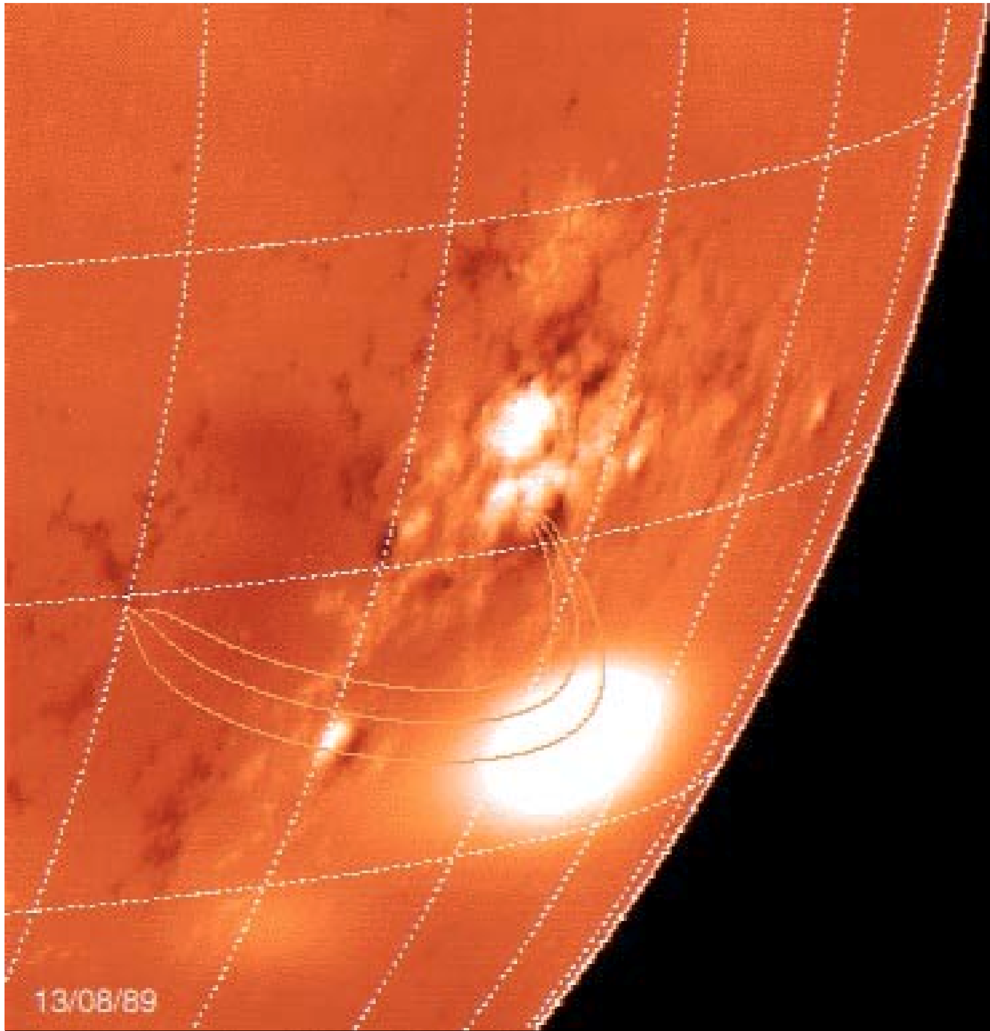
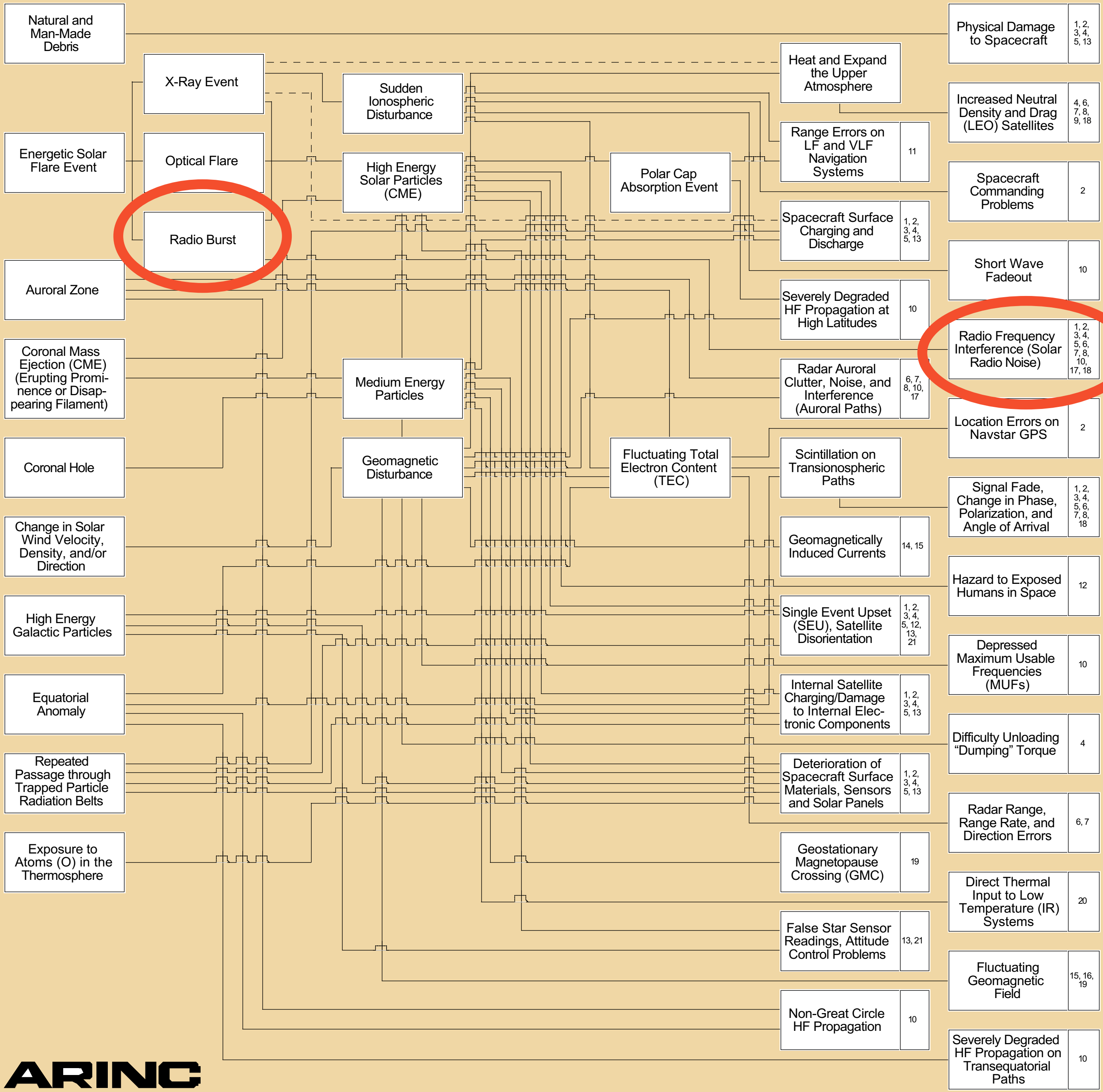


Thierry Dudok de Wit
University of Orléans, France

Radio Monitoring of the Sun and Space Weather



ARINC

1. Communications Satellites

Anik	Intelsat
DSCS	Leasat
FLTSATCOM	Milstar
AFSATCOM	UFO

2. Navstar Global Positioning System (GPS)
3. Defense Support Program (DSP)
4. Defense Meteorological Satellite Program (DMSP) and Other Low Earth Orbit (LEO) Satellites
5. Geostationary Operational Environmental Satellite (GOES) and Other Geostationary Meteorological Satellites
6. Tactical Warning and Attack Assessment (TW/AA) and Space Surveillance Network (SSN) Mechanical Tracking Radars

ALCOR (Kwajalein)	Kaena Point
ALTAIR (Kwajalein)	Millstone Hill
Antigua	MMW (Kwajalein)
Ascension	NAVSPASUR
Clear	Pirinclik
Haystack	TRADEX (Kwajalein)
Haystack Auxiliary (HAX)	

7. TW/AA and SSN Phased Array Radars

Cobra Dane	PARCS
Eglin	Pave Paws
Fylingdales	Thule

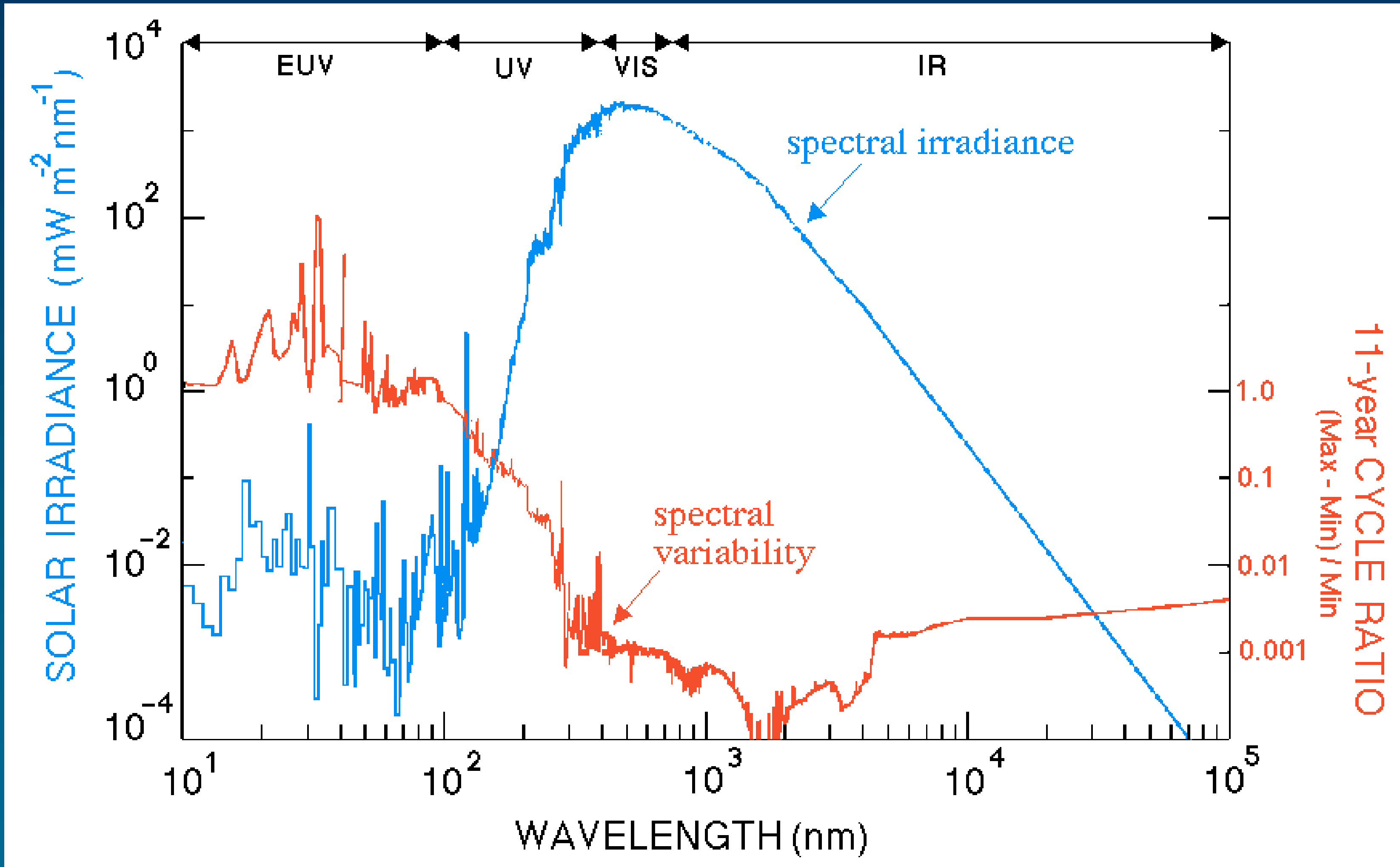
8. Passive Radio Frequency (RF) Tracking Receivers
9. Ground-Based Electro-Optical Deep Space Surveillance (GEODSS) System and Other Optical Tracking Systems

   GEODSS - Socorro, Maui, and Diego Garcia
   Air Force Maui Optical Station (AMOS)
   Maui Optical Tracking and Identification Facility (MOTIF)

10. High Frequency (HF) Communications Systems
    HF Direction Finding
    Fixed and Relocatable OTH-B Radar Systems
11. Low Frequency (LF) Long Range Navigation (Loran) and Very Low Frequency (VLF) Omega Navigation Systems
12. Astronauts On Board the Space Shuttle and Passengers On Board High Altitude Aircraft (SST, U-2)
13. Launch Vehicles
14. Electric Power Transmission Lines, Petroleum Pipelines, and Telecommunications Cables
15. Precision Instruments, Manufacturing Equipment, and Computers
16. Magnetic Compasses, Navigation, and Survey Instruments (Homing Pigeons)
17. Very High Frequency (VHF) Communications Systems
18. Air Force Satellite Control Network (AFSCN) and Other Spacecraft Ground Tracking Stations
19. Satellites that Depend Upon the Earth's Magnetic Field for Reference in Spin Axis Alignment
20. Spacecraft with Passive Radiators Designed to Operate at Temperatures Below 100 K
21. Spacecraft that Depend Upon Star Patterns for Attitude Control

– – – Dashed line indicates theoretically possible, but unlikely, impact.

Radio waves : the other side of the solar spectrum



Radio waves ➔➔

Why are radio measurements of interest for space weather ?

- Radio measurements presently provide the best remote access to fast earthbound CMEs
- Coronal magnetograms can be made with radio measurements in the GHz range (no other instrument can)
- Radio imaging, coordinated with other observations, should allow the complete evolution of flare-CME events to be tracked

But the radio observation of CMEs is still a largely unexplored territory

Outline

- The physics behind solar radio emissions
- What are the different radio signatures of the Sun ?
- What aspects of radio emission are relevant for space weather ?
  - → radio imaging
  - → radio bursts
  - → triangulation
  - → interplanetary scintillation
- Existing and future facilities

The physics of solar radio emissions

just a brief introduction...

