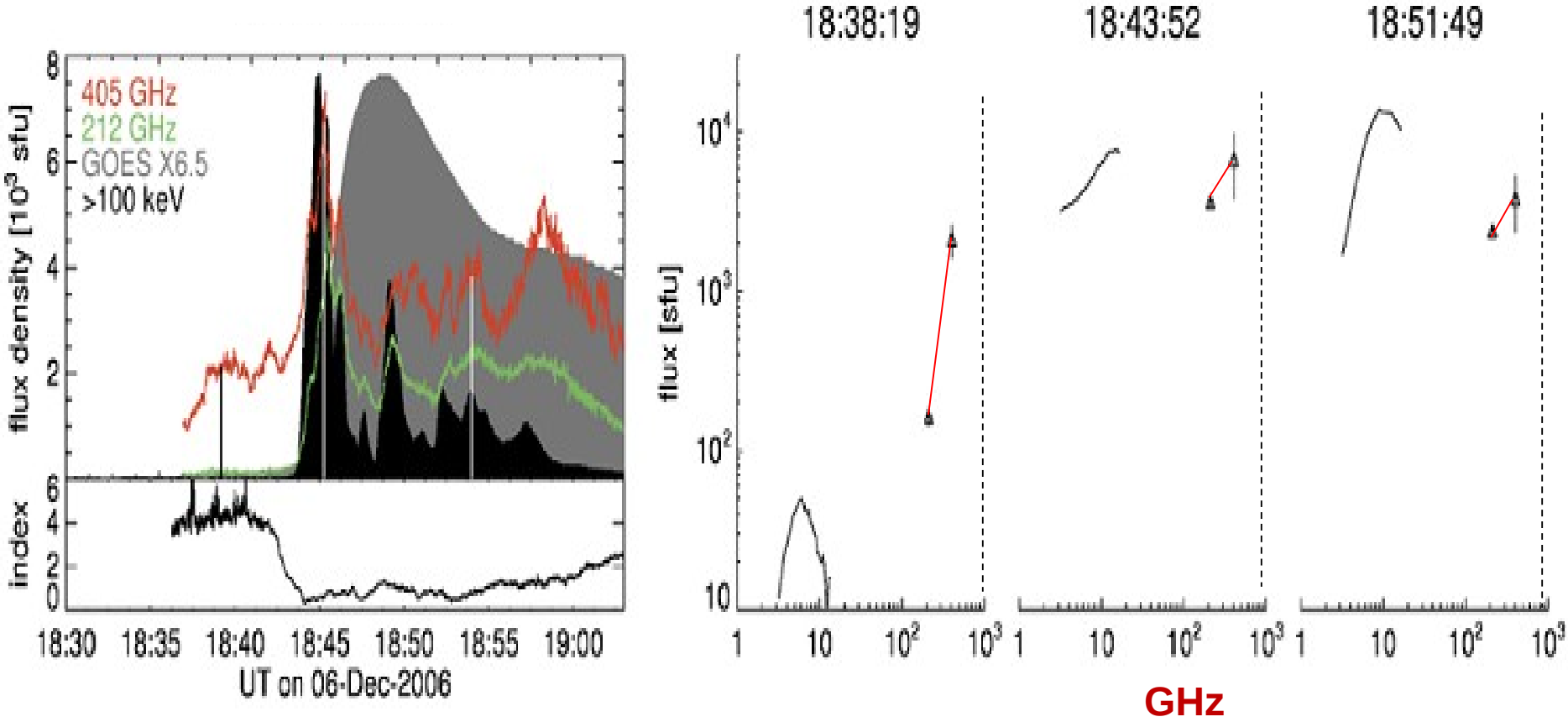
2 November 2003



Normalized linear-scale light curves, and at the bottom the variation of the spectral index inferred from the 405/212 GHz ratio;right: spectra. The smooth gray curves represent the GOES soft X-ray channel; the black curves are the HXR flux from RHESSI. Vertical lines on the light curves designate the times of the individual spectra.

Krucker et al.,Astron Astrophys Rev (2013)

6 December 2006



Normalized linear-scale light curves, and at the bottom the variation of the spectral index inferred from the 405/212 GHz ratio;right: spectra. The smooth gray curves represent the GOES soft X-ray channel; the black curves are the HXR flux from RHESSI. Vertical lines on the light curves designate the times of the individual spectra.

Krucker et al.,Astron. Astrophys. Rev. (2013)

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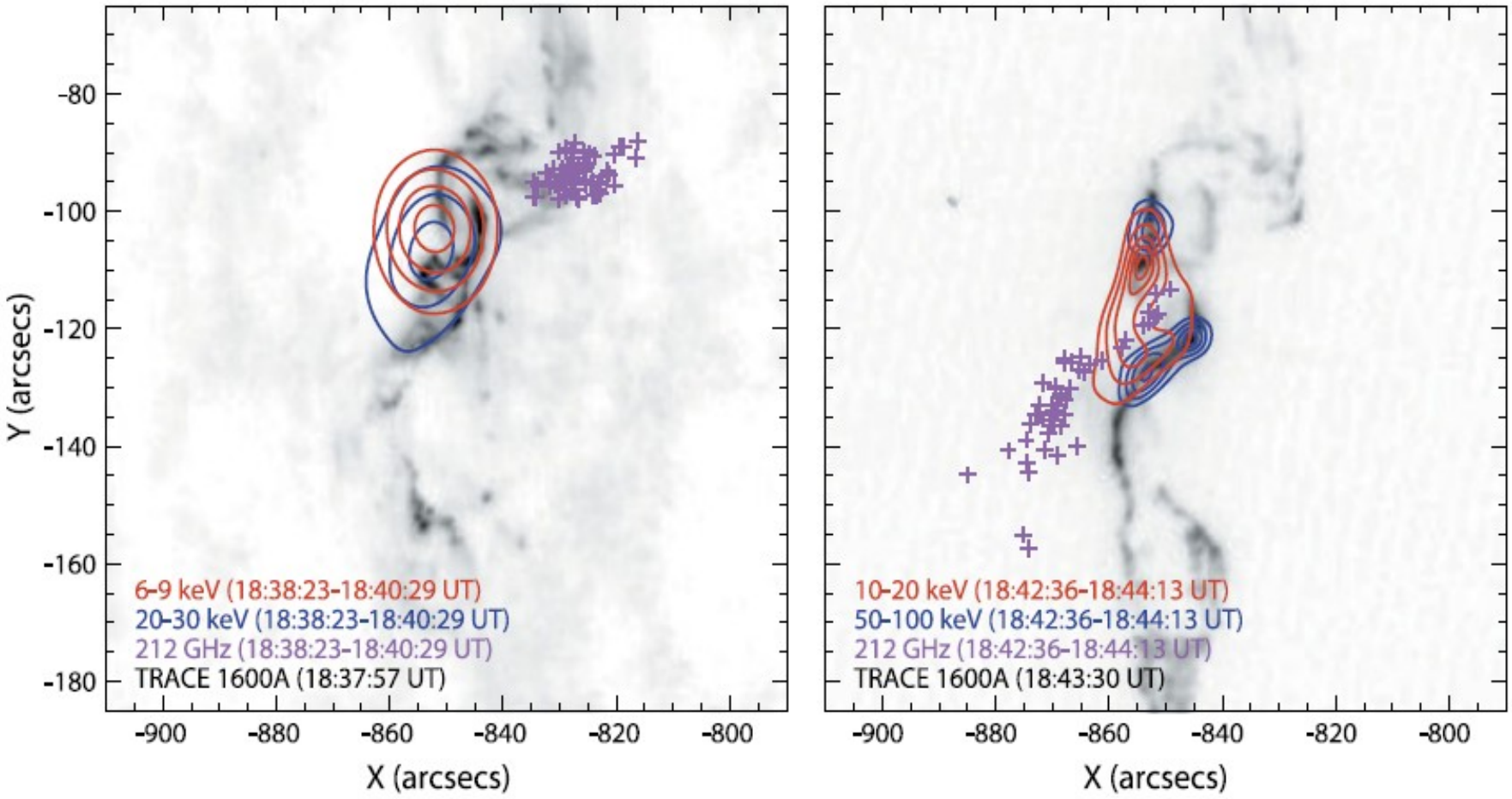


Time-resolved imaging of SOL2006-12-06T18:47 during (left) the rise phase of the event, and (right) the main impulsive peak. The underlying gray-scale image is a 1600 Å UV continuum image from TRACE, red contours show the location of predominantly thermal soft X-rays, blue contours show higher- energy non-thermal hard X-rays, and the purple crosses show sequential measurements of the location of the 212 GHz source from SST data. ***Krucker et al.,Astron Astrophys Rev (2013)***

