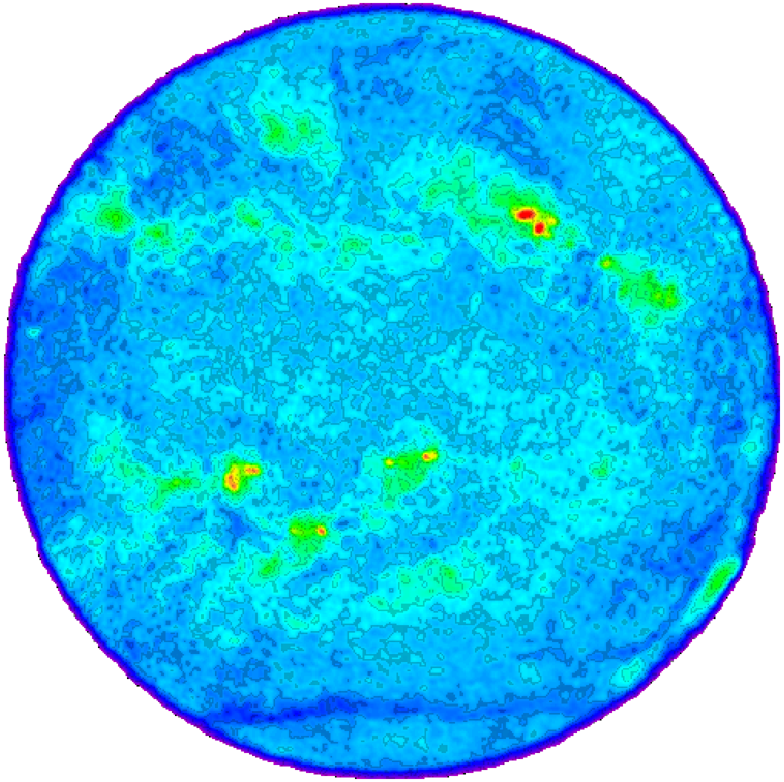
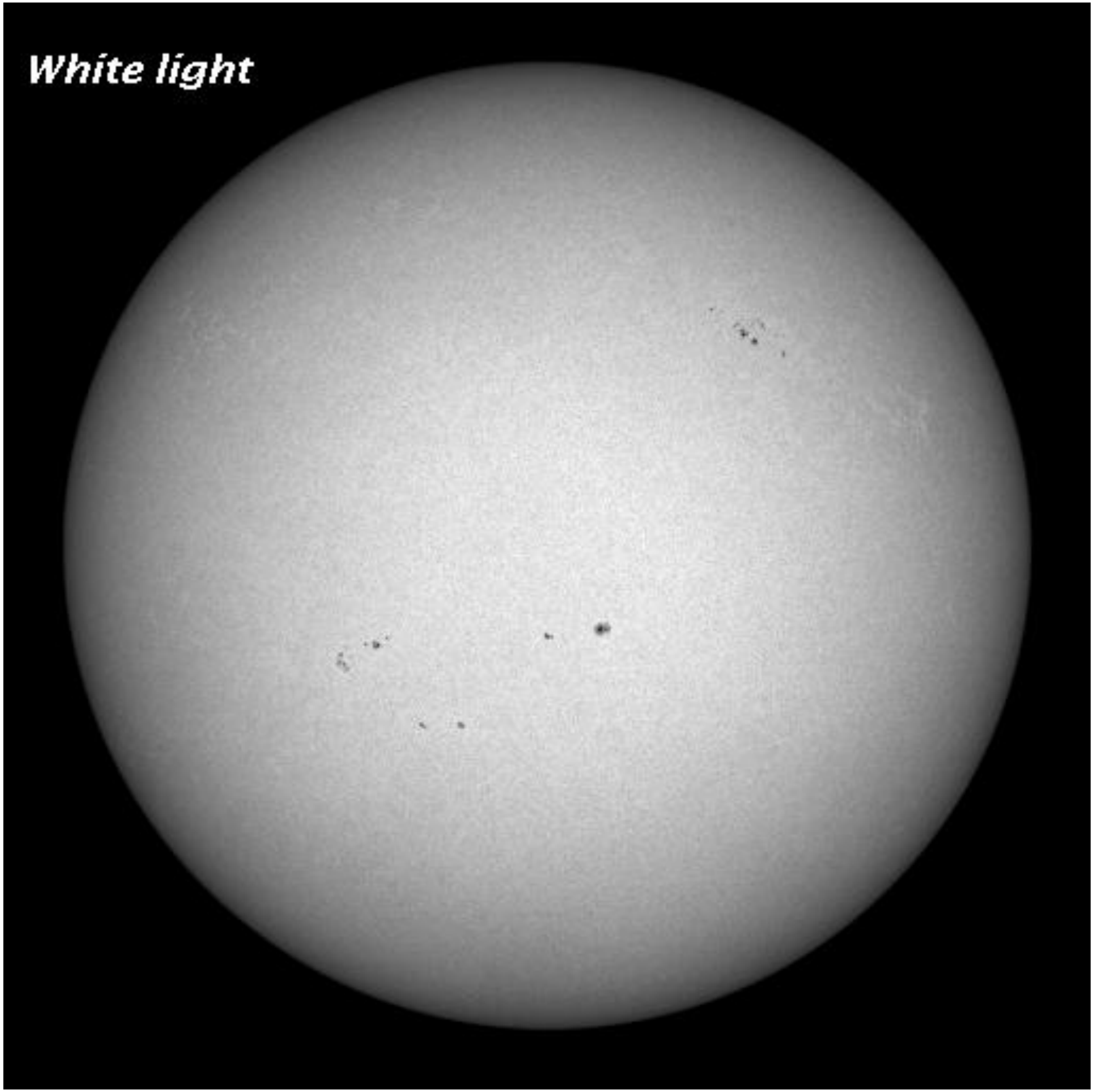


The Sun as a Radio Star

Stephen White
Space Vehicles Directorate
Air Force Research Laboratory

The Sun at Optical, Radio, UV Wavelengths



$$\text{Flux} = T_b \times \text{area}$$

where, if optically thick,

brightness temperature T_b = electron temperature T_e

Radio Emission Mechanisms

- **Bremsstrahlung** due to thermal plasma occurs throughout the solar atmosphere and is the dominant mechanism in most of the corona. It is optically thin above a few GHz and usually weakly polarized.
- **Gyroresonance emission** (emission from nonrelativistic thermal plasma at low harmonics of the electron gyrofrequency 2.8 B MHz) is strong wherever $B > 300$ G in the corona and produces optically thick emission in active regions which may be highly polarized.
- **Gyrosynchrotron emission** (emission by mildly relativistic electrons at harmonics 10-100 of the gyrofrequency) is produced by nonthermal electrons in flares.
- **Plasma emission** is produced by energetic electrons at low harmonics of the plasma frequency: produces bright highly polarized bursts at low frequencies

Steady solar flux

Solar disk flux is dominated by thermal bremsstrahlung

Solar cycle variation is due to a combination of optically thin thermal emission from the corona plus gyroresonance.

The solar radio cycle is much smaller than the X-ray variation

Solar radio disk temperatures

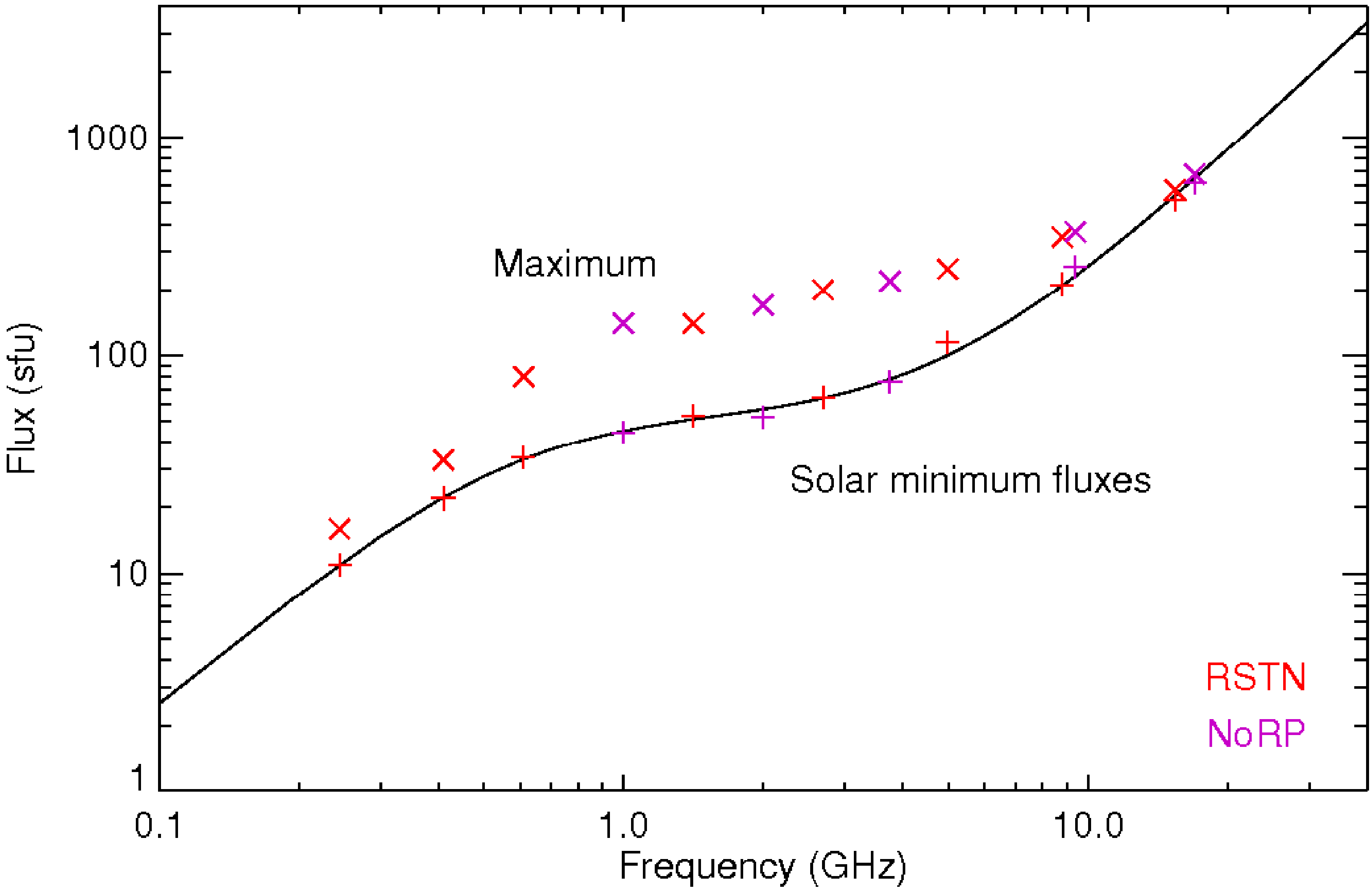
Disk brightness temperatures:

600000 K at 0.3 GHz - optically thick corona
100000 K at 1 GHz - optically thin corona
35000 K at 3.75 GHz - upper chromosphere
17000 K at 9.4 GHz - upper chromosphere
10000 K at 17 GHz - chromosphere
7000 K at 86 GHz - chromosphere

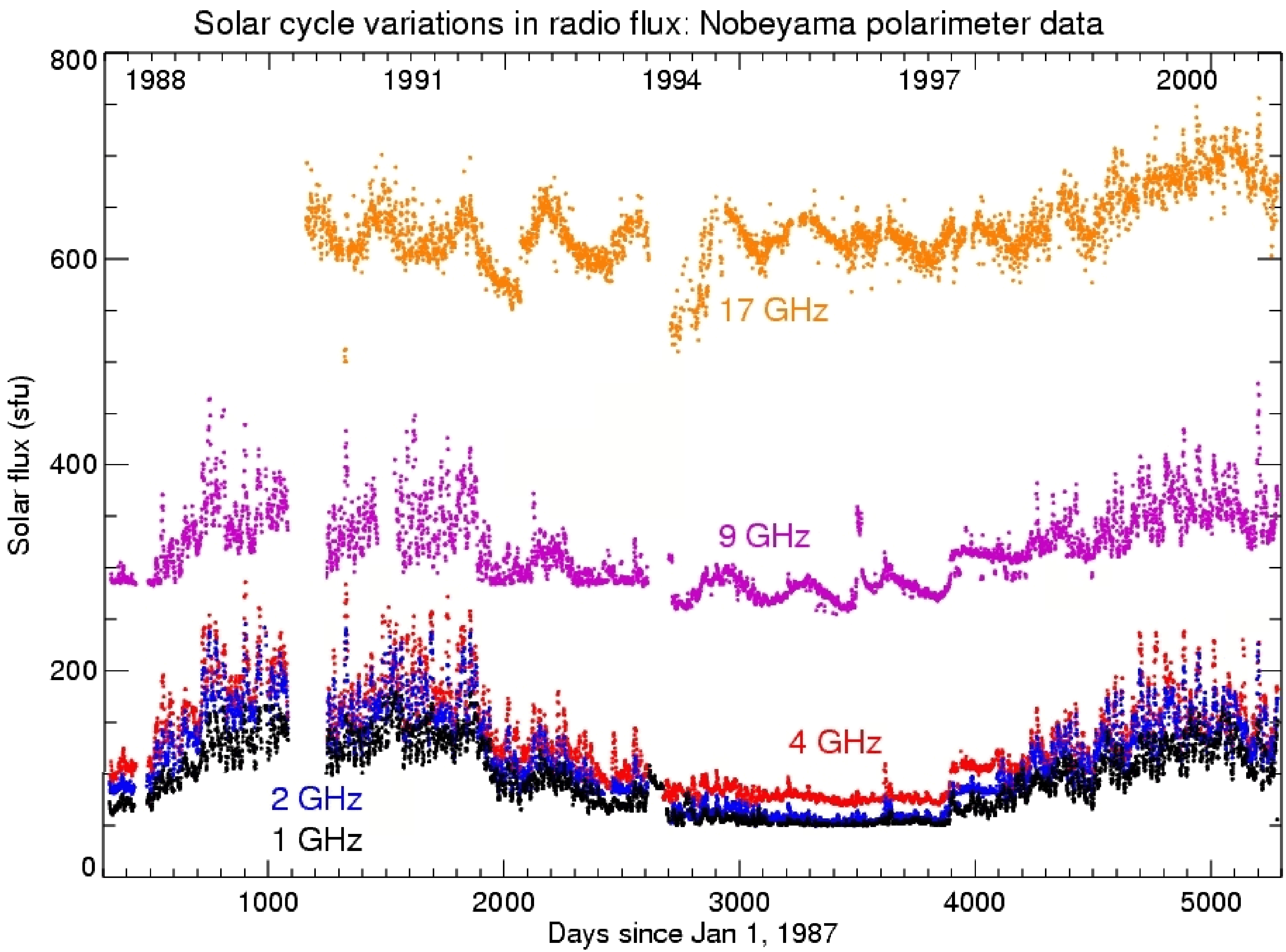
Solar radio flux = disk area x T x $(\text{frequency})^2$

Star at 5 pc = 10^{-12} flux of Sun at 1 AU
1 mJy at 5 pc = 10^{5} sfu at Sun

Need T = 5 10^{6} K over whole solar disk at 10 GHz to produce this flux.