How it started

- In 1942, J.S. Hey (GB), who was working on radars, noticed that inference occurred during solar flares
- In 1943, J.C. Southworth (USA) started studying the Sun in the cm frequency range
- After the war, a lot of veterans of the radar effort turned to radio astronomy

Solar radio emission : some facts

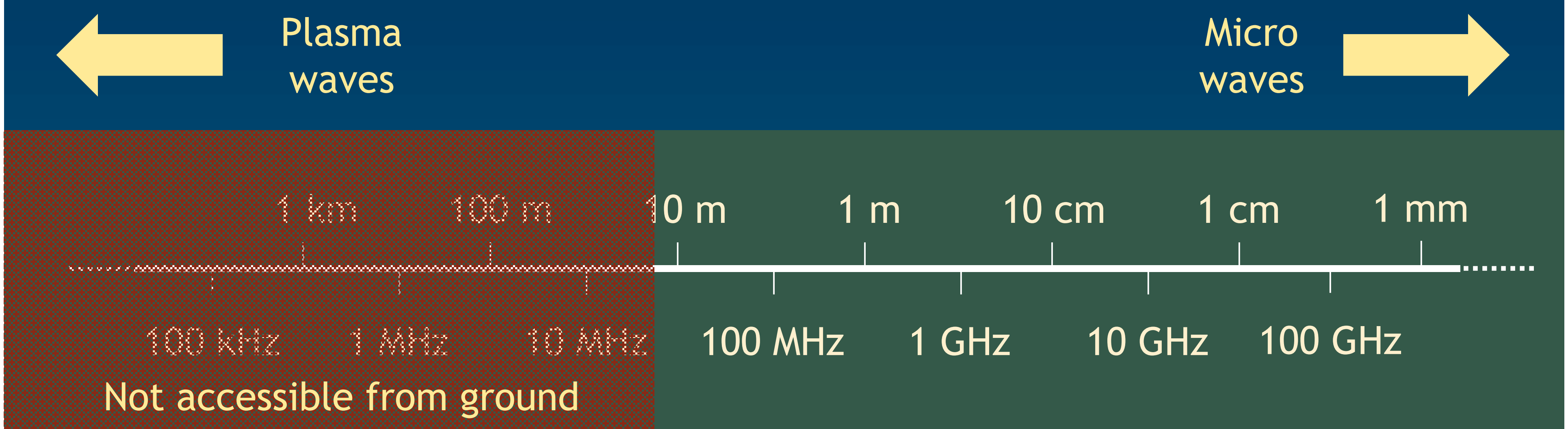
- There are *3 distinct radio emission mechanisms* in the solar atmosphere
  - → Thermal free-free bremsstrahlung
  - → Gyromagnetic emission
  - → Plasma emission

- The spectrum in the (10 MHz - 10 GHz) range is dominated by the former two

- Spectral lines play no role and most of the polarisation is affected by Faraday rotation

- The emission exhibits a rich dynamics near active regions and shocks

Radio waves : the characteristic figures



Plasma waves / Thermal free-free emission / Gyrosynchrotron emission (synchrotron emission)

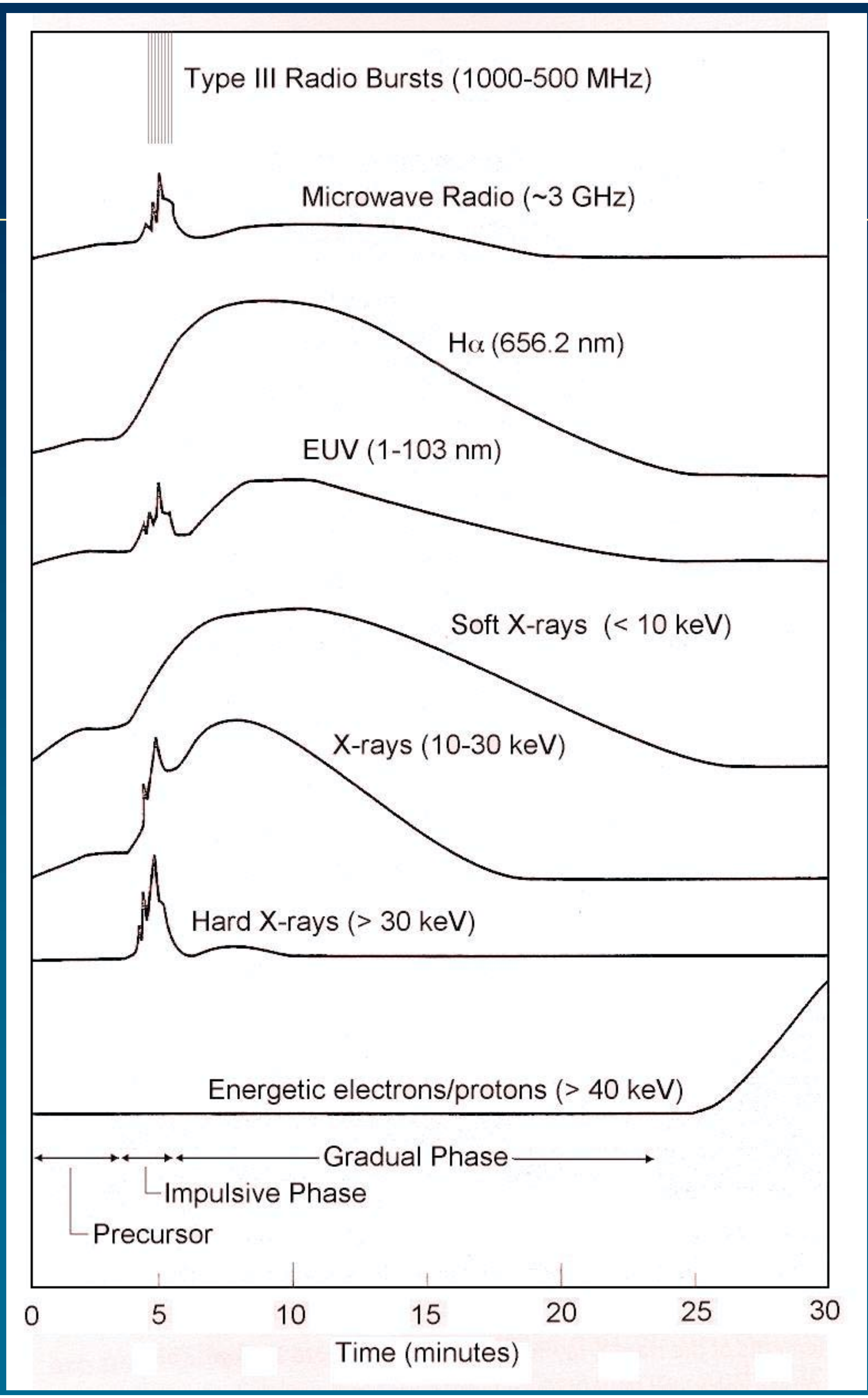
- coherent plasma waves are excited by energetic electron beams through nonlinear mechanisms
- electromagnetic waves are emitted at the local plasma frequency, or harmonics thereof

➔ *they're the ones that are of interest for space weather*

A solar flare as seen at various wavelengths

Microwave emission (GHz) is strongly correlated with hard X-ray emission, and to a lesser extent with EUV emission

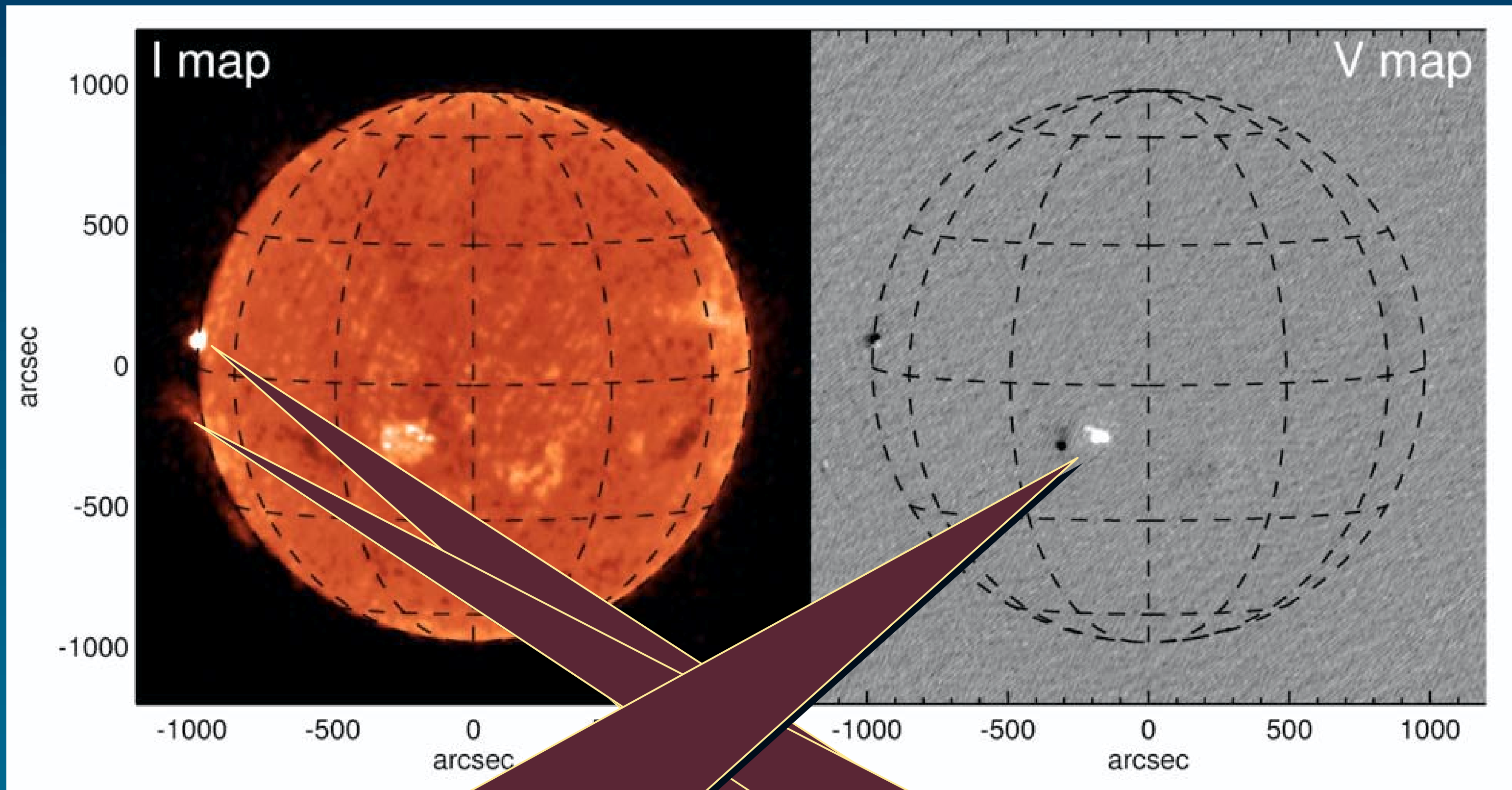
➔ they all describe the same population of energetic electrons



Radio imaging at high frequencies

The Sun in cm wavelengths (17 GHz)

Total intensity | Circular polarisation only



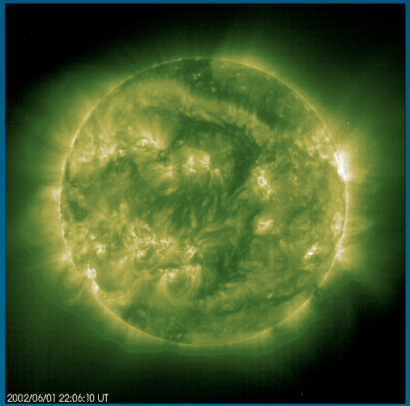
... T. Bastian

active regions with strong magnetic fields (>1500 G in the corona), emitting circularly polarised gyrosynchrotron emission

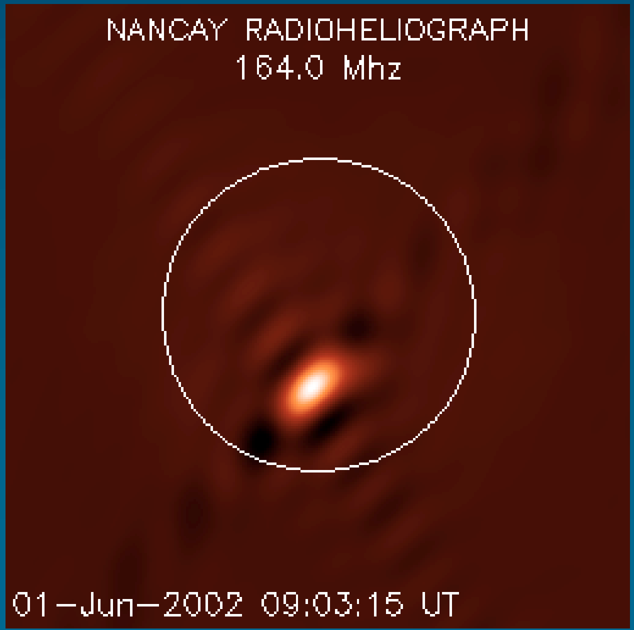
... ences (associated with ... emitting bremsstrahlung ... 00 keV electrons

The Sun in m wavelengths (150-300 MHz)