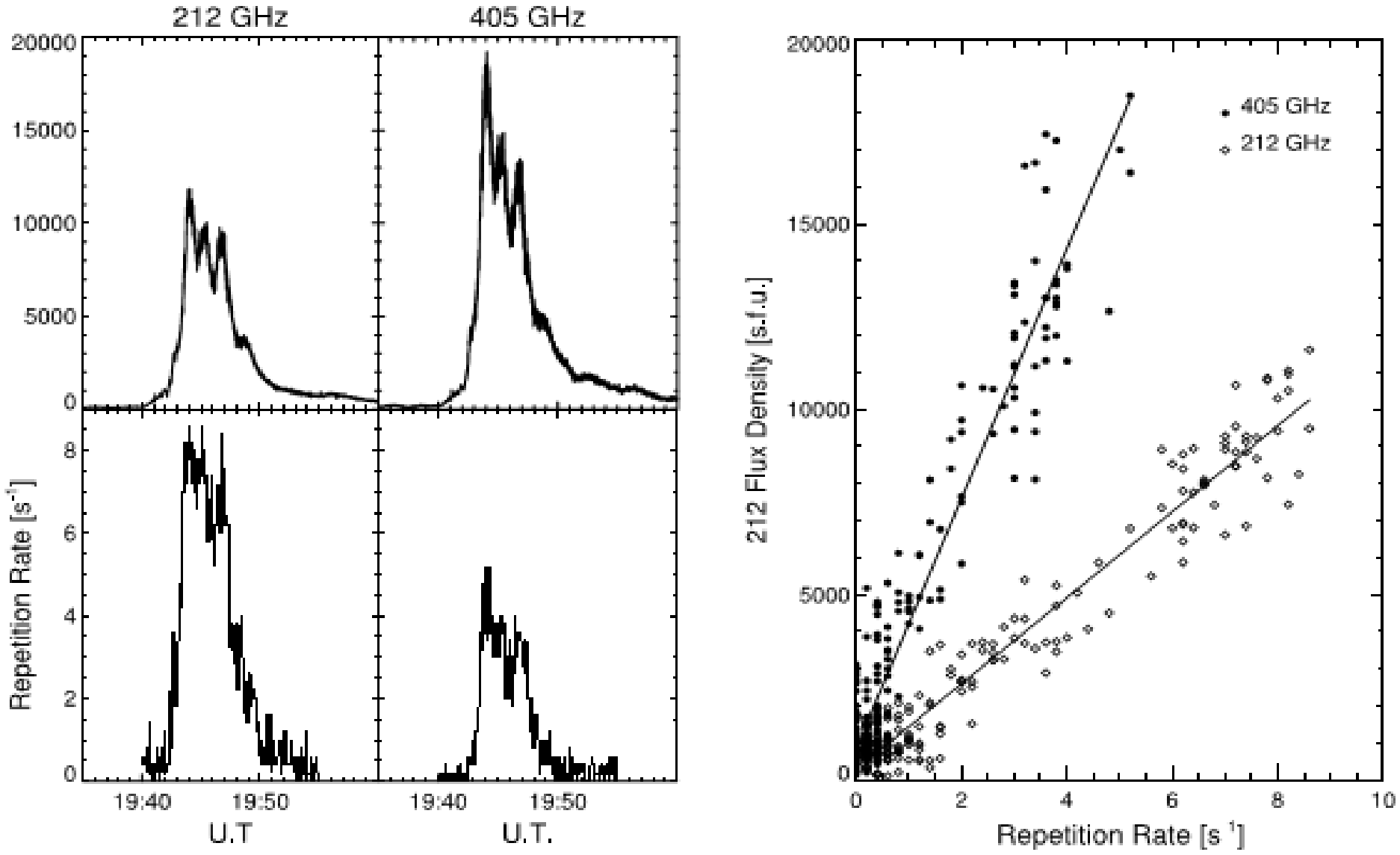
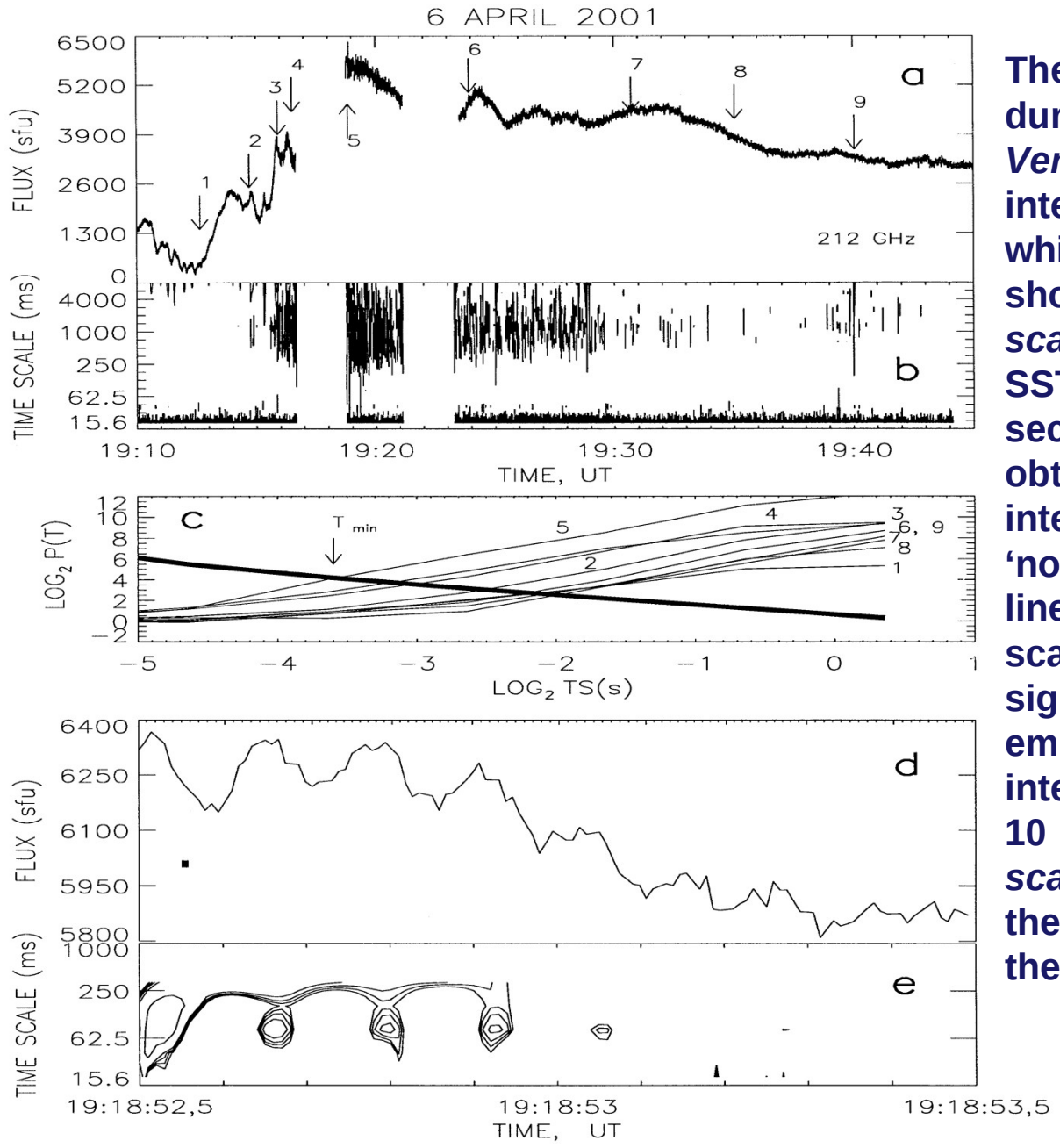
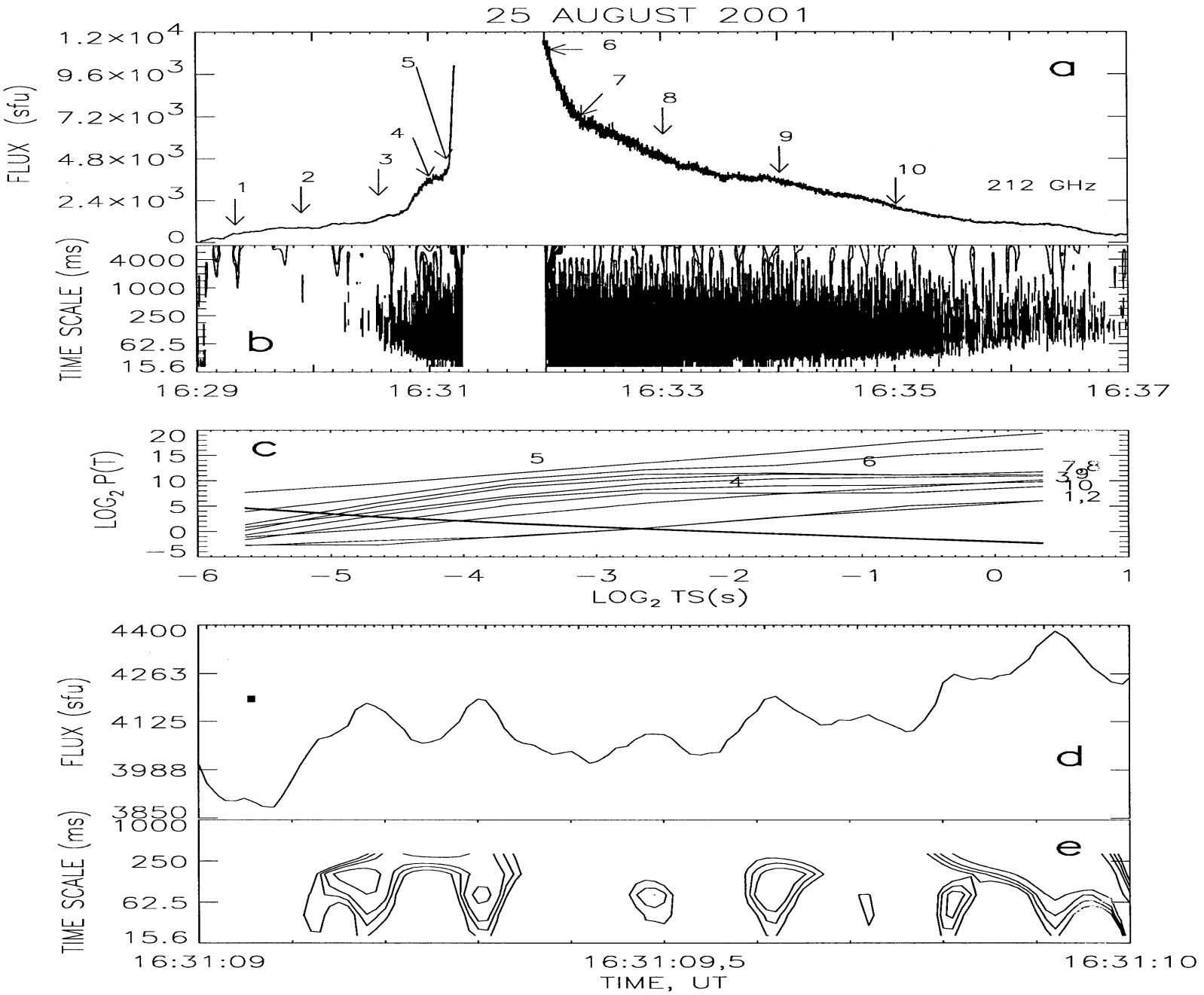


