OPERATIONAL SPACE WEATHER FUNDAMENTALS

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L'Aquila - ITALY

Solar Radio Bursts and Their Forecasting

MAURO MESSEROTTI[1,2,3]

[1]INAF-Astronomical Observatory of Trieste, Trieste, Italy

[2]University of Trieste, Department of Physics, Trieste, Italy

[3]INFN-Trieste Division, Trieste, Italy

E-Mail: mauro.messerotti@inaf.it

Introducing Myself aka
Current Roles of Mauro Messerotti, Retiree But Not Too Much...

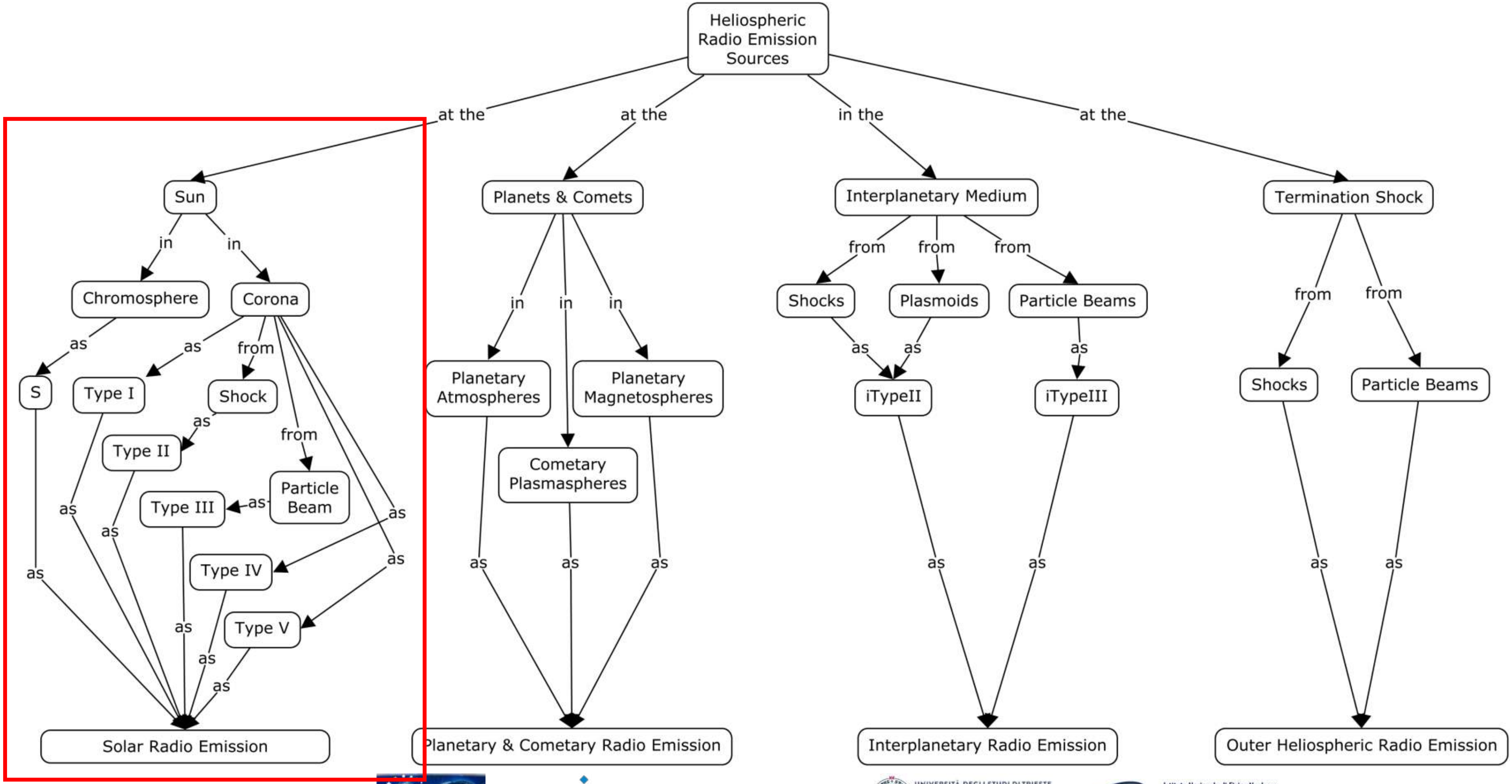
- INAF Research Associate with Research Assignment
- Senior Advisor for Space Weather, INAF Science Directorate
- Former Coordinator, Project "INAF National Network of Space Weather Services"
- Adj. Professor, Dept. of Physics, University of Trieste, of
  - Meteorology and Climatology of Space
  - Physics of Space-Geospace Interactions
  - Methods for Image Processing
- Adj. Professor, National Doctorate in Space Science & Technology, Space Weather
- Adj. Professor, Luiss Business School, Course on Space Economy, Space Weather
- Co-opted Member, Panel on Space Weather, Committee on Space Research (COSPAR)
- Co-opted Member, European Science Foundation (ESF), European Space Science Committee (ESSC), Solar System Exploration Panel (SSEP)
- Member, Steering Board, ESA Space Weather Working Team
- Senior Advisor, Trieste Solar Radio Weather Centre

Scheme of the Presentation

- RADIO EMISSIONS IN THE SOLAR ATMOSPHERE
- SOLAR RADIO WEATHER AND DIRECT EFFECTS IN GEOSPHERE
- THE FORECAST OF SOLAR RADIO WEATHER
- THE ROLE OF SOLAR RADIO BURSTS IN THE SPACE WEATHER FRAMEWORK
- ANN APPROACHES FOR THE PREDICTION OF THE 10.7 CM RADIO INDEX
- CONCLUSIONS