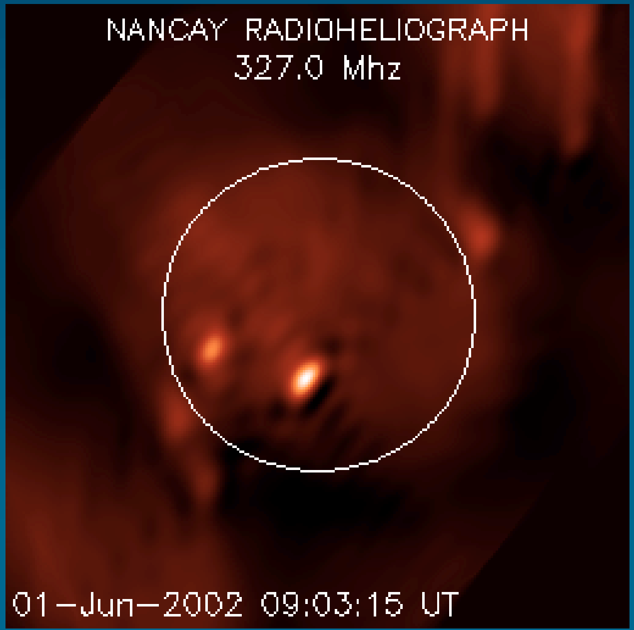
EUV (EIT Fe195)



f=164 MHz

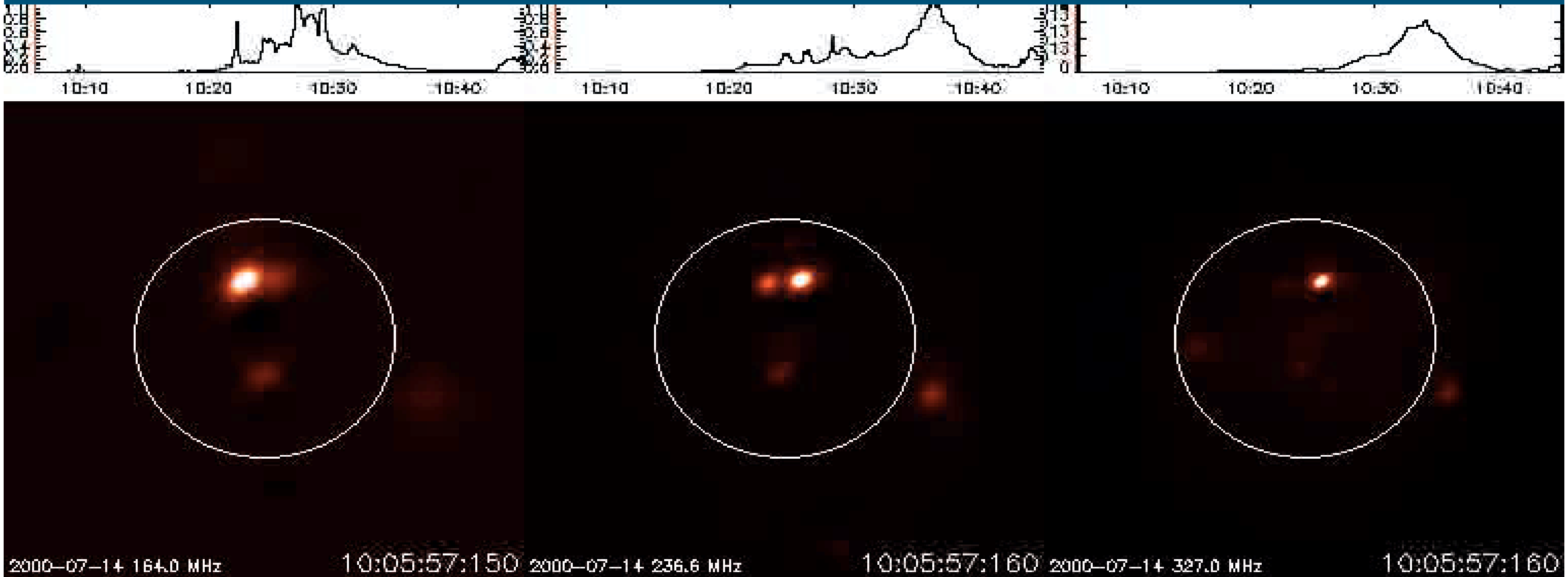


f=327 MHz



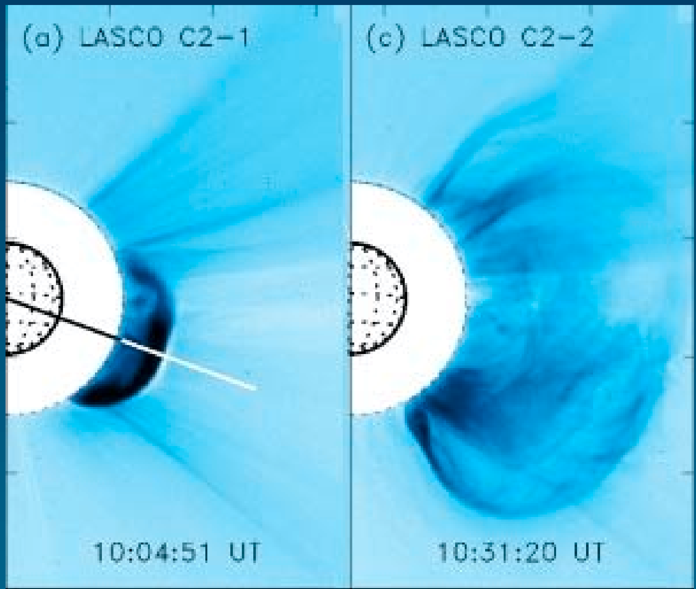
The Bastille-day event in m wavelengths

f=164 MHz *f=236 MHz* *f=327 MHz*

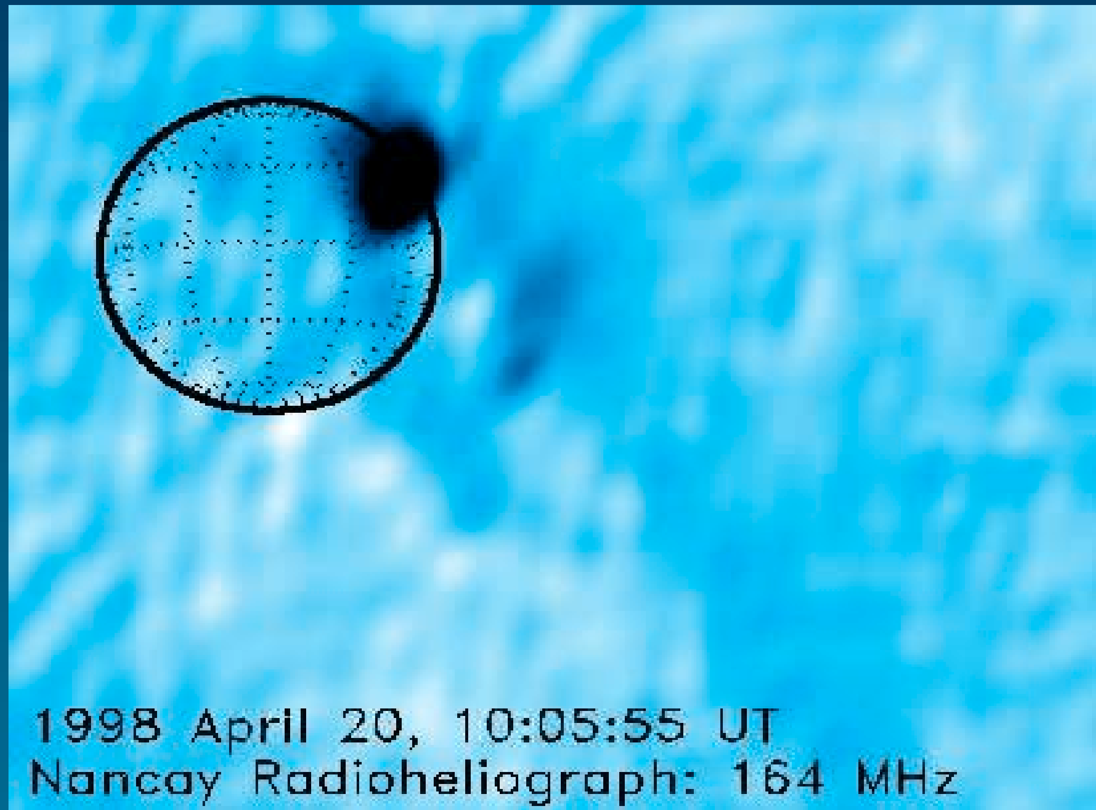


(Nançay radioheliograph, K.-L. Klein, 2001)

A CME in m wavelengths

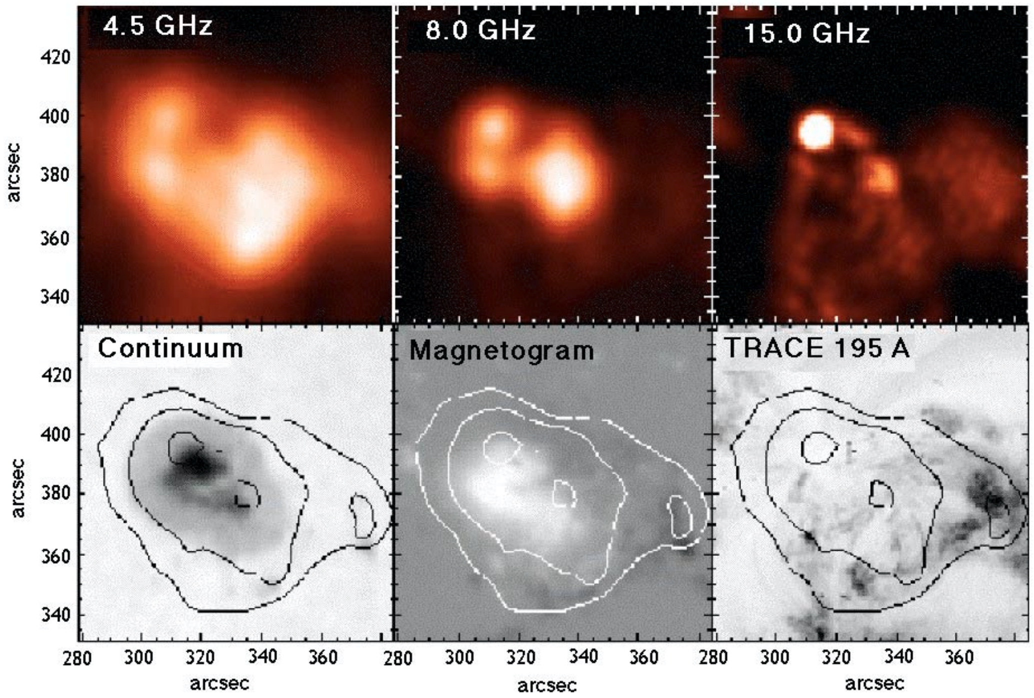


Two successive images from the LASCO coronagraph

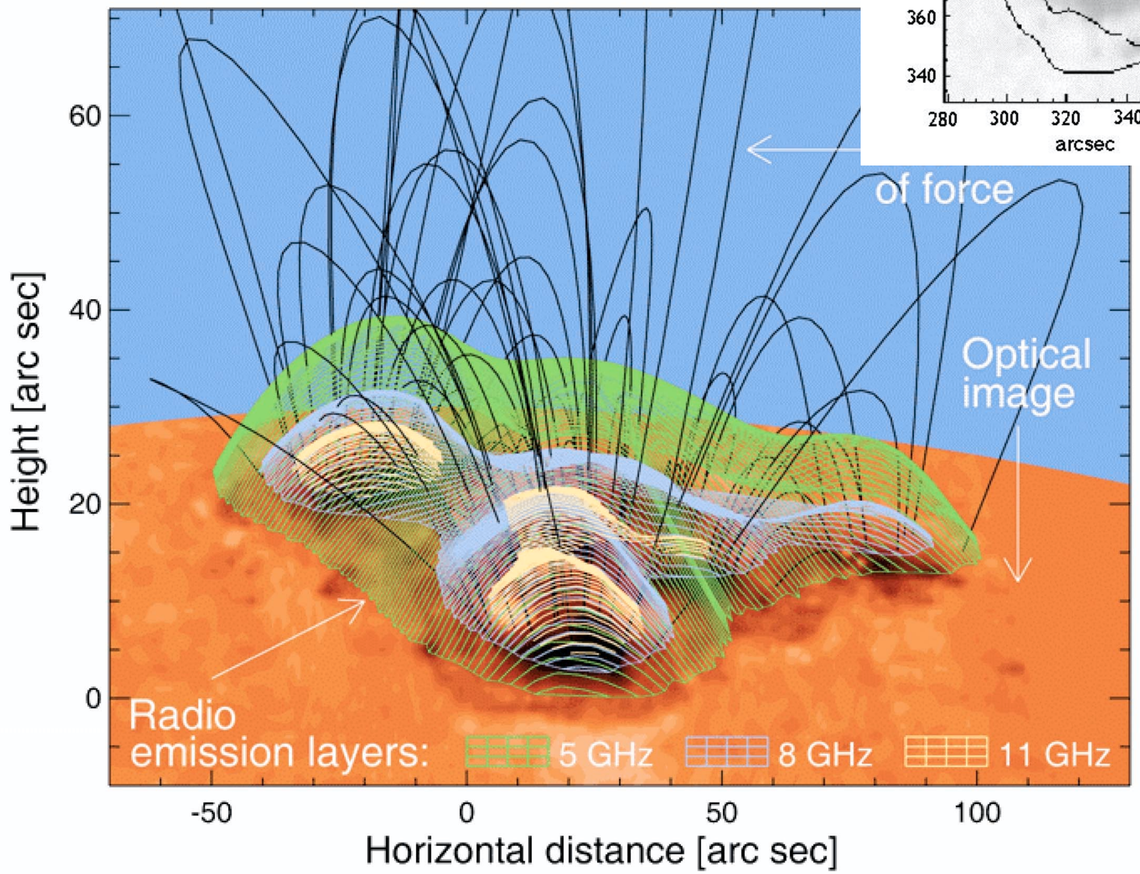


Movie from the Nançay radioheliograph @ f=164 MHz : synchrotron emission from relativistic electrons accelerated at the shock

Gyromagnetic emission



Comparison between radio emission (from the VLA) and optical measurements (T. Bastian)



In regions where the magnetic field is strong, synchrotron emission (1-30 GHz range) can be used to determine iso-B surfaces

J. Lee

The various uses of radio emission in solar physics

- The emission at higher frequencies (visible, EUV, ...) is optically thin in the corona, whereas radio emission is mostly optically thick