Fig. 12 *Left*: Top panels show the flux densities at 212 and 405 GHz for SOL2003-11-04, *bottom panels* show the repetition rate of the fast pulsations observed at these frequencies. *Right*: the linear relation is obtained when we plot the mean flux density vs. the repetition rate (Kaufmann et al. 2009)



The SST 212 GHz flux time profile during solar flare on 6 April 2001. *Vertical arrows* indicate the 3-s time intervals (from 1 to 9) of the data for which time-averaged *scalegrams* are shown in panel (c). (b) The *scalograms* evaluated from 10-ms SST data during the event. (c) The 3-seconds averaged *scalegrams* obtained during the selected intervals (1–9). The *thick line* is a 'noise' level *scalogram*. Above this line the confidence level of time scales is 99%, i.e., they are significant. The 212 GHz flare-emission time profile during sample interval of 1 s ((d) time constant is 10 ms) and corresponding part of *scalograms* (e) *Vertical thick bar* on the left in (d) corresponds to 3 times the r.m.s. noise fluctuations level.

***Makhmutov et al., Solar Phys.*, 2003,**



***Makhmutov et al., Solar Phys.*, 1998, 2003,**

RESULTS:

We present the results of the analysis of experimental data obtained with high time resolution, related to the solar observations of ***Quiet Sun*** Regions, ***Active Regions*** and ***Solar Flares*** by the multibeam Submillimeter Solar Telescope (SST) at 212 GHz. A multi-resolution analysis technique based on *Wavelet Transformation* is applied to study the radio emission time structures well above noise level.

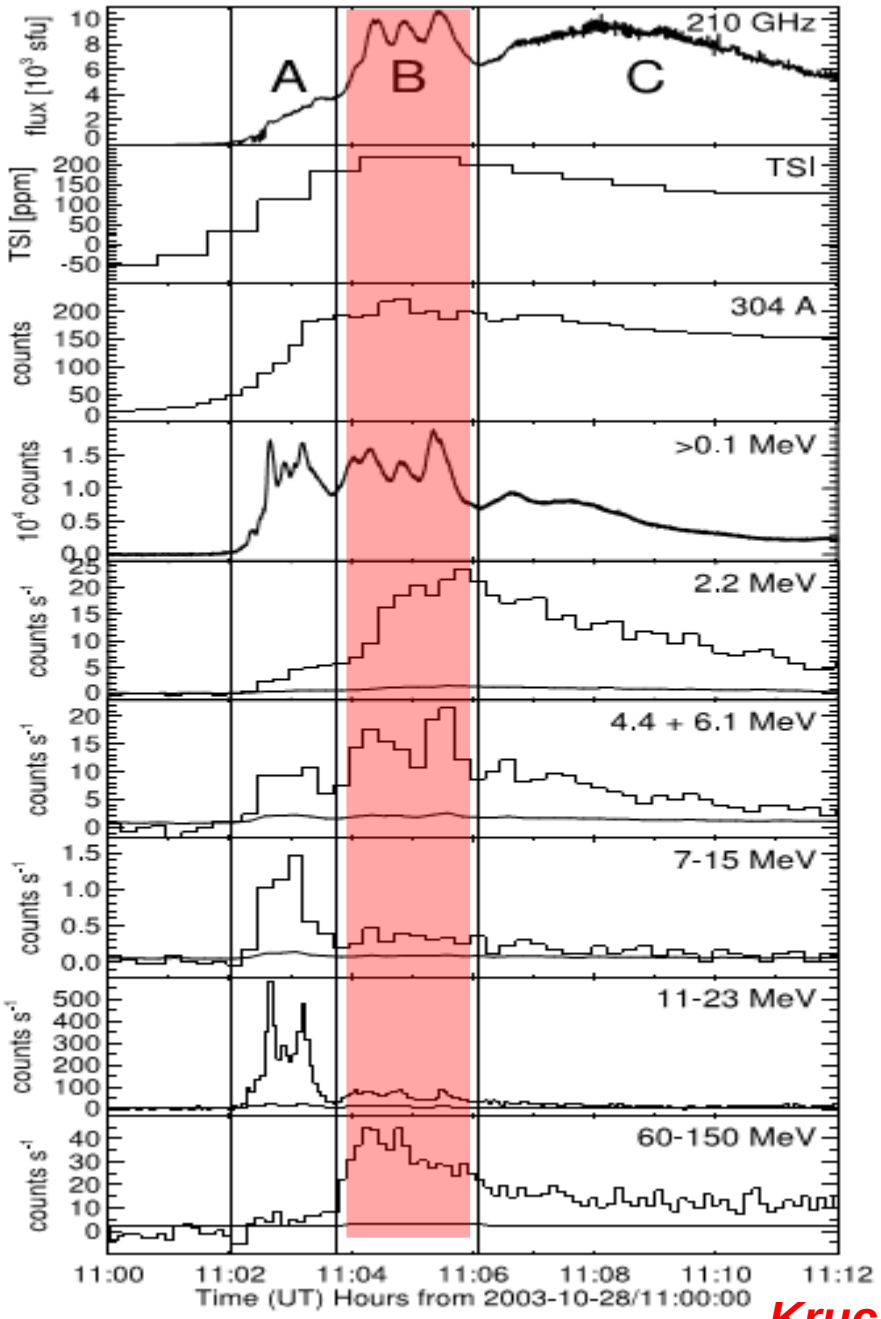
As a preliminary result, we show

1.the existence of 212 (*7, 89.4*) GHz emission time variations in the range from a few tens of millisecond up to few seconds during Quiet Sun, Active region and Solar Flare observations,

2.when a solar flare is in progress the power of the time variations is increasing, especially in the subsecond time range.

3....

V. S. Makhmutov, J.-P. Raulin, C. G. Giménez de Castro, P. Kaufmann, E. Correia, T. Luethi, A. Pacini, A. Melo, Solar radio emission time structures as observed by the (SST), *Workshop on Radiophysics with the Frequency Agile Solar Radiotelescope (FASR)* National Radio Astronomy Observatory Green Bank, WV 24944, USA, 23-25 May, 2002; http://www.ovsa.njit.edu/data/web/PPT_Files/raulin.pdf



Multi-wavelength light curves for the event SOL2003-10-28, T11:10.