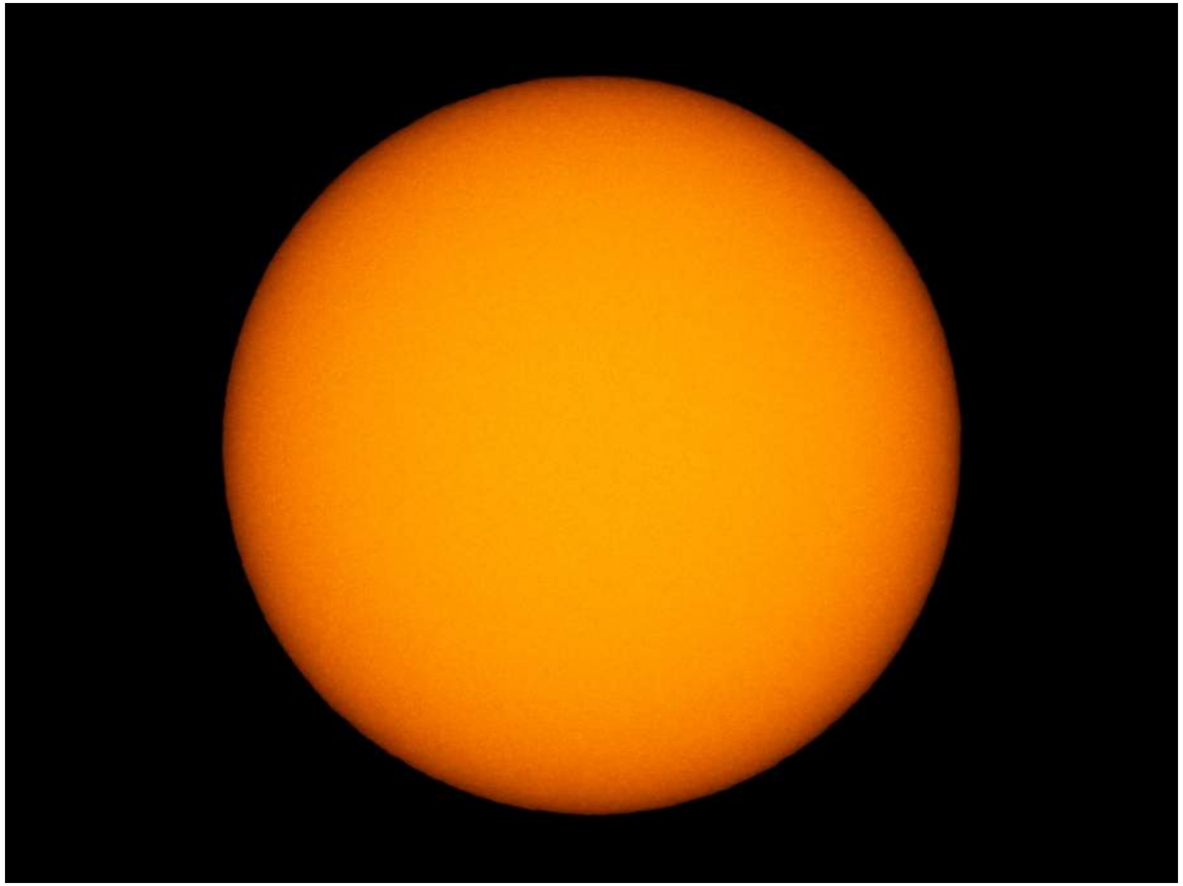
Radio Emissions in the Solar Atmosphere

Radio Emission Sources in Heliosphere

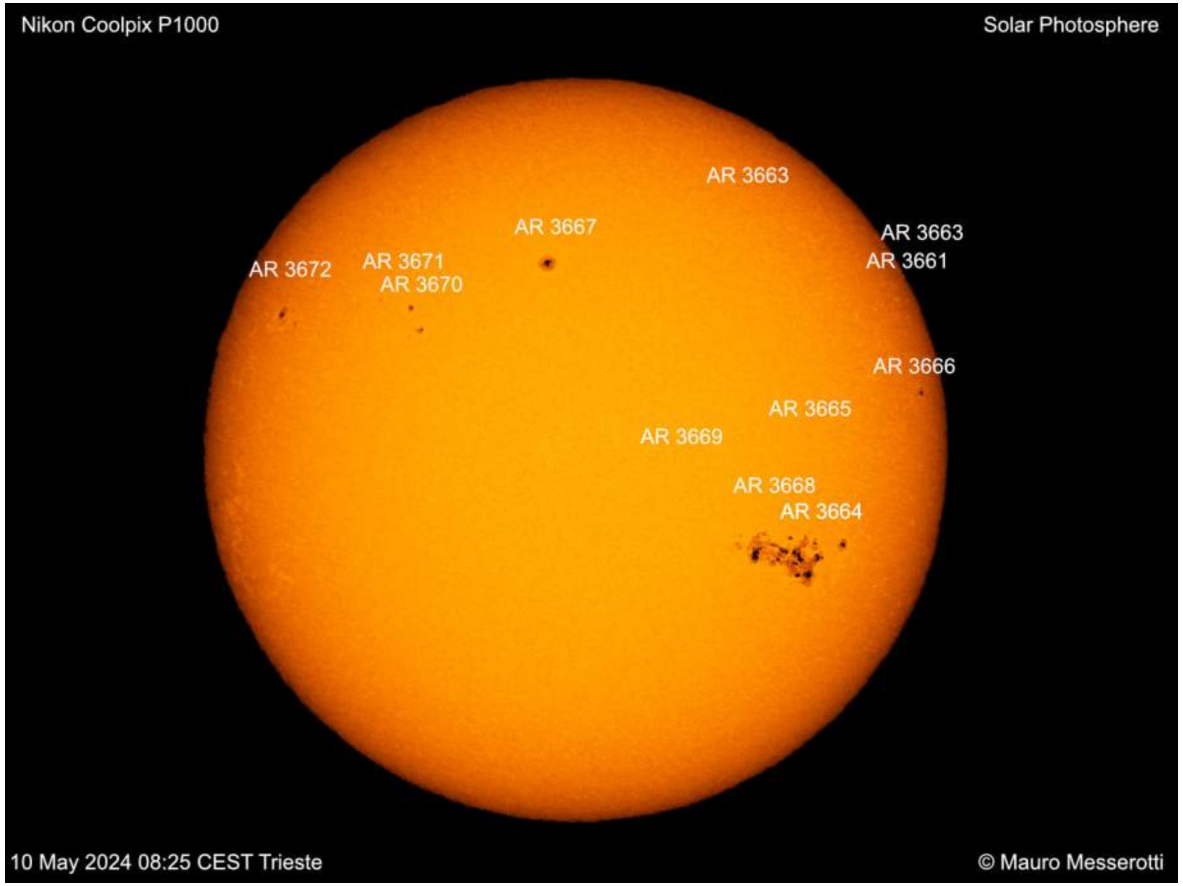


The Quiet and the Active Sun

The Quiet Sun in 2020



The Active Sun on 10 May 2024



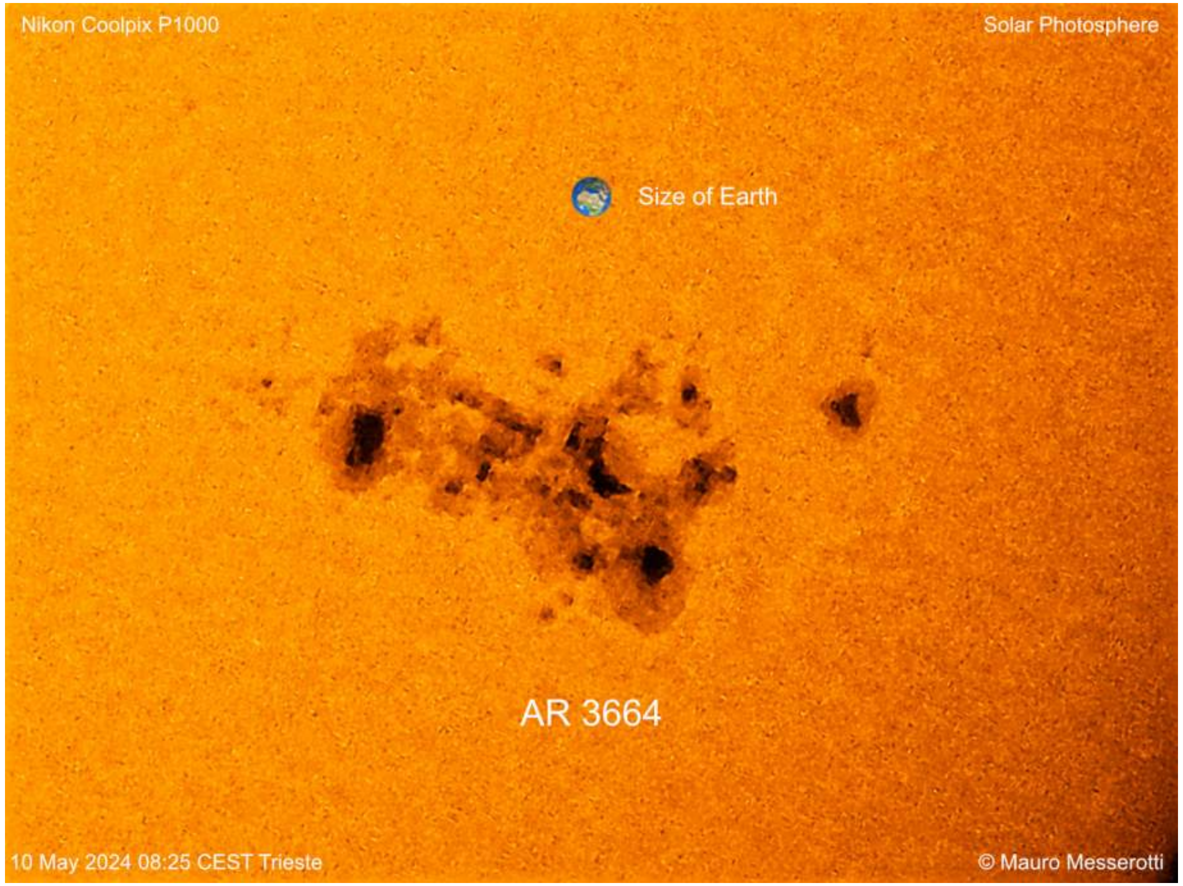
Number of Sunspots, Area and Magnetic Complexity

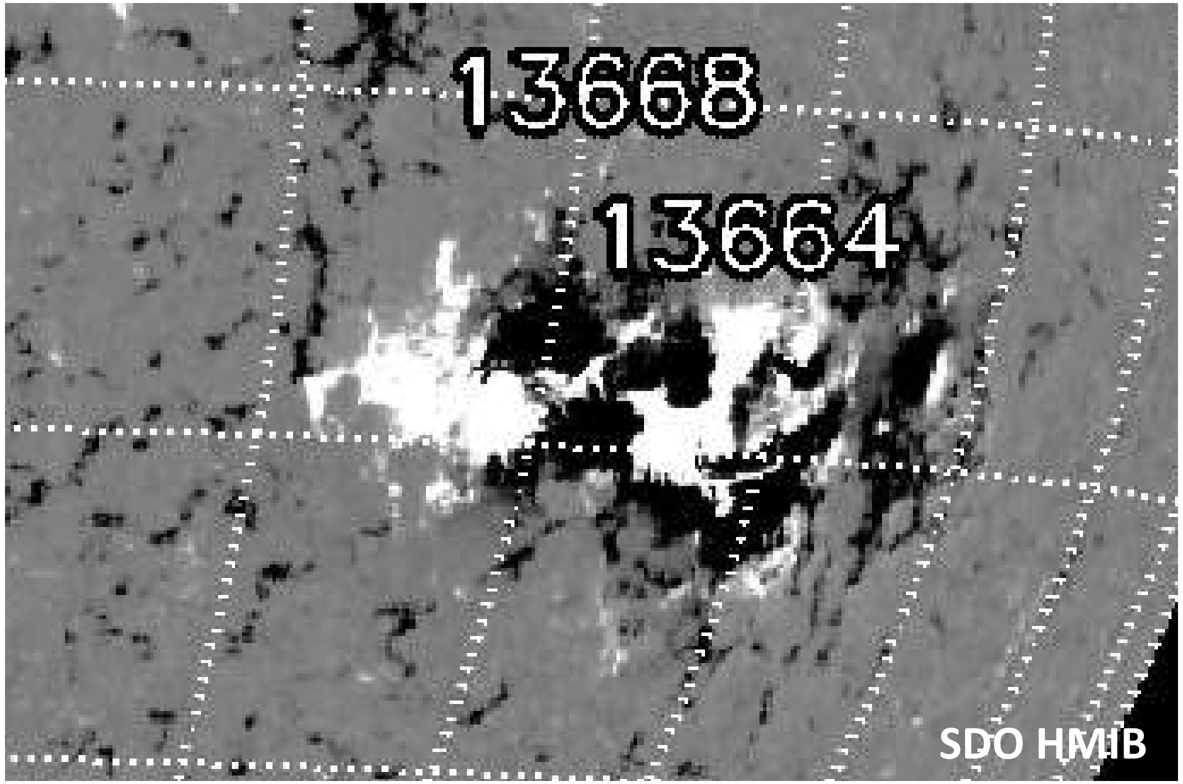
AR 3664 on 10 May 2024

81 sunspots 1090 MH 16 Earth's diameter

Magnetic Complexity

$\boldsymbol{\beta\gamma\delta}$





Solar Radio Emission Processes

Physical Nature of Solar Radio Emissions

- In the (mm-m) wavelenght range solar radio emissions are:
  - **incoherent radiation** generated by continuous processes
  - **coherent radiation** generated by nonlinear resonant processes involving the
    - electron plasma frequency

      $$f_{pe}(R) = 8973 \cdot 10^{-6}\sqrt{N_e(R)}\ \ \text{MHz}$$

    - electron gyrofrequency

      $$f_{ce}^{s} = s \cdot f_{ce} = s \cdot (2.80 \cdot B)\,\text{MHz} \qquad (s = 1, 2, 3, \ldots)$$

    - harmonics of the above
  - no emission or absorption spectral lines from atomic or molecular transitions observed
  - radio recombination lines from ions in the mm-cm band are undetectable due to the extreme pressure broadening

Indirect EM Emission Processes

- PLASMA RADIATION

It is a coherent mechanism involving:

1. the generation of plasma waves at the electron plasma frequency or its second harmonics via various plasma instabilities, i.e. wave growth in an unstable plasma configuration where a source of free energy exists (i.e. higher number of degrees of freedom in the plasma; e.g. an injected nonthermal particle beam which originate Langmuir waves via a beam-plasma instability or a loss-cone distribution of electrons which excites upper hybrid waves and Bernstein modes)

2. the conversion of such longitudinal plasma waves into transverse em waves via various cohalescence/scattering processes (Polarized in the o-mode) !!

Conversion of Plasma Waves Into EM Waves

Langmuir waves are converted into transverse em waves near the local plasma frequency f_{pe} or its second harmonic ($2\ f_{pe}$) according to different processes.

- Fundamental emission (f_{pe})
  - IP type III bursts (in-situ observations)

A Langmuir wave decays into a daughter Langmuir wave and an ion-sound wave $L \Rightarrow L' + S$, which coalesces with another Langmuir wave into a radio wave $L + S \Rightarrow T$.

  - Coronal type III bursts (?)

- Harmonic emission ($2\ f_{pe}$)

Two Langmuir waves with frequency f_{pe} coalesce $L + L' \Rightarrow T$

Frequency and Momentum Matching

To get a reasonable efficiency in the conversion process, it must be assured

- **Frequency matching** $\omega_t = \omega_L + \omega_3$

  e.g. For fundamental radiation $\omega_t \approx \omega_L \approx \omega_{pe}$ and hence ω_3 must be small (low-frequency wave)

- **Momentum matching** $\mathbf{k}_t = \mathbf{k}_L + \mathbf{k}_3$

  e.g. As $|\mathbf{k}_t| << |\mathbf{k}_L|$ it must be $\mathbf{k}_3 \approx -\mathbf{k}_L$

Three possible processes:

1. Scattering by the electric field by thermal ions
2. Scattering by low-frequency waves (ion-sound, lower-hybrid)
3. Direct conversion by high gradient density inhomogeneities

Direct EM Emission Processes

- THERMAL FREE-FREE EMISSION (Bremsstrahlung)
  Individual electrons are deflected in the Coulomb field of ions
  (Unpolarized em waves - Occurs almost everywhere) !!

- INCOHERENT GYRORESONANCE and
  GYROSYNCHROTRON EMISSION
  Gyration of electrons around magnetic field lines prevails over
  collisions (gyroresonance – non-relativistic,
  gyrosynchrotron – mildly relativistic,
  synchrotron – highly relativistic electrons)
  (Polarized em waves in x-mode - Dominates at mm-cm wavelengths) !!

Various possibilities:

- gyroresonance radiation from thermal electrons
- gyrosynchrotron radiation from thermal electrons
- gyrosynchrotron radiation from power-law electrons
- synchrotron radiation from power-law electrons
- Razin-Tsytovich: suppression of gyrosynchrotron emission at low f

Direct EM Emission Processes (cont’d)

- **ELECTRON CYCLOTRON MASER**

Radiation is amplified by the MASER at frequencies near the electron-cyclotron frequency and its low-harmonics.

To operate the MASER requires:

a) a population inversion in the electron distribution as compared with the equilibrium (the pump for the MASER);

b) a relatively strong magnetic field or low-density plasma so that the electron-cyclotron frequency is somewhat larger than the electron plasma frequency.

The free energy is directly converted into coherent em radiation.

Invoked to explain high brightness temperature, spiky emissions

Propagation of Radio Waves in the Solar Corona

Radio Emission Observables

- Radio domain ⇒ Rayleigh-Jeans approximation $h\nu \ll k_B T$
- Specific Intensity: $\mathcal{I}_\nu = k_B T_B \nu^2 / c^2$ T_B Brightness Temperature
- Source Function: $\mathcal{S}_\nu = k_B T_{\text{eff}} \nu^2 / c^2$ T_{eff} Effective Temperature
- Spatially unresolved observations [S_ν] = [sfu]

  1 solar flux unit (sfu) = 10^{-22} W m^{-2} Hz^{-1}

- Imaging instruments are characterized by an angular resolution determined by the antenna beam solid angle Ω_{bm}

  The measured quantity is the Flux density per beam:

  $$\langle S_\nu \rangle_{bm} = k_B \langle T_B \rangle_{bm} \nu^2 \Omega_{bm} / c^2$$

  with $\langle T_B \rangle_{bm}$ the mean brightness temperature over the beam Ω_{bm}

Radio Emission Sources

- For an **optically thick** source, which emits **incoherent radiation**

$$T_B = T_{\rm eff}$$

with $T_{\rm eff}$ **kinetic temperature** if the source is in thermal equilibrium or **mean energy** of **emitting electrons** otherwise

- For an **optically thin** source

$$T_B \approx \tau_\nu T_{\rm eff}$$

with τ_ν the **optical depth**

The microphysics of the specific emission mechanism is embodied in the **absorption coefficient** κ_ν through $\tau_\nu = \int \kappa_\nu \, dl$

For **coherent emission** one can have $T_B \gg T_{\rm eff}$

Radio Flux Density and Polarisation

- The **Flux density S** for one polarization is related to T_b by

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

where $d\Omega$ is a differential solid angle and the integral is over the projected area of the source.

- The **Circular Polarization (CP) degree** is

$$r_c = (T_{b,x} - T_{b,o})/(T_{b,x} + T_{b,o})$$

and is therefore related to the brightness temperature not to S, which is an integrated observable (!)