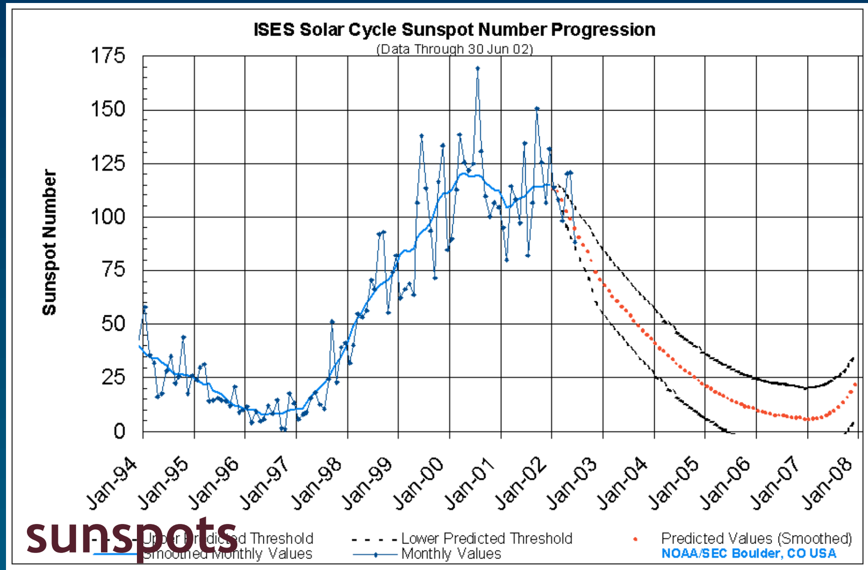
  ➔ multifrequency radio emission can be used to ‘peel away’ layers of the solar atmosphere

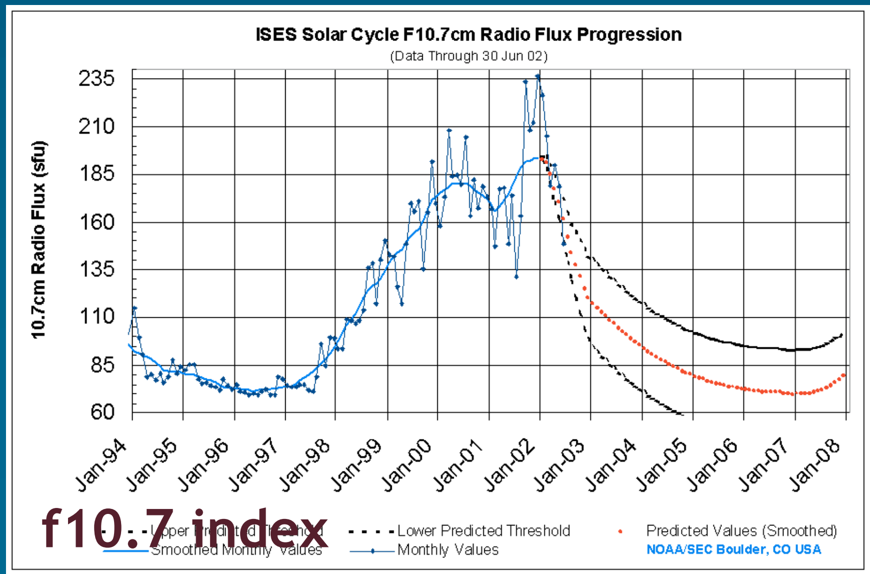
- radio data provide an almost direct access to the temperature and/or the magnetic field. They are the key the understanding of particle acceleration.

- radio emission presently provides the best technique for determining magnetic fields in the corona

A proxy for sunspots : the f10.7 index

- For historical and practical reasons, the radio emission at 10.7 cm (3 GHz), integrated over the whole solar surface, is widely used today as an proxy for the sunspot number.





A proxy for sunspots : the f10.7 index

- Almost all thermospheric and ionospheric models still use the f10.7 index as a proxy for the electromagnetic energy input from the Sun.
- There have been suggestions to replace it with spectral lines from the EUV range

Conclusion : in space weather, an easily accessible but empirical quantity is often preferable to a physically more meaningful quantity that isn't readily available

Radio bursts

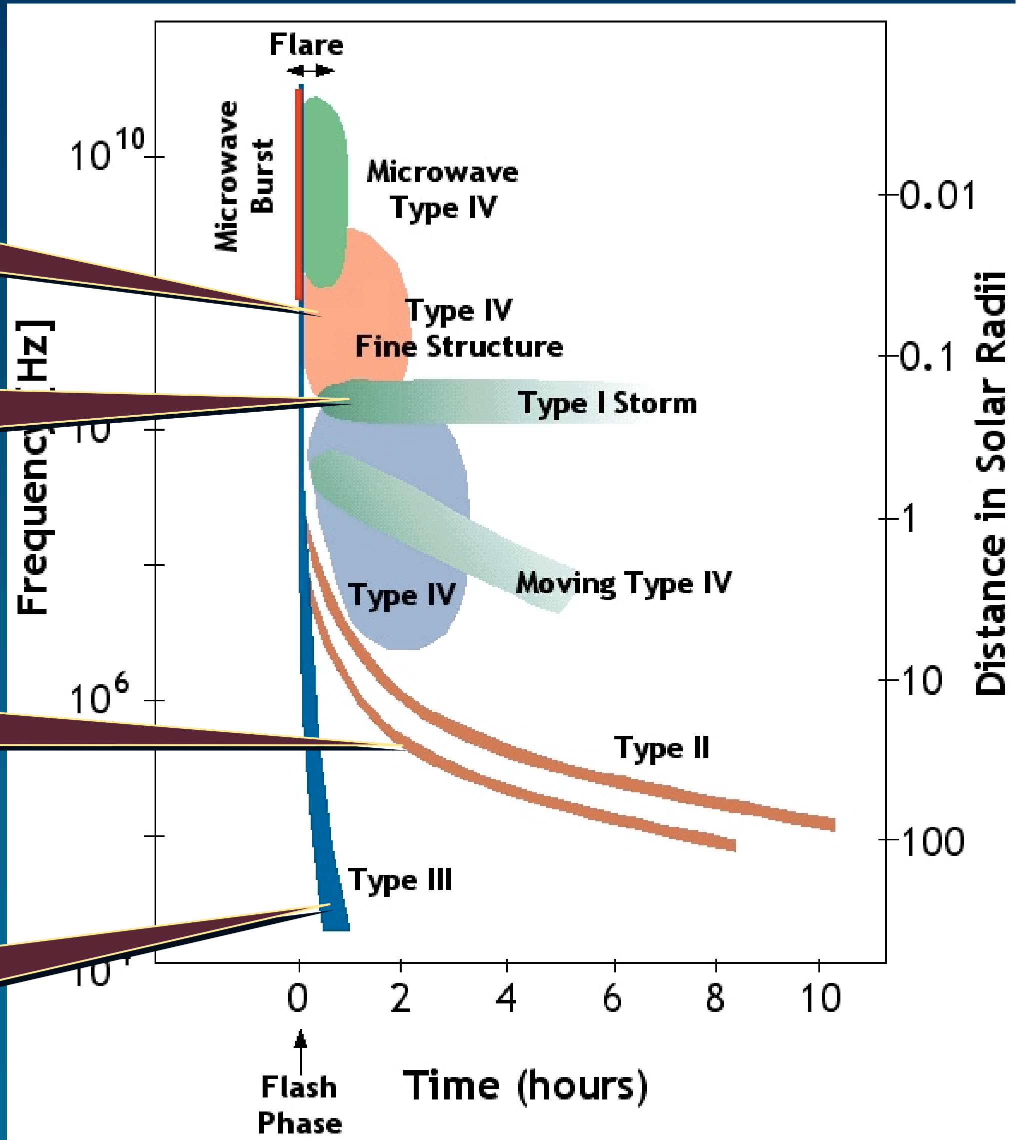
A taxonomy of solar radio bursts

Type IV : broadband gyro-synchrotron emission associated with flares

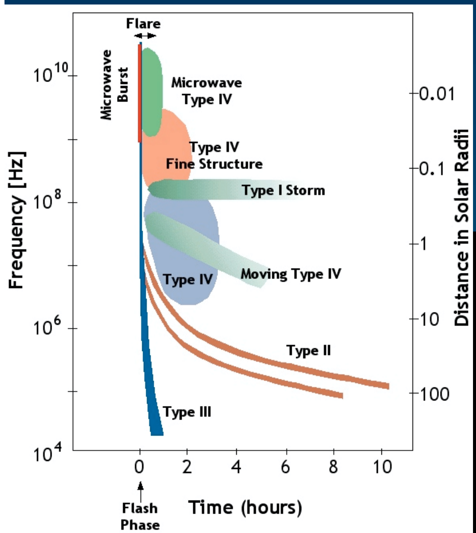
Type I : continuous radio emission, due to plasma turbulence; enhanced during flares

Type II : generated by shock waves in the corona or in interplanetary space

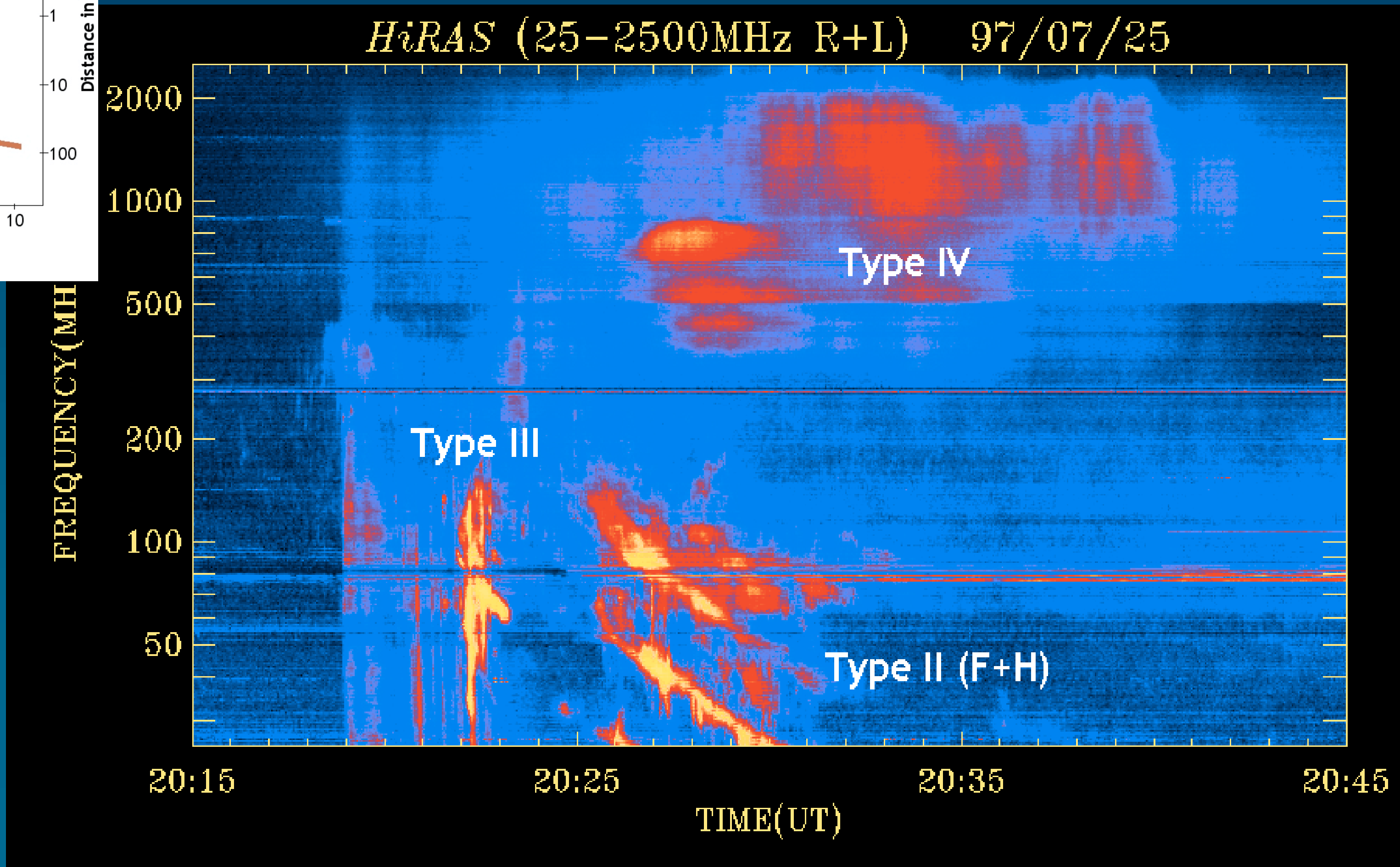
Type III : plasma waves generated by energetic electrons. Often associated with flares