From top to bottom,

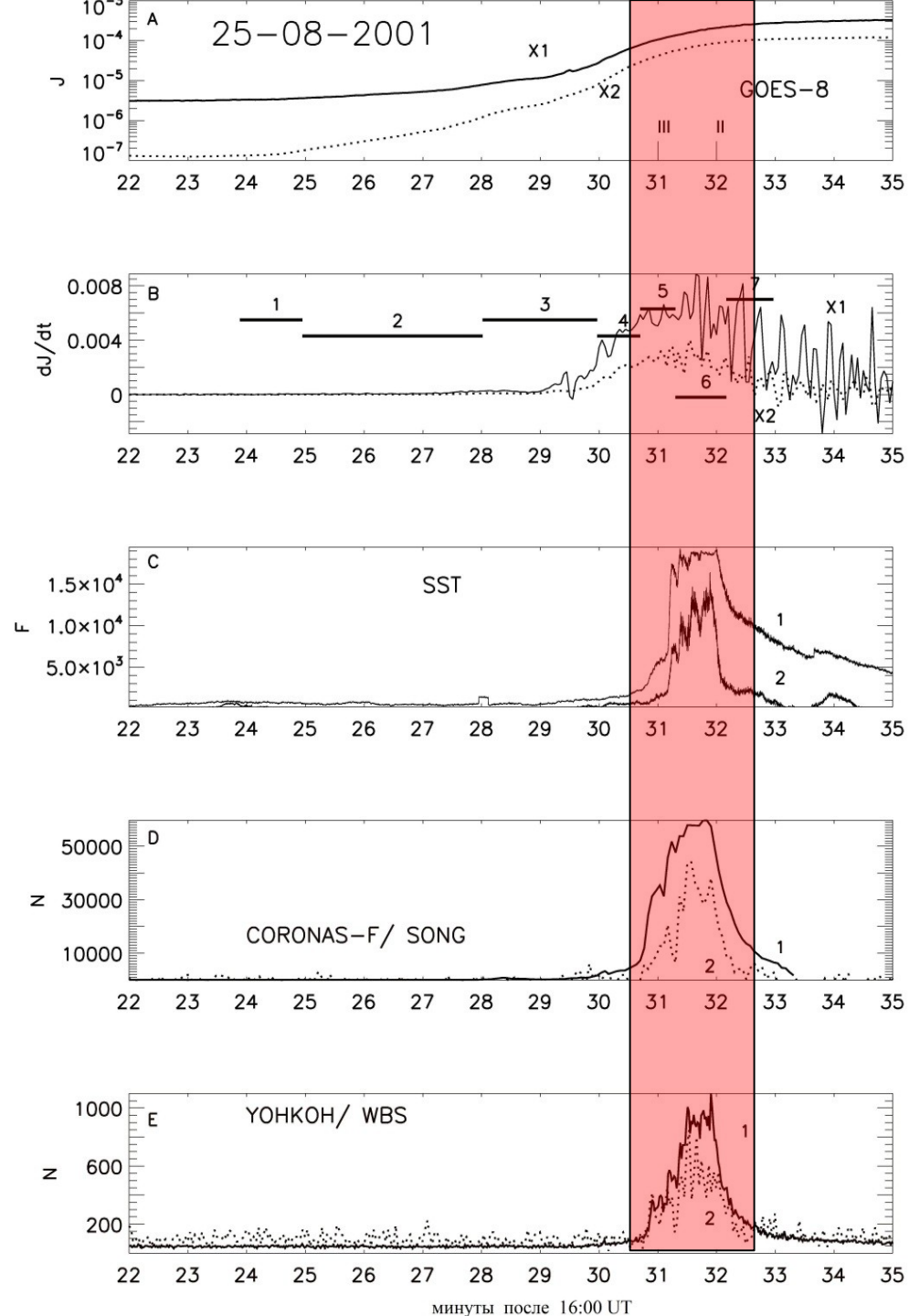
- **the 210 GHz signal,**

- **total solar irradiance (TSI; Woods et al.2006),**

- **HeII304 AA time profile (from SOHO/CELIAS),**

- **four light curves in the hard X-ray and γ-ray range between**
  - **0.1 and 15 MeV from INTEGRAL (Kiener et al.2006),**
  - **and 11–23 MeV and 60–150 MeV light curves (from SONG).**

Krucker et al.,Astron. Astrophys. Rev. (2013)

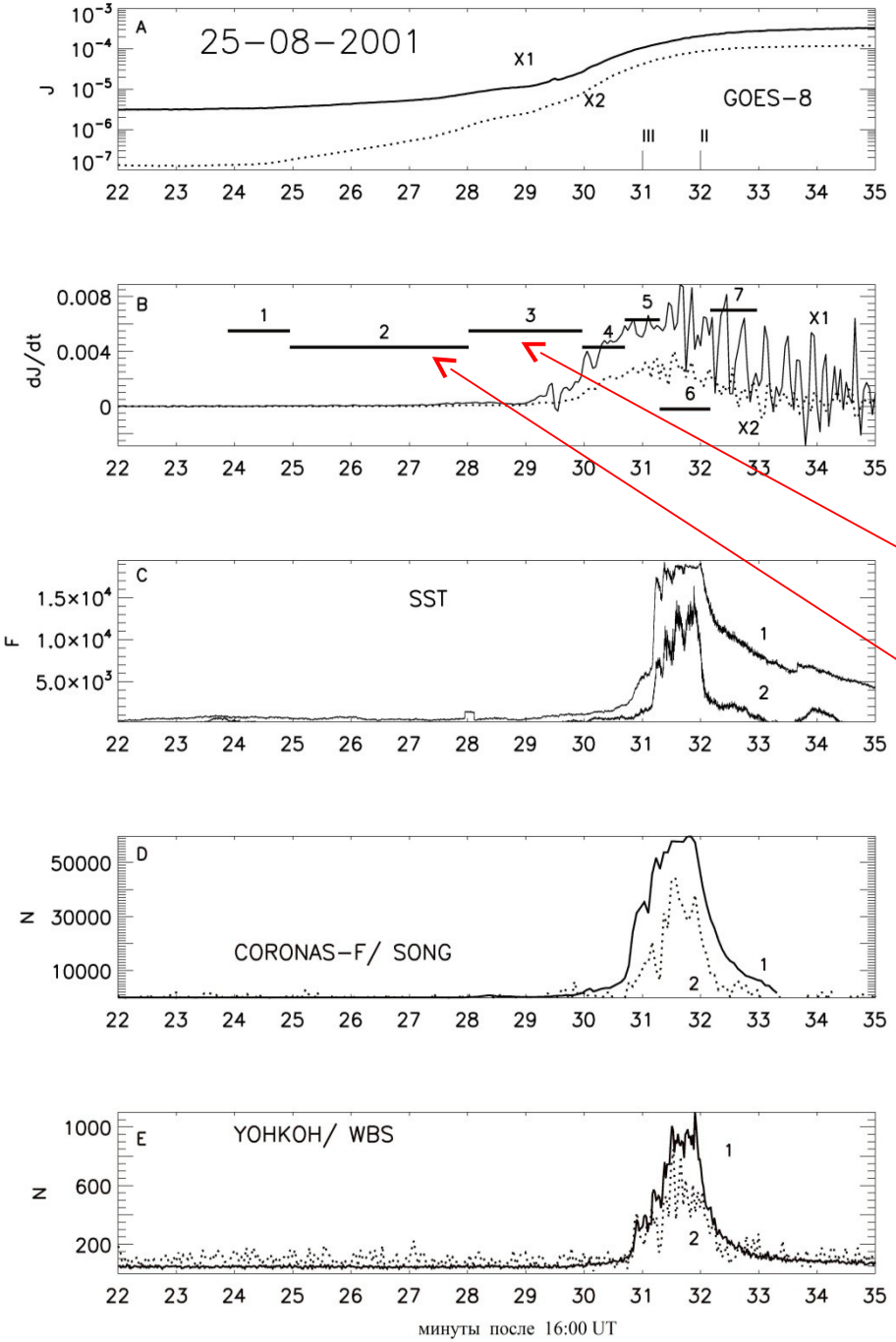


Временные профили потоков рентгеновского излучения измеренного на ИСЗ GOES в диапазоне 1–8 A˚(X1; поток J в Вт/м²) и 0.5–4 A˚(X2) и их первые производные по времени (B). Вертикальными штрихами отмечены времена начала радиовсплесков II и III типов [1]. Горизонтальные штрихи: интервалы времени, для которых определены спектры гамма- и радио излучений (*B*).

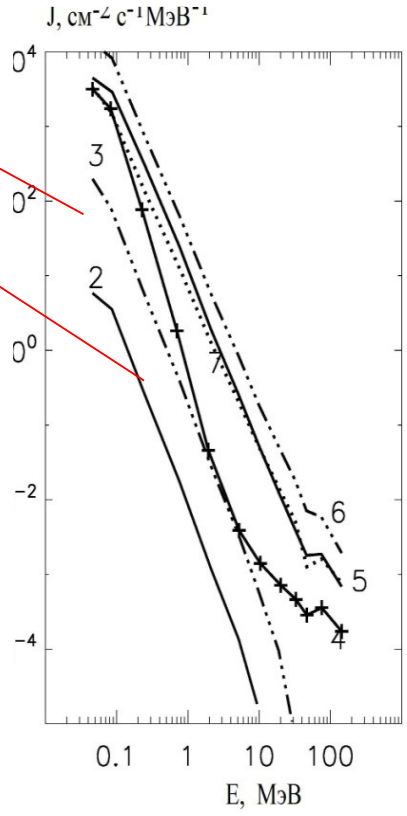
C: **временной ход субмиллиметрового радиоизлучения по данным SST на частоте 210 ГГц (кривая 1) и 405 ГГц (кривая 2) (*F* в единицах *sfu;* [4]).**

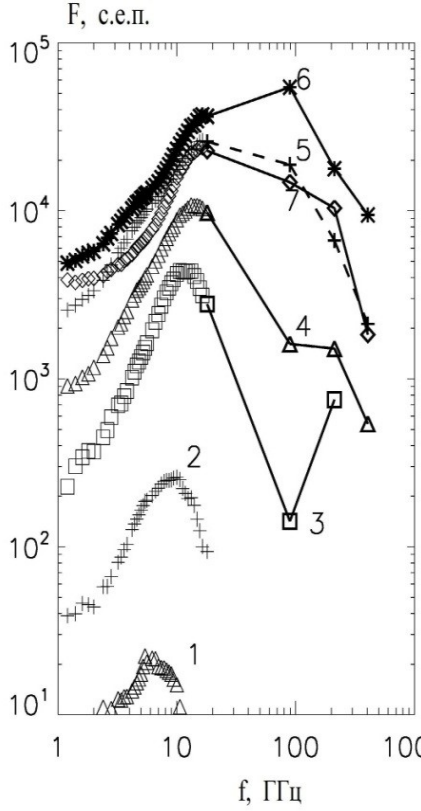
***D*:потоки гамма-излучения измеренные прибором СОНГ в интервале энергии E_γ=0.15-0.5 МэВ (кривая 1; N - отн. ед.) и E_γ=41-60 МэВ (кривая 2). *E*: потоки гамма-излучения с энергией E_γ=0.27-1.04 МэВ (кривая 1, N - отн. ед.) и E_γ=3.37-13.6 МэВ (кривая 2) по данным спектрометра WBS/GRS на борту ИСЗ YOHKOH.**