It is related to the magnetic field polarity at the source

The Electromagnetic Modes

- Coronal plasma ~ cold magnetized plasma
- It behaves like a birefringent medium
- A radio wave is splitted into two components with different velocity and polarization: the ordinary (o) mode and the extraordinary (x) mode, but the (z) and whistler modes can propagate as well.
- The magnetoionic theory can describe the propagation of the above modes
- The x- and o-modes can propagate from the source to ∞
- The z- and whistler modes are prevented by stopbands in the refractive index

The Quasi-Circular (QC) Approximation

- Let us define $X = (\nu_{pe}/\nu)^2$ and $Y = \nu_{Be}/\nu$ where ν is the frequency of the wave, ν_{pe} the electron plasma frequency and ν_{pe} the electron cyclotron frequency

- When $Y \sin^2\theta/2(1-X)\cos\theta \ll 1$ with θ angle between the em wave normal and the magnetic field vector, the QUASICIRCULAR APPROXIMATION holds

- The propagation of the x- and o-modes is adequately described by the QC approximation in many cases of interest

- The radiation is very nearly circularly polarized

- The observables are the TOTAL INTENSITY (Stokes I) and the CIRCULARLY POLARIZED RADIATION (Stokes V) parameters

The Quasi-Transverse (QT) Approximation

- When $Y \sin^2\theta/2(1-X)\cos\theta >> 1$ with θ angle between the em wave normal and the magnetic field vector, the QUASITRANSVERSE APPROXIMATION holds

- The radiation is linearly polarized at the source

- Faraday rotation is very large in the coronal medium and differential Faraday rotation across typical receiver bandwidths and/or the differential Faraday rotation from the front to back of an optically thin source washes out the linear polarization completely

- No linearly polarized solar radio emission was observed to date

Mode Coupling

Propagation effects can modify the observed polarization

- WEAK MODE COUPLING The magnetoionic theory prevails and the wave modes propagate independently

  When the wave cross a QT region (the longitudinal component of the magnetic field changes sign), the SENSE OF CP REVERSES

- STRONG MODE COUPLING The magnetoionic theory breaks down and the magnetoionic modes are no longer independent

  When the wave cross a QT region, the x- and o-modes couples, and the SENSE OF CP REMAINS UNCHANGED.

Under certain conditions, mode coupling can play a role in DEPOLARIZING the radiation.

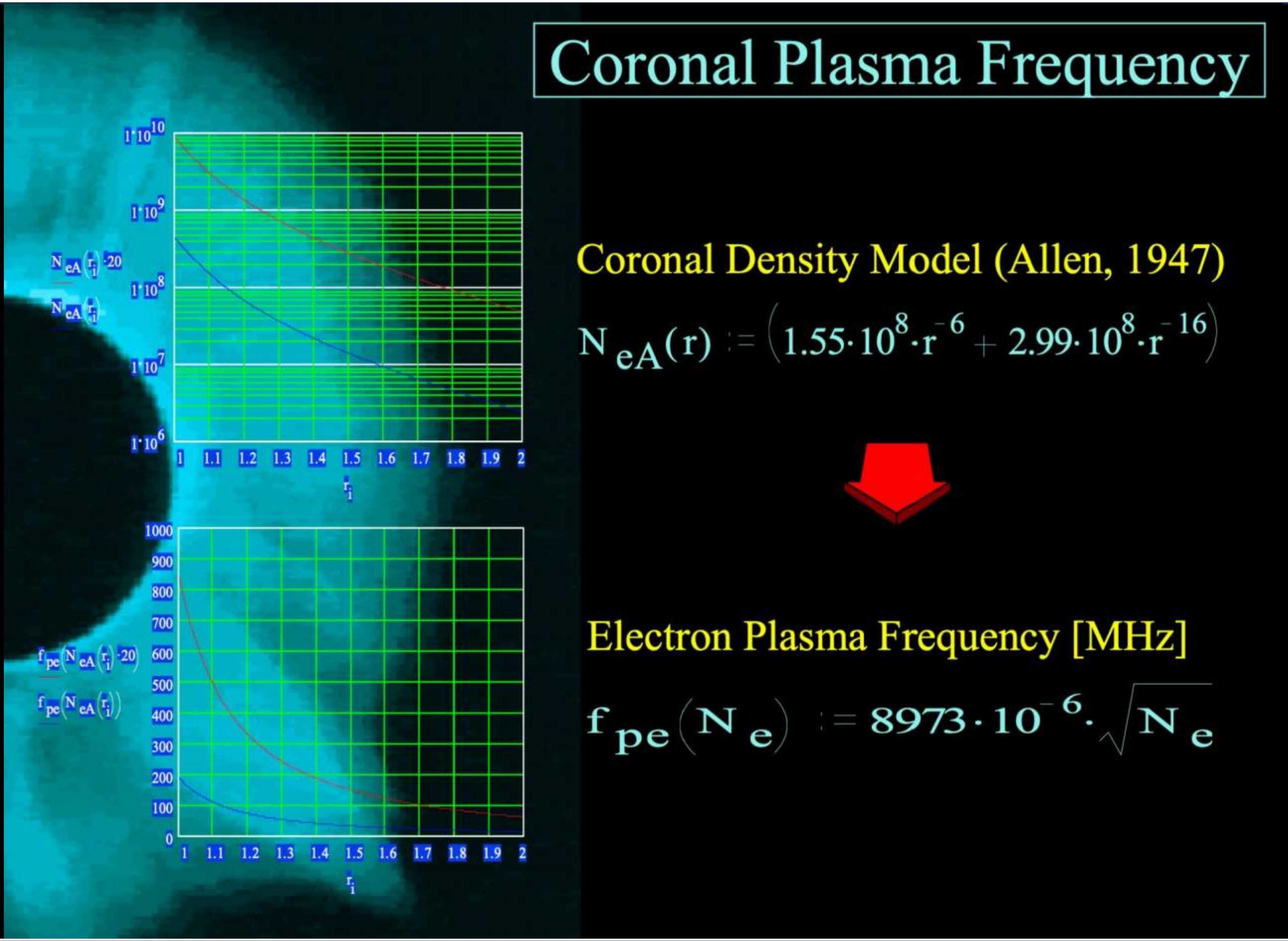
Approximate Location of Solar Radio Sources

The Local Plasma Frequency and Radio Wave Propagation

The local plasma frequency $f_p = f_p(R,\theta,\varphi)$

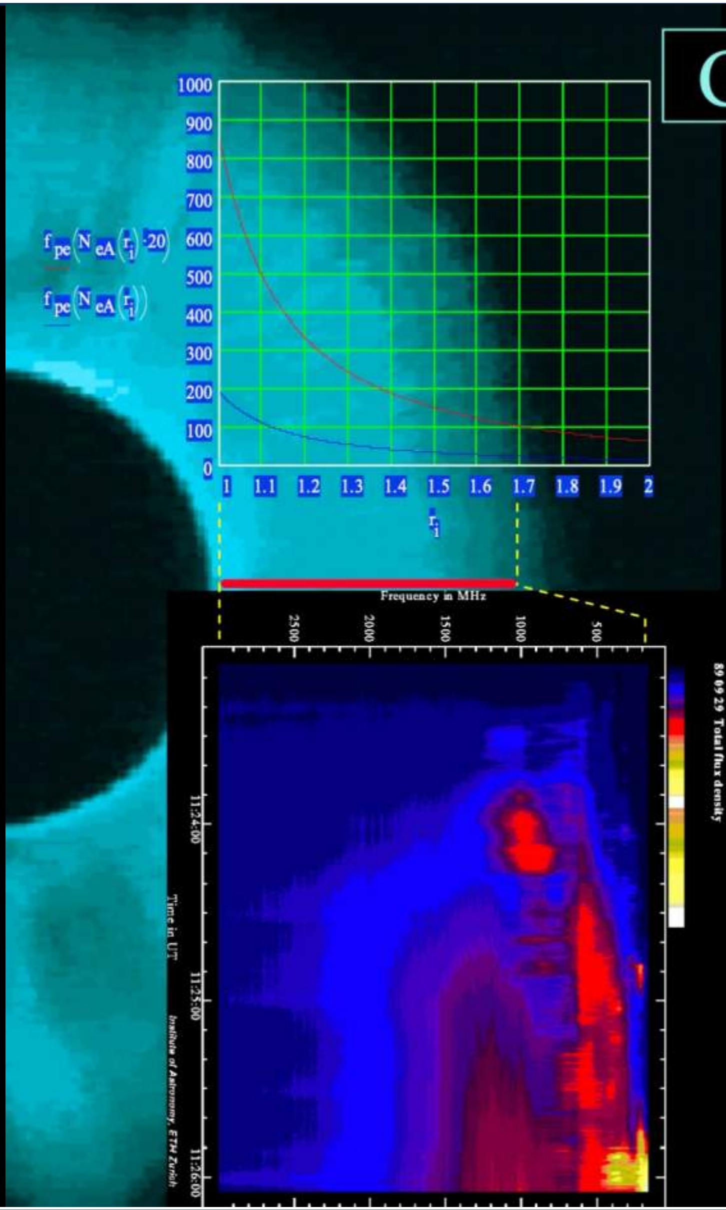
- is a nonlinear functional of the plasma electron density N_e
- is a nonlinear functional of the radial distance R
- determines propagative and non-propagative conditions:
  - $f_{wave} > f_p$ propagation
  - $f_{wave} = f_p$ reflection (vanishing refraction index $\mu^2=1-(f_p/f_{wave})^2=0$)
  - $f_{wave} < f_p$ absorption (imaginary refraction index)

The Coronal Plasma Frequency



Coronal Radio Diagnostics

Coronal Radio Diagnostic



$f_{pe} = f_{pe}(N_e)$

$N_e = N_e(r)$

$\Rightarrow$ $f_{pe} = f_{pe}(r)$

EM Waves with frequency f propagate if and only if
$f \geq f_{pe}(r)$
i.e. are emitted by the layer at radial distance r

$\Downarrow$

Radio Spectrum

$S = S(f, t)$

Average Source Height of Solar Radio Emissions

WITH THE DUE CAUTIONS AND ADOPTING THE PROPER CORRECTIONS WHEN MODELLING, WE CAN SAY THAT SOLAR RADIO EMISSIONS OCCUR IN THE FOLLOWING BANDS ACCORDING TO THE LOCATION OF THE SOURCE:

- mm chromosphere to low corona
- cm low corona
- m inner corona
- dam outer corona
- hm IPM
- km IPM to 1 AU

Effects of Density Irregularities on Solar Radio Wave Propagation

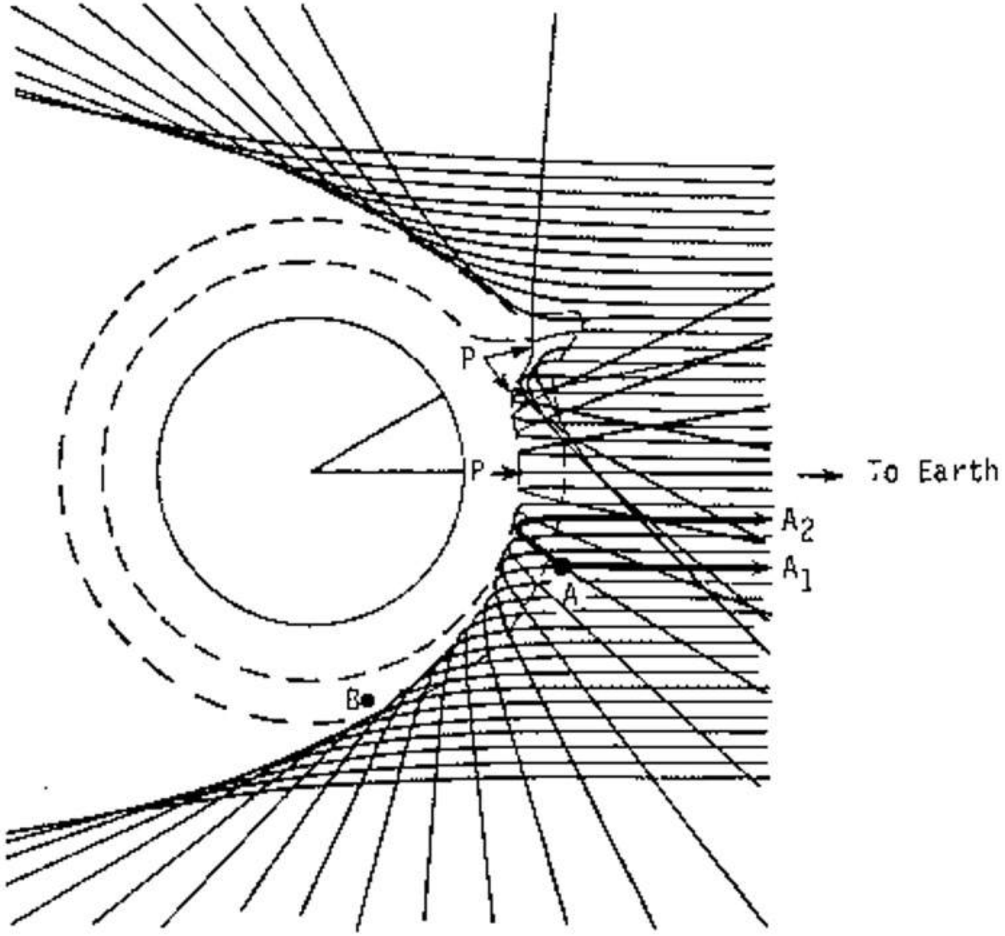
Refraction of Radio Waves on Large-Scale Coronal Structures

$$n = (1 - \omega_p^2 / \omega^2)^{1/2}$$

$$\bar{v}_g = c n \hat{k}$$

$$\frac{d\bar{x}}{ds} = \hat{k}$$

$$\frac{d(n\hat{k})}{ds} = \frac{\partial n}{\partial x}$$



McLean and Melrose (1985)

Refraction makes the radiation **more directive**

Refraction and Scattering of Radio Waves on Random Coronal Inhomogeneities

$$\langle \delta^2 \rangle^{1/2} = 0.94 (f_p / f)^2 (\varepsilon^2 / h)^{1/2} (\delta s)^{1/2}$$

R.M.S. ANGULAR DEVIATION

$\varepsilon \rightarrow$ *r.m.s. relative fluctuation* $\Delta \quad N_e / N_e$

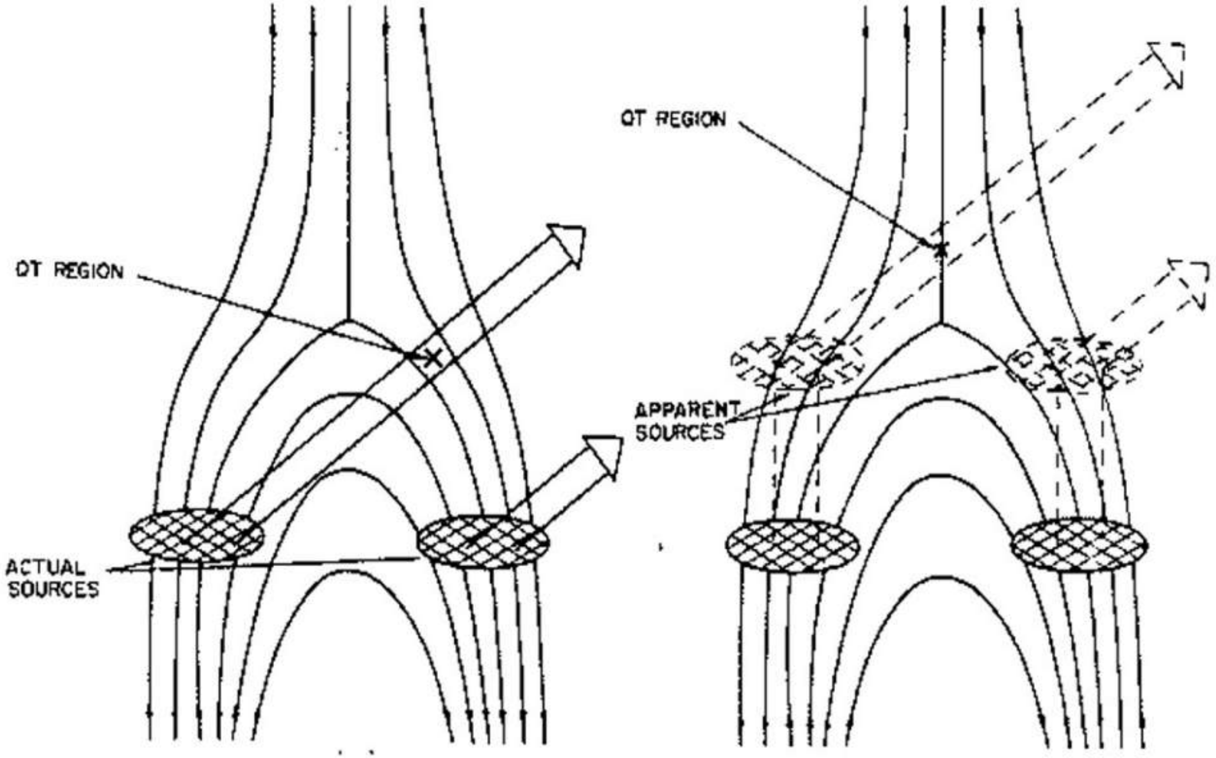
$h \rightarrow$ *correlation coefficient of fluctuations*

Steinberg et al. (1971)

$\varepsilon = 10^{-2} \, h = 5 \cdot 10^{-5} R_o$

Riddle (1974)

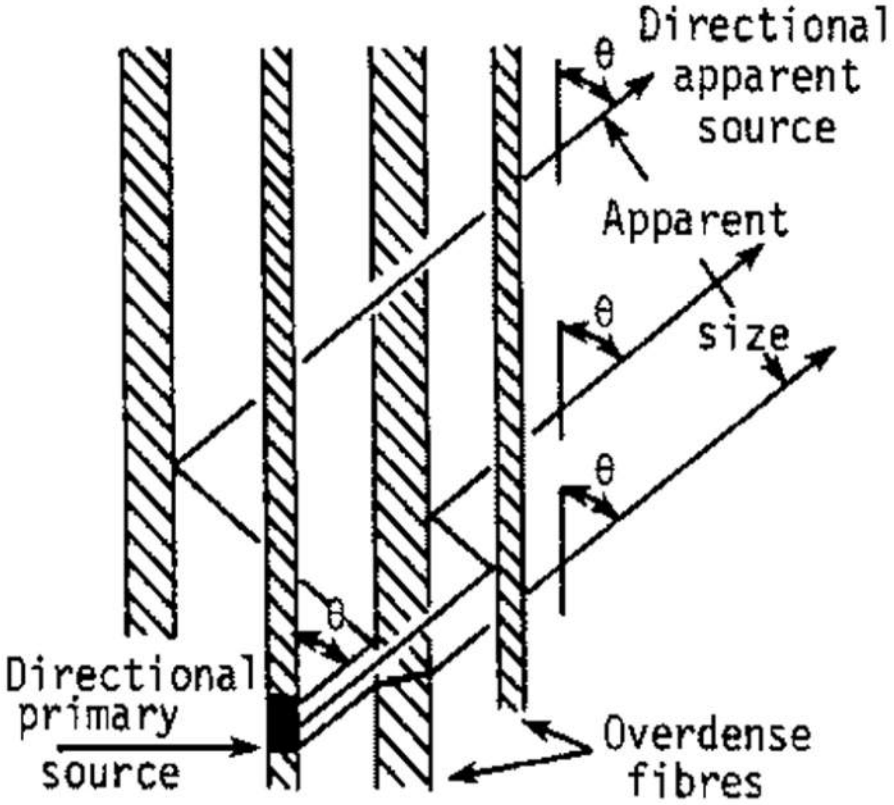
$\varepsilon = 0.02 \, h = 5 \cdot 10^{-4}$



Melrose, 1973; Elgaroy, 1977

Scattering makes the radiation less directive and increases the apparent source size. Bastian (1994) has pointed out that angular broadening is relevant to frequencies of several GHz or more and limits the angular resolution at which compact sources can be imaged,

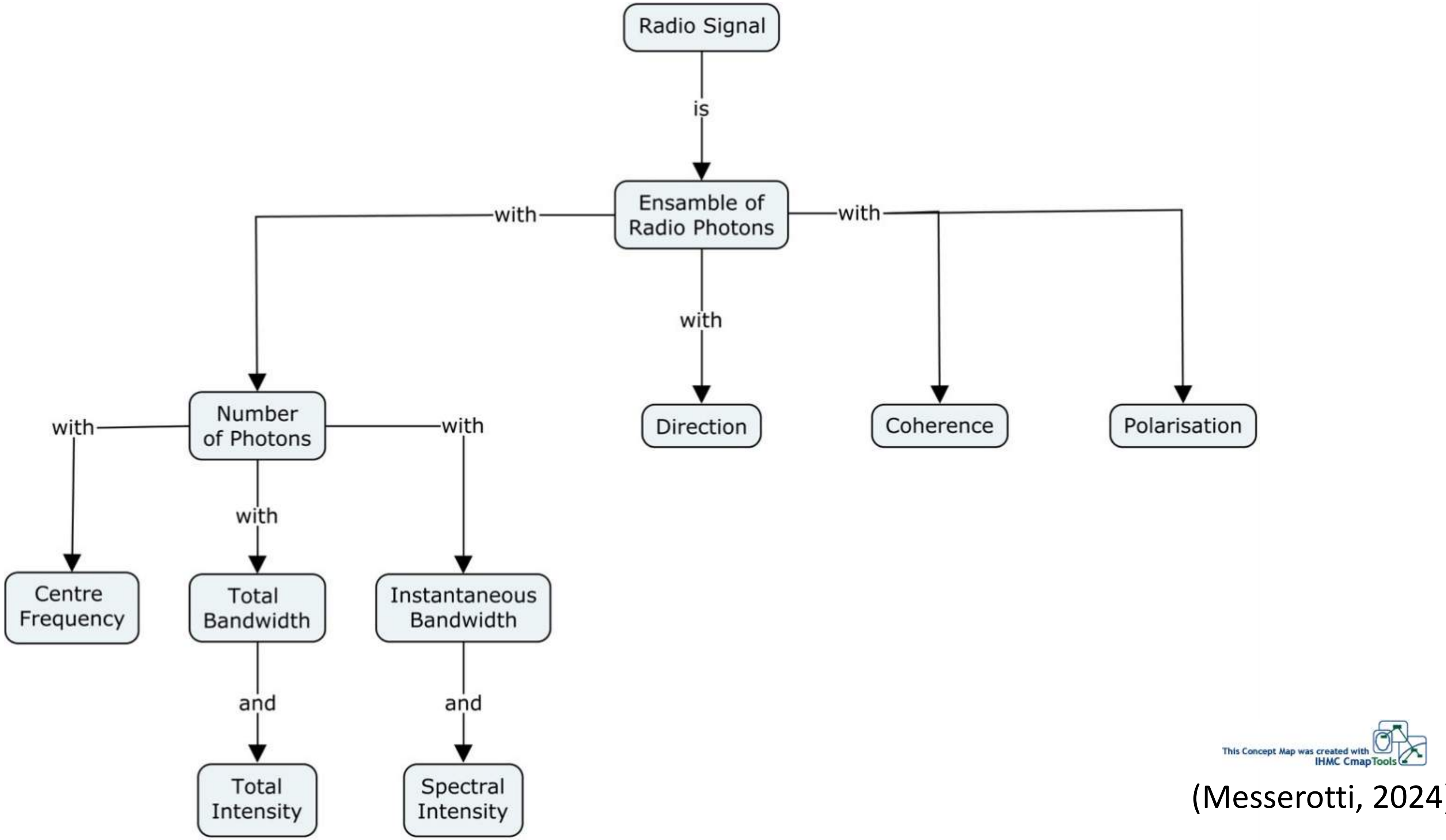
Reflection of Radio Waves on Ordered Coronal Structures (Fibers)



Bougeret and Steinberg (1977)

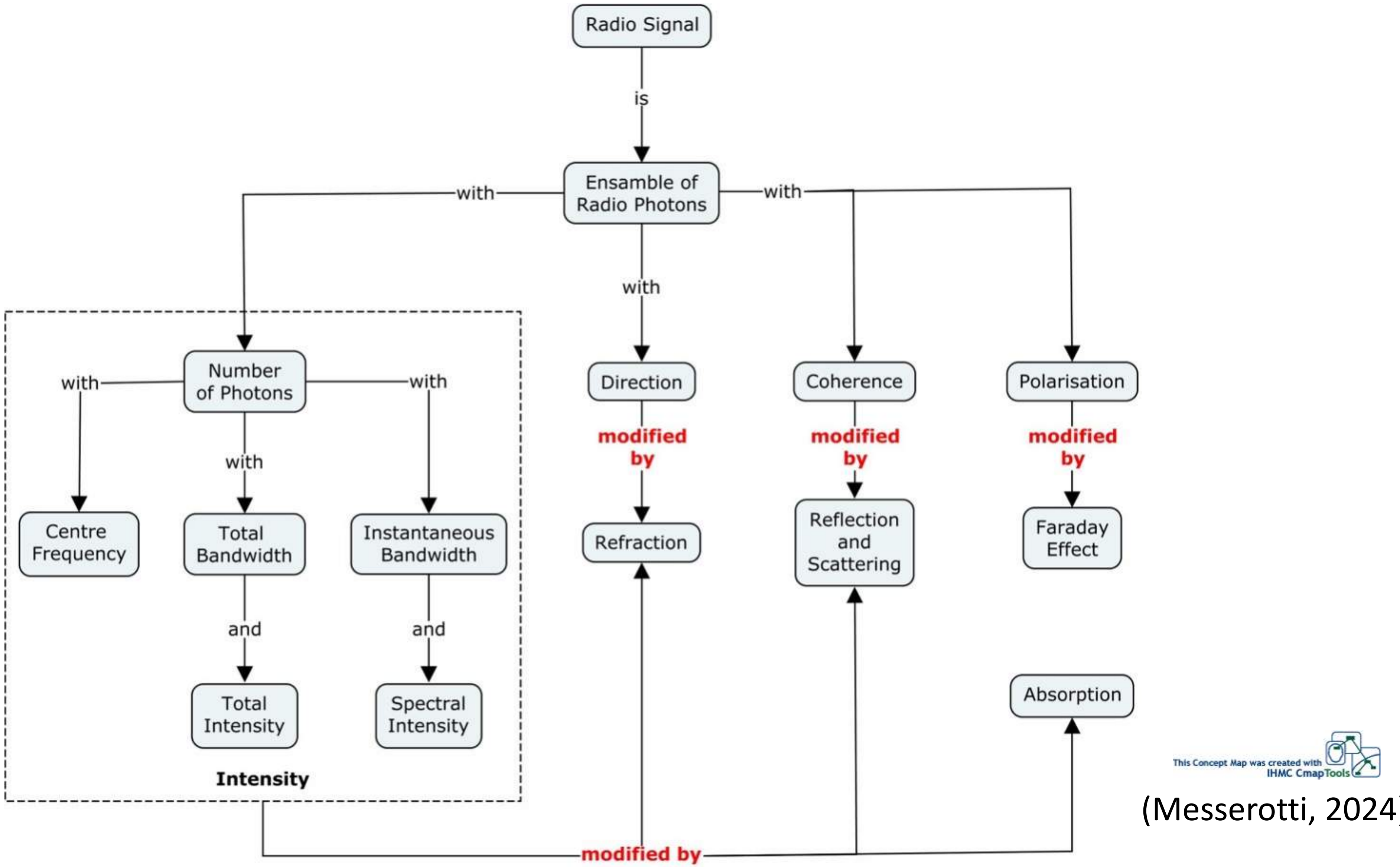
Reflection maintains the directivity and increases the apparent source size

Physical Characteristics of a Radio Signal



(Messerotti, 2024)

Modifications of a Radio Signal



(Messerotti, 2024)

Solar Radio Weather

Radio Emissions From Solar Plasma

- The Sun is made of magnetised plasma at temperature and density which decrease nonlinearly from the core to the atmosphere

- The quiet Sun plasma of the Photosphere and Chromosphere originates a broadband radio emission by thermal mechanisms

- The active Sun plasma in localised regions of the Photosphere, Chromosphere and Corona originates narrowband radio emissions by nonthermal mechanisms

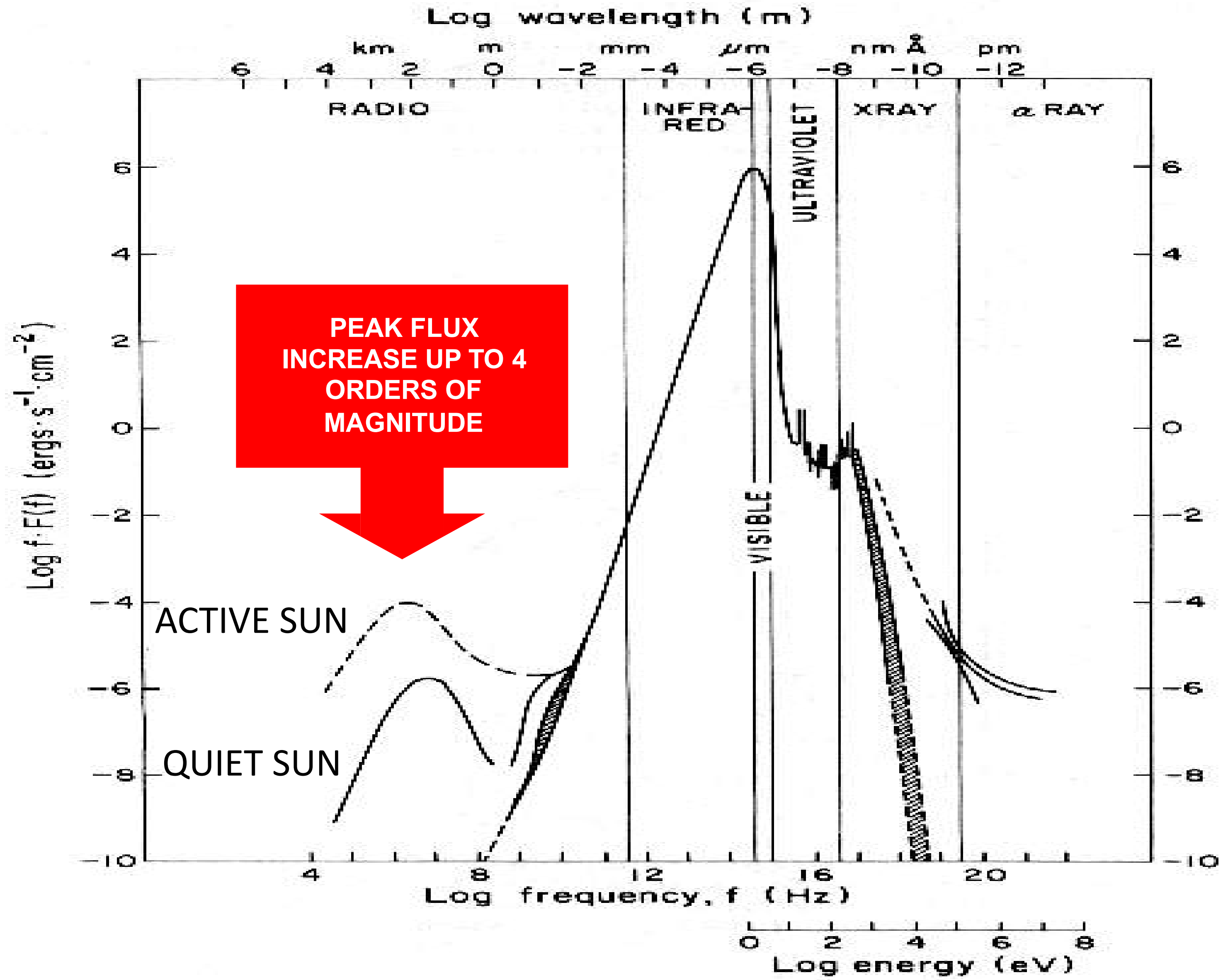
Solar Radio Weather

- THE SUN IS A SOURCE OF BROAD- AND NARROW-BAND RADIO EMISSIONS GENERATED BY COHERENT AND INCOHERENT PROCESSES

- SUCH RADIO EMISSIONS CAN INCREASE BY SEVERAL ORDERS OF MAGNITUDE UNDER PERTURBED SOLAR CONDITIONS

- **SOLAR RADIO WEATHER** REFERS TO THE PHYSICAL STATE OF THE SUN AS AN ENSAMBLE OF RADIO SOURCES

The Solar Radiation Spectrum



Direct Effects of Solar Radio Weather

Direct Effects of Solar Radio Weather

- SOLAR RADIO WEATHER SPANS FROM QUIET TO HIGHLY PERTURBED CONDITIONS, ACCORDING TO THE ORIGINATED LEVEL OF SOLAR RADIO NOISE

- TRAVEL TIME OF SOLAR EM EMISSIONS TO THE EARTH IS 8.3 MINUTES

- RADIO COMMUNICATION SYSTEMS (E.G. SATELLITE-BASED LOCALISATION, AVIATION, AND MOBILE COMMUNICATION SYSTEMS) ARE PROMPTLY AND DIRECTLY INTERFERED UNDER SPECIFIC CONDITIONS WITH NO INTERMEDIATE PROCESS AND/OR AGENT

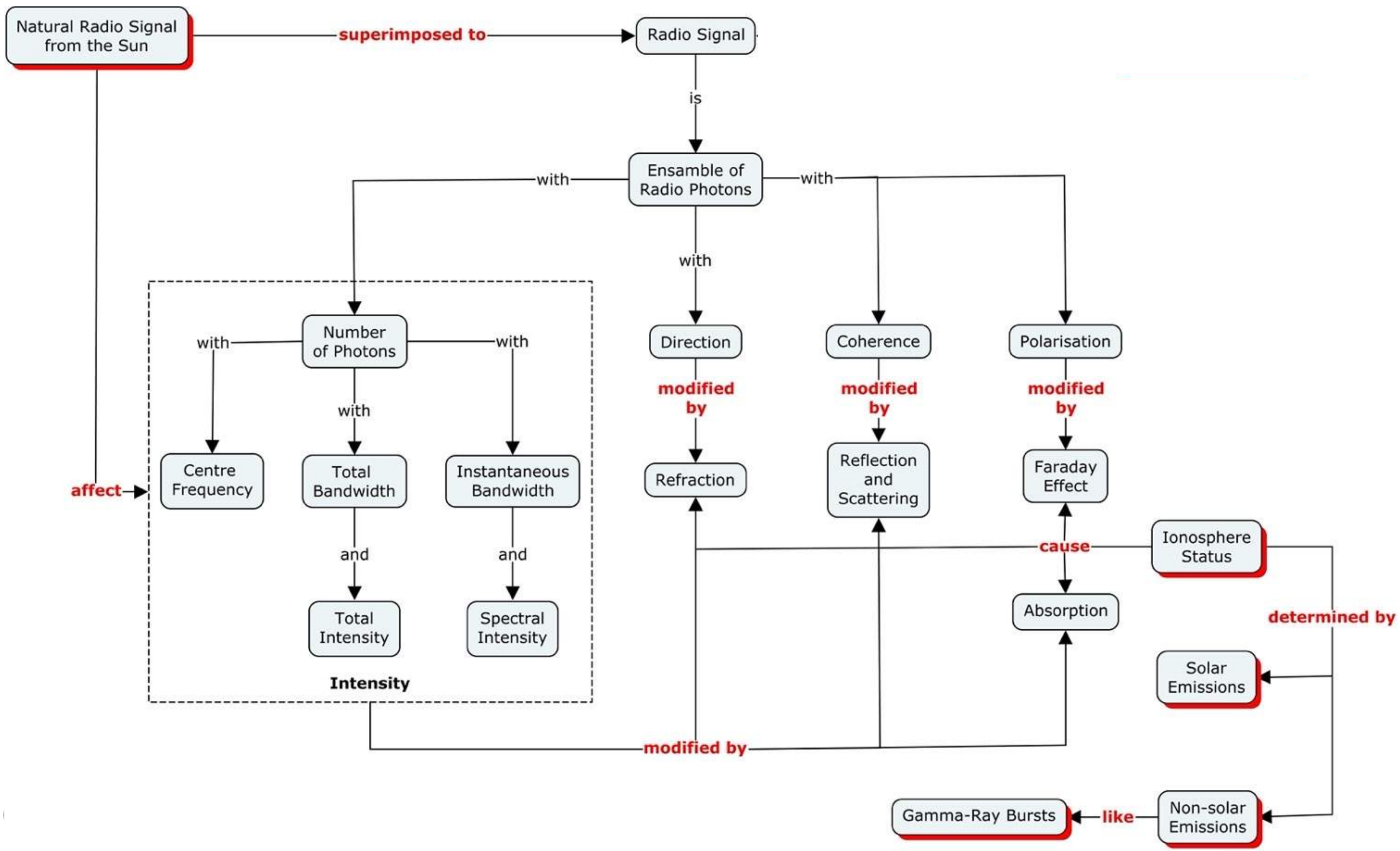
The Sun as a Source of Interfering Radio Noise

- The Sun is a non-directional, broadband, non/polarised radio source

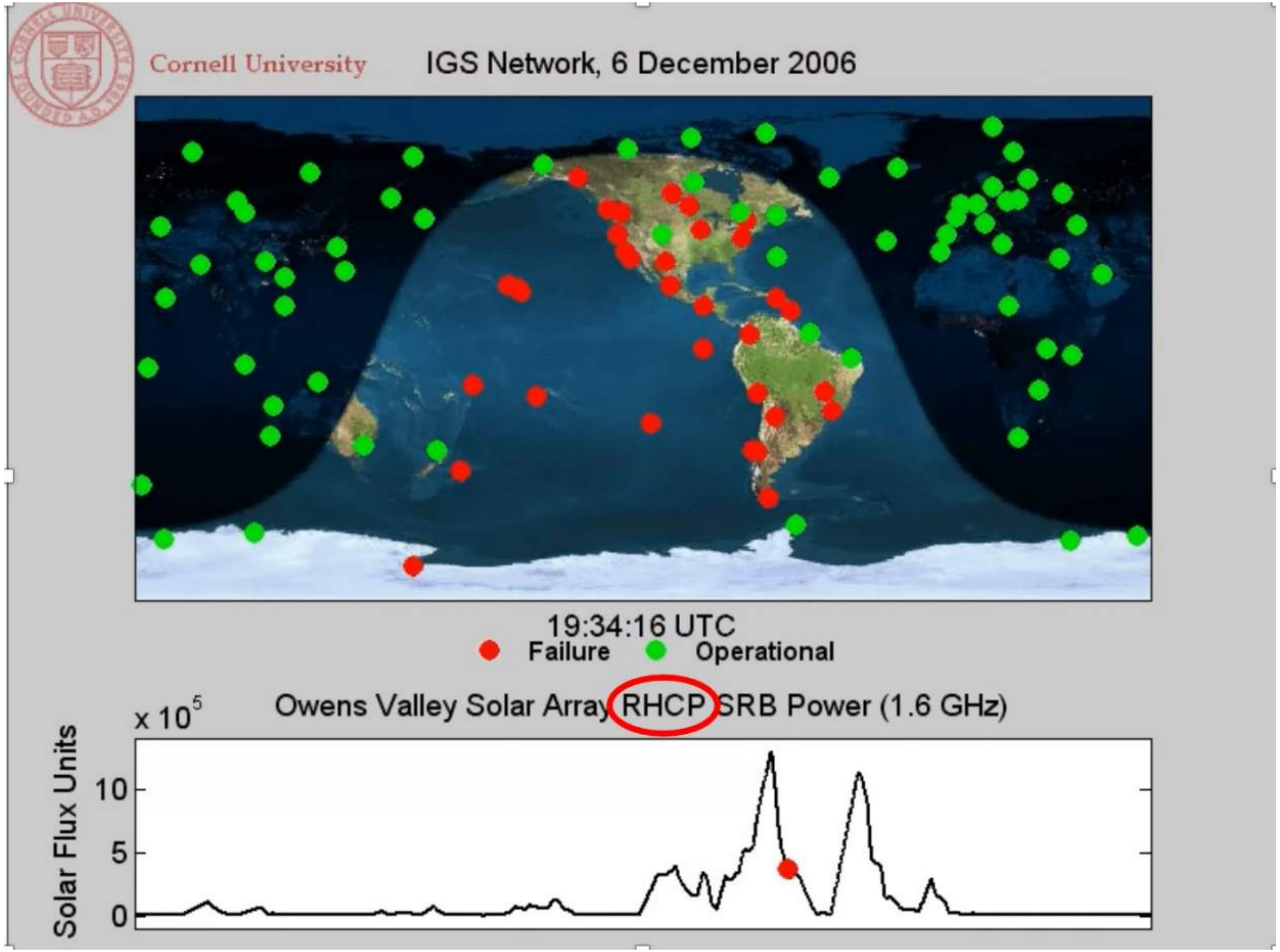
- Solar radio noise can
  - increase by several orders of magnitude during significant radio events
  - persist at high intensity levels from minutes to hours

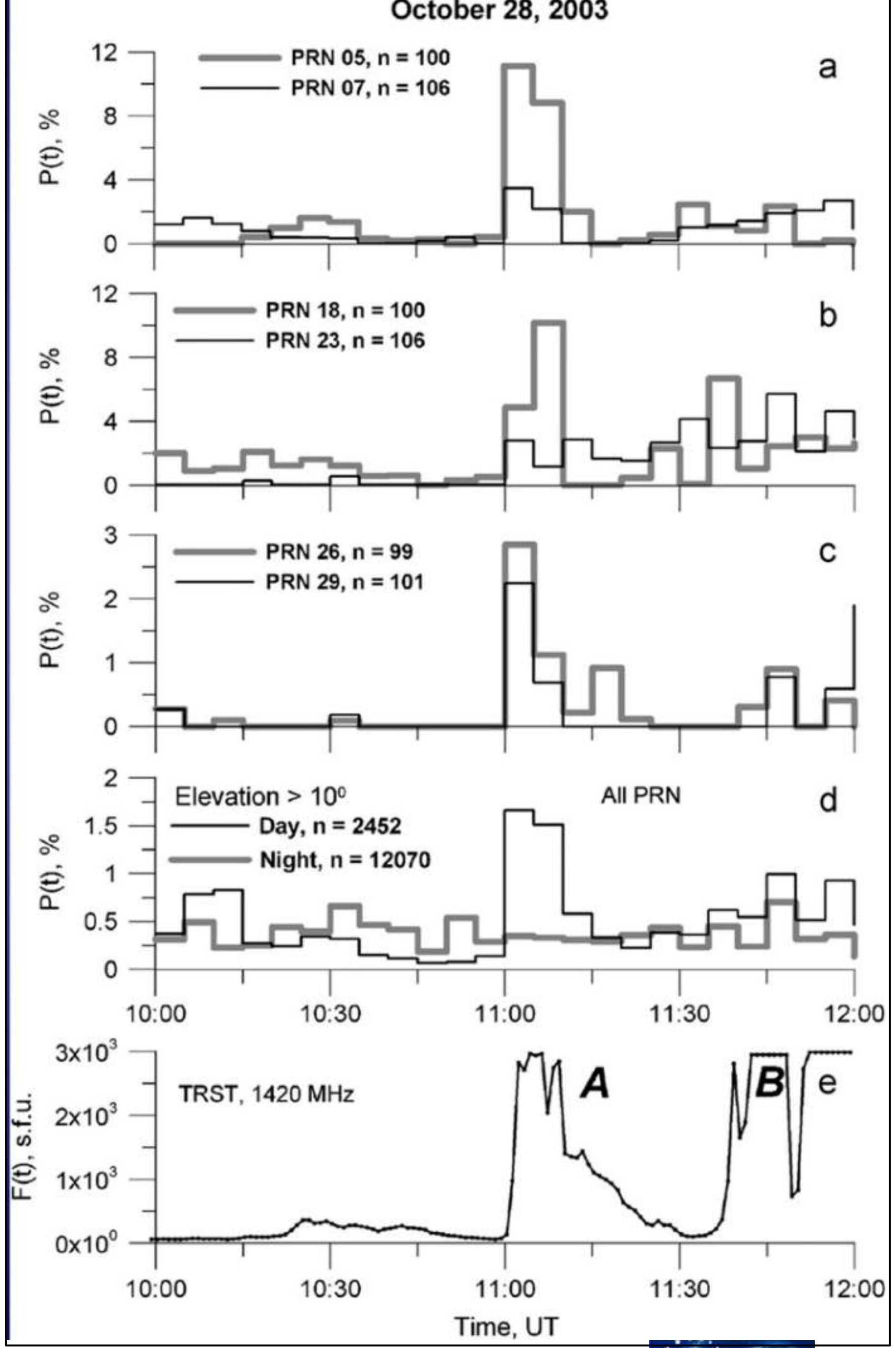
- Enhanced solar radio noise can perturb
  - HF radio communications
  - mobile radio communications
  - receivers for satellite geolocation systems
  - augmentation systems
  - radars
  - satellite radio communications

Radio Interference by a Solar Radio Signal



Impact of a Solar Radio Burst on GPS Receivers on 6 December 2006





Interference to GPS receivers on 28.10.2003

PHASE SHIFT DURING THE SOLAR FLARE OF 28.10.2003 DETECTED BY GPS RECEIVERS LOCATED IN THE ILLUMINATED TERRESTRIAL HEMISPHERE

RELATIVE DENSITY OF PHASE SLIP L1-L2 FOR ALL (d) AND FOR SINGLE GPS SATELLITES (a), (b) AND (c)

FLOW F(t) OF SOLAR RADIO EMISSION WITH **RIGHT CIRCULAR POLARIZATION** (RHCP) DETECTED AT 1420 MHz BY TRIESTE SOLAR RADIO SPECTROPOLARIMETER (c)

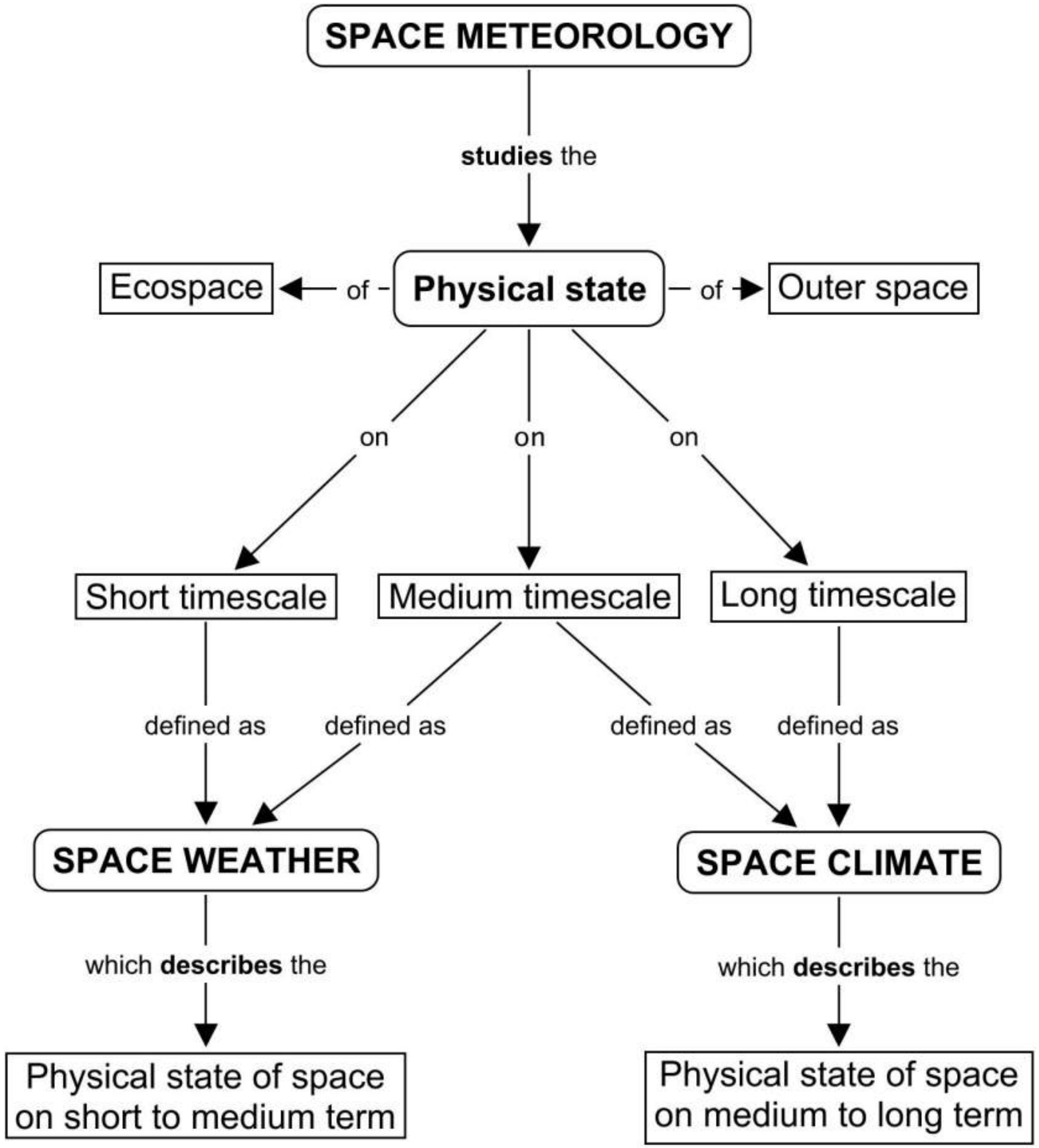
Afraimovich et al., 2008

So We Want to Predict Solar Radio Weather and SRBs...

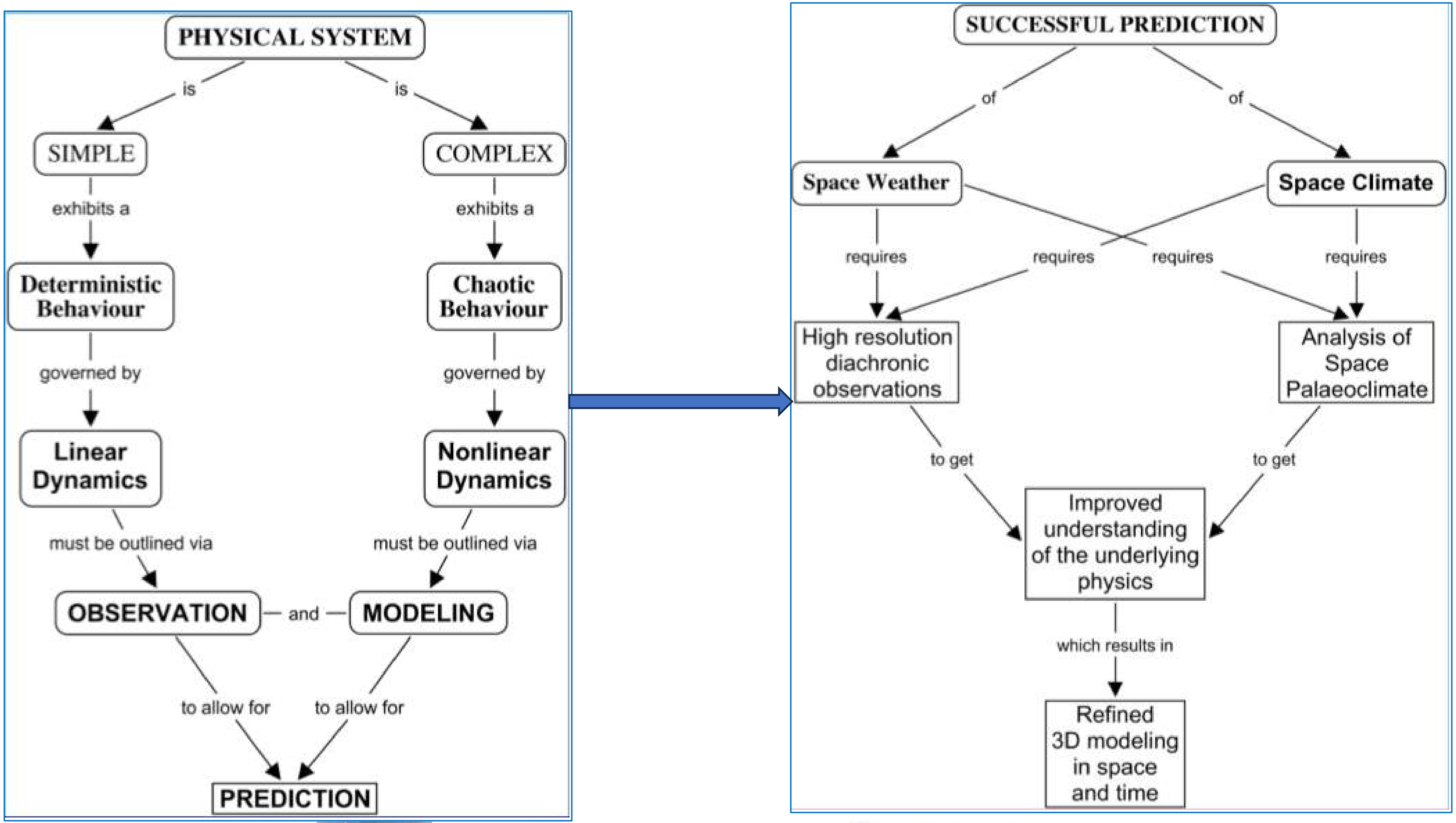
THAT'S TOO FUNNY...IN THE FOLLOWING I WILL EXPLAIN WHY IT IS SO

Considerations on the Forecast of Solar Radio Weather

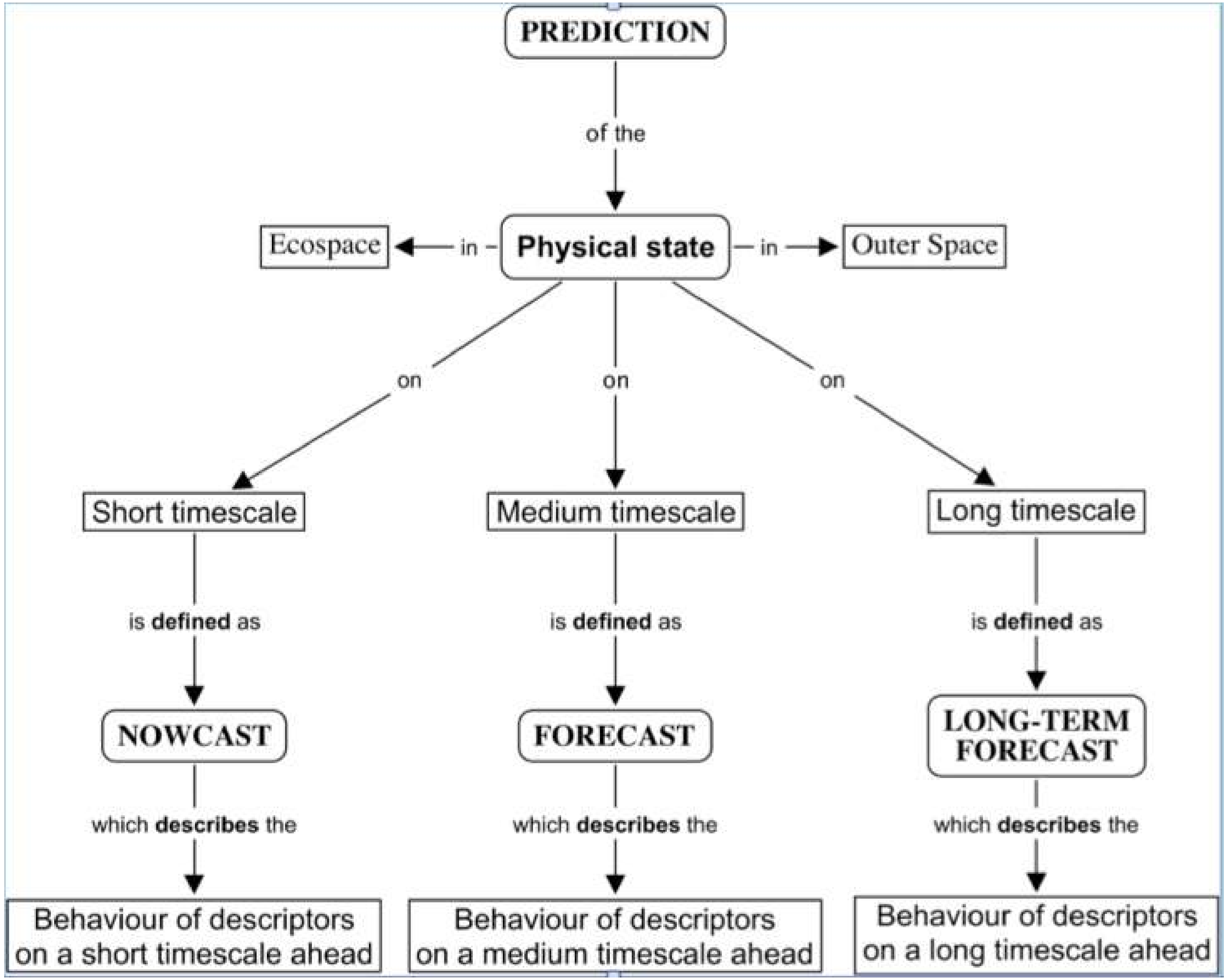
Meteorology of Space



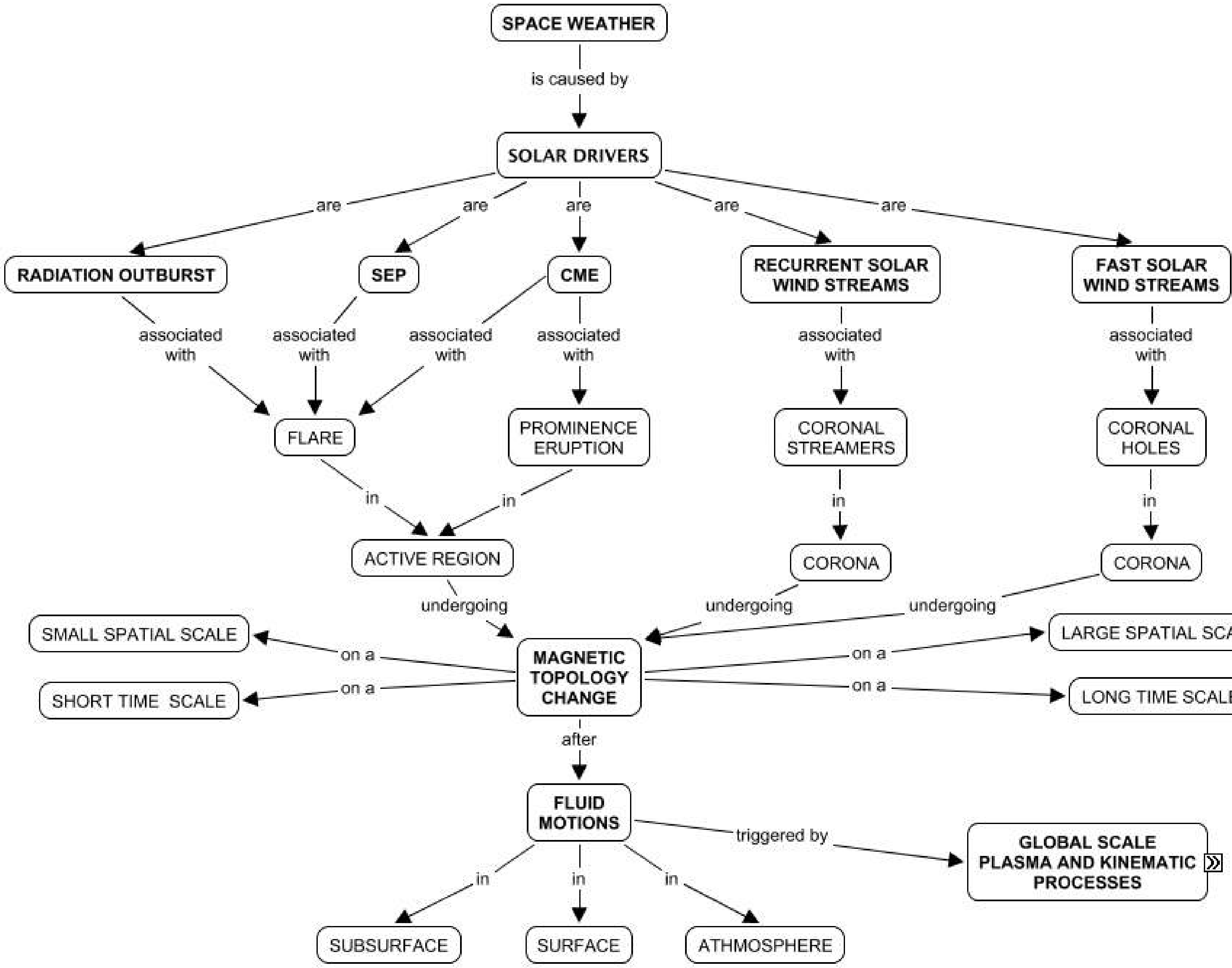
The Forecast of the State of a Physical System



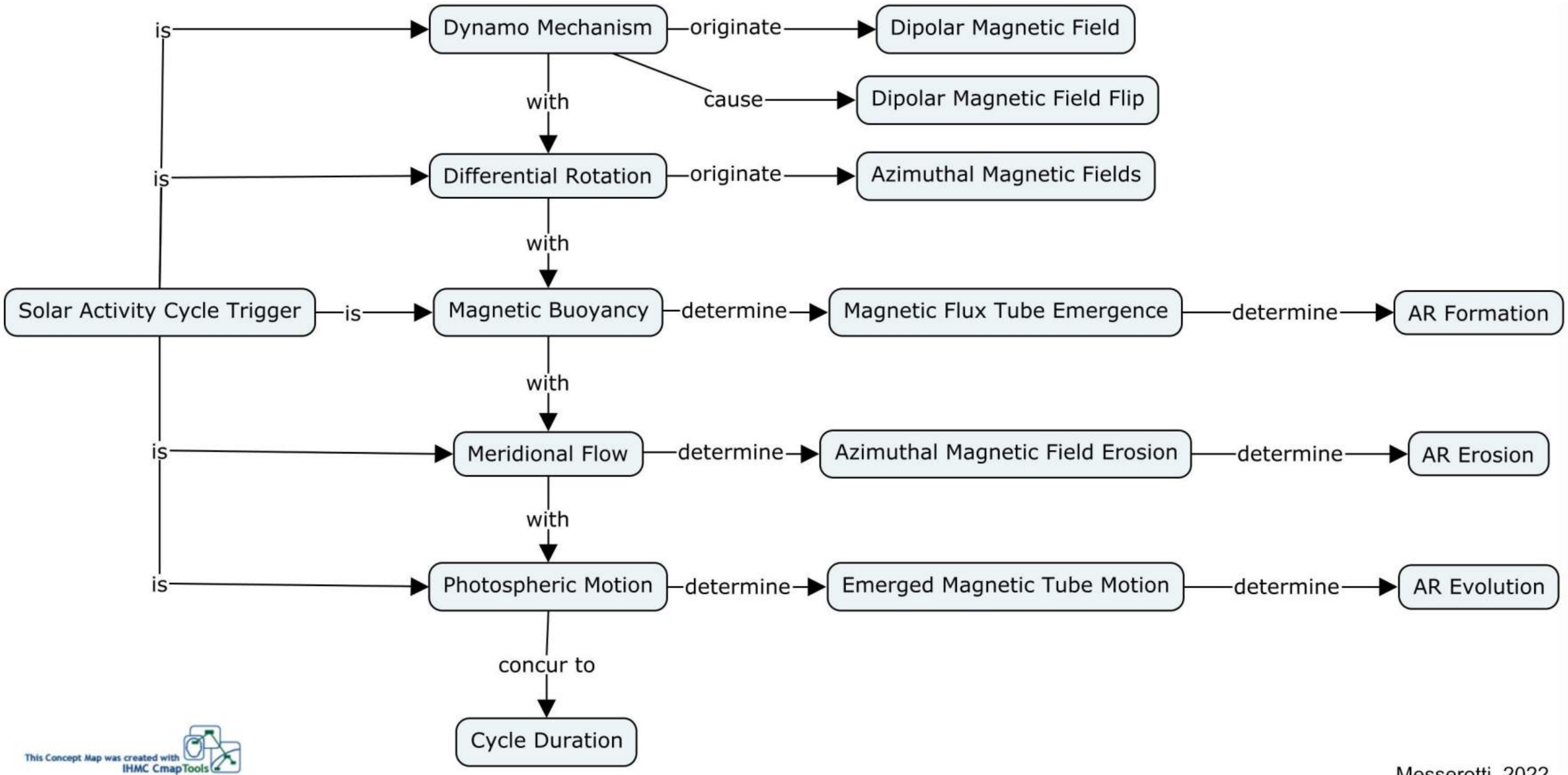
The Prediction of the Physical State of a System



Solar Drivers of Space Weather

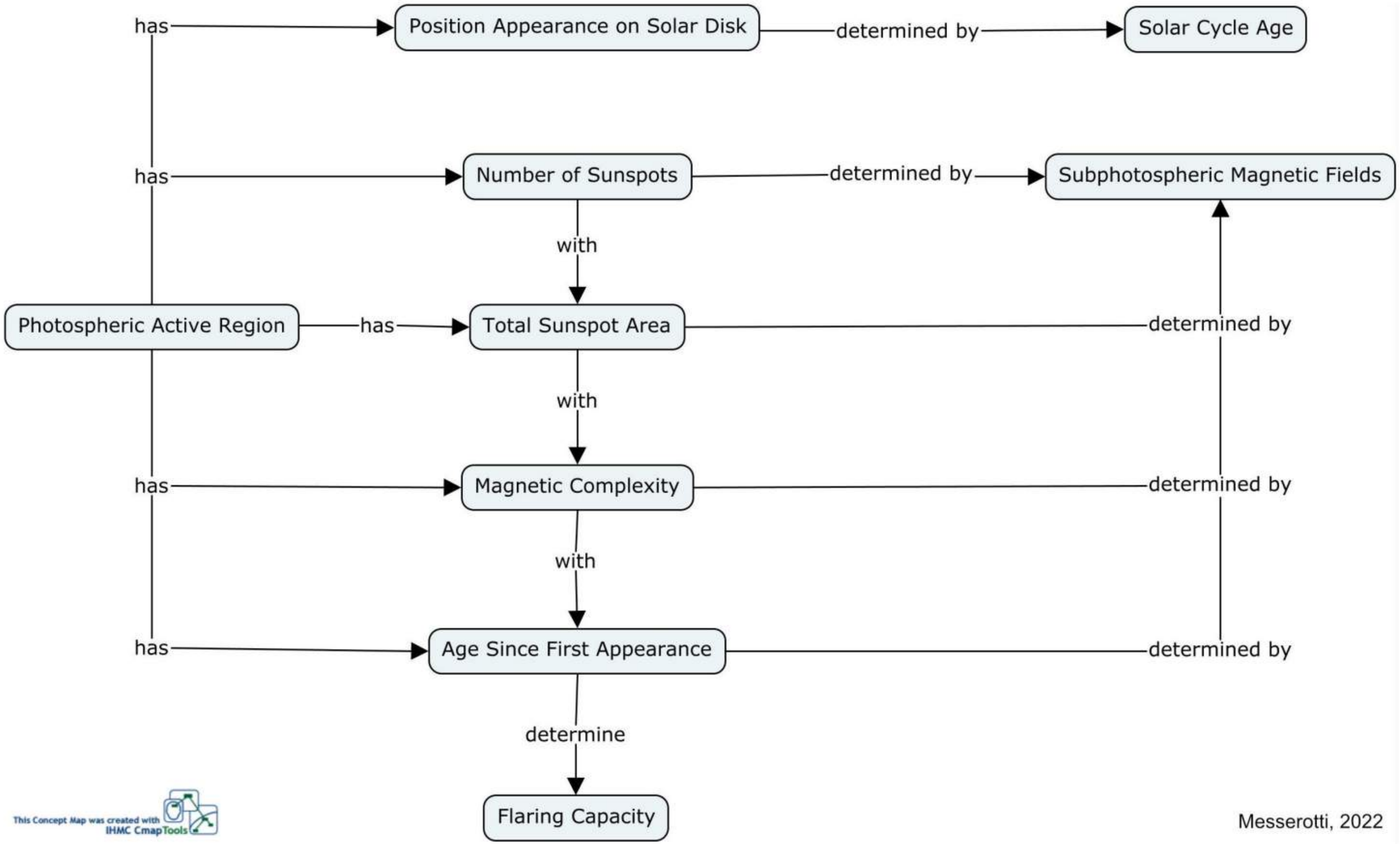


Solar Active Region Trigger Evolution



Messerotti, 2022

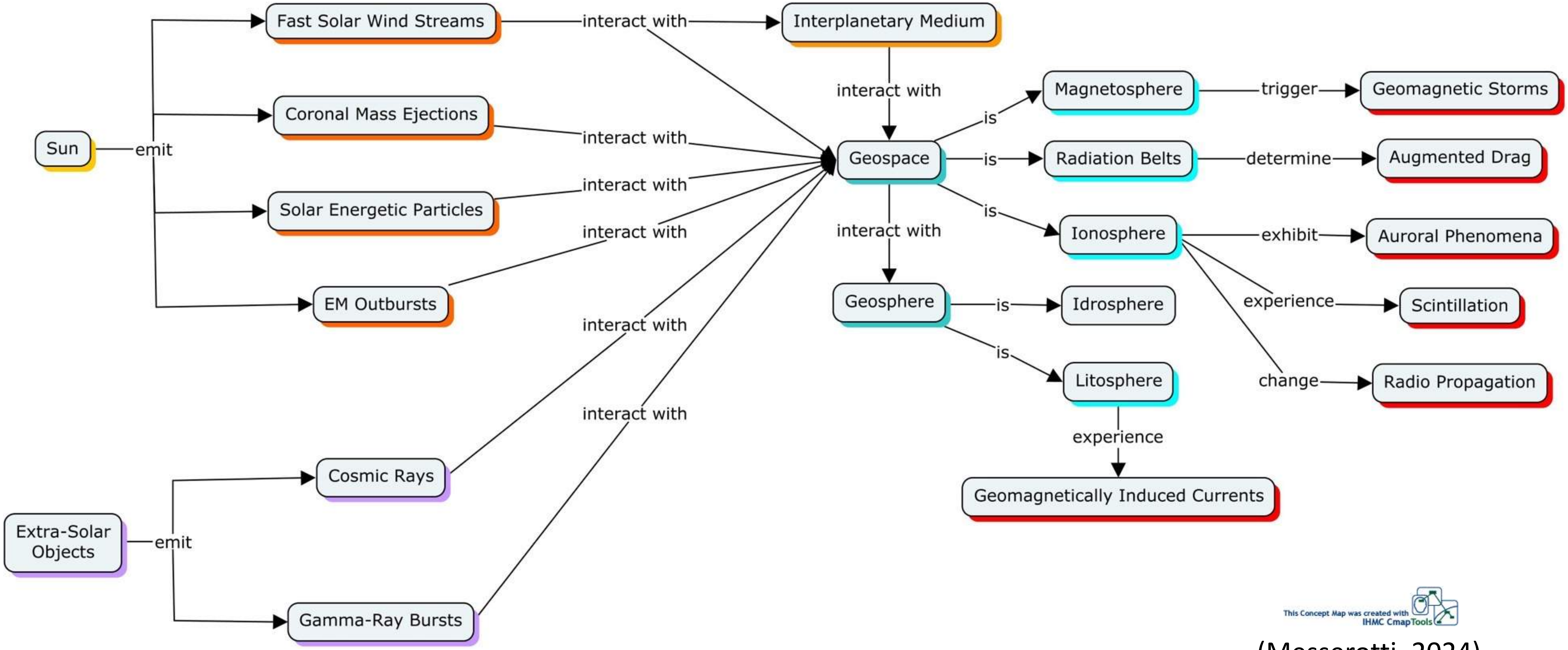
Characterisation of a Solar Active Region



Current Capacity to Predict Solar Weather

ACCORDING TO MAURO MESSEROTTI

Simplified Synopsis of Space Weather Domains and Impacts



(Messerotti, 2024)

The Modern Paradigm for Space Weather

- SPACE WEATHER MONITORING MEANS TO OBSERVE THE PHENOMENOLOGY WITH EARTH- AND SPACE-BASED INSTRUMENTS
- SPACE WEATHER SCIENCE MEANS TO MODEL THE PHENOMENOLOGY BASED ON OBSERVED DATA AND TO-DATE PHYSICAL KNOWLEDGE
- SPACE WEATHER OPERATIONS MEANS TO USE VALIDATED SCIENCE MODELS TO NOWCAST AND FORECAST SPACE WEATHER PHENOMENA AND IMPACTS
- A FEEDBACK FROM OPERATIONS TO SCIENCE AND BACKWARDS TO OPERATIONS HELPS IMPROVING THE MODELS AND, IN TURN, THE OPERATIONS (R2O2R)

The Experimental Scenario

- OBSERVATIONS ARE OFTEN NOT DIACHRONIC BYT FRAGMENTARY IN TERMS OF TIME, ENERGY, AND SPACE COVERAGE

- THE SUN IS A PHYSICAL SYSTEM CONSTITUTED BY A SET OF NONLINEARLY-COUPLED PHYSICAL SUBSYSTEMS WHICH EXHIBIT A CHAOTIC COMPLEX BEHAVIOUR

- THE SAME AS ABOVE HOLDS FOR ALL THE PHYSICAL SYSTEMS WHICH SOLAR PERTURBATIONS INTERACT WITH

The Theoretical Scenario

- EFFECTIVE MODELLING REQUIRES COMPREHENSIVE SETS OF DATA

- CHAOTIC COMPLEX SYSTEMS ARE VERY CHALLENGING TO BE MODELLED

- THE NONLINEAR SET OF EQUATIONS THAT DESCRIBE A LIMITED SUBSET OF A CHAOTIC COMPLEX SYSTEM IS USUALLY A SET OF ILL-POSED PARTIAL DIFFERENTIAL EQUATIONS WHICH IS VERY SENSITIVE TO MINIMAL CHANGES IN THE INITIAL CONDITIONS. THIS RESULTS IN A SET OF SOLUTIONS WHICH CONSTITUTE A DIVERGENT SPAGHETTI-LIKE SET AND THIS MAKES IMPOSSIBLE A ROBUST PREDICTION OF THE STATES AHEAD OF THE SYSTEM

- A CASCADE OF MODELS FROM THE SUN TO THE EARTH THAT HAVE TO BE ADEQUATELY INTERFACED IS QUITE CHALLENGING TO BE OPTIMISED

The Operational Scenario

- THE PROCESS OF VALIDATION FOR THE TRANSITION FROM SCIENTIFIC TO OPERATIONAL MODELS BASED ON STANDARD PROCEDURES IS QUITE LONG AND DEMANDING

- OPERATIONAL MODELS USED IN APPLICATIONS TO FORECAST KEY PHENOMENA DESCRIPTORS ARE LIMITED AND STILL NOT SATISFACTORY FROM THE POINT OF VIEW OF THE RELEVANT CONFIDENCE LEVEL

- THE AVAILABLE OPERATIONAL MODELS DO NOT COVER ALL THE NEEDED ASPECTS OF SPACE WEATHER PHENOMENOLOGY AND IMPACTS

Current Forecasting Capacity for Solar Weather (According to MM)

IDEAL FORECASTING CAPACITY	CURRENT FORECASTING CAPACITY
ACTIVE REGION EMERGENCE	NOWCASTING
MAGNETIC EVOLUTION OF ACTIVE REGIONS	NOWCASTING / FORECASTING (EXPERIMENTAL)
FLARE TOPOLOGY AND DYNAMICS	NOWCASTING / FORECASTING (EXPERIMENTAL)
IMPULSIVE PHOTON EMISSION WITH SPECTRUM AND SPECTRAL ENERGY PEAK **E.G. SOLAR RADIO EMISSIONS**	NOWCASTING
MASS EJECTION GENERATION FROM THE SOLAR CORONA (CME) WITH MASS, TOPOLOGY, SPEED, DIRECTION AND MAGNETIC TOPOLOGY	NOWCASTING
A. TIME OF ARRIVAL ON EARTH (ON A PLANET)	NOWCASTING / FORECASTING (EXPERIMENTAL)
B. STRENGTH OF IMPACT AND INTENSITY OF MAGNETIC DISTURBANCES CAUSED BY IT	NOWCASTING / FORECASTING (EXPERIMENTAL)
ACCELERATION OF ENERGETIC PARTICLES (SEP) WITH SPECIES, DIFFERENTIAL ENERGY SPECTRUM, FLUENCE AND RIGIDITYÀ	NOWCASTING
A. TIME OF ARRIVAL ON EARTH (ON A PLANET)	NOWCASTING / FORECASTING (EXPERIMENTAL)
B. STRENGTH OF IMPACT AND INTENSITY OF MAGNETIC DISTURBANCES CAUSED BY IT	NOWCASTING

(M. Messerotti, 2020-2024)

Specific Forecast Approach

- WHAT
  - EVENT OCCURRENCE →
    - SINGLE EVENT CATEGORY
    - NO EVENT BY-PRODUCTS
- DESCRIBED BY
  - PROBABILITY & CONFIDENCE LEVEL →
    - LOW CONFIDENCE LEVEL
- HOW
  - PHYSICS-BASED MODEL
  - EMPIRICAL MODEL
  - HYBRID MODEL
  - STATISTICAL MODEL
  - MACHINE/DEEP LEARNING

  →
  - VERY FEW
  - MANY
  - VERY FEW
  - QUITE A NUMBER
  - INCREASING NUMBER
- APPLIED TO
  - INDEX/PROXY TIME SERIES
  - IMAGE TIME SERIES
  - IMAGE CUBE TIME SERIES

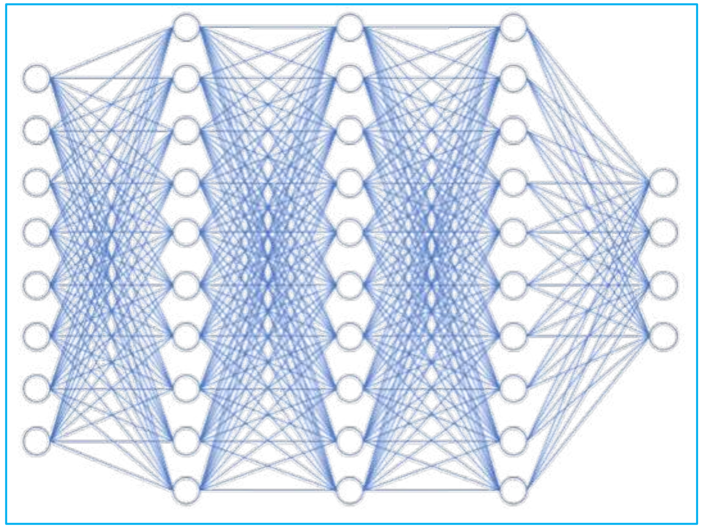
  →
  - MOST WIDELY USED
  - MODERATELY USE
  - VERY LIMITED USE

Forecasting Techniques Based on Artificial Intelligence

A. ARTIFICIAL NEURAL NETWORKS

B. AUTOMATIC LEARNING (MACHINE LEARNING)

C. IN-DEPTH LEARNING (DEEP LEARNING)