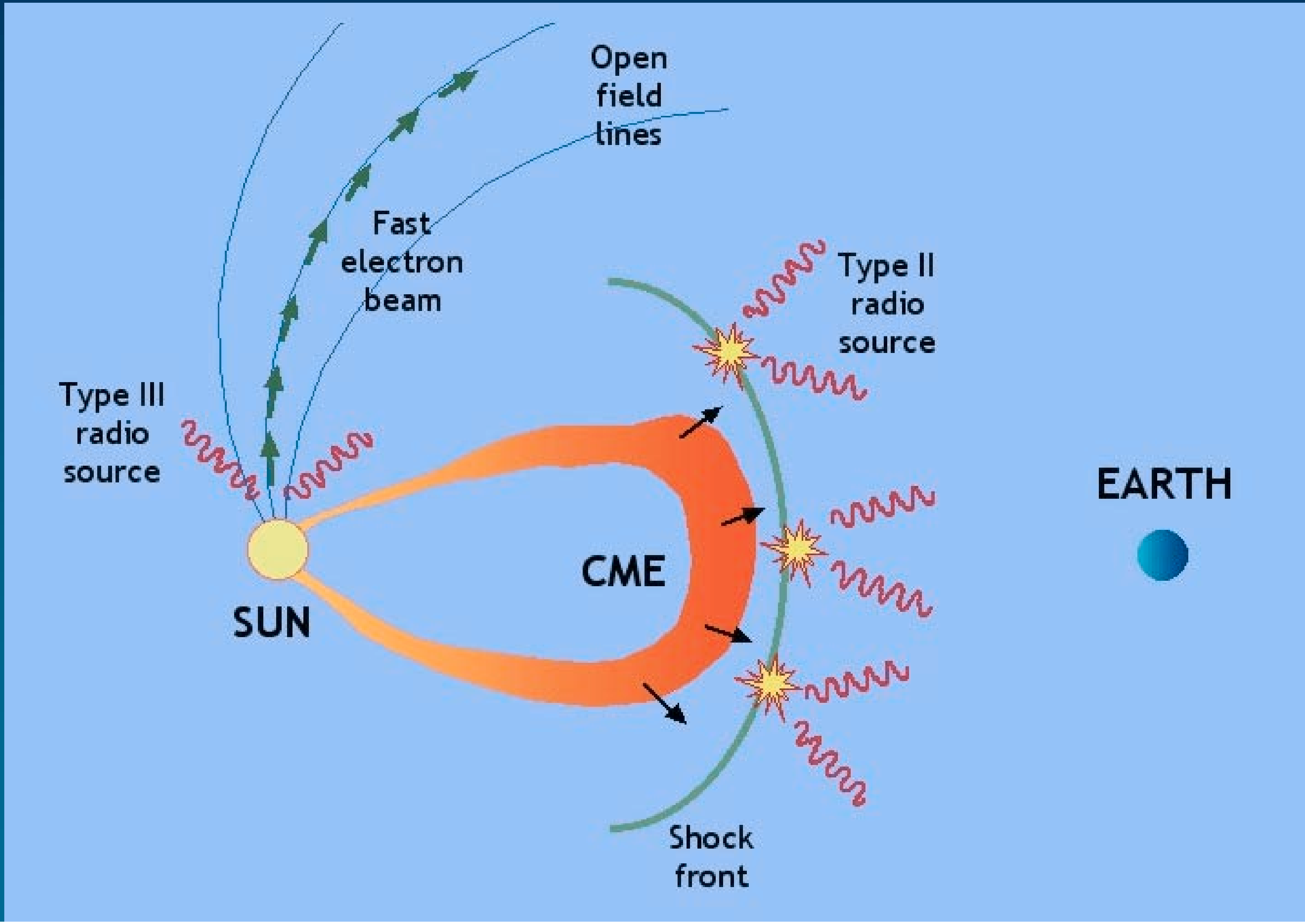
Example : radio bursts from the corona

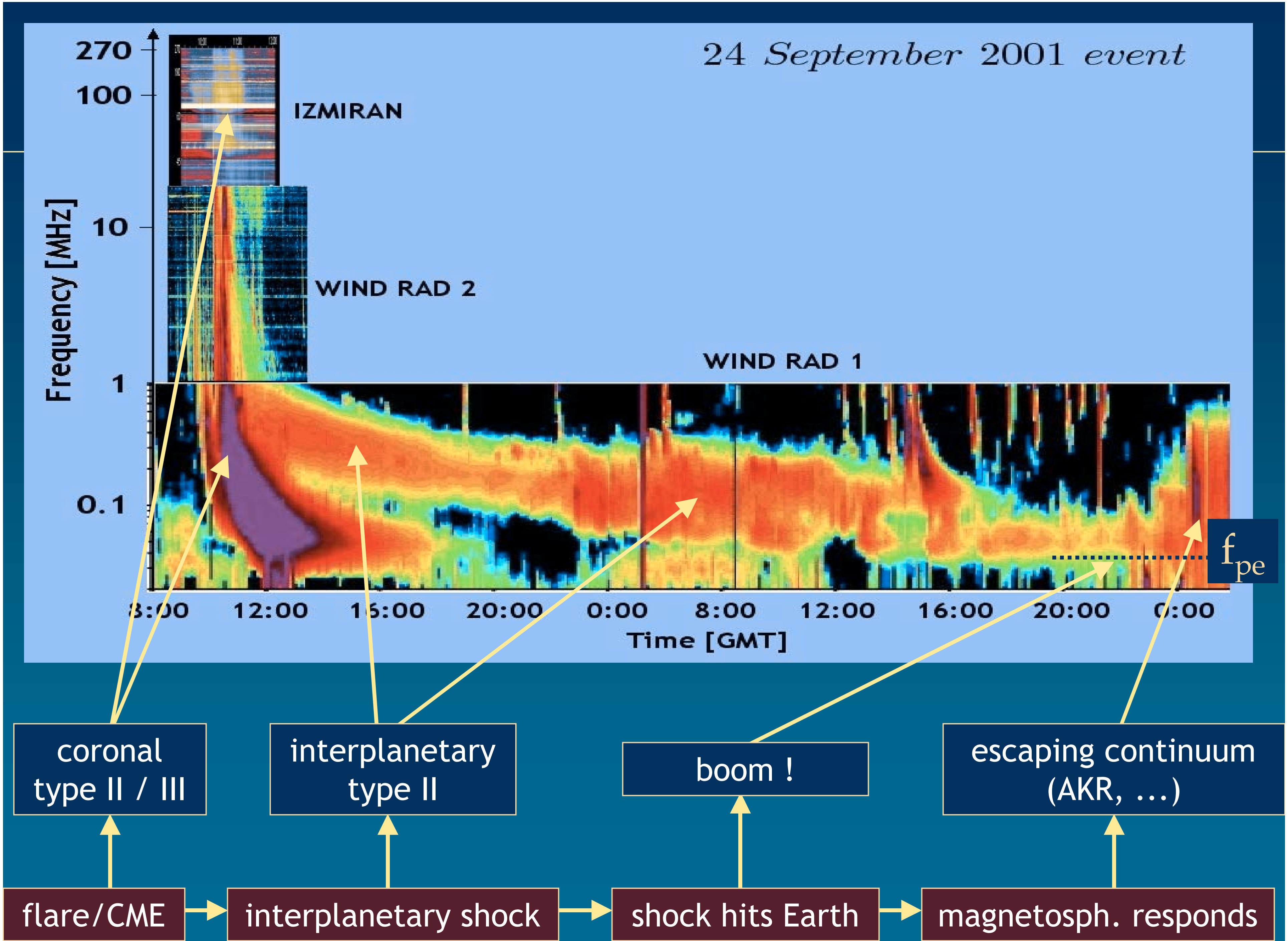


Hiraiso radiospectrograph

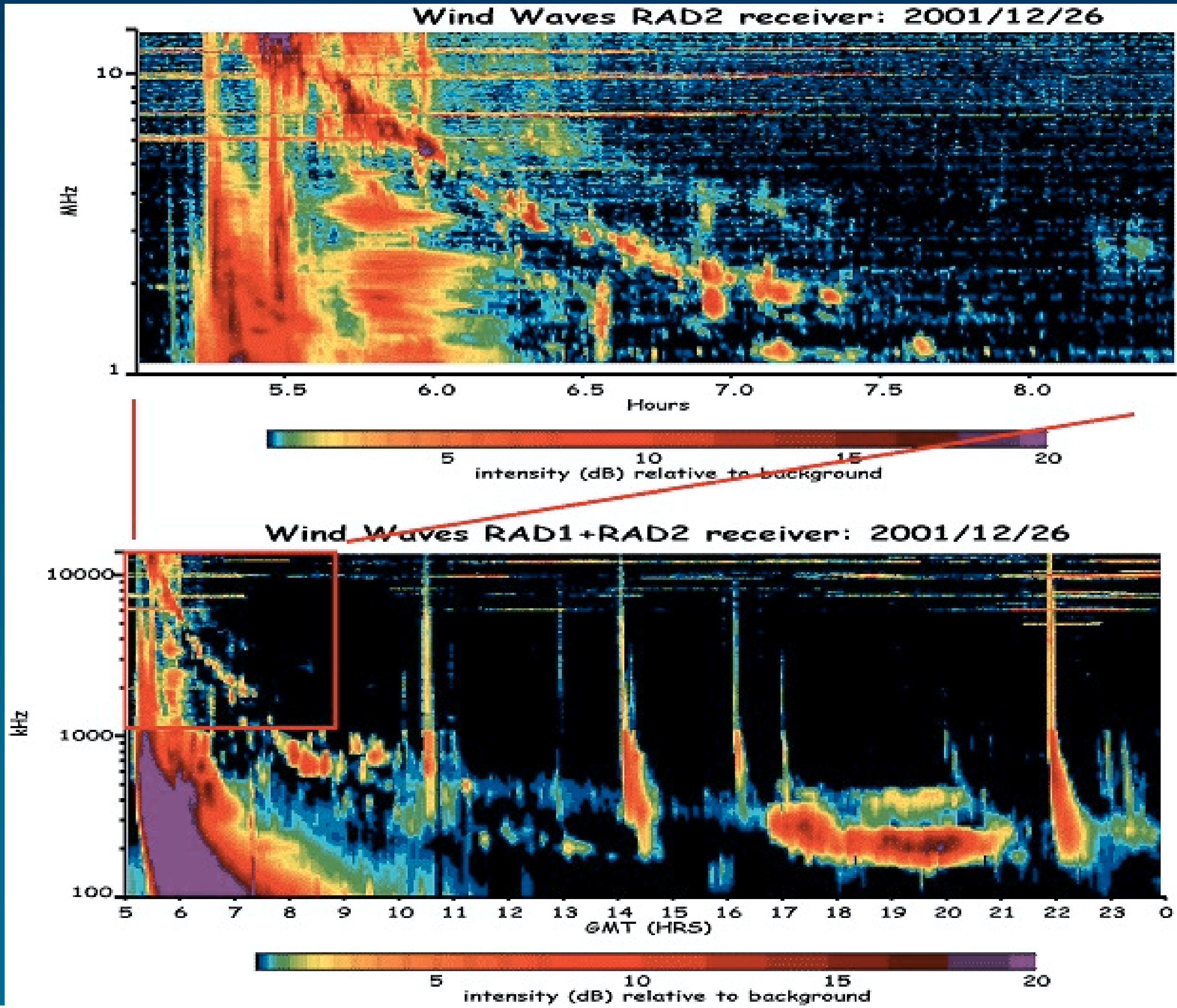


Interplanetary type II and type III bursts

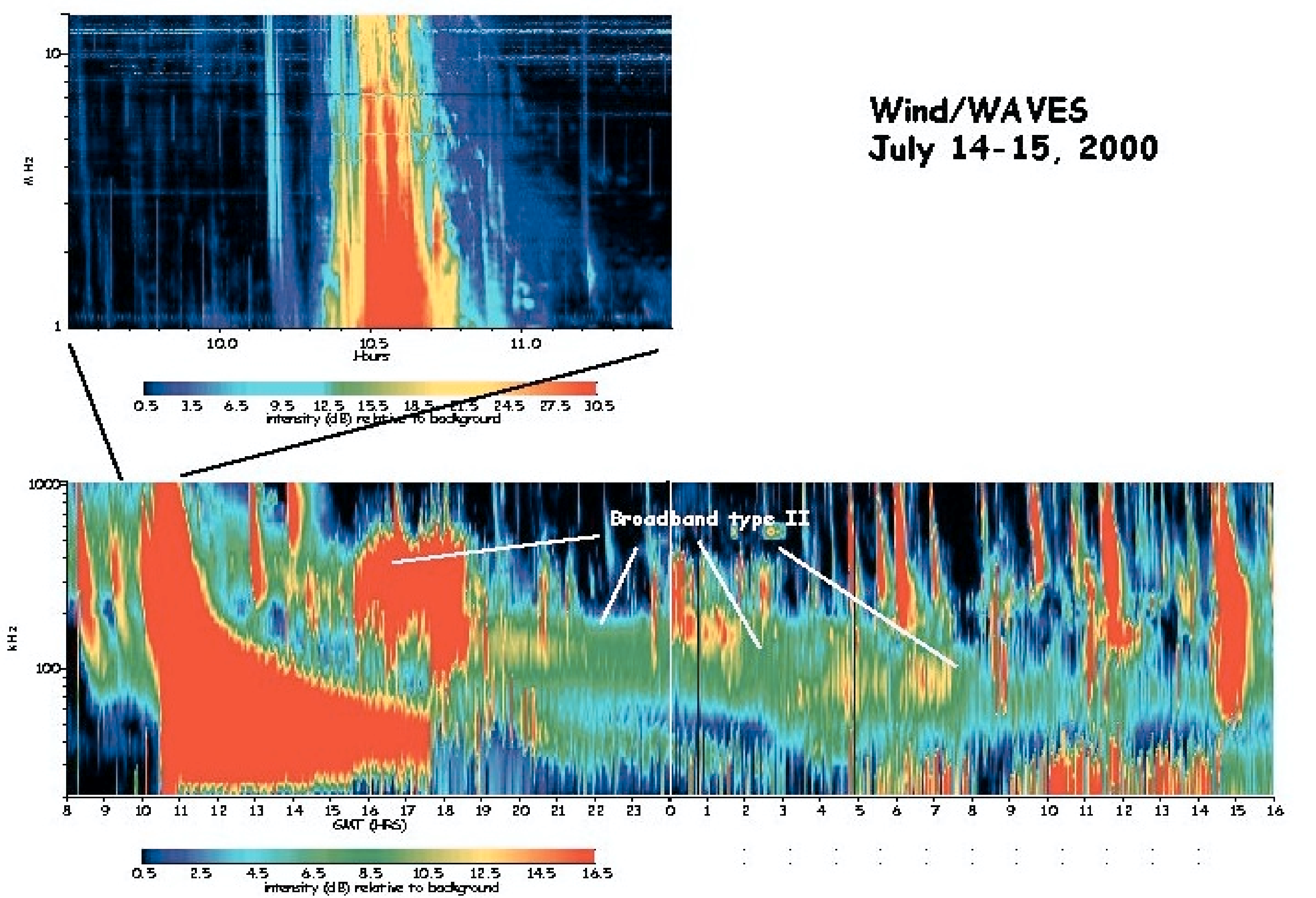



24 September 2001 event
270
100
10
1
0.1
Frequency [MHz]
IZMIRAN
WIND RAD 2
WIND RAD 1
f_{pe}
8:00
12:00
16:00
20:00
0:00
8:00
12:00
16:00
20:00
0:00
Time [GMT]
coronal type II / III
interplanetary type II
boom !
escaping continuum (AKR, ...)
flare/CME
interplanetary shock
shock hits Earth
magnetosph. responds