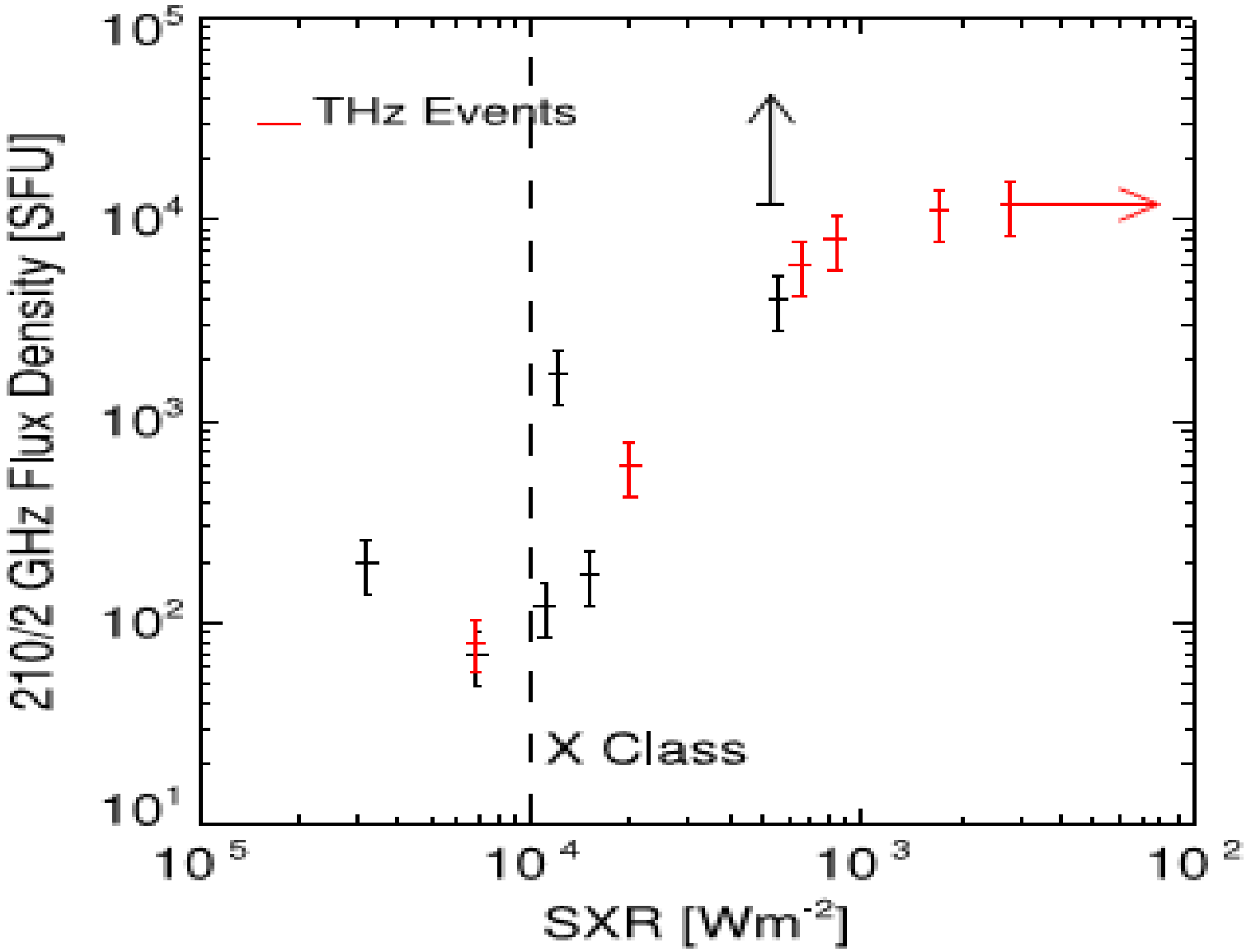
Makhmutov V. S., Kurt V. G., Yushkov B. Yu., Grechnev V. V. , Kaufmann P. , Raulin J. -P. , Bazilevskaya G. A. , Stozhkov Yu. I., BRAS, V. 75, № 6, p. 747-750, 2011



Makhmutov V. S., Kurt V. G., Yushkov B. Yu., Grechnev V. V., Kaufmann P., Raulin J.-P., Bazilevskaya G. A. , Stozhkov Yu. I.,
BRAS, V. 75, № 6, p. 747-750, 2011







Correlation of 210 GHz flux with GOES1–8 Å. The uncertainties shown for the former are a uniform 30 %; events with THz components are in red

ApJ, v.768, N2, p.134, 2013

A bright impulsive solar burst detected at 30 THz

P. Kaufmann, S. M. White, S. L. Freeland, R. Marcon, L.O.T. Fernandes, A.S. Kudaka, R.V. de Souza, J.L. Aballay, G. Fernandez, R. Godoy, A.Marun, A.Valio, J.-P. Raulin, C.G. Giménez de Castro

Abstract

Ground- and space-based observations of solar flares from radio wavelengths to gamma-rays have produced considerable insights but raised several unsolved controversies. The last unexplored wavelength frontier for solar flares is in the range of submillimeter and infrared wavelengths. Here we report the detection of an intense impulsive burst at 30 THz using a new imaging system. The 30 THz emission exhibited remarkable time coincidence with peaks observed at microwave, mm/submm, visible, EUV and hard X-ray wavelengths. The emission location coincides with a very weak white-light feature, and is consistent with heating below the temperature minimum in the atmosphere. However, there are problems in attributing the heating to accelerated electrons. The peak 30 THz flux is several times larger than the usual microwave peak near 9 GHz, attributed to non-thermal electrons in the corona. The 30 THz emission could be consistent with an optically thick spectrum increasing from low to high frequencies. It might be part of the same spectral component found at sub-THz frequencies whose nature remains mysterious. Further observations at these wavelengths will provide a new window for flare studies.

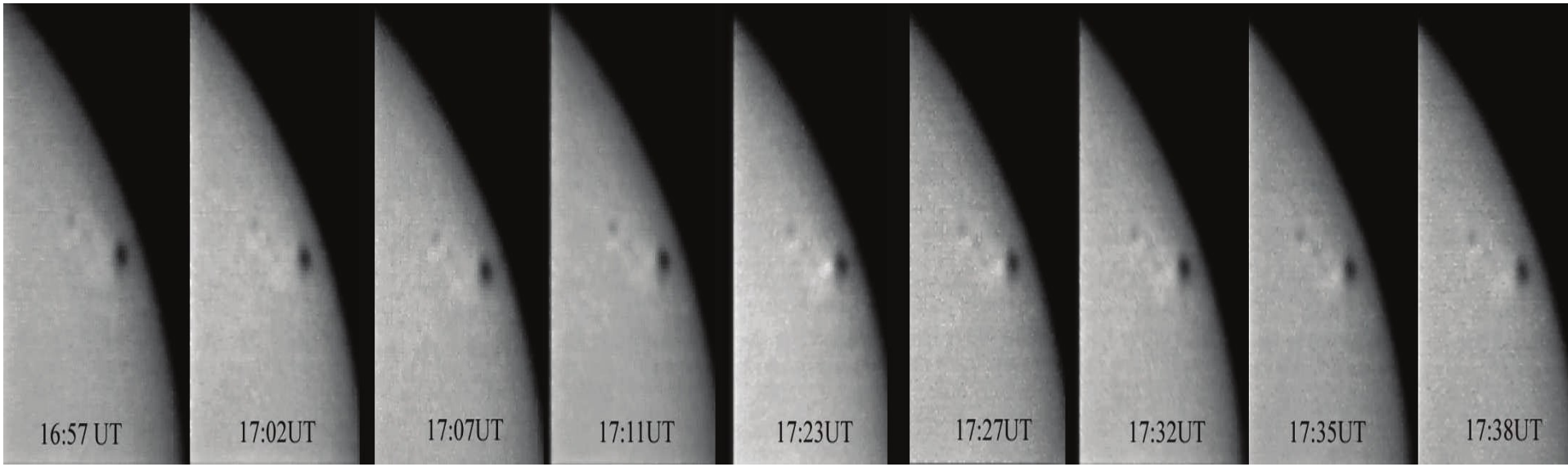
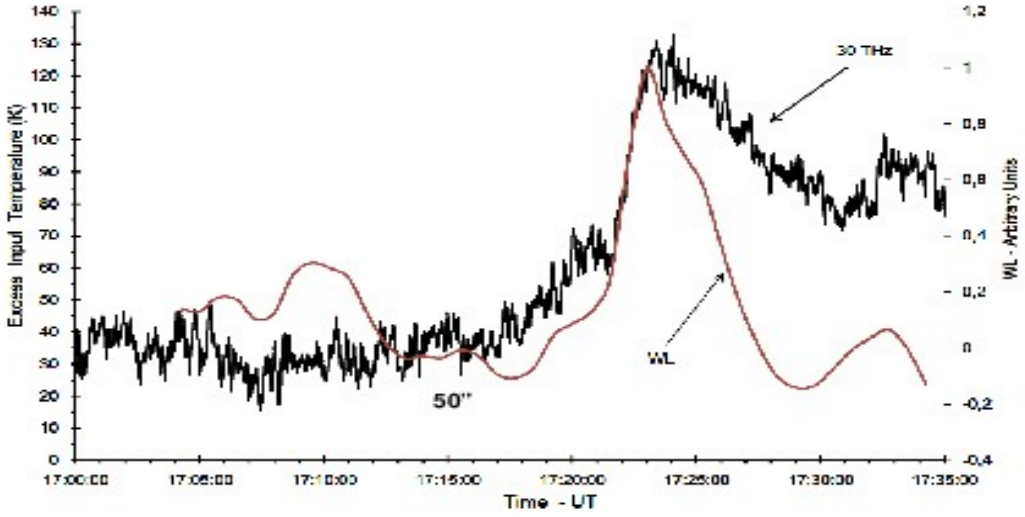


Fig. 1. Sequence of 30 THz frames showing the burst brightening up east of the sunspot.