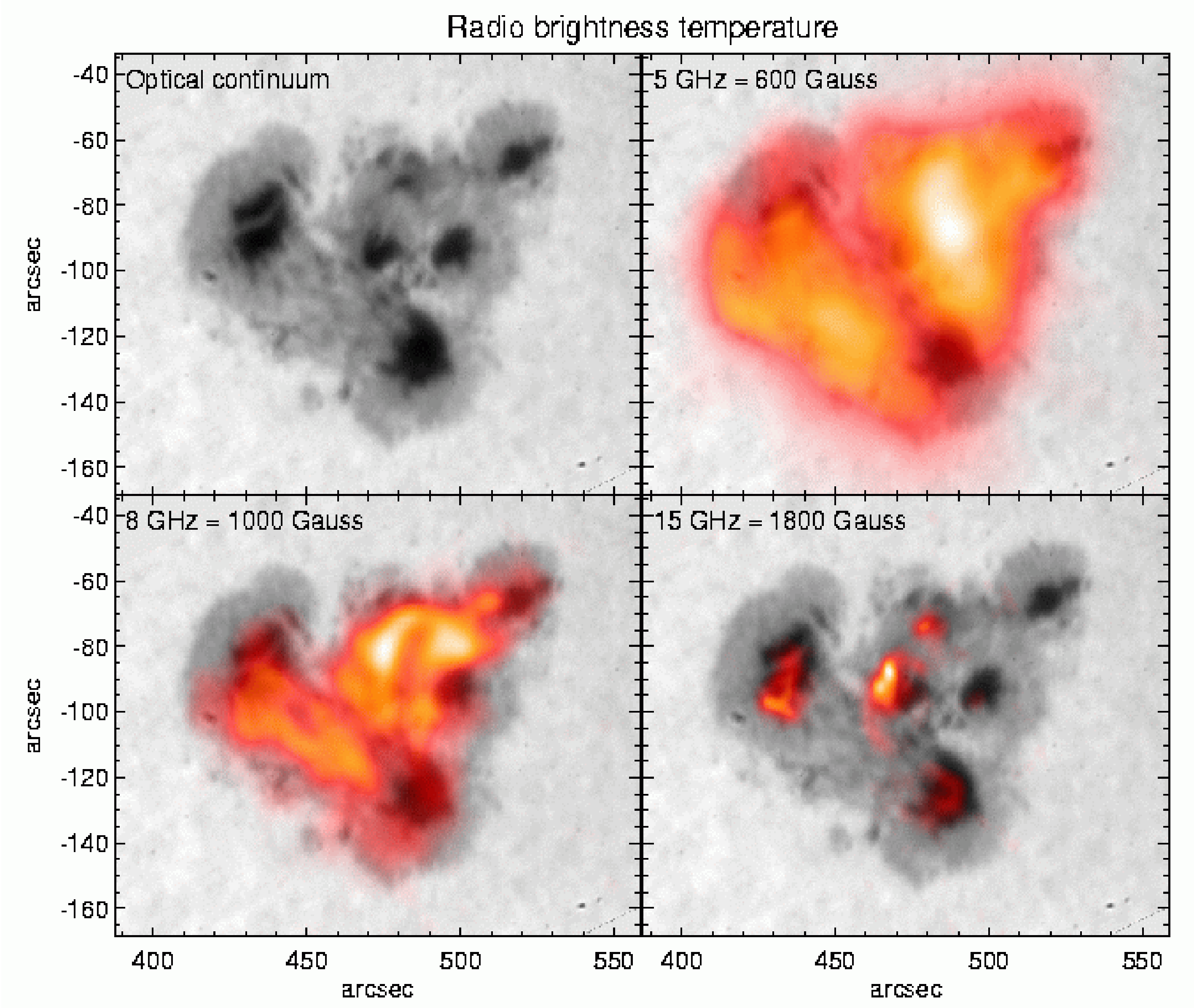

Flux (sfu)
1000
100
10
1
0.1
1.0
10.0
Frequency (GHz)
Maximum
Solar minimum fluxes
RSTN
NoRP

The Radio Sun Cycle

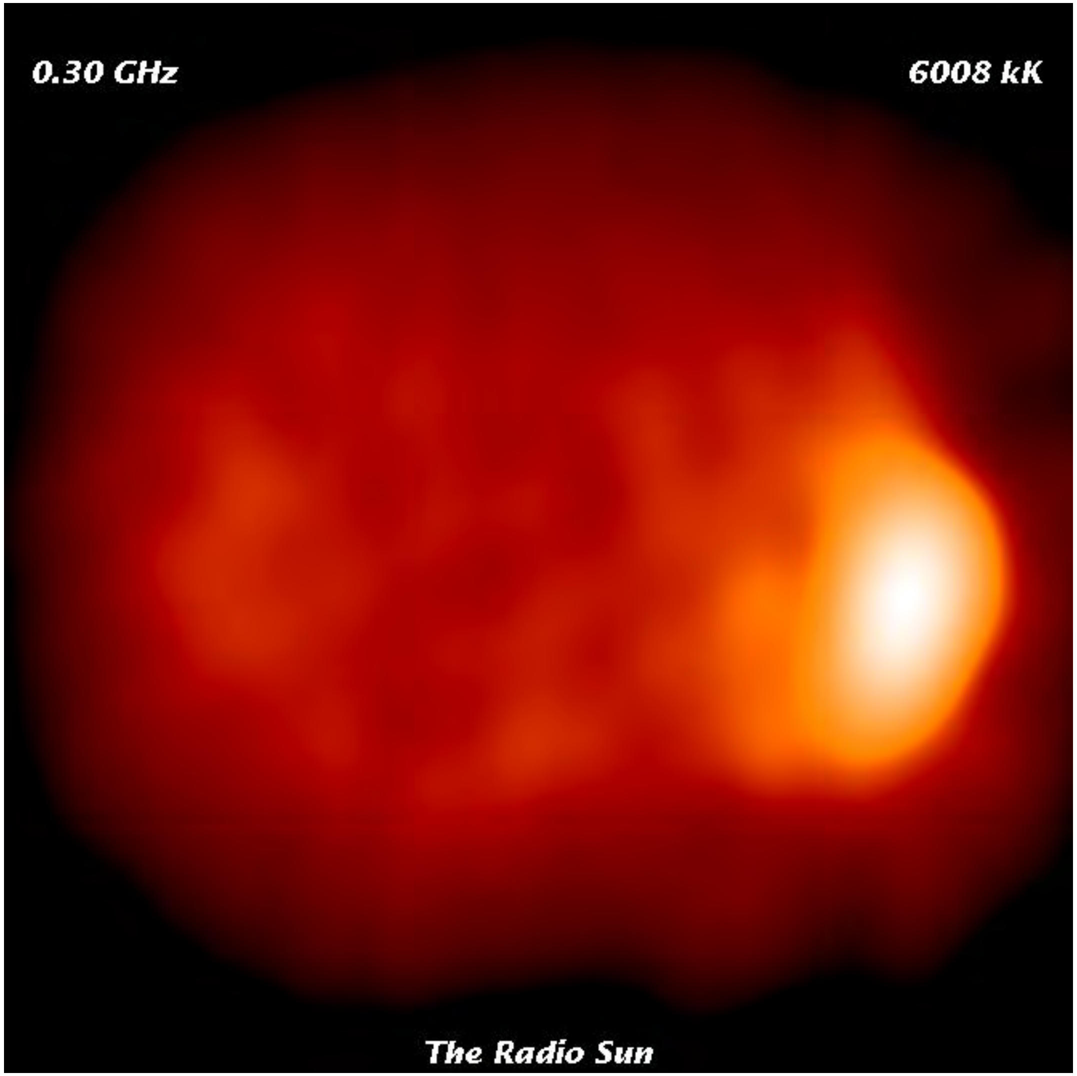


Radio Emission from Magnetic Fields

Region showing strong shear: radio images show high B and very high temperatures in this region



The Radio Sun in Frequency



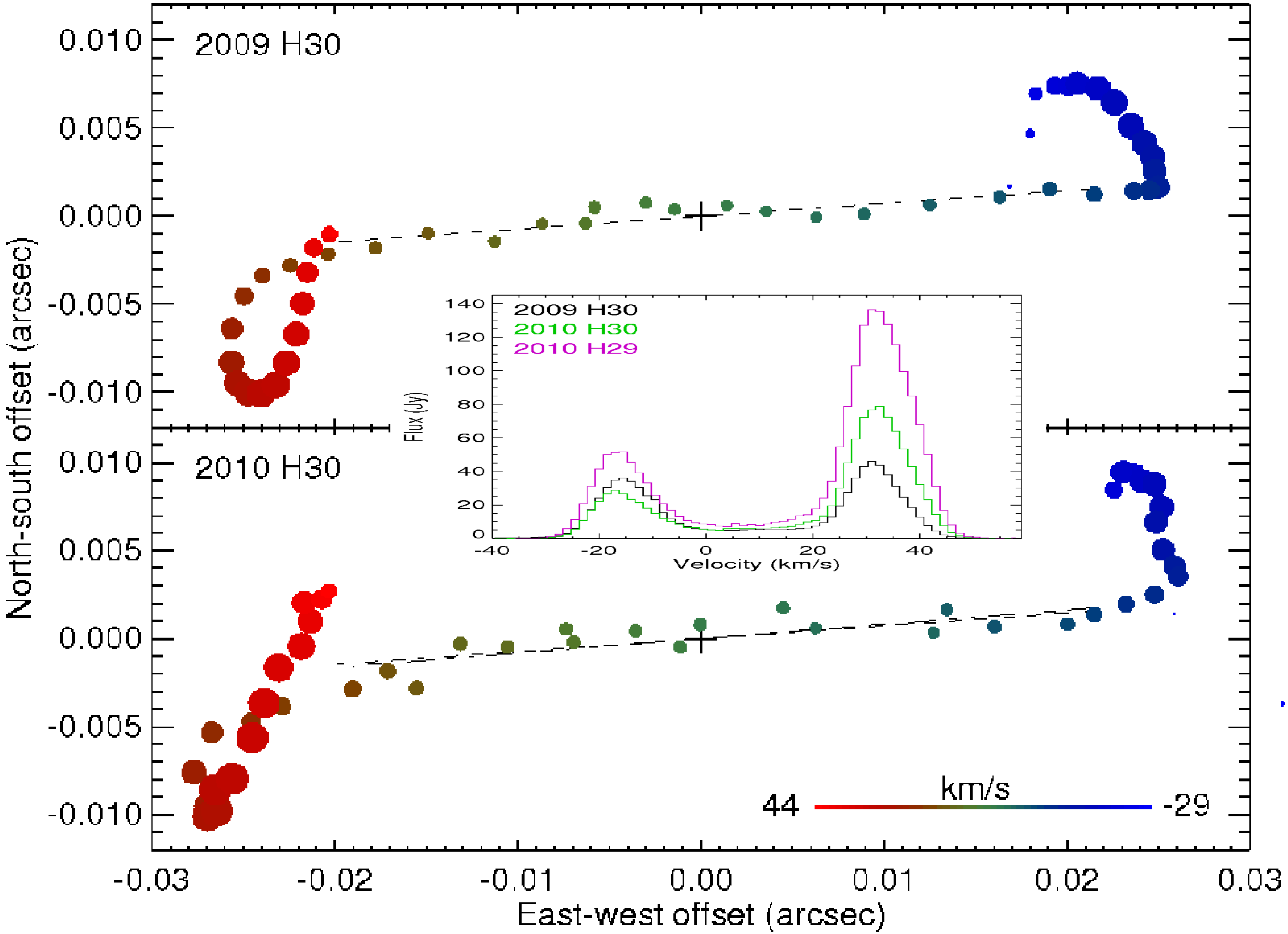
Gyroresonance emission

Opposite to free-free, opacity increases with temperature

Gyroresonance emission has no clear spectral signature

Stars covered with kilogauss fields could be completely optically thick due to gyroresonance