Example of type II and type III emission



Another example : the Bastille-day event



How to easily track type II emissions

Type II emissions occur at the plasma frequency or harmonics thereof

$$f \propto k\, f_{pe} \propto \sqrt{n_e}$$

but the plasma density on average varies as

$$n_e \propto r^{-2}$$

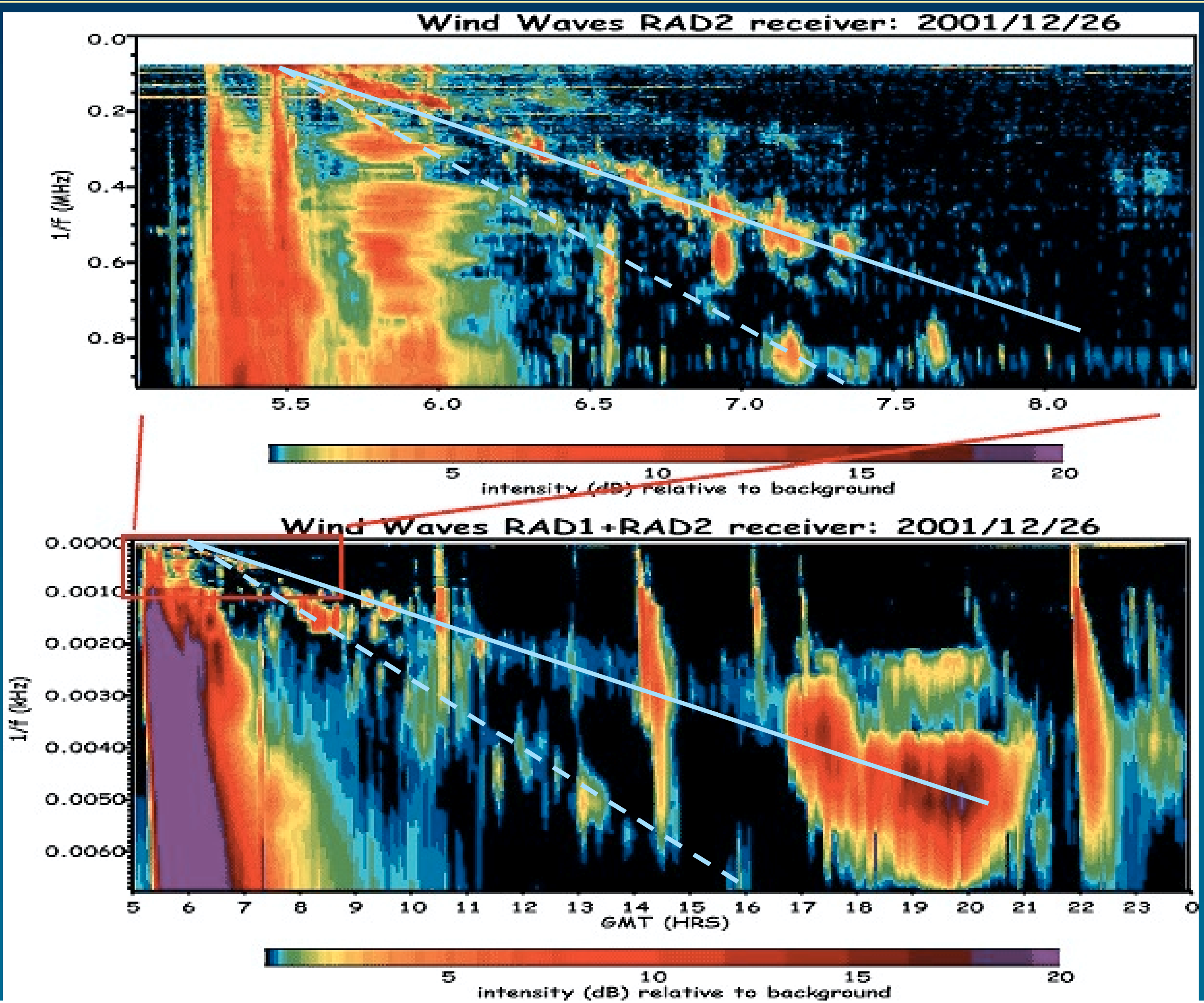
In interplanetary space, the shock front propagates at constant speed

$$r \propto v(t - t_0)$$

➔ *By plotting 1/f vs time, we should observe straight lines*

$$1/f \propto v(t - t_0)$$

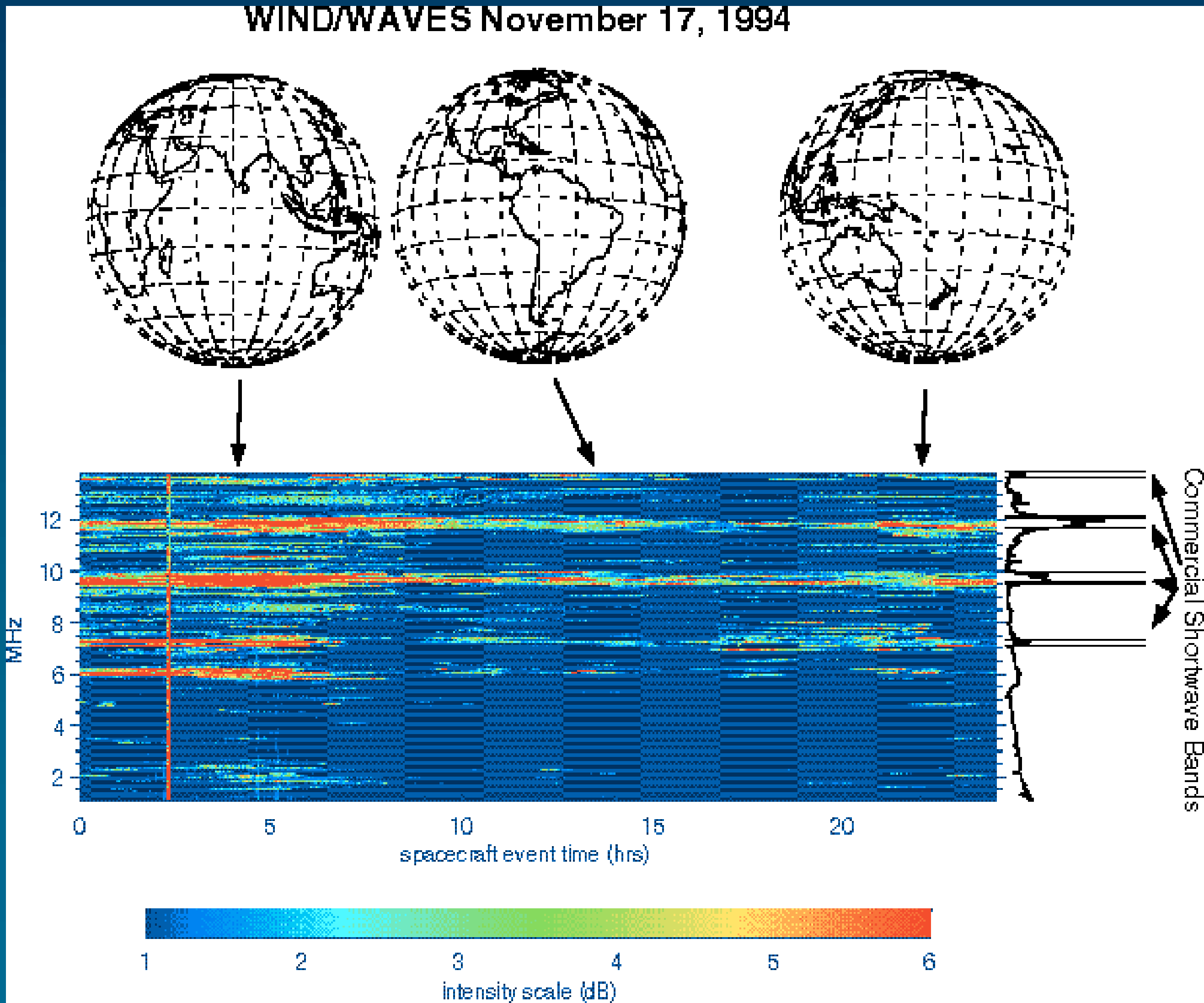
Representation of type II emissions



A problem : interference with man-made emissions

The intensity of artificial emission sources varies with time and geographical location

At 1’000’000 km altitude, a 100 kW isotropic emitter radiates as much as the Sun

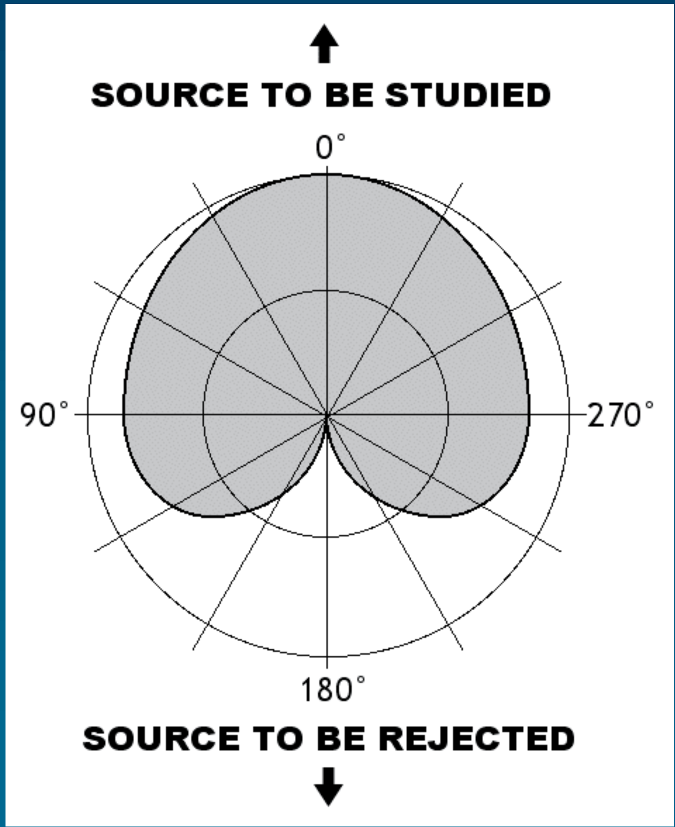


How to avoid pollution ?

- Move the detector as far away as possible from the Earth.
  ➔ the L1 Lagrange point is ok

- Use several detectors to do interferometry and better reject interference

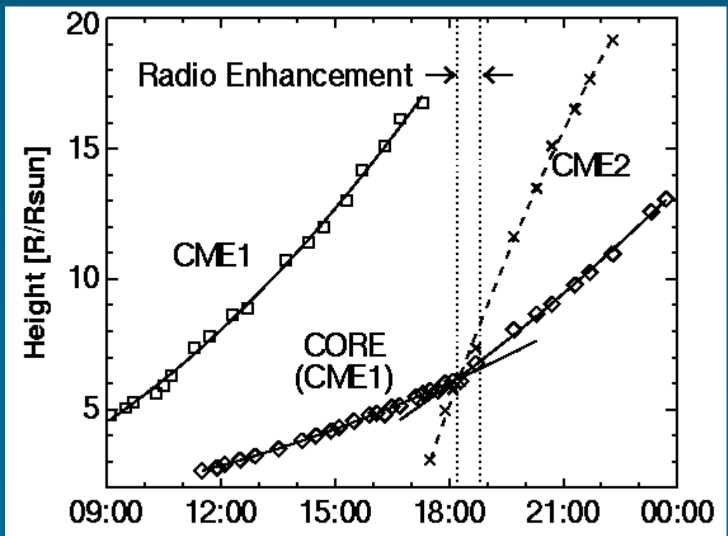
- Digitize the raw signals as much as possible in order to do digital (≠ analogue) post-processing



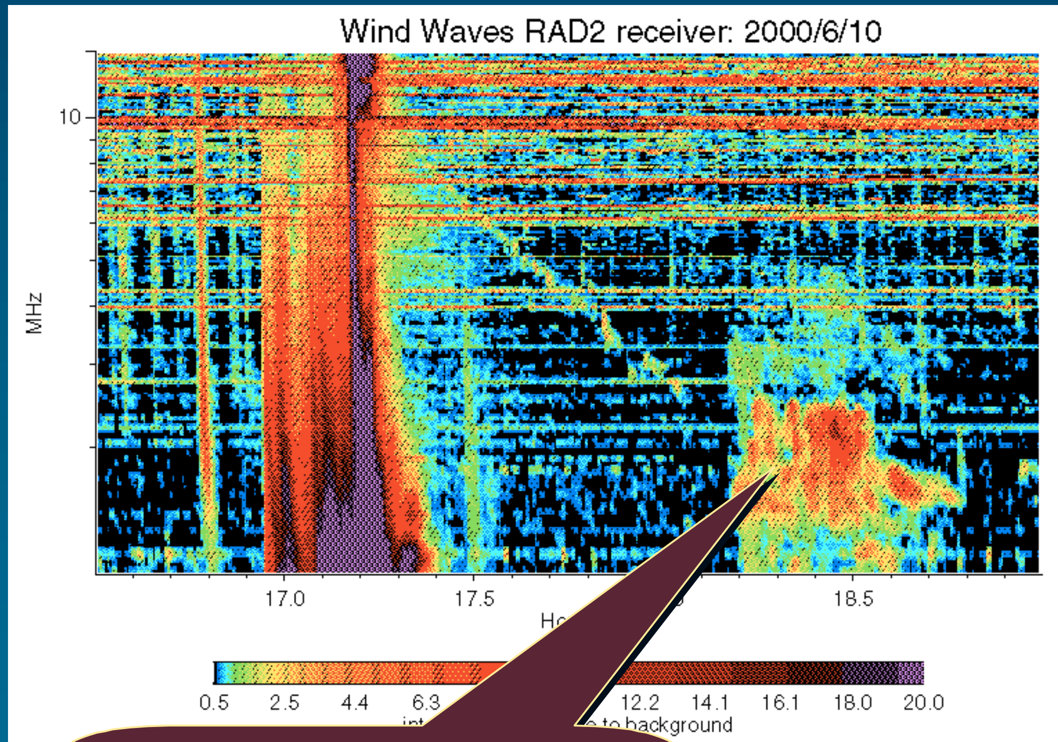
Real life tends to be more complicated

Type II emission is sensitive to local plasma conditions :

- → intensity and presence of harmonics depends on local conditions
- → *cannibalism* between CMEs with different speeds may affect the emission



(Gopalswamy, 2000)



Fast CME2 catches up slow (invisible) CME1

How relevant are type II bursts for Space Weather ?