Kaufmann et al., ApJ, v.768, N2, p.134, 2013



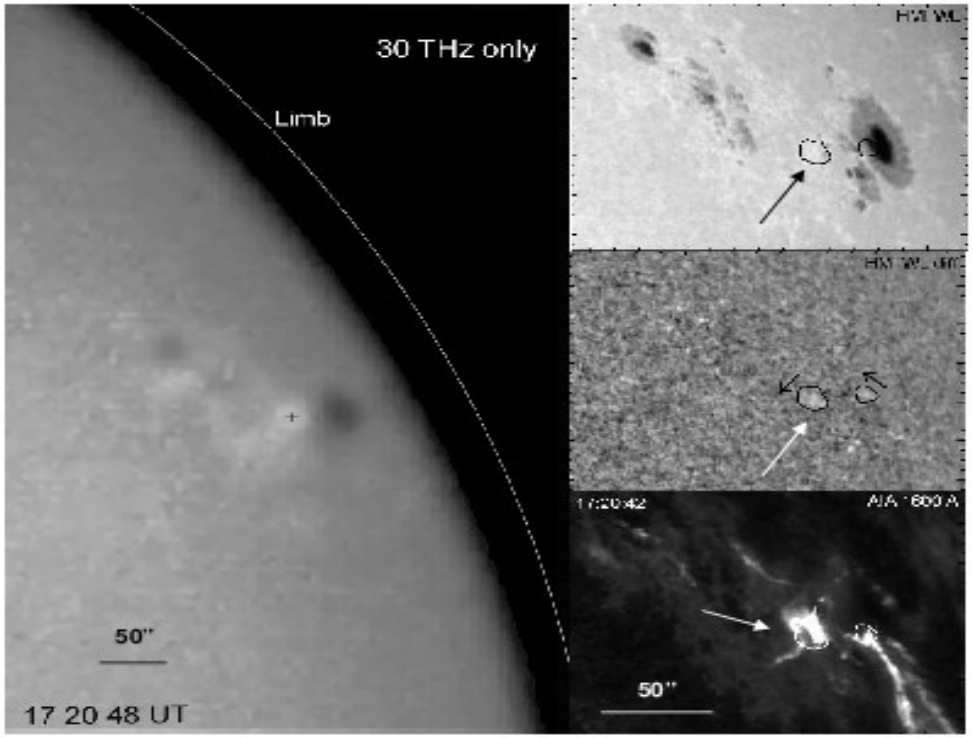
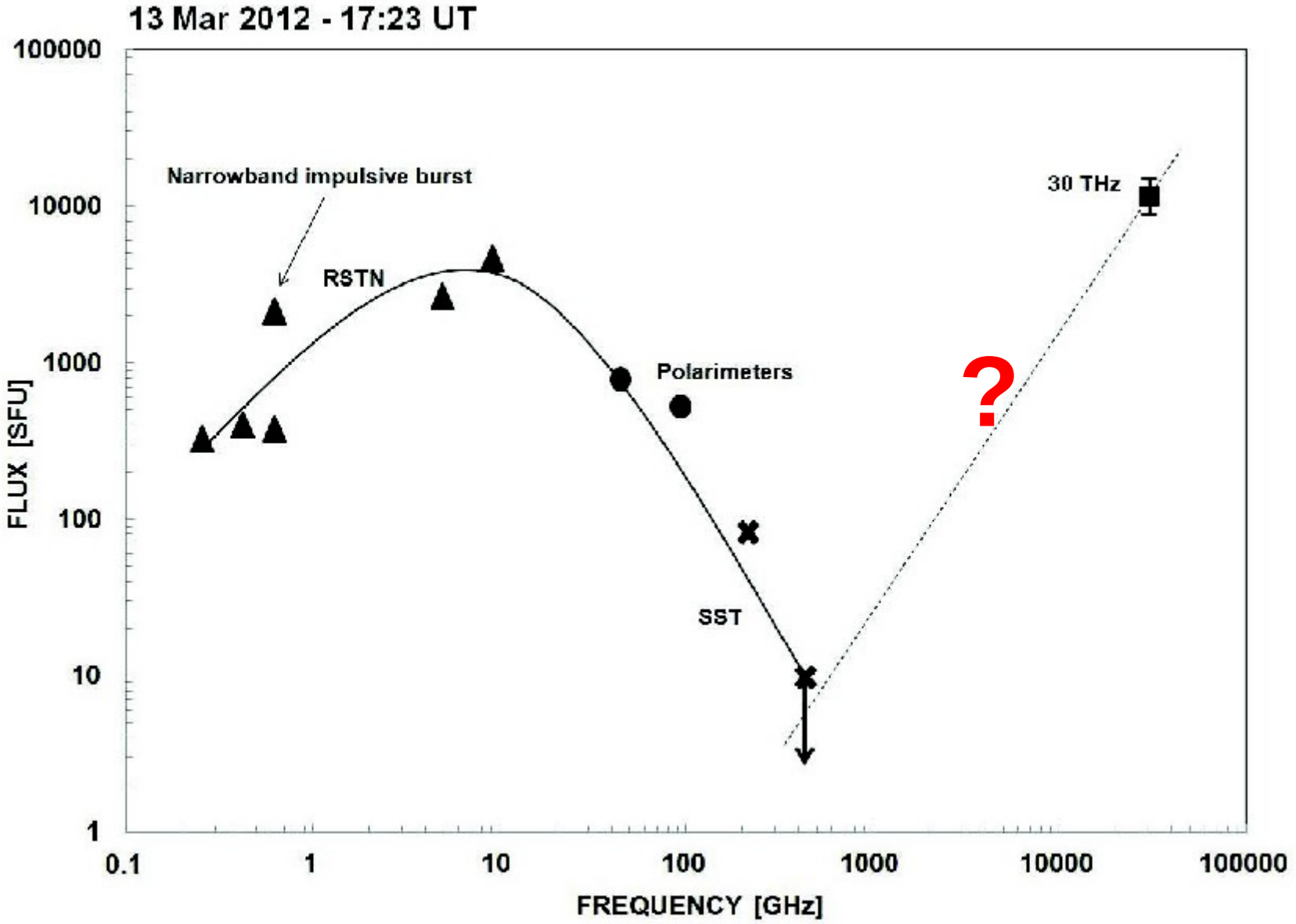


Fig. 3. The top panel shows the 30 THz and white-light time profiles of the impulsive solar burst observed March 13, 2012, obtained with 0.61 and 45 second cadence, respectively. The 30 THz ordinates are in degrees K in a scale calibrated using the photosphere – outside sky temperature difference (described in the text). The bottom images show at left the 30 THz brightening at the beginning of the impulsive rise, at 17:20:48 UT with a cross indicating the center of emission. The display range in this image is scaled to emphasize disk features and exaggerates the amount of limb darkening. At right the white light image of the flare region, top (from SDO/HMI), the white-light difference image produced by subtracting a preflare image from images summed around 17:24 UT (middle), and a 1600 Å image (bottom, from SDO/AIA at 17:31 UT) showing the flare ribbons. The solid contours represent the two white-light features seen in the middle right panel. Arrows indicate the 30 THz burst position that coincides with the eastern features at white-light and 1600 Å.

Kaufmann et al., ApJ, v.768, N2, p.134, 2013



Radio to mid-IR spectrum for the March 13, 2012 solar burst (M8 flare, 13.03.2012, 17:20 UT in NOAA1429 (N18W50).

Kaufmann et al., ApJ, v.768, N2, p.134, 2013

К особенностям солнечного суб-терагерцового излучения (<410 ГГц) можно отнести следующее:

1. наличие субсекундных вариаций, амплитуда которых нарастет с приближением к максимуму события.

2. наличие временной корреляции субтер. излучения с рентгеновским и гамма-излучением, etc.

3. положение “частоты излома” (появление ТГц компоненты) в спектре радиоизлучения может изменяться как в течение события, так и от события к событию.