MWC 349 recom line: CARMA 1 mm data



Stellar winds

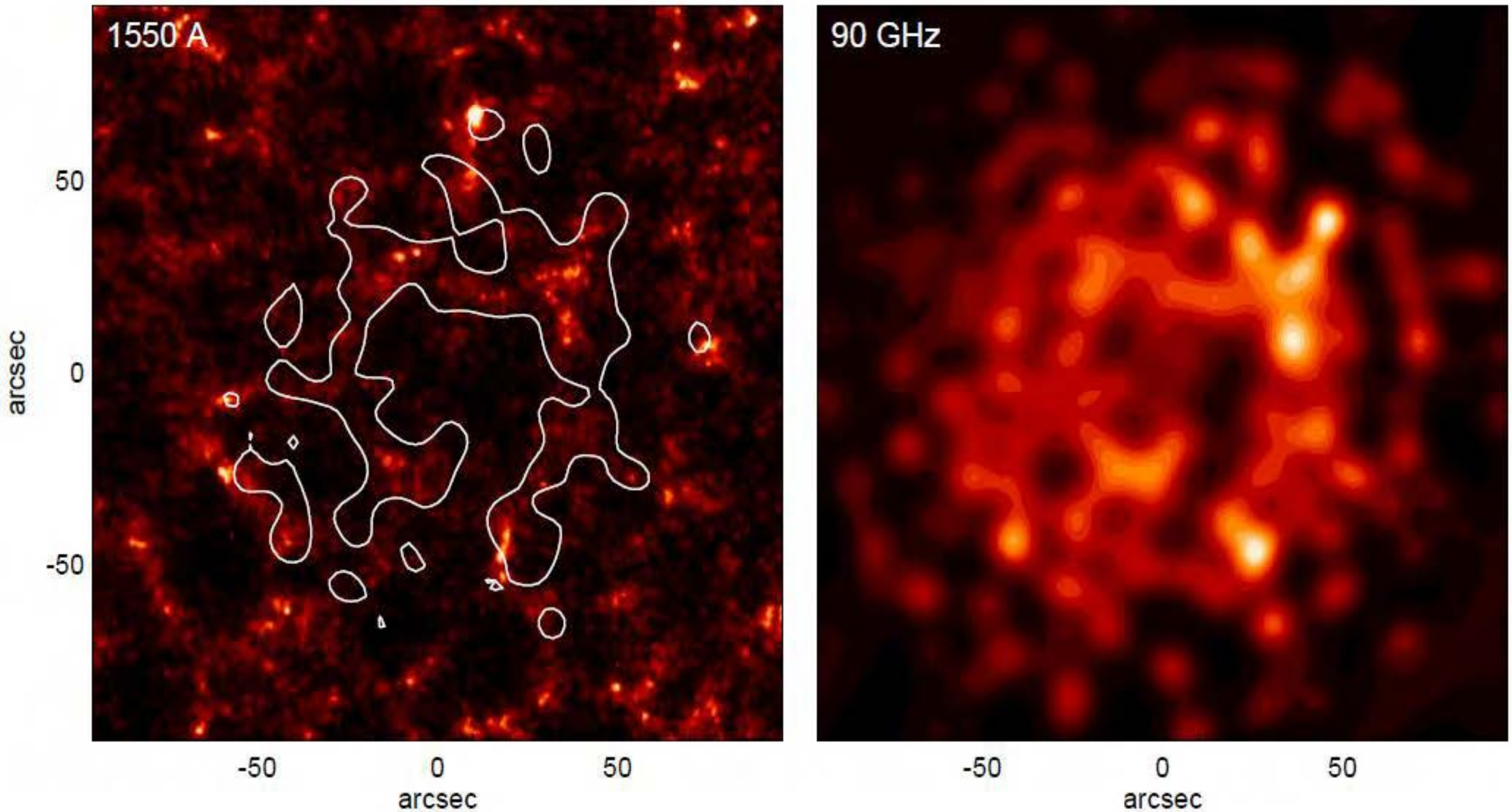
Solar wind is optically thin at all useful frequencies

So far, no active dwarf has a wind detectable in radio

If wind is 10^4 K, need a very large optically thick source, then can't see anything below the wind

If wind/corona is 10^7 K (gyroresonance), source can be smaller

CARMA map of the chromosphere



2008 Sep 26 data: in conjunction with TRACE UV observations. CARMA image with 10” beam (two dish sizes!)

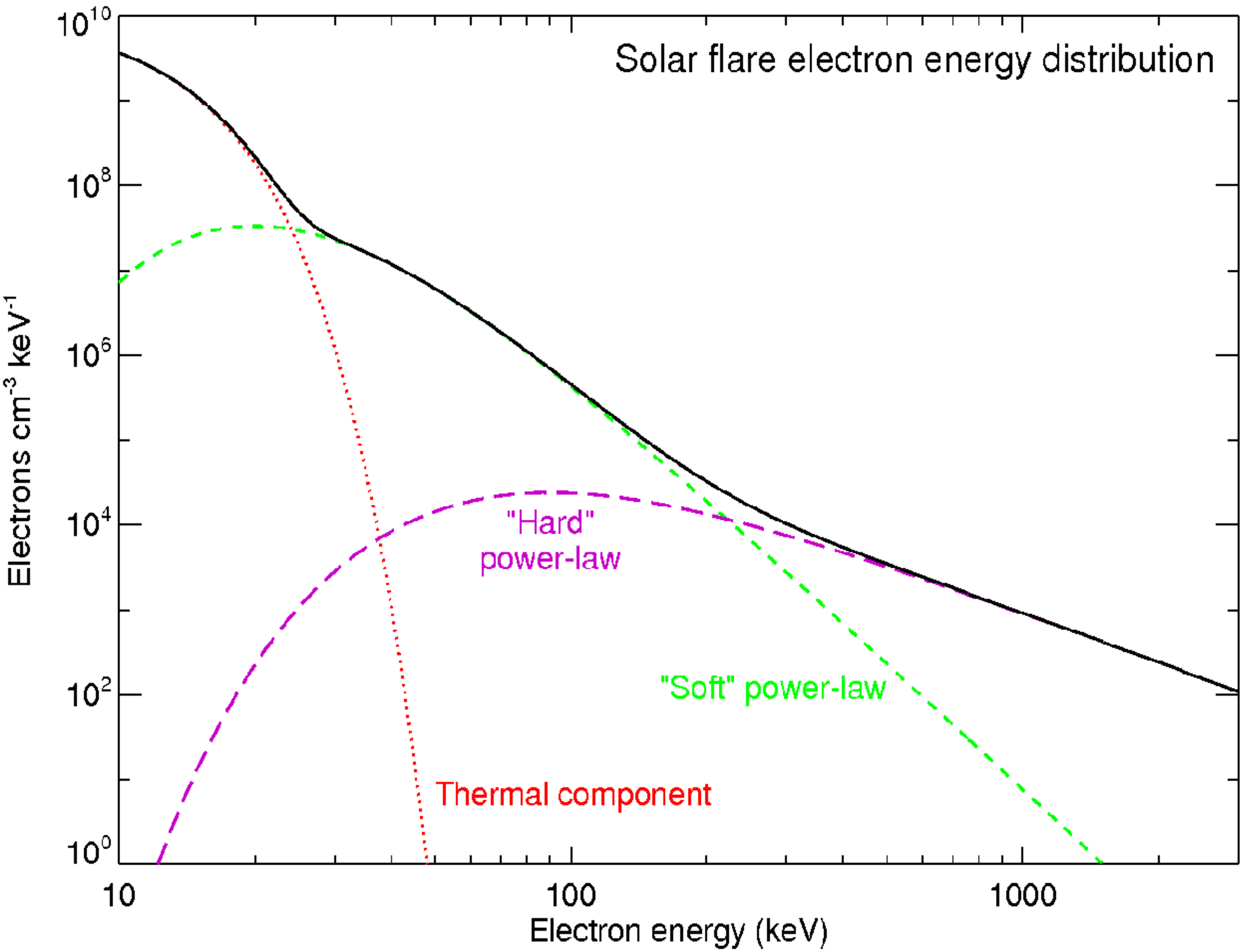
Gyrosynchrotron emission from the Sun

Solar flares above 2 GHz dominated by gyrosynchrotron emission from nonthermal electrons gyrating in coronal fields, but spectra are too broad

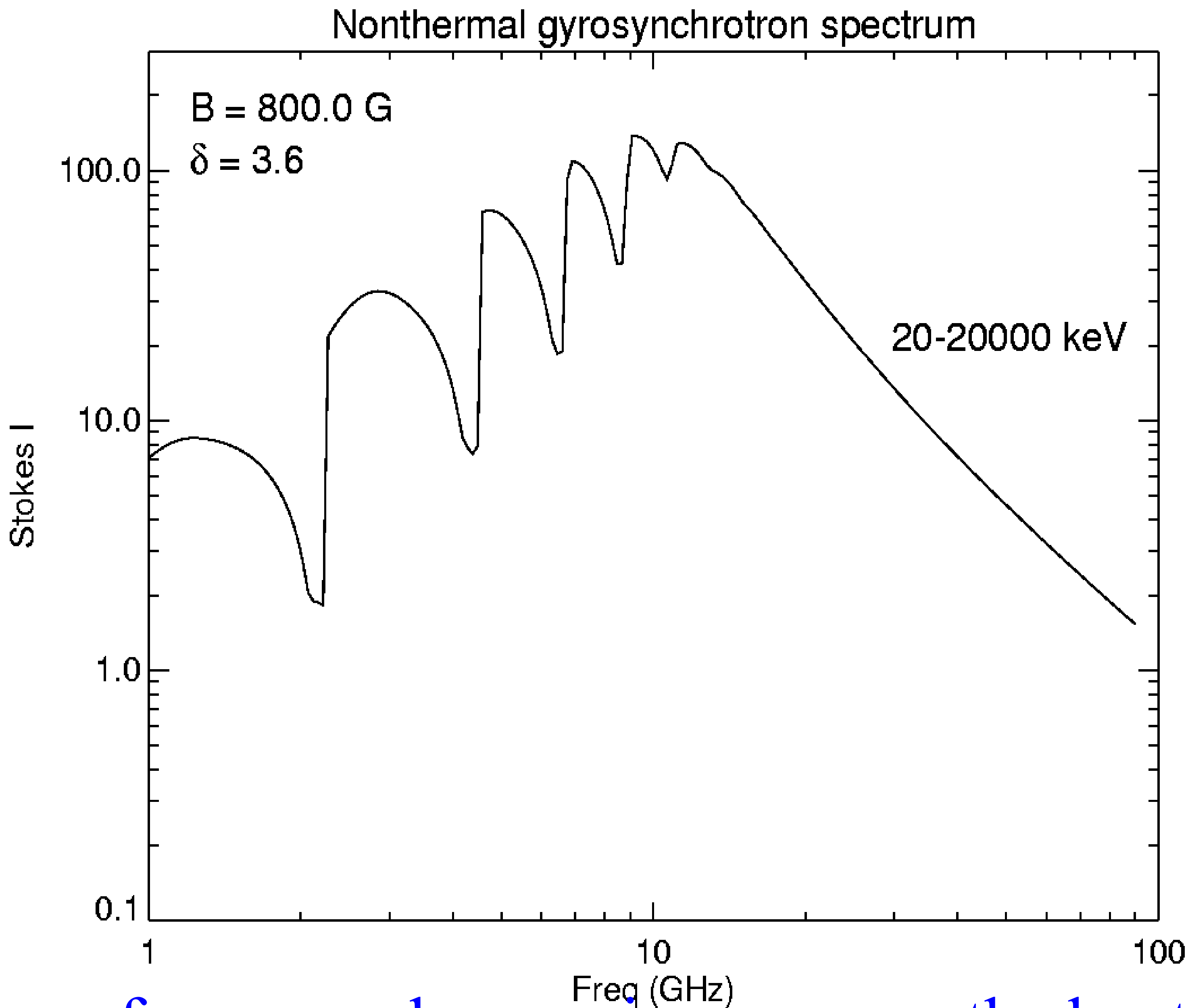
Stellar quiescent emission: too flat?