- ☺ Good proxy for earthbound fast CMEs : > 80% of type II emissions give geoeffective CMEs
- ☺ Method is simple and can be automated
- 😐 Sensitive detectors are needed
- ☹ type II emissions are not the universal panacea
  - → they are weak and can easily be polluted
  - → we can’t measure them from ground
  - → the physics is not well understood

**** Intermission ****

How does one measure radio emission ?

How does one measure radio emission ?

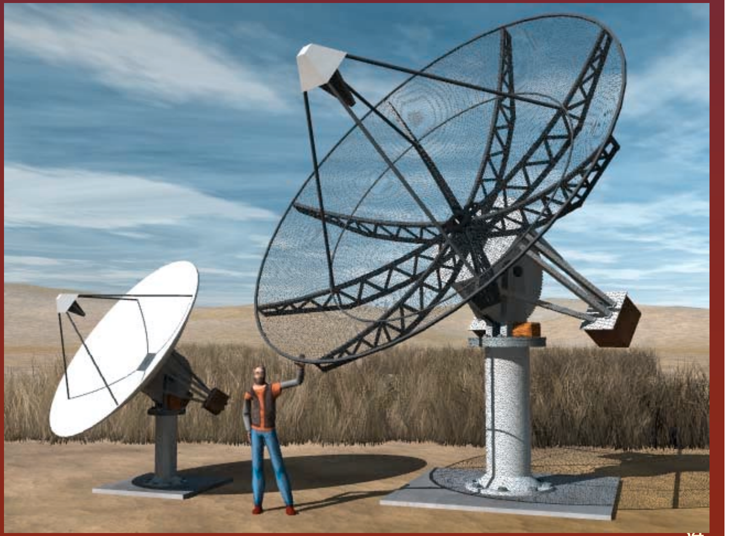
1) Ground spectrographs

- good spectral resolution (>20 MHz) but no spatial resolution
- examples : Tremsdorf (D), Nançay (F), Culgoora (AUS), ...

Tremsdorf (D)

Bleien (CH)

FASR (project)



How does one measure radio emission ?

2) Ground interferometers

- good spatial resolution but limited spectral resolution
- spatial resolution requires large arrays
- examples : Nobeyama (J), Nançay (F), VLA (USA), ...

Nobeyama (J)

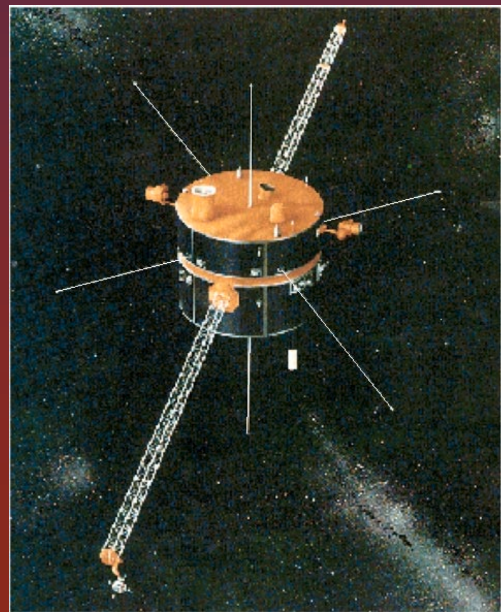
Nançay (F)

LOFAR (project)

How does one measure radio emission ?

3) Space-borne instruments

- usually with electric field antennae (wires)
- good spectral resolution, no spatial resolution
- no ionospheric cutoff
- examples : Ulysses/URAP, Wind/WAVES, ...



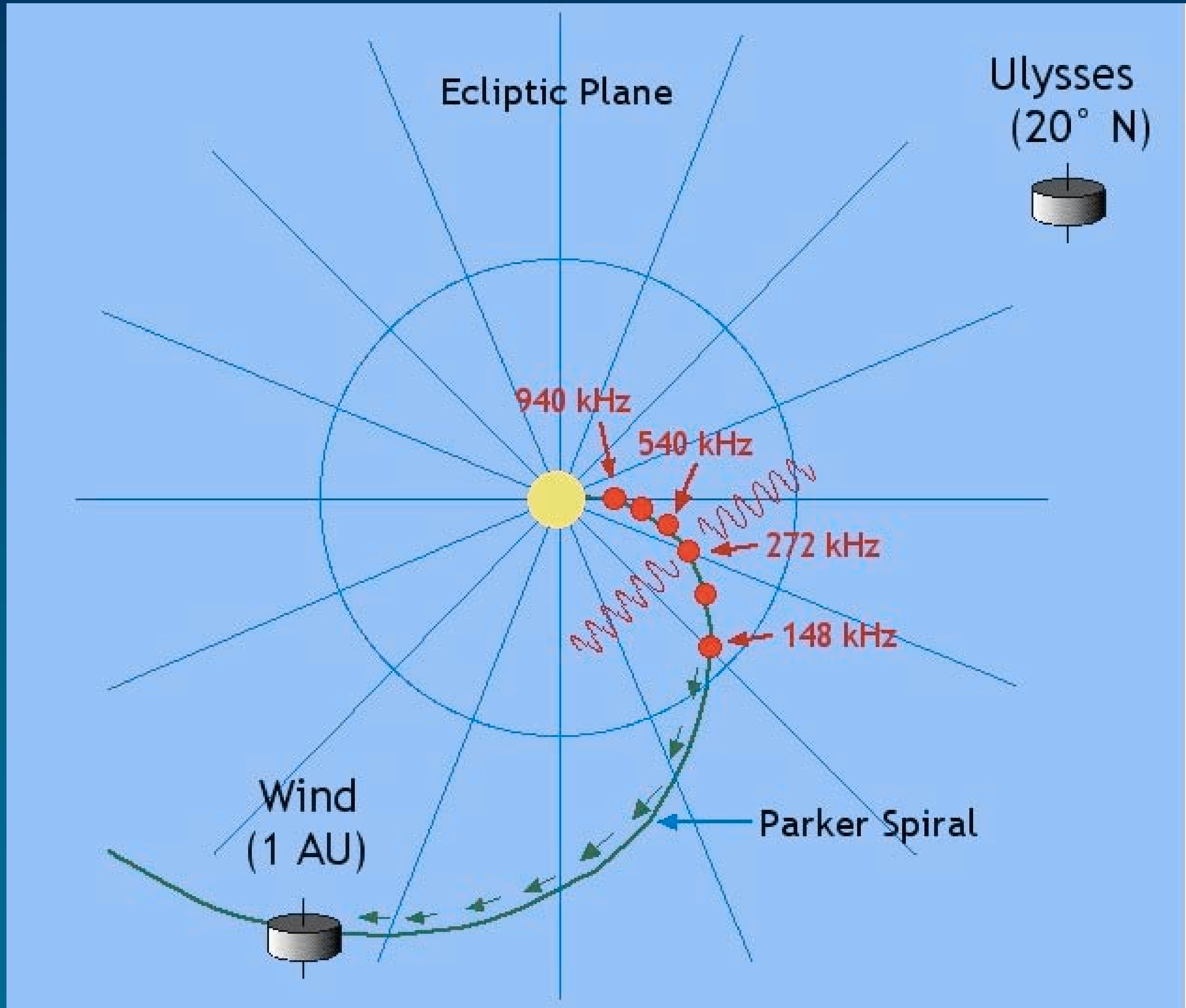
WIND / Waves

Triangulation

Example : radio triangulation by WIND and Ulysses

The derived trajectory of the type III radio burst follows an expected Parker spiral path.

The results of the radio triangulation combined with a drift rate analysis give an average electron exciter speed of 0.3c.



(after Reiner et al., JGR, 1998)

How relevant is triangulation for Space Weather ?

☺ Concept is simple : this will be tried out with Stereo

☹ Works so far for type III bursts only = not a good proxy for CMEs

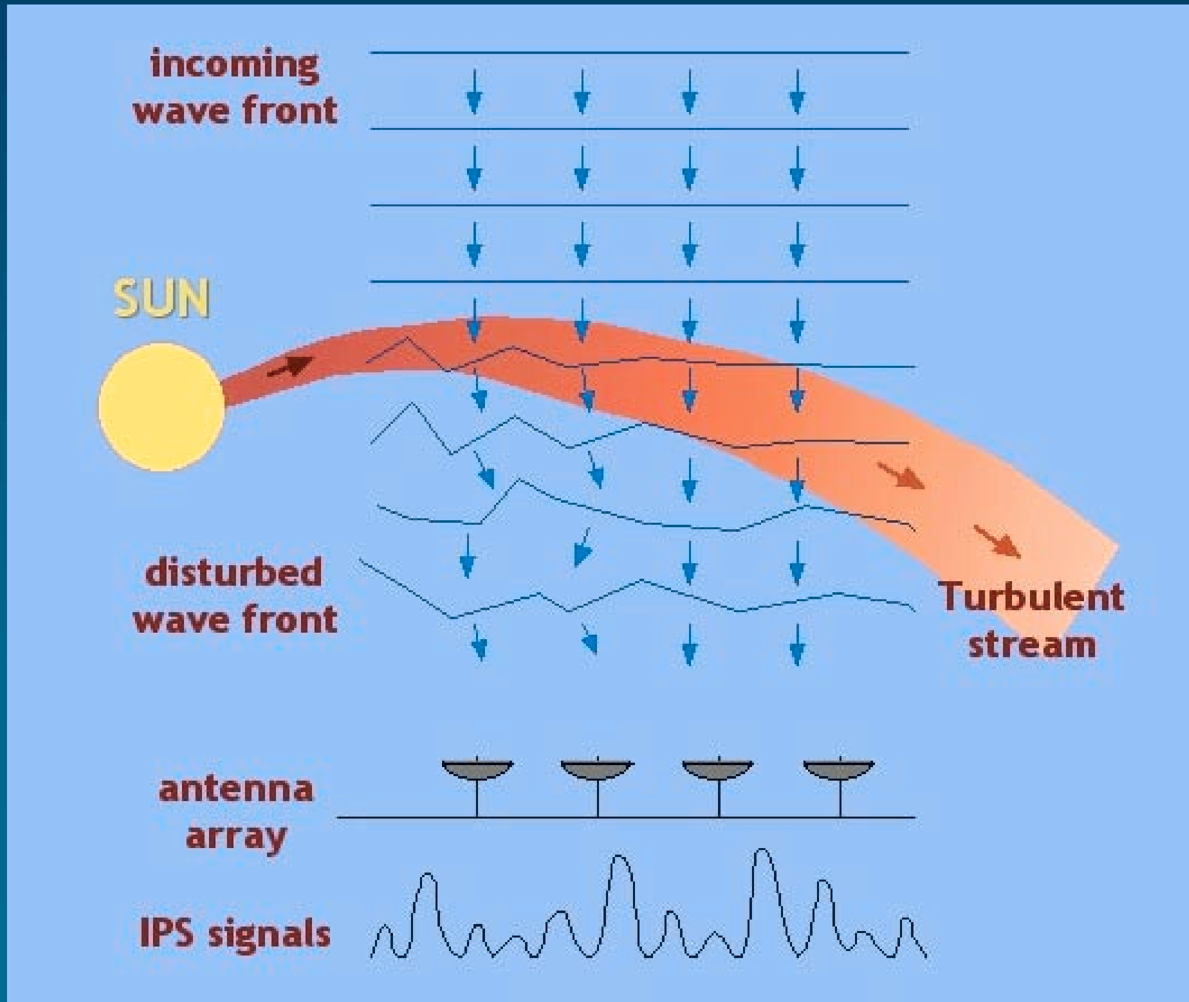
☹ Needs three satellites for the accurate location of the radio sources

Interplanetary Scintillation (IPS)

IPS : how does it work ?

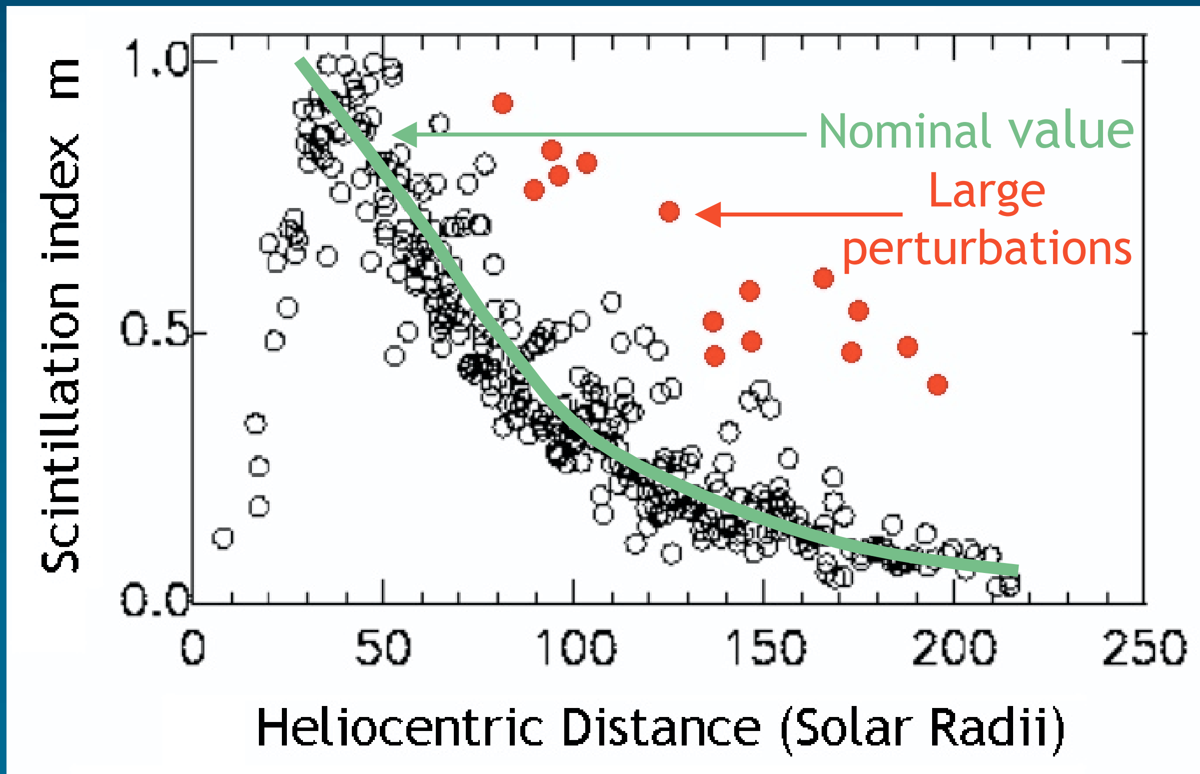
The wave-front of radio waves coming from compact sources (quasars) is deformed by density fluctuations.