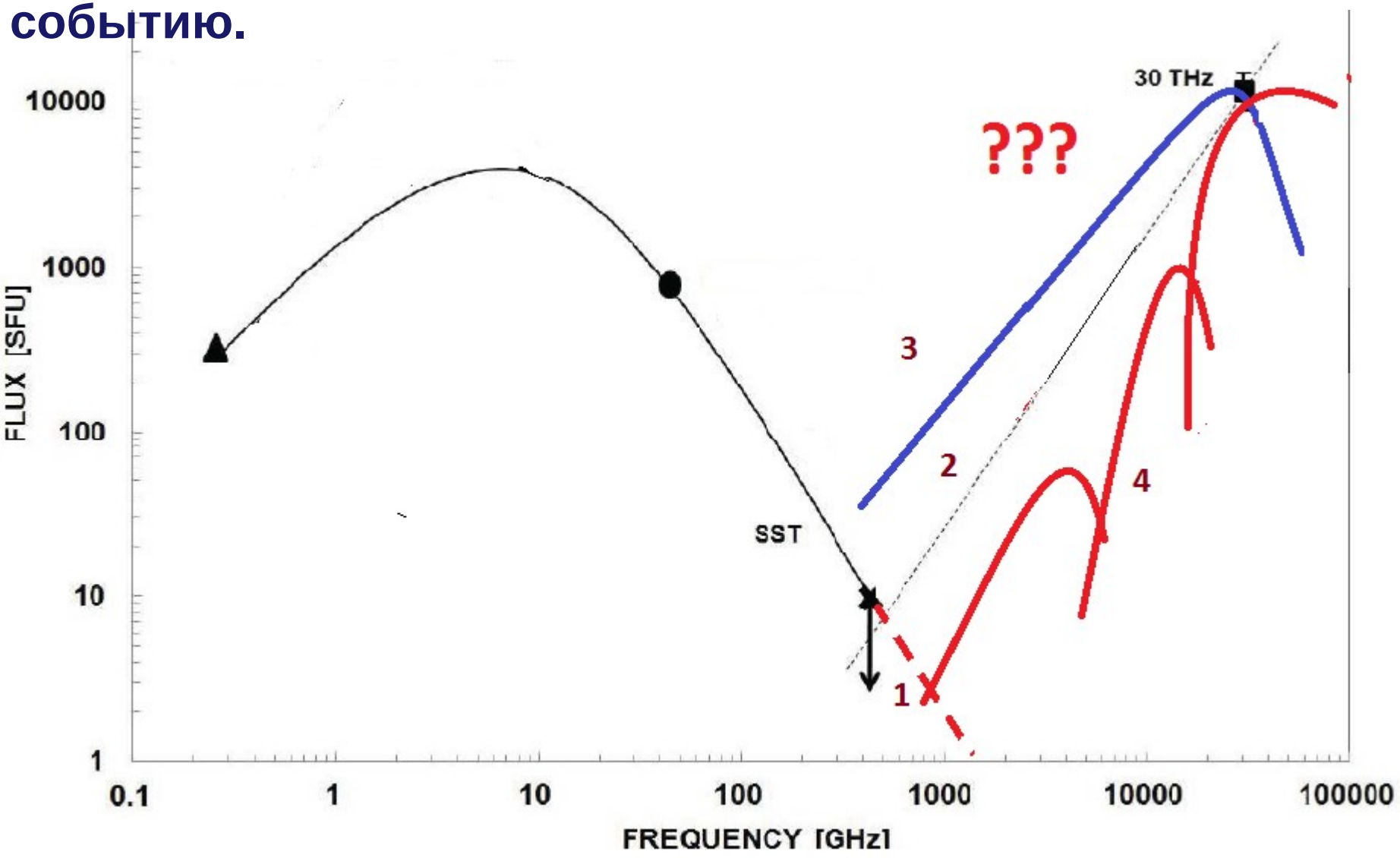


Table 2 Summary of mechanisms that can produce positive THz slopes

Mechanism	Arguments for	Arguments against	Ref.
Free–free	Known mechanism	Conflict with SXR for impulsive phase	(1), (3), (9)
Synchrotron (electrons)	Known mechanism	Extreme parameters required	(2), (3), (9)
Synchrotron (positrons)	Known mechanism Correlation with γ-rays	Extreme parameters required Conflicts with γ-ray intensity	(2), (3)
Synchrotron (thermal)	Known mechanism	Extreme parameters required Conflict with HXR	(7)
Cherenkov	Correlation with γ-rays	Dielectric properties unknown Highly relativistic particles needed Inadequately studied	(4)
Microbunching	Correlation with γ-rays	THz from synchrotron Bunching mechanism unknown Coronal μwaves unclear	(5)
Plasma emission	Correlation with γ-rays High luminosity	Free–free absorption	(6)
Diffusive radiation	Correlation with γ-rays	Origin of Langmuir waves Extreme parameters required	(4)
Synchrotron maser	Correlation with γ-rays	Extreme parameters required Inadequately studied	(8)
Inverse Compton	Correlation with γ-rays	Insufficient ambient photons	(4)

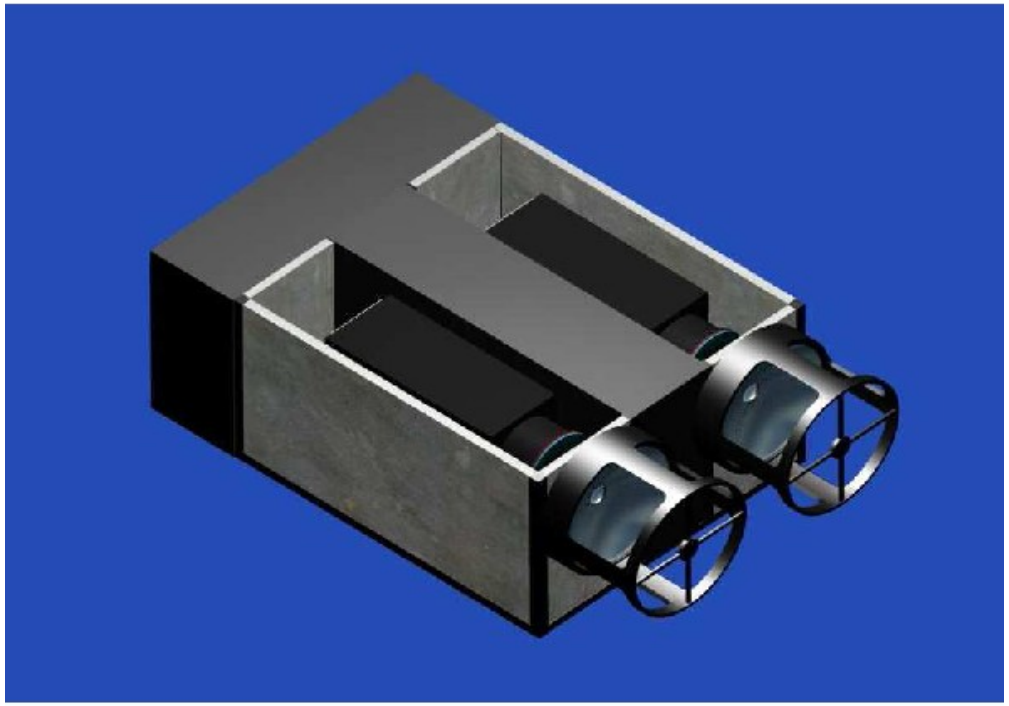
(1) Bastian et al. (1998); (2) Silva et al. (2007); (3) Trottet et al. (2008); (4) Fleishman and Kontar (2010); (5) Kaufmann and Raulin (2006); (6) Sakai and Nagasugi (2007a); (7) Costa et al. (2013); (8) This paper; (9) Kaufmann et al. (2009)

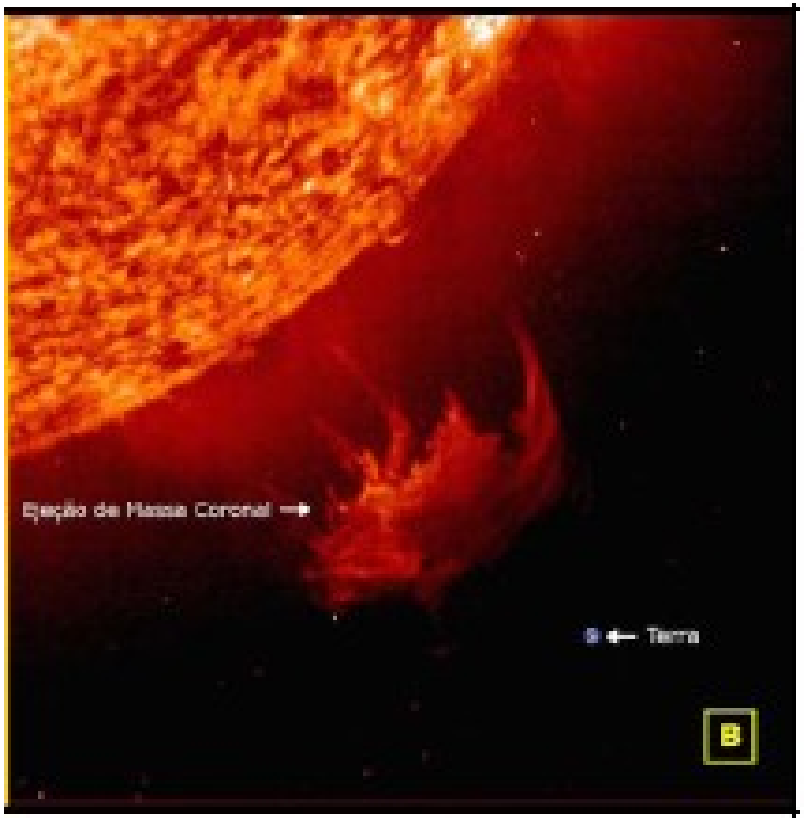
По-видимому, “ТГц - особенность” присутствует в эл.-м. излучении большинства солнечных вспышек. Она может начинать “проявляться” на разных частотах в диапазоне ~100 ГГц – несколько ТГц.

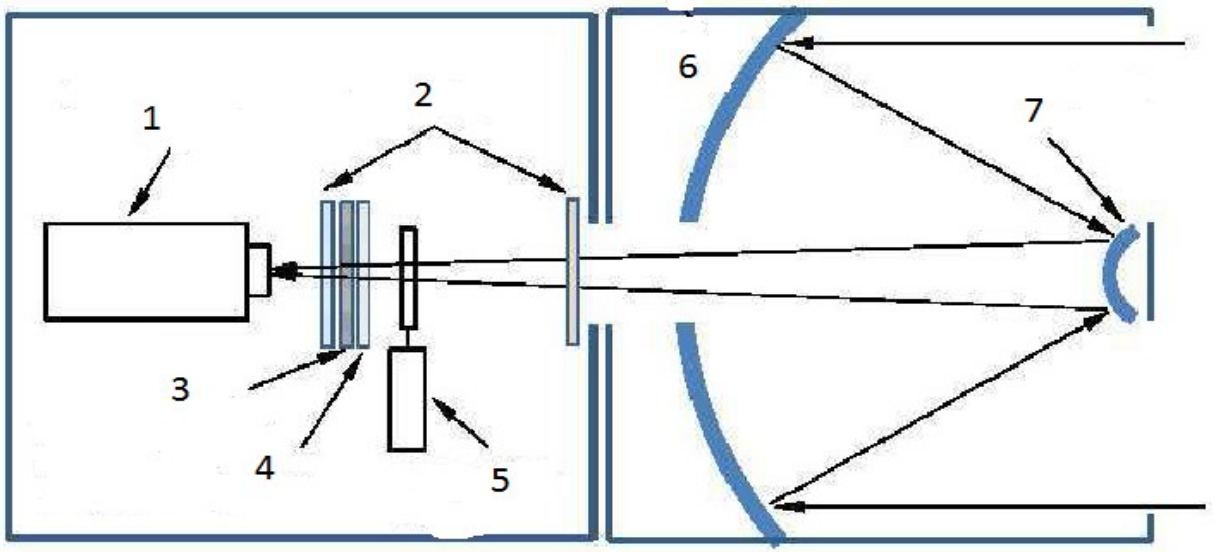
Необходимы одновременные экспериментальные наблюдения QS-областей, активных областей и солнечных вспышек в области частот от 100 ГГц – 30 ТГц.

« СОЛНЦЕ — ТЕРАГЕРЦ »

- ЦНИИМАШ (2011- н.в.)
- Прогр. Президиума РАН № 22 (2012 - н.в.)







Предполагаемая схема прибора (одной ячеки-блока) для детектирования солнечного терагерцового излучения в проекте СОЛНЦЕ-ТЕРАГЕРЦ. 1 - опто-электрический приемник (ячейка Голея) ; 2 - входные окна (ТРХ) ; 3 - черная низкочастотная мембрана (Tydex; для выделения излучения с λ > 20 микрон или f < 15 ТГц); 4 - металлические ячейки (отверстия)- узкополосные резонансные фильтры на заданную частоту (например, 1, 2, 3 Тгц ...); 5 - резонансный прерыватель; 6 - сферическое вогнутое зеркало с шероховатой поверхностью; 7 - выпуклое сферическое зеркало с защитой справа. Источник детектируемого излучения расположен справа

The Development of THz Photometers to Observe Solar Flares from a Stratospheric Platform

P. Kaufmann*, E. Correia**, L.O.T Fernandes*, C.G. Gimenez de Castro, A.S. Kudaka, J.-P. Raulin, A. Válio
Escola de Engenharia, CRAAM
Universidade Presbiteriana Mackenzie
São Paulo, SP, Brazil
pierrekau@gmail.com

R. Marcon
Instituto de Física Gleb Wataghin
Universidade Estadual de Campinas
Observatório Solar "Bernard Lyot"
Campinas, SP, Brazil

E.C. Bortolucci, J.A. Diniz, M.B. Zakia,
*Centro de Componentes Semicondutores
Universidade Estadual de Campinas,
Campinas, SP, Brazil

Jacobus W. Swart
Faculdade de Engenharia Elétrica e de Computação
Universidade Estadual de Campinas,
Campinas, SP, Brazil

N. Machado, A. Abrantes
Propertech Ltda.
Jacareí, SP, Brazil

C. M. da Silva
Neuron Ltda.
São José dos Campos, SP, Brazil

V. Nicolaev, A. Timofeevsky
Tydex Co.
Saint Petersburg, Rússia

M. Lebedev
Special Astrophysical Observatory of Russian Academy of Sciences, Saint Petersburg, Russia

A. Shih
National Aeronautical and Space Administration/GSFC
Greenbelt, MD, USA

G. Hurford, R. Lin
University of California, SSL, Berkeley, CA, USA

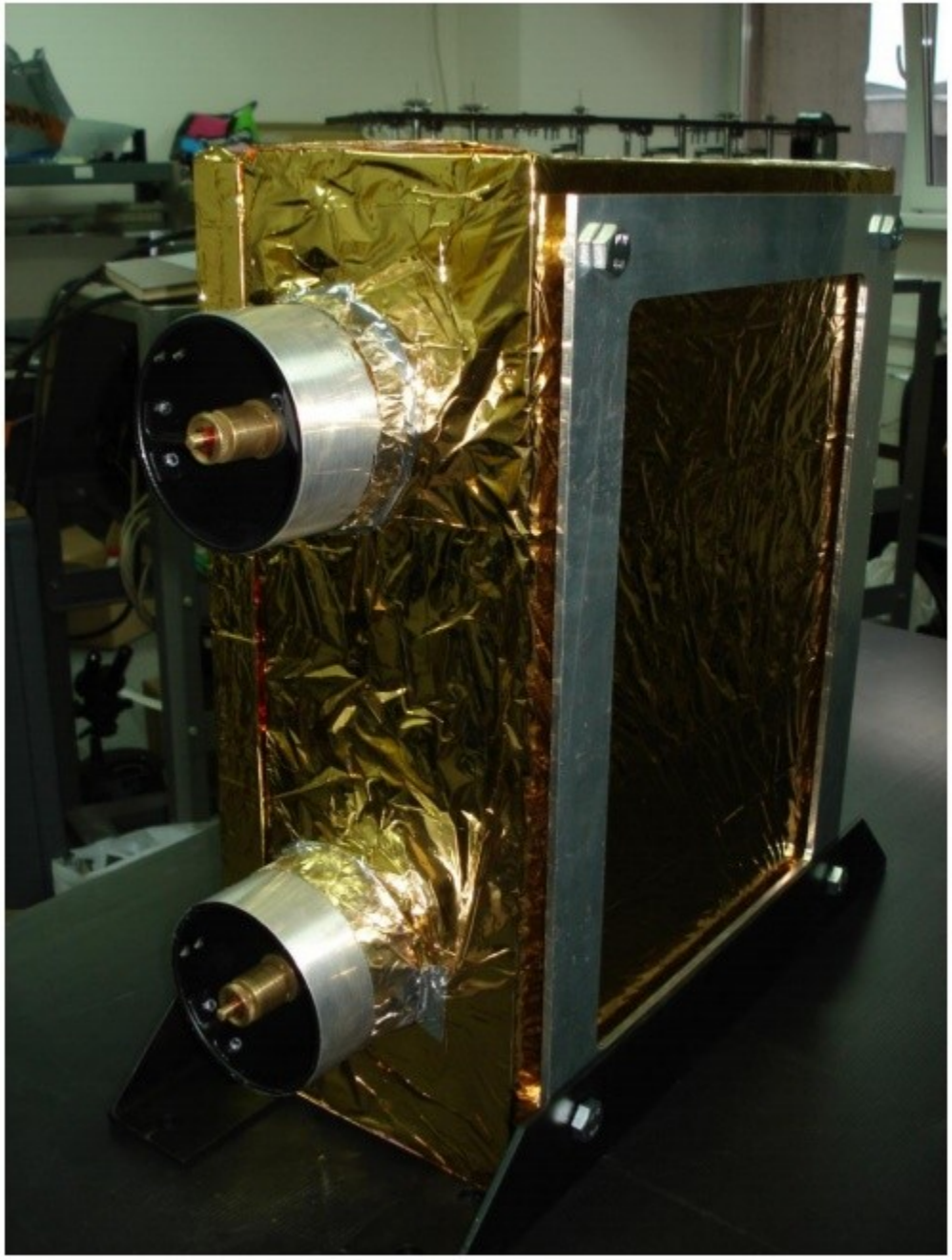
V.S. Makhmutov, Y. I. Stozkhov
Lebedev Physics Institute,
Moscow, Russia

A. Marun, P.Pereyra, R. Godoy, G. Fernandez
Complejo Astronomico El Leoncito, CONICET
San Juan, Argentina

T. Villela
**Instituto Nacional de Pesquisas Espaciais,
São José dos Campos, SP, Brazil

The newly found solar flare spectral component with intensities increasing for larger sub-THz frequencies, brings challenging constraints for interpretation. Higher THz frequencies observations are needed to understand the nature of the mechanisms involved. A two-frequency THz photometer system was developed to observe outside the terrestrial atmosphere on stratospheric balloons. Two 76 mm diameter telescopes were designed to observe the whole solardisk detecting small relative temperature changes caused by flaresat localized positions at 3 and 7 THz. Golay cell detectors are preceded by low-pass filters to suppress visible and near IR radiation, band-pass filters, and choppers. It can detect temperature variations smaller than 1 K with time resolution of a fractionof a second, corresponding to small burst intensities. The photometers are assembled in a thermal controlled box to which dataacquisition and telemetry systems are coupled. A laboratory THz photometer prototype was developed. The SOLAR-T flying model has been completed. It is planned to fly on board of long-duration stratospheric balloon flights in 2013-2015. One will be coupled to the GRIPS gamma-ray experiment in cooperation with University of California, Berkeley, USA with one test flight in US, and a 2 weeks flight over Antarctica during local summer. Another flight over Russia (one week) is planned incooperation with the Lebedev Physics Institute, Moscow, during local summer

TYDEX BOX – PHOTO FRONT VIEW



TYDEX BOX – PHOTO BACK VIEW

TYDEX BOX – PHOTO CONECTORS VIEW

Девятая ежегодная конференция

Физика плазмы в Солнечной системе

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Научные программы Президиума РАН №22 и ОФН РАН №15

Спасибо за внимание !