Thermal gyrosynchrotron has never been seen

Double power-law energy distribution

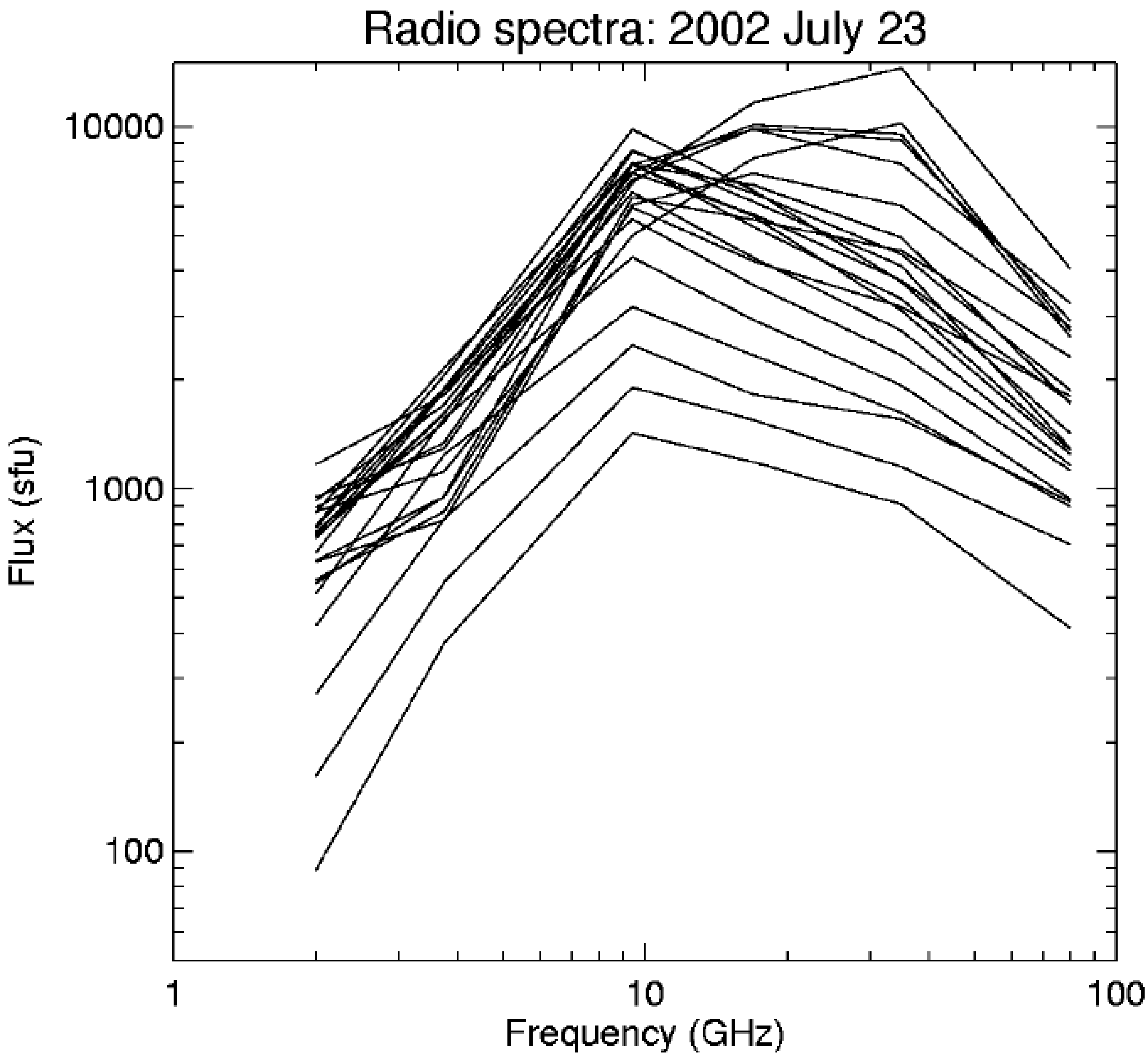


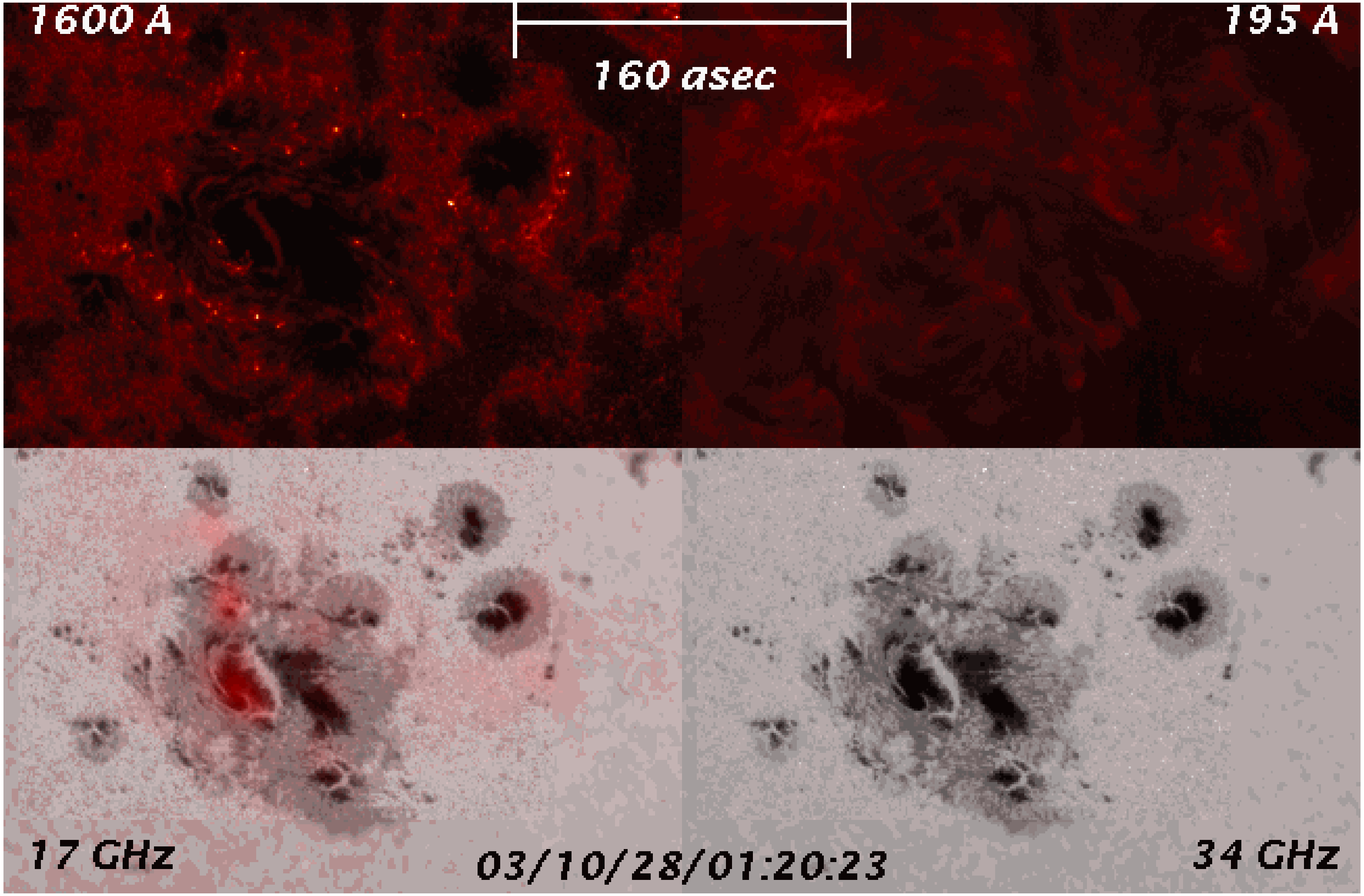
Gyrosynchrotron flare spectrum



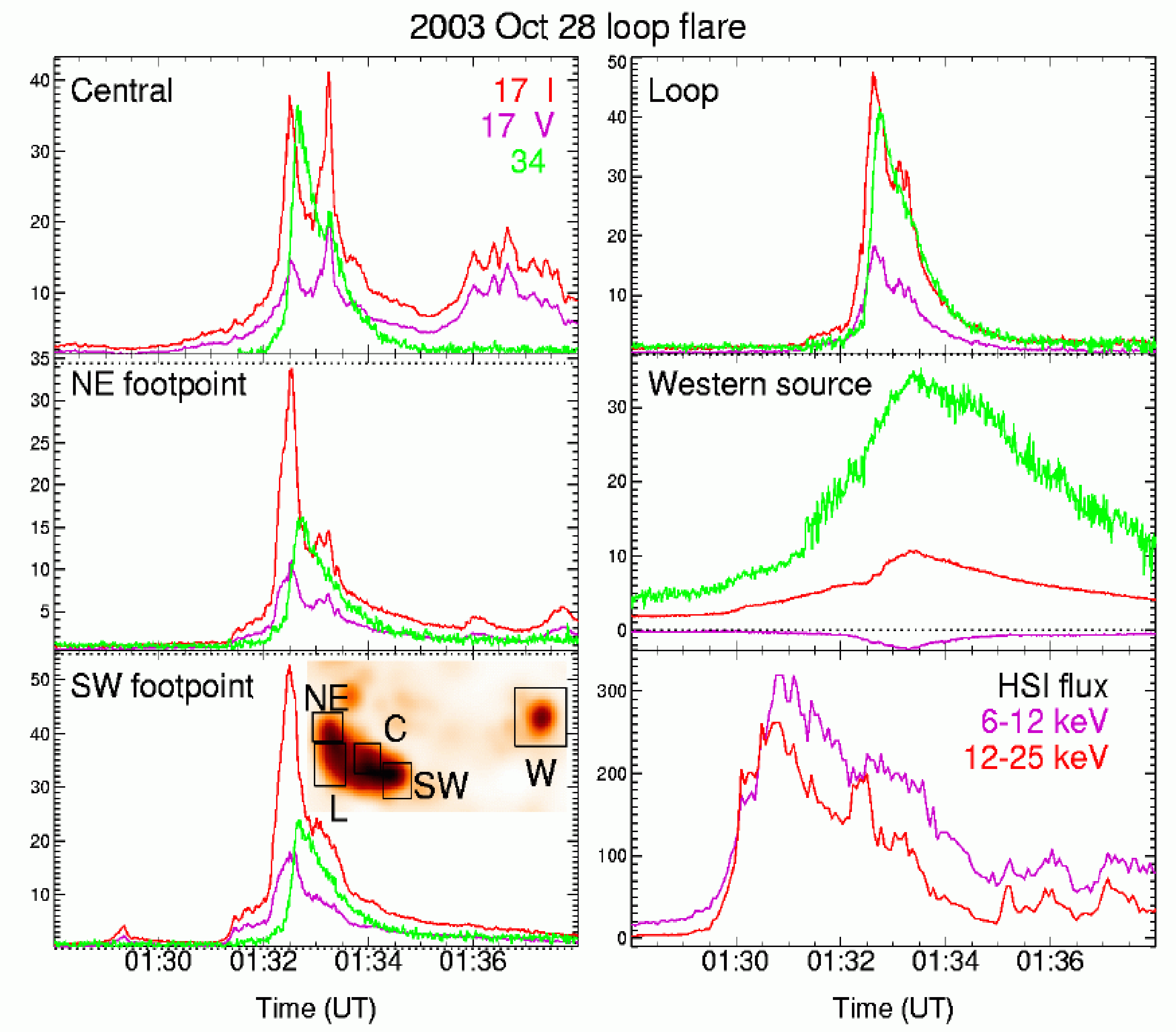
Low-frequency harmonics are smoothed out by variations in B

2002 July 23: radio spectra



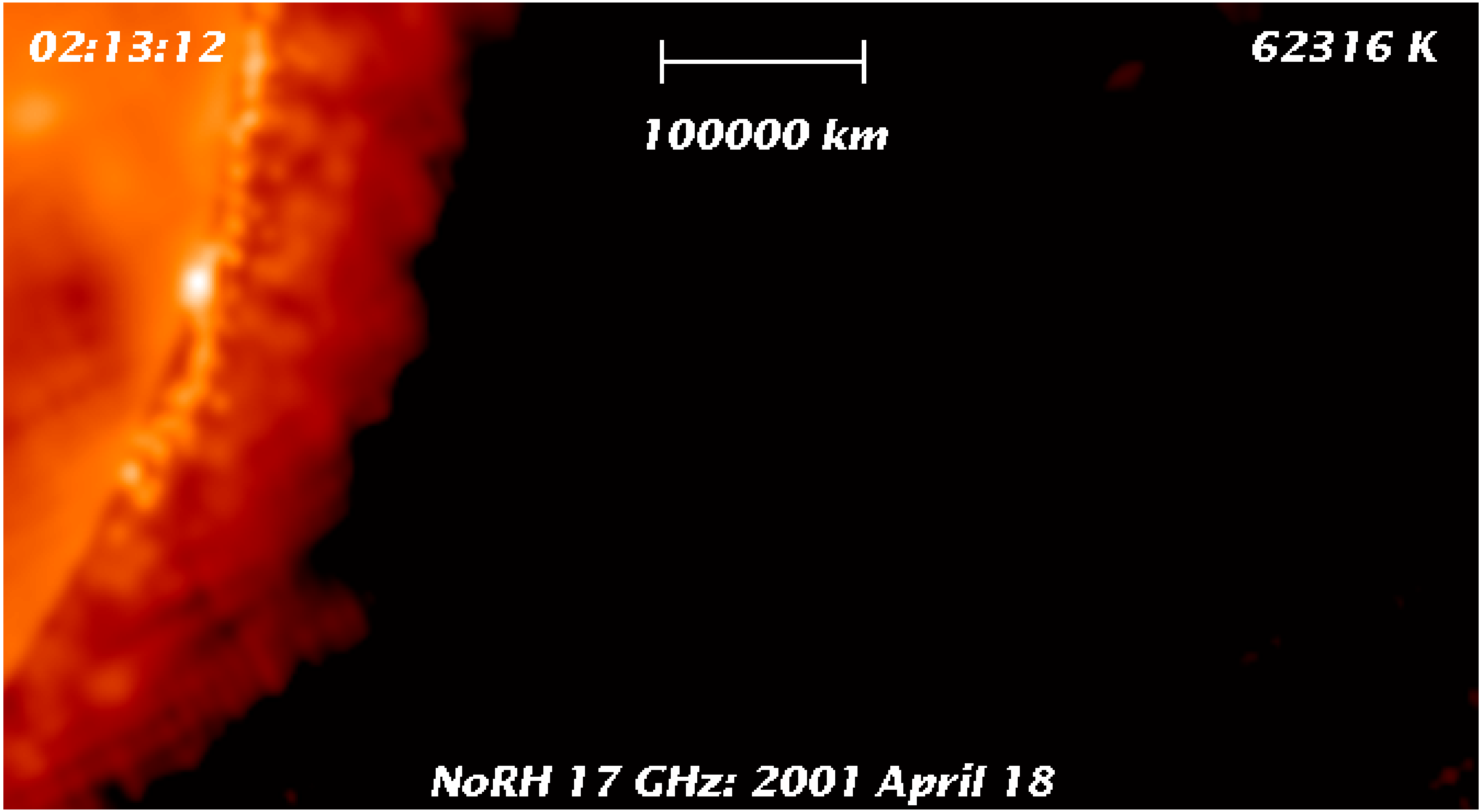


1600 A
160 asec
195 A
17 GHz
03/10/28/01:20:23
34 GHz

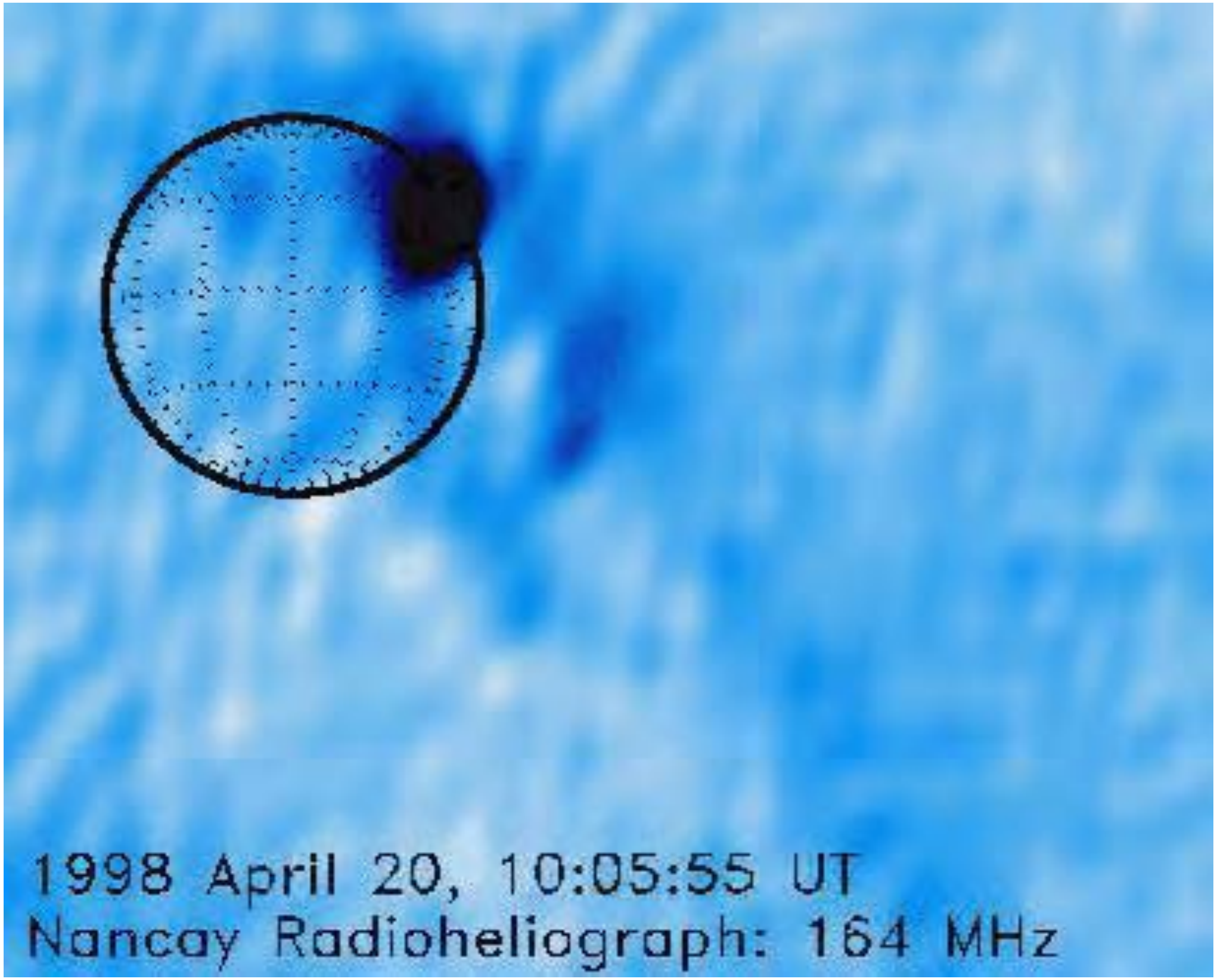


2003 Oct 28 loop flare
Central
17 I
17 V
34
Loop
NE footpoint
Western source
SW footpoint
NE
C
SW
W
L
HSI flux
6-12 keV
12-25 keV
01:30
01:32
01:34
01:36
Time (UT)

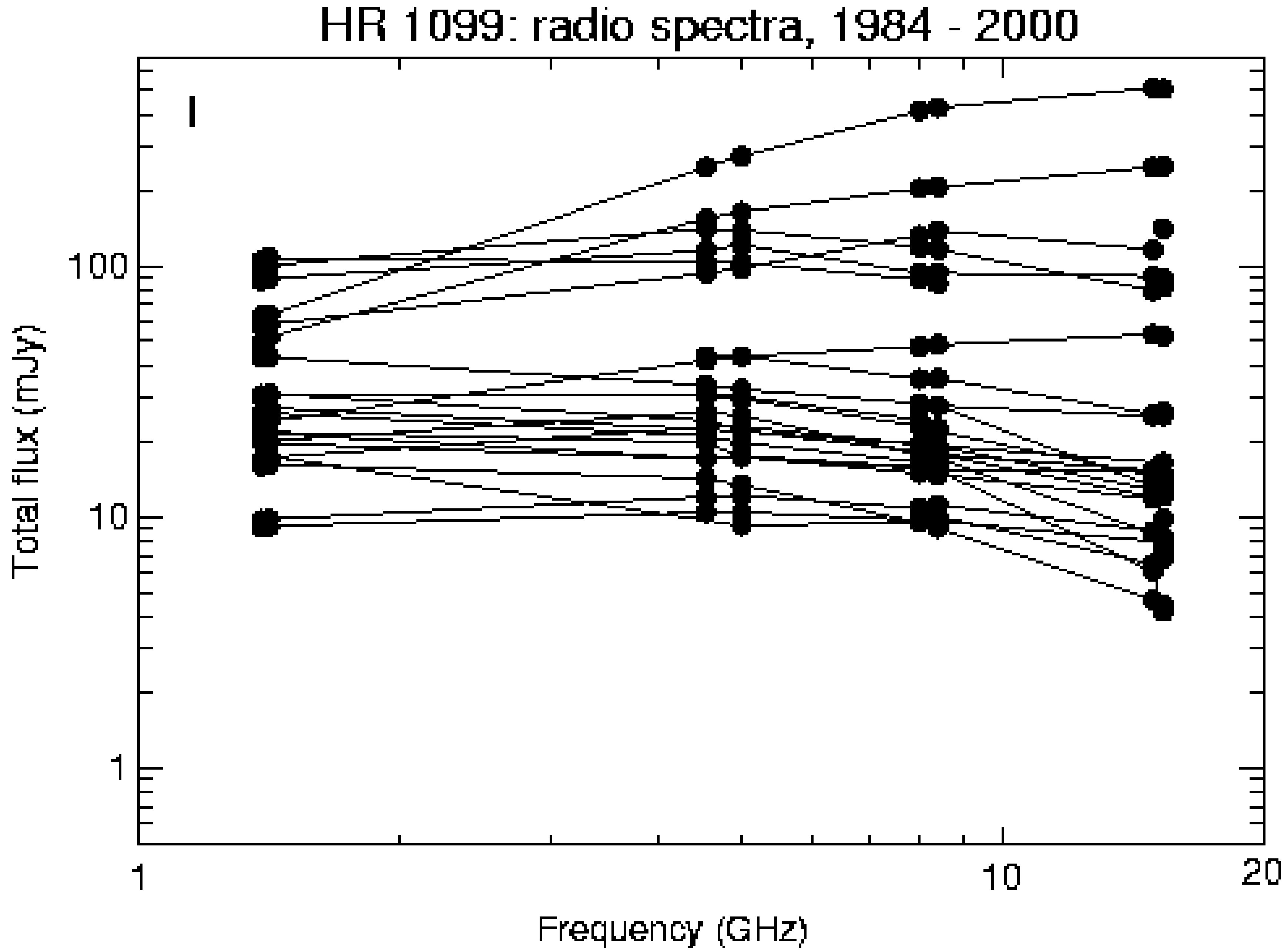
Radio movie of an eruption behind the limb



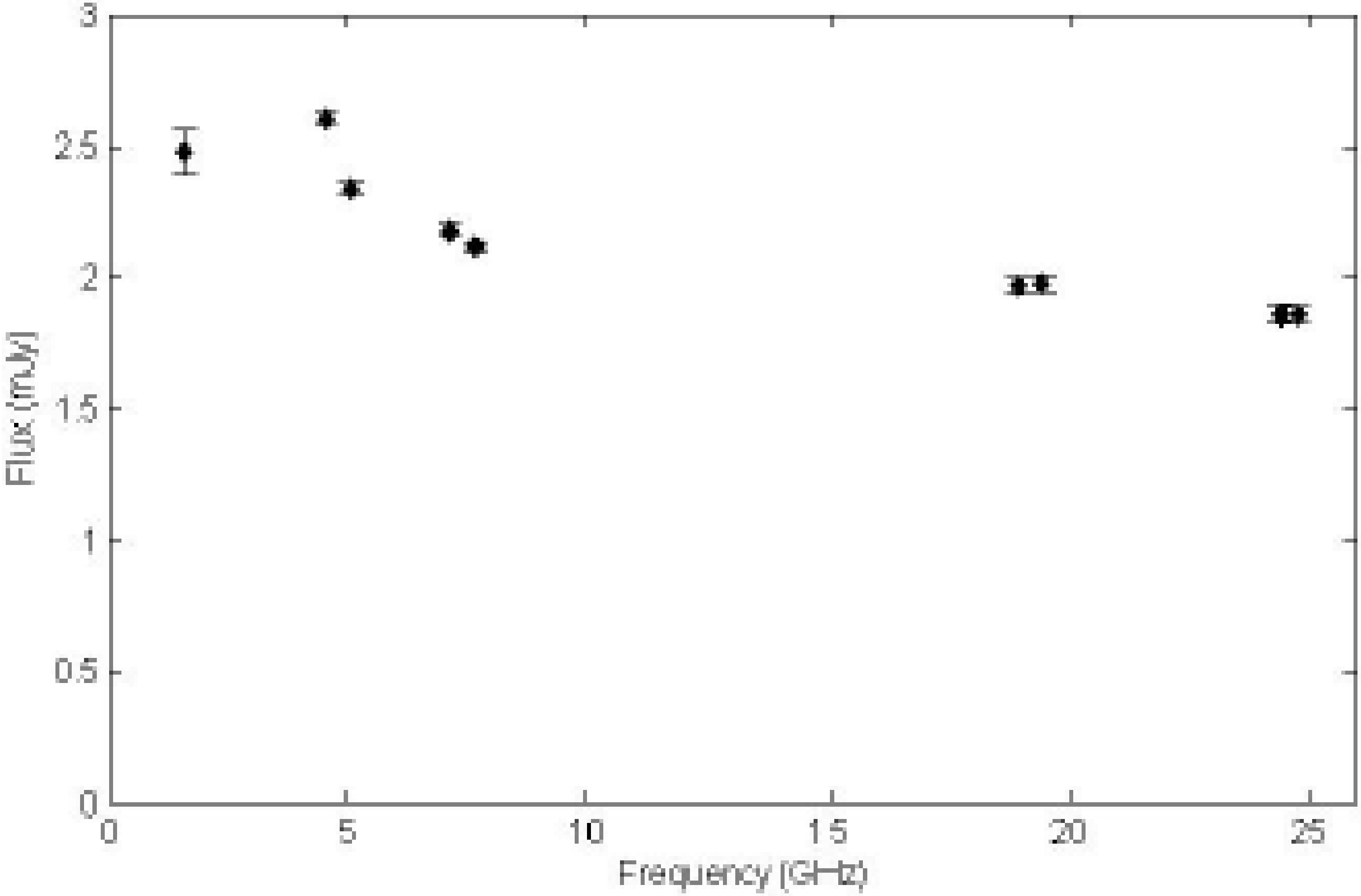
Radio observation of a mass ejection



Bastian, Pick, et al., 2001, ApJL 558, L65


HR 1099: radio spectra, 1984 - 2000
I
Total flux (mJy)
100
10
1
1
10
20
Frequency (GHz)

Radio spectrum of UV Cet: gyrosynchrotron



Hallinan

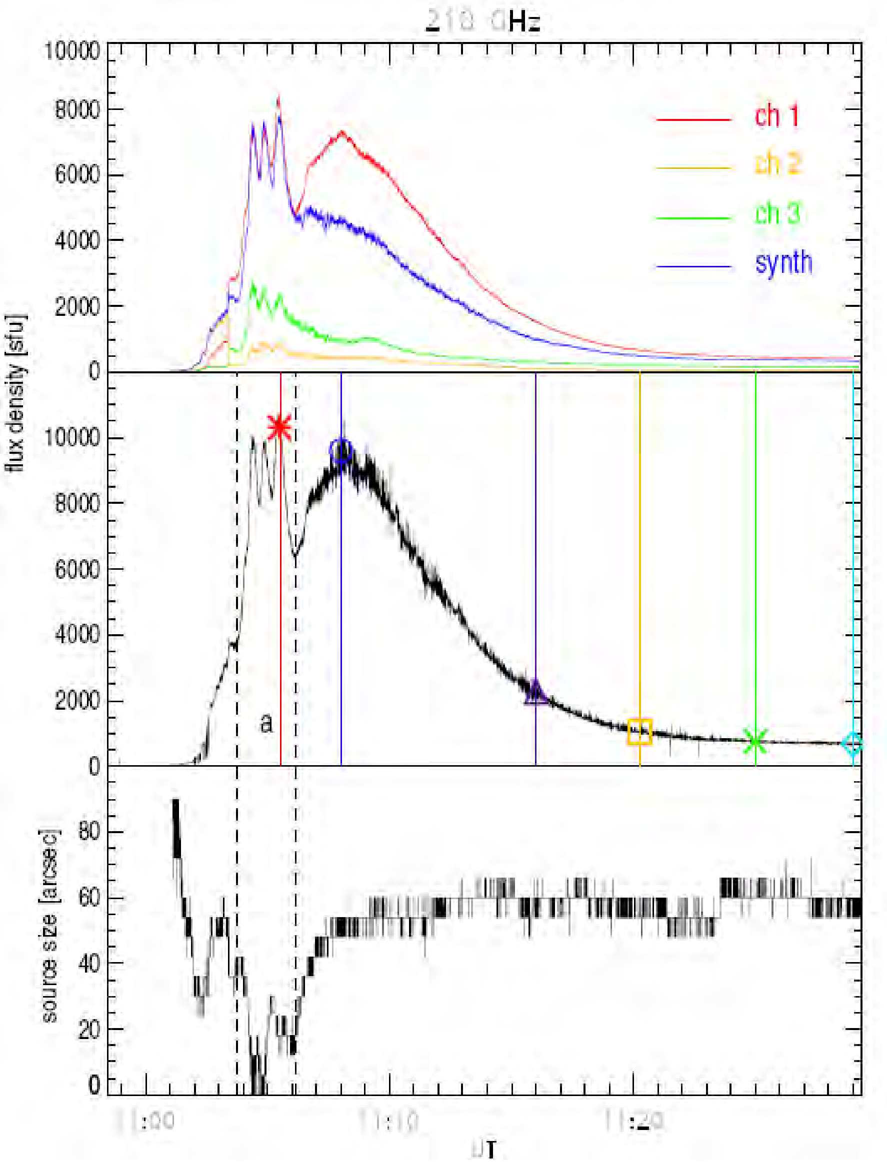
The biggest flares?

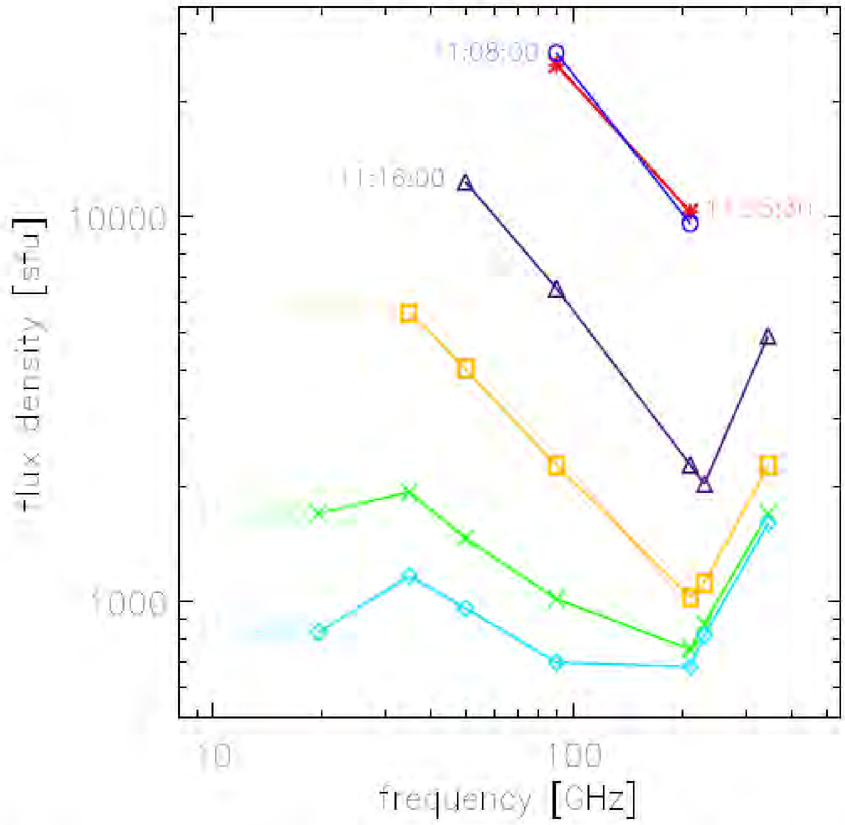
Work recently on what the biggest solar flare might be – probably 10 times bigger than anything in recent history

May be 10^6 sfu = 10^{10} Jy at centimeter wavelengths

Existing stellar flares are bigger than this

28.10.2003: GOES X17.2 Flare





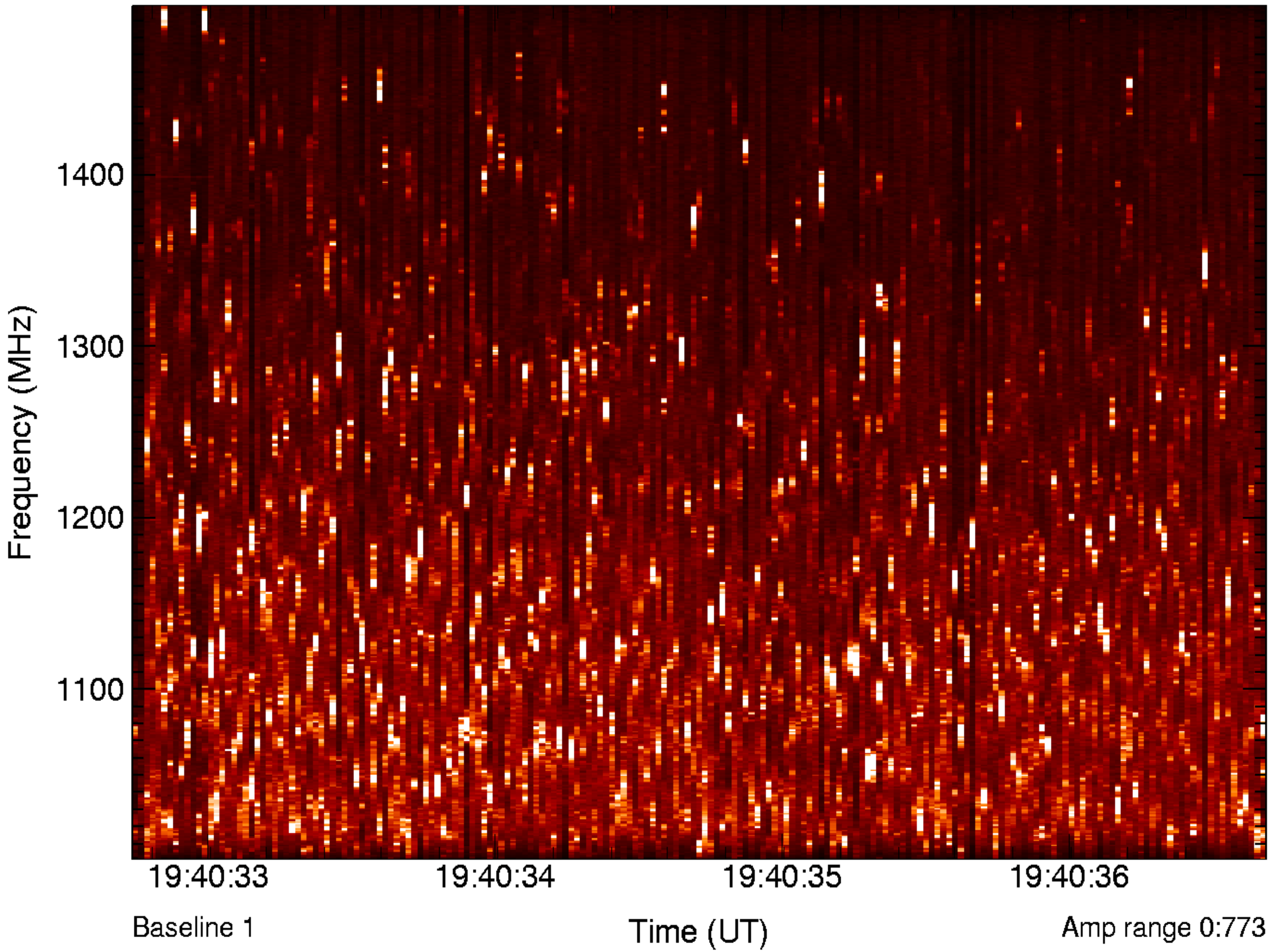
T. Lüthi et al., A&A, **420**, *361–370, 2004*

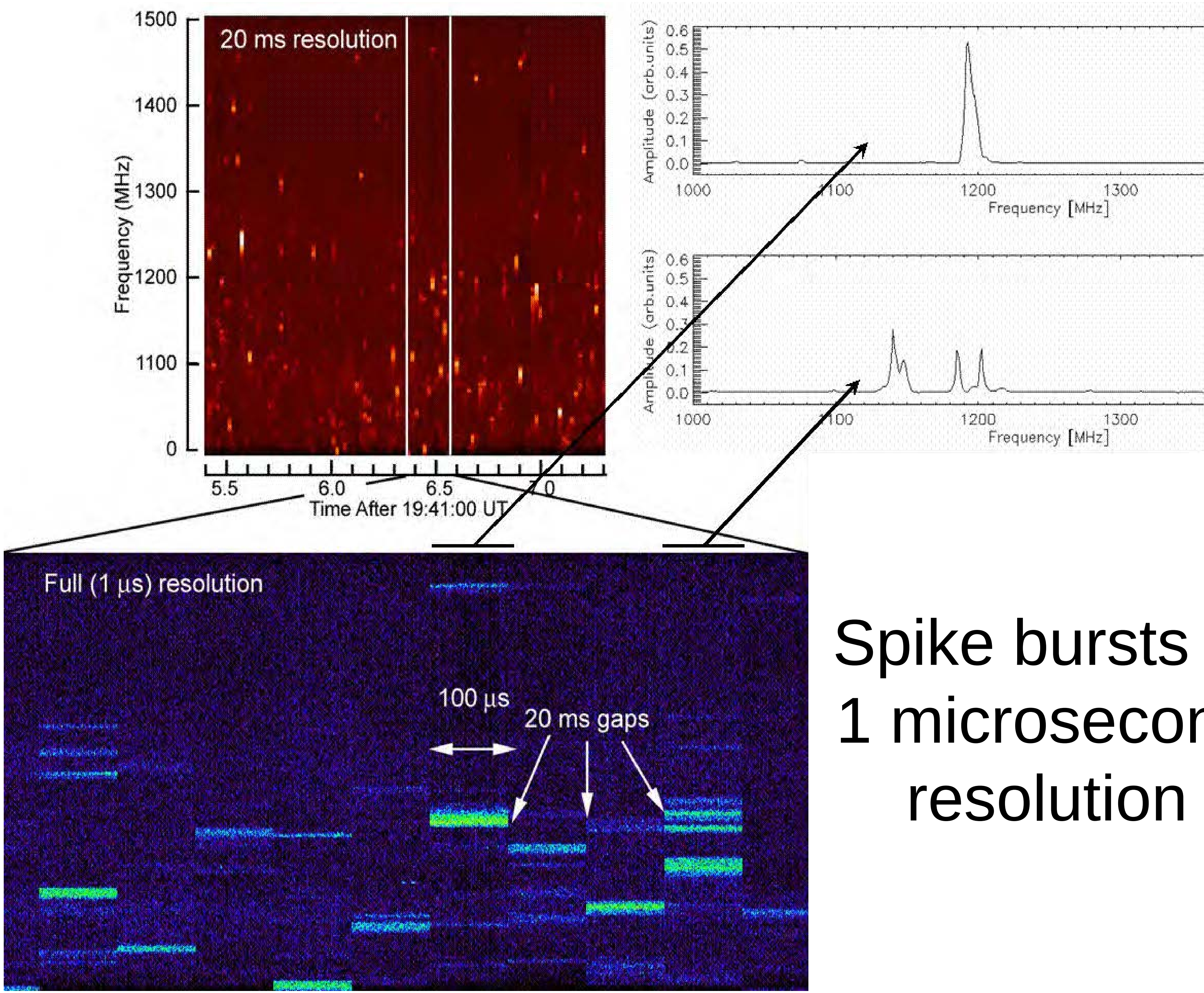
Electron cyclotron maser emission

Solar examples are spike bursts, very high brightness temperature: don't match the stellar examples which are more like Jupiter, but …

Magnetic CP stars and cool dwarfs – who knew?

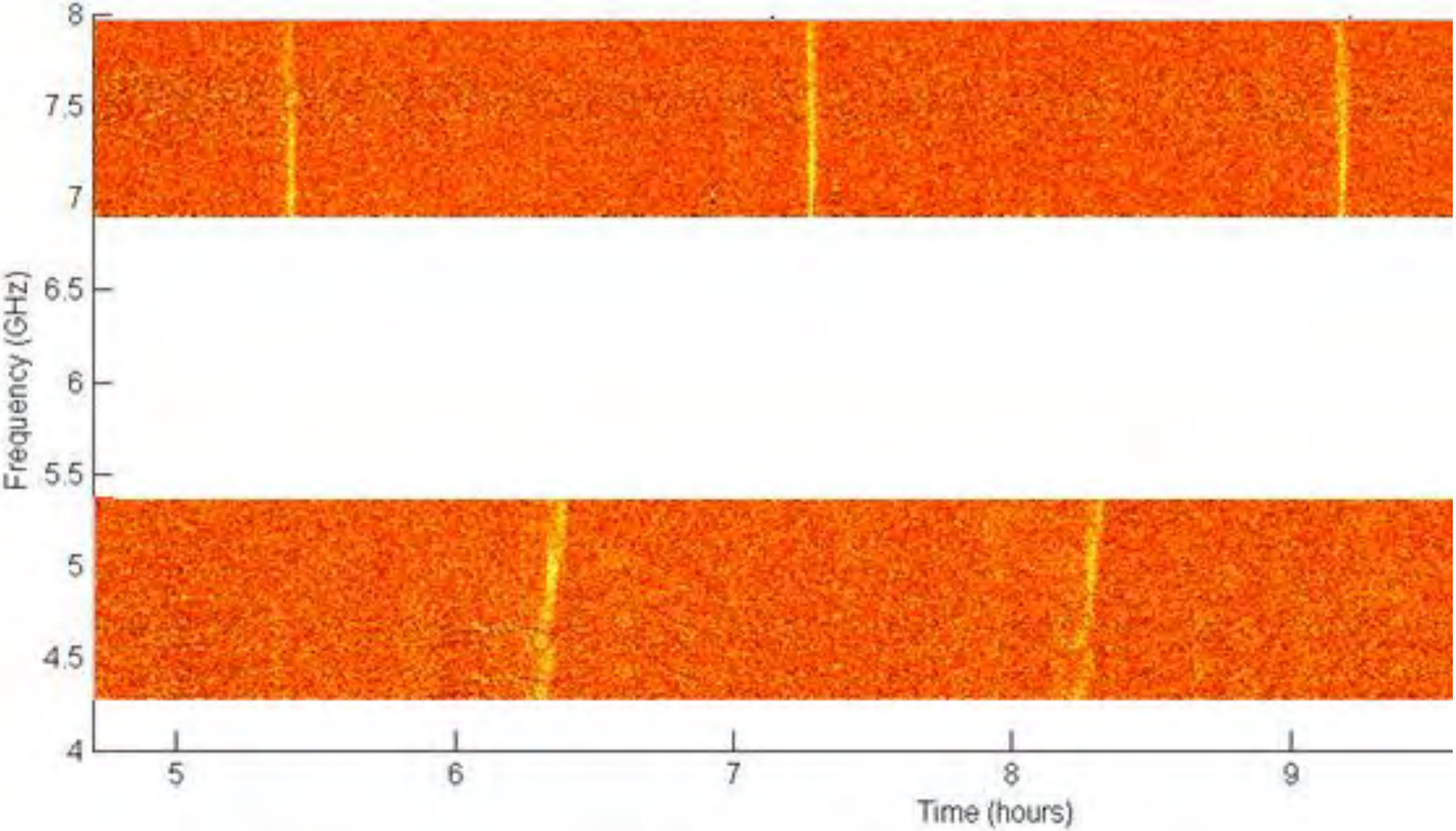
Solar electron cyclotron maser: “spike bursts”





Spike bursts at 1 microsecond resolution

Pulses from a cool dwarf



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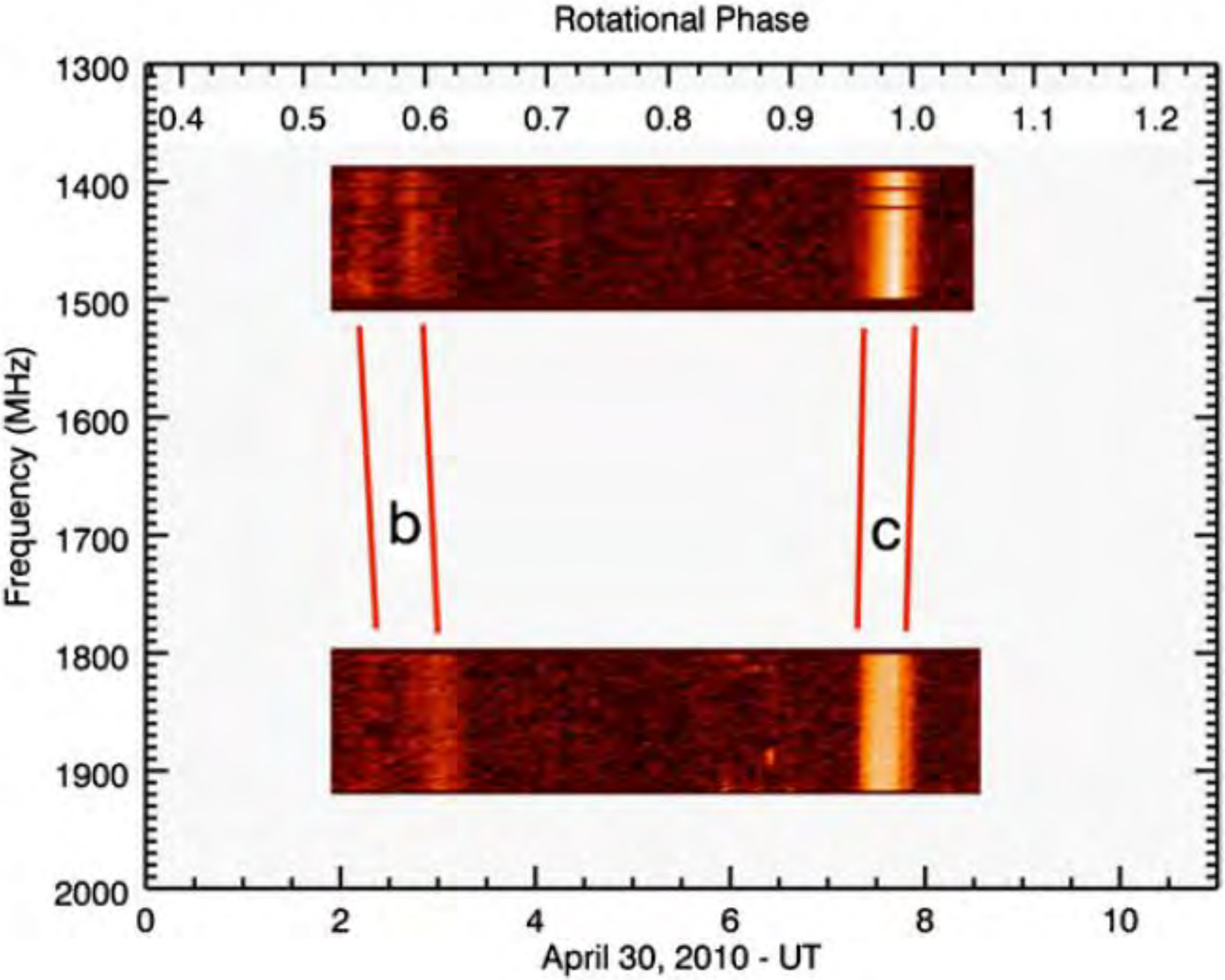
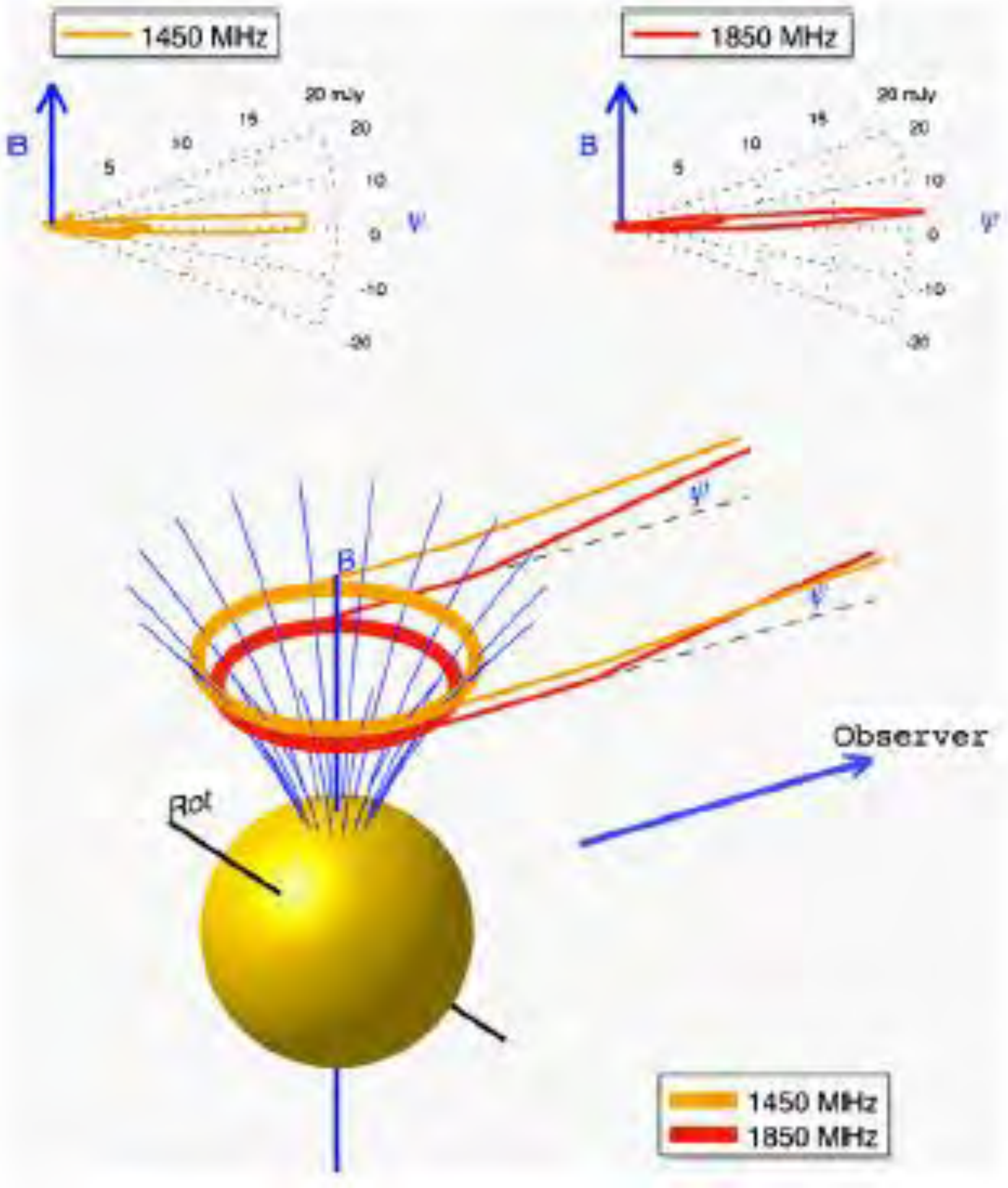


Magnetic Cp star CU Vir: Trigilio et al, 2011



Offset rotator, pole=3000G

Model: auroral emission orthogonal to the magnetic field

(Trigilio et al 2011)

Plasma emission

Dominates frequencies below 2 GHz on the Sun, thermal absorption limits at higher frequencies (but possible on stars)

Produced by electron beams, shocks, ….

Jury still out on whether Type II bursts require coronal mass ejections

Lots of frequency structure

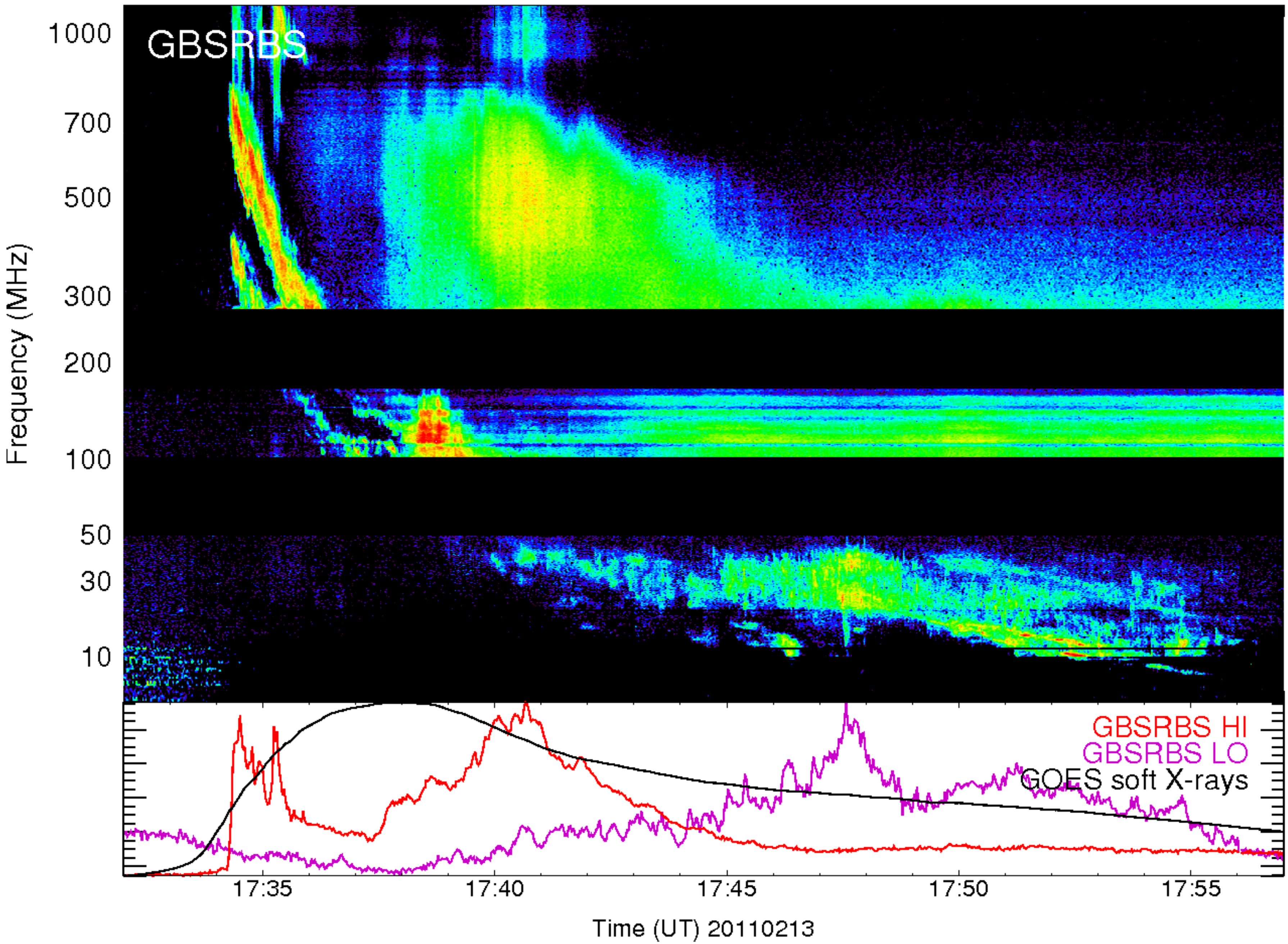
Solar Radio Bursts

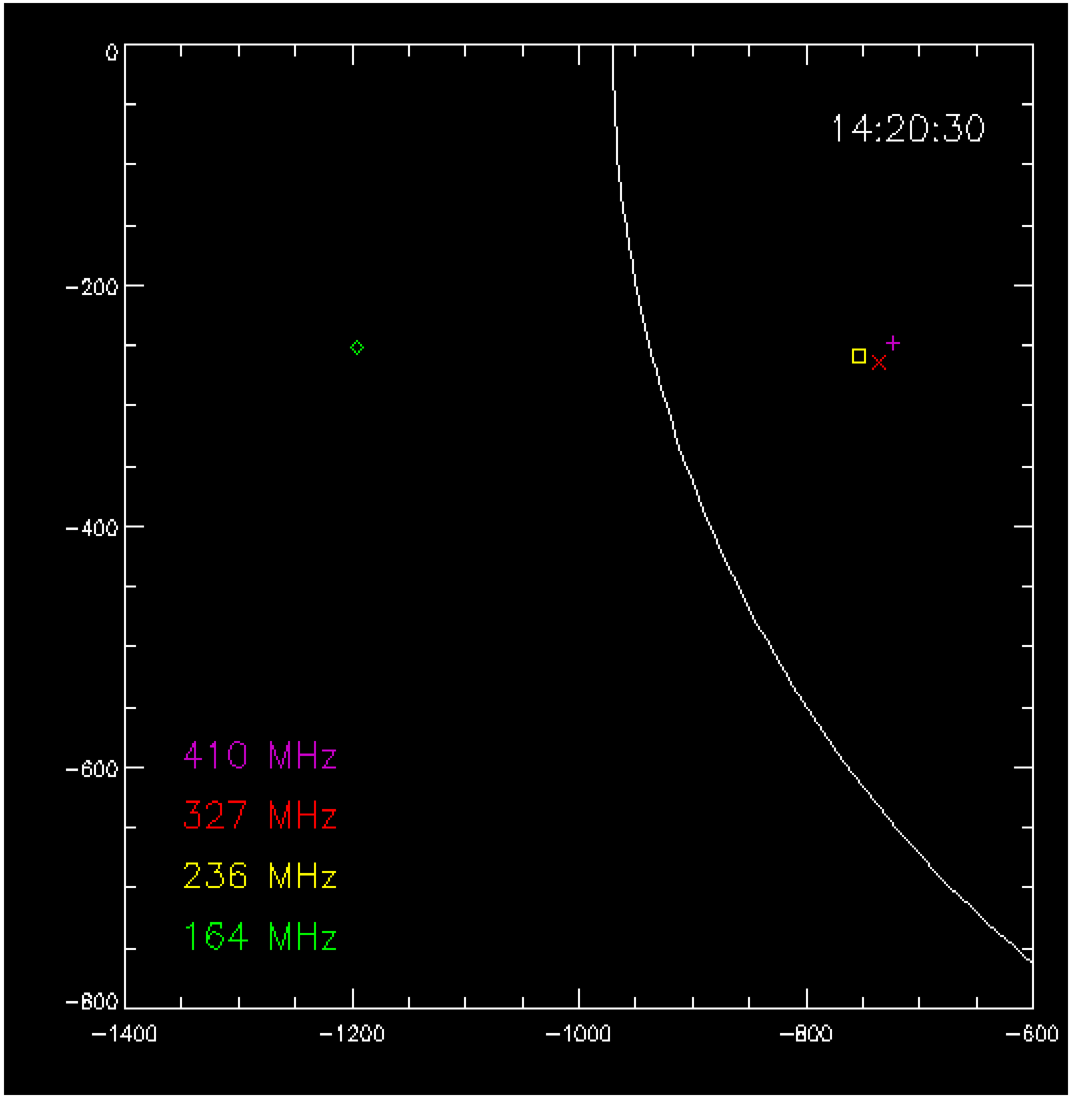
Type III bursts: fast frequency drift rate, due to electron beams on open field lines, bump on tail instability, locally narrowband

Type II bursts: slower frequency drift rate, speeds of order Alfven speed, typically see split bands at f_p and $2f_p$ simultaneously: shocks!

Type IV bursts: broadband, start in extended phase of flares, often show vertical structure on spectra that could be modulations or fast-drift: mechanism unclear

Type II burst (shock) + Type IV



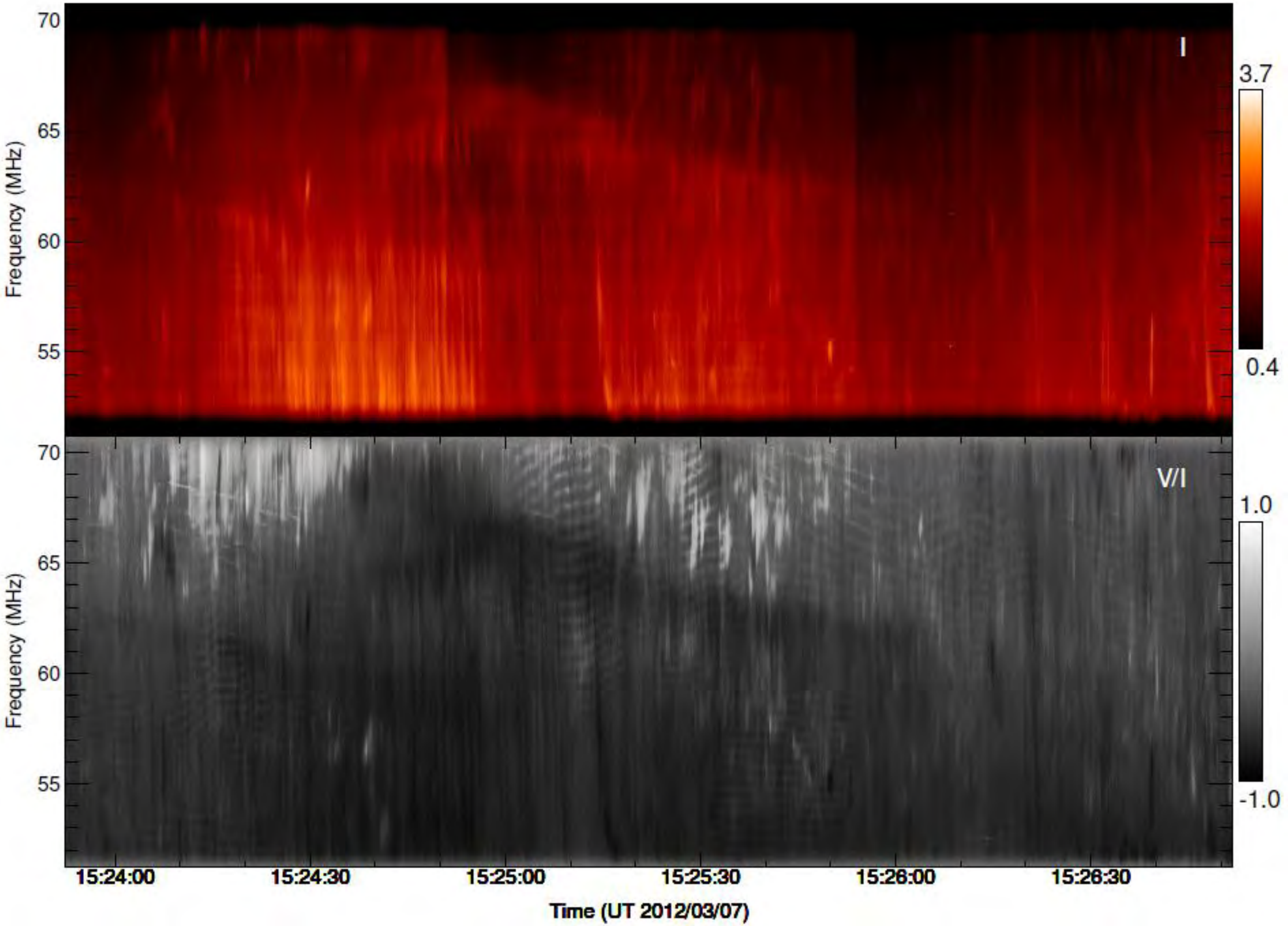


Nancay Radioheliograph source positions versus time at 4 frequencies

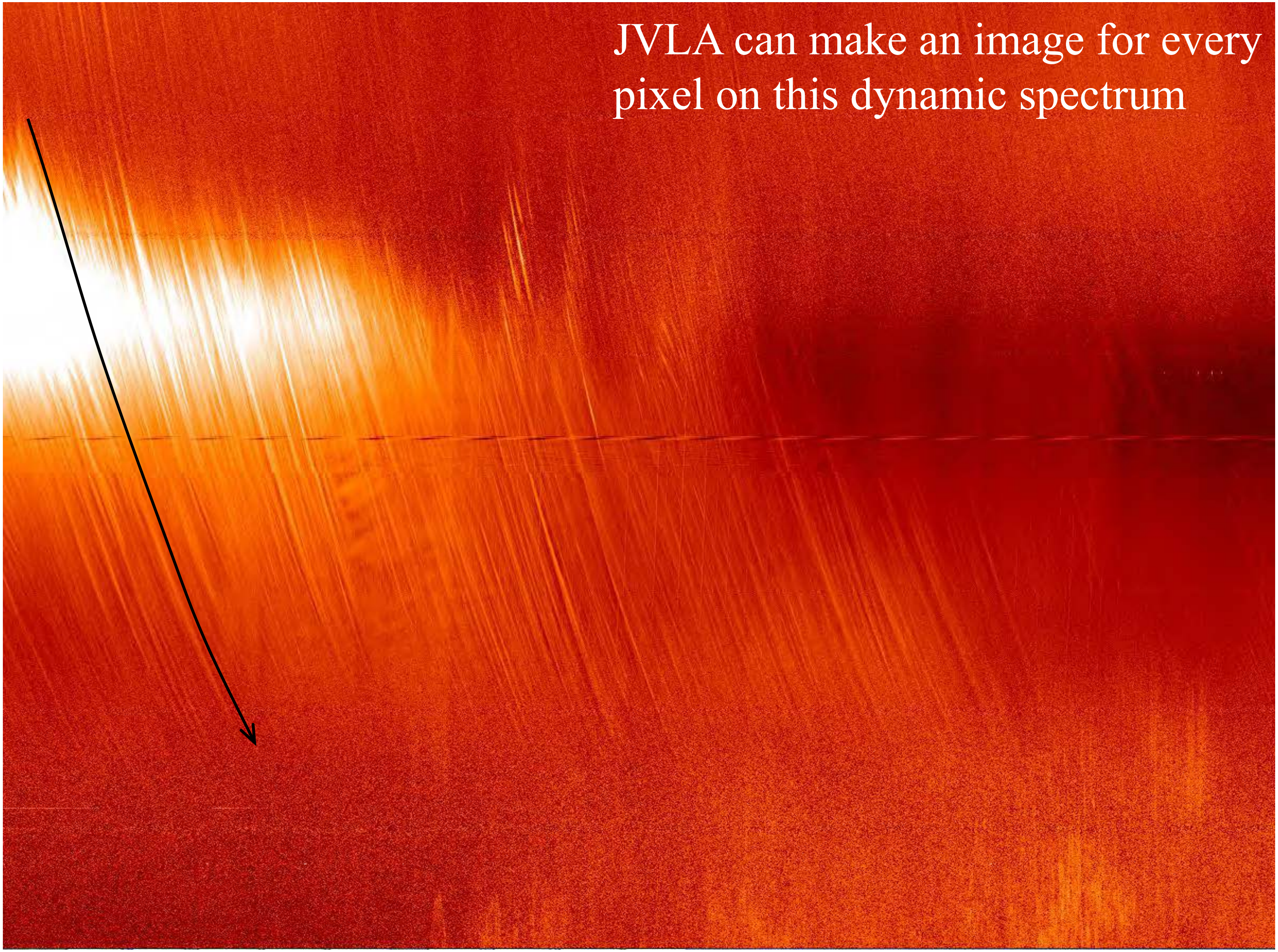
South-eastern source is Type II

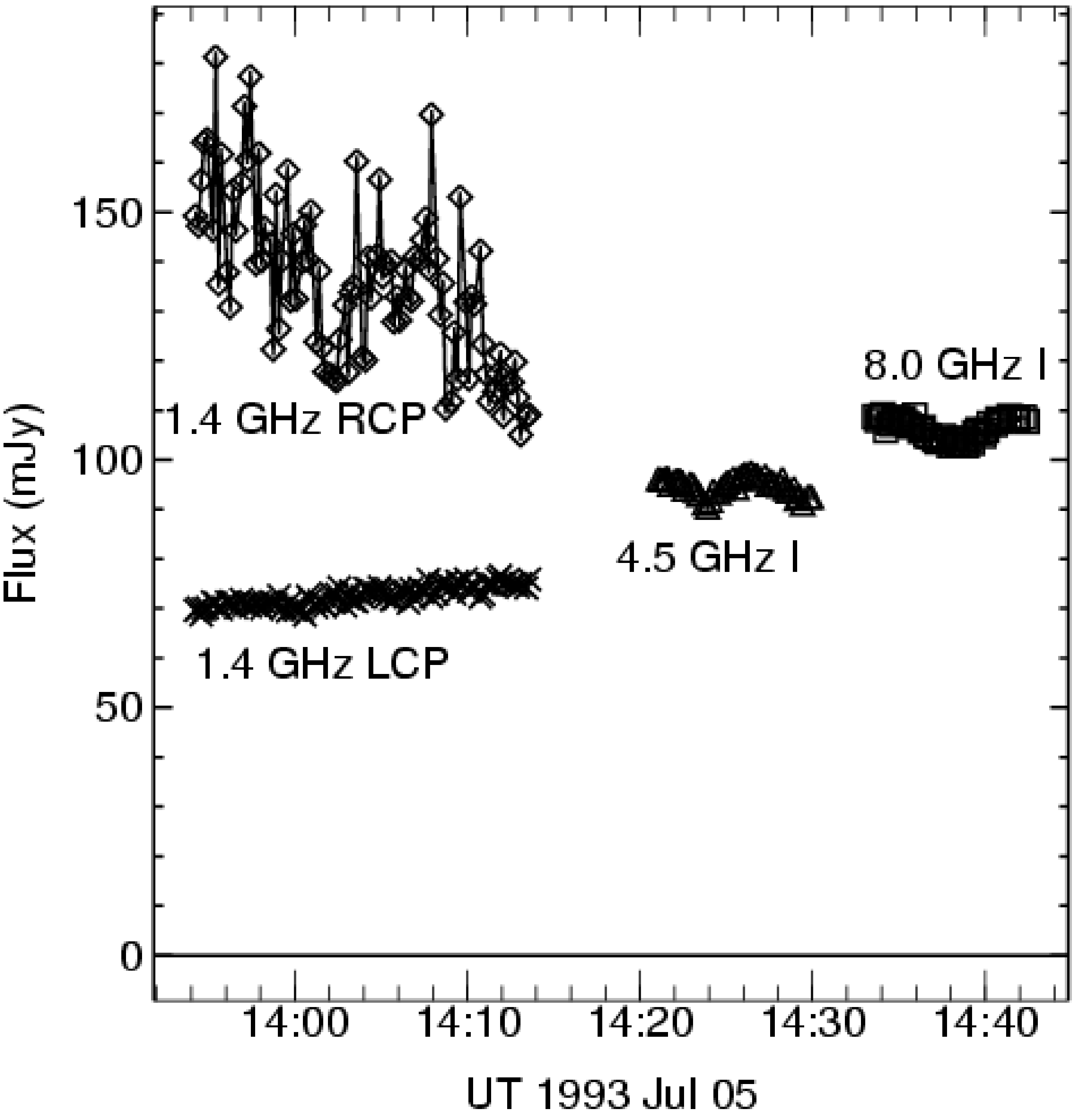
Western/north-eastern source is a Noise Storm

Frequency structure in a noise storm (LWA)



1-2 GHz, 50 msec resolution (Chen, Bastian)





HR 1099
(RS CVn)

VLA data

New solar instrumentation

FASR (Frequency Agile Solar Radiotelescope)
Expanded Owens Valley Solar Array
LOFAR
Long Wavelength Array
MWA
Chinese Solar Radio Heliograph
Siberian Solar Radio Telescope

OVSA Upgrade Specifications

Frequency range	1 – 18 GHz
Number of data channels	2 (dual polarization)
IF bandwidth	500 MHz per channel
Frequency resolution	Raw: 122 kHz (4096 spectral channels) Science: ~50 MHz
Time resolution	Sample time: 20 ms Full Sweep: 680 ms
Polarization	Full Stokes (IQUV)
Number correlator inputs per data channel	16
Number and type of antennas	Five 2-m equatorial Eight 2-m azel Two 27-m equatorial (night-time and cal. only)
Angular resolution	$57''/\nu_{GHz} \times 51''/\nu_{GHz}$
Array size	1.08 km EW x 1.22 km NS

OVSA EXPANSION PROJECT

Dale E. Gary
Professor, Physics, Center for Solar-Terrestrial Research
New Jersey Institute of Technology

Chinese Spectral Radio Heliograph (CSRH)

PI: Yihua Yan

Funded project of the Chinese Academy of Sciences: $7.3M (stimulus package money!).

Designed to be very similar to FASR: wide frequency range, log-spiral antenna configuration.

Located in Inner Mongolia, intended to start observing in 2010.

Frequency range 0.4-15 GHz.

Chinese groups have no background in interferometry and will have to develop these techniques.

Expected to start in the decimetric range (0.4-2 GHz) as the initial phase: test-bed in place near Beijing.

[MWA station and 32T layout](#)

[Building out to 128 stations, great for solar](#)

Siberian Solar Radio Telescope (SSRT)

Solar Submillimeter Telescope (Argentina/Brazil)