By correlating receiver signals, one can estimate the density fluctuation level integrated along lines of sight



IPS and heliospheric disturbances

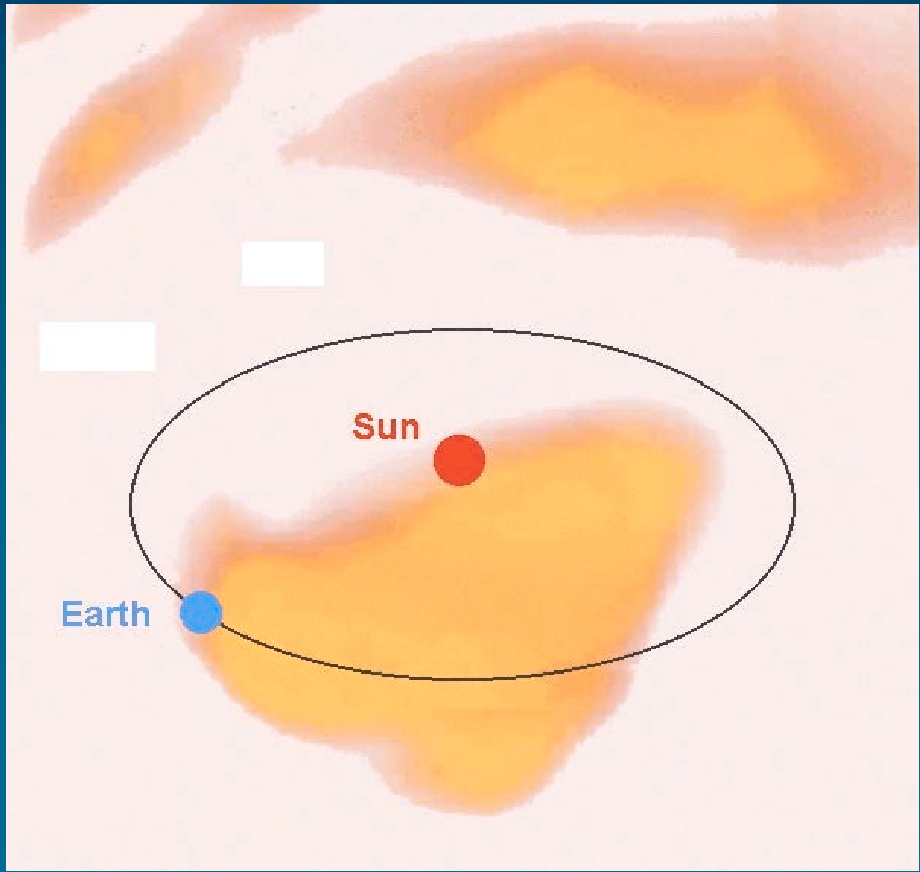
- High density disturbances are characterised by a fluctuation level (I.e. scintillation index) that exceeds the nominal value



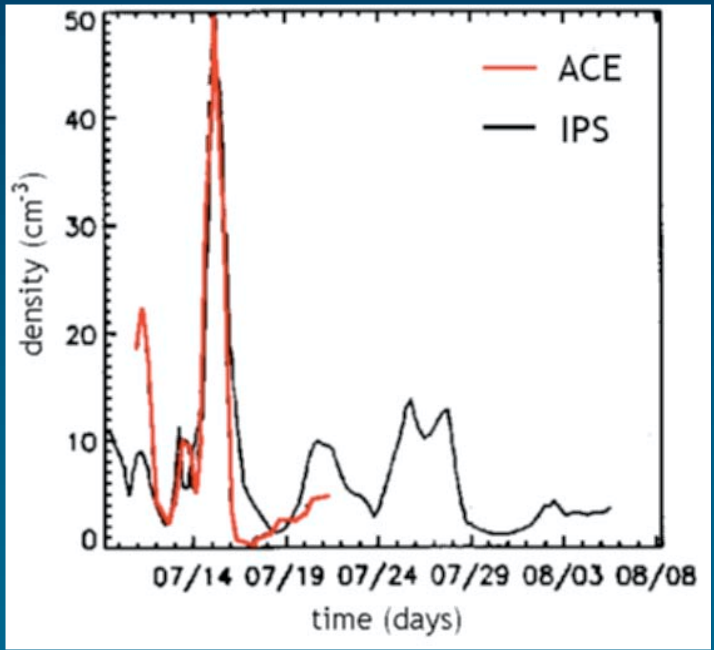
IPS and CMEs

View of the density distribution of the Bastille day CME as it reached the Earth's orbit (ellipse) on 15 July 2000.

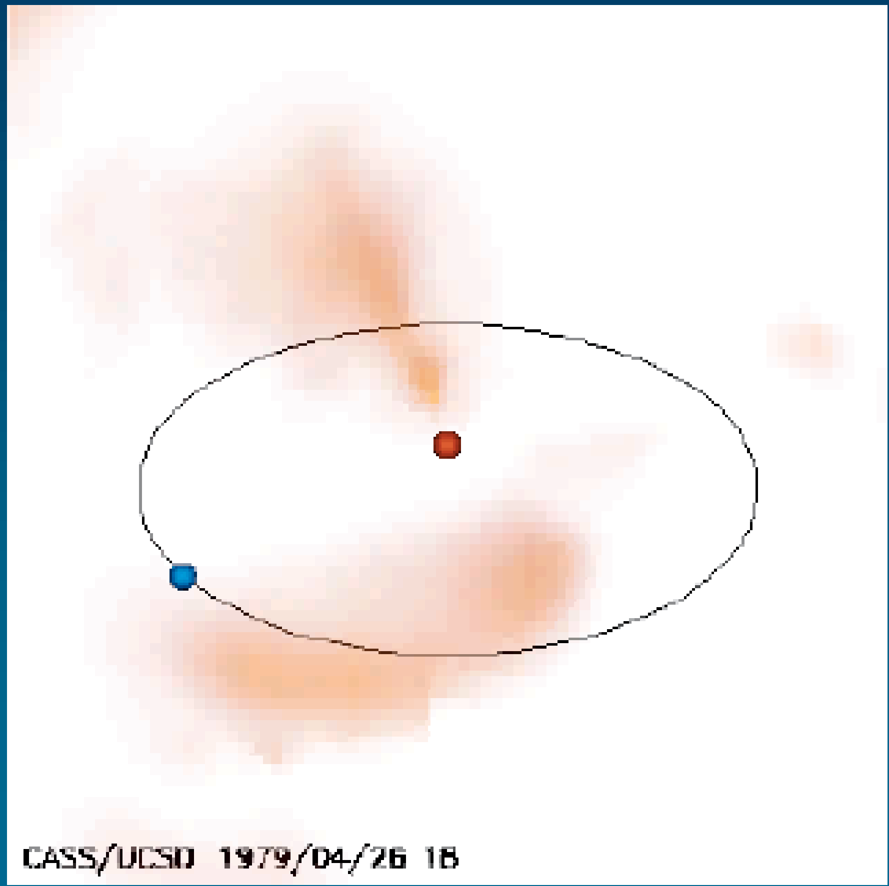
The observer is located 3 AU from the Sun and 30° above the ecliptic plane (Jackson et al., JGR, 1998)



IPS : an example



Comparison with ACE in situ density measurements



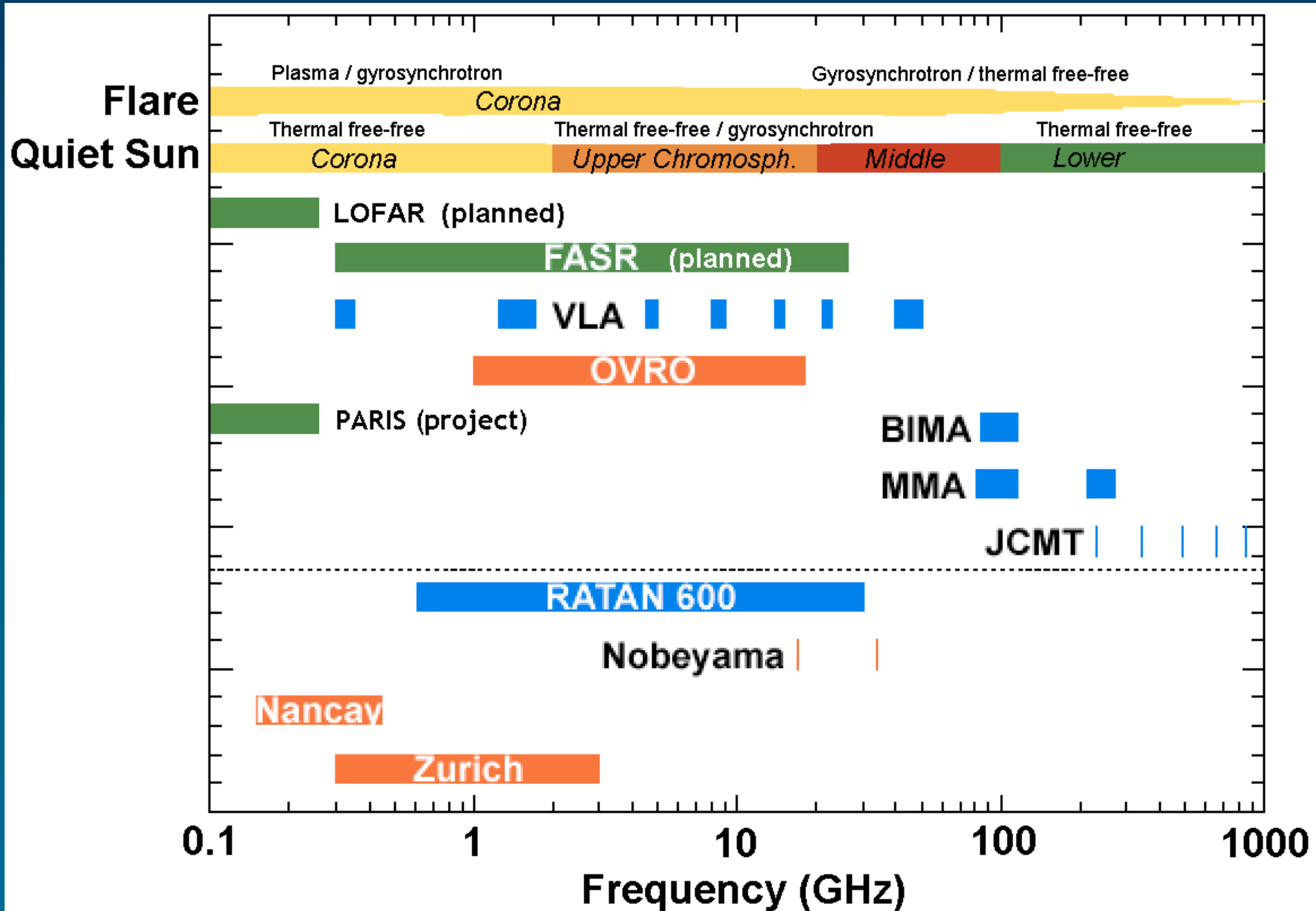
Five weeks of reconstructed density perturbations (Jackson, UCSD)

How relevant are IPS for Space Weather ?

- ☺ Good for solar remote sensing
- ☺ Potentially useful for forecasting the arrival of heliospheric perturbations
- 😐 Time resolution (~1 day) and spatial resolution (a dozen radio sources) are too limited for doing good 3D imaging of the heliosphere
- ☹ Requires a lot of computation (tomography)
- ☹ IPS doesn't tell us anything about the topology of the magnetic field, which is essential for assessing geoeffectiveness

What next ?

Existing and planned facilities



The future : how some would like to have it…

- *Ground radio interferometry* (30 MHz - 3 GHz) :
  - → need good frequency and time resolution (< 1 second)
  - → digitize the emission as much as possible for better flexibility
  - → full time coverage requires at least 3 facilities equally distributed in longitude
  - → close international collaboration and intercalibration are crucial
  - → must have free and easy access to data

- *Space radio interferometry* (100 kHz - 100 MHz)
  - → need a fleet of nanosatellites to do radio interferometry from space
  - → electromagnetic pollution is strongly reduced at high orbits
  - → allows permanent coverage of the Sun
  - → but feasibility not yet proven...

Some useful links

- Links to solar radio observatories http://srbl.caltech.edu/links.html
- The WIND/WAVES homepage http://lep694.gsfc.nasa.gov/waves/contents.html
- The STEREO/SWAVES homepage http://www-lep.gsfc.nasa.gov/swaves/swaves.html
- The FASR homepage http://www.ovsa.njit.edu/fasr/
- The LOFAR homepage http://www.lofar.org
- Community of European Solar Radio Astronomers http://www.astro.phys.ethz.ch/rapp/cesra/cesra_home_nf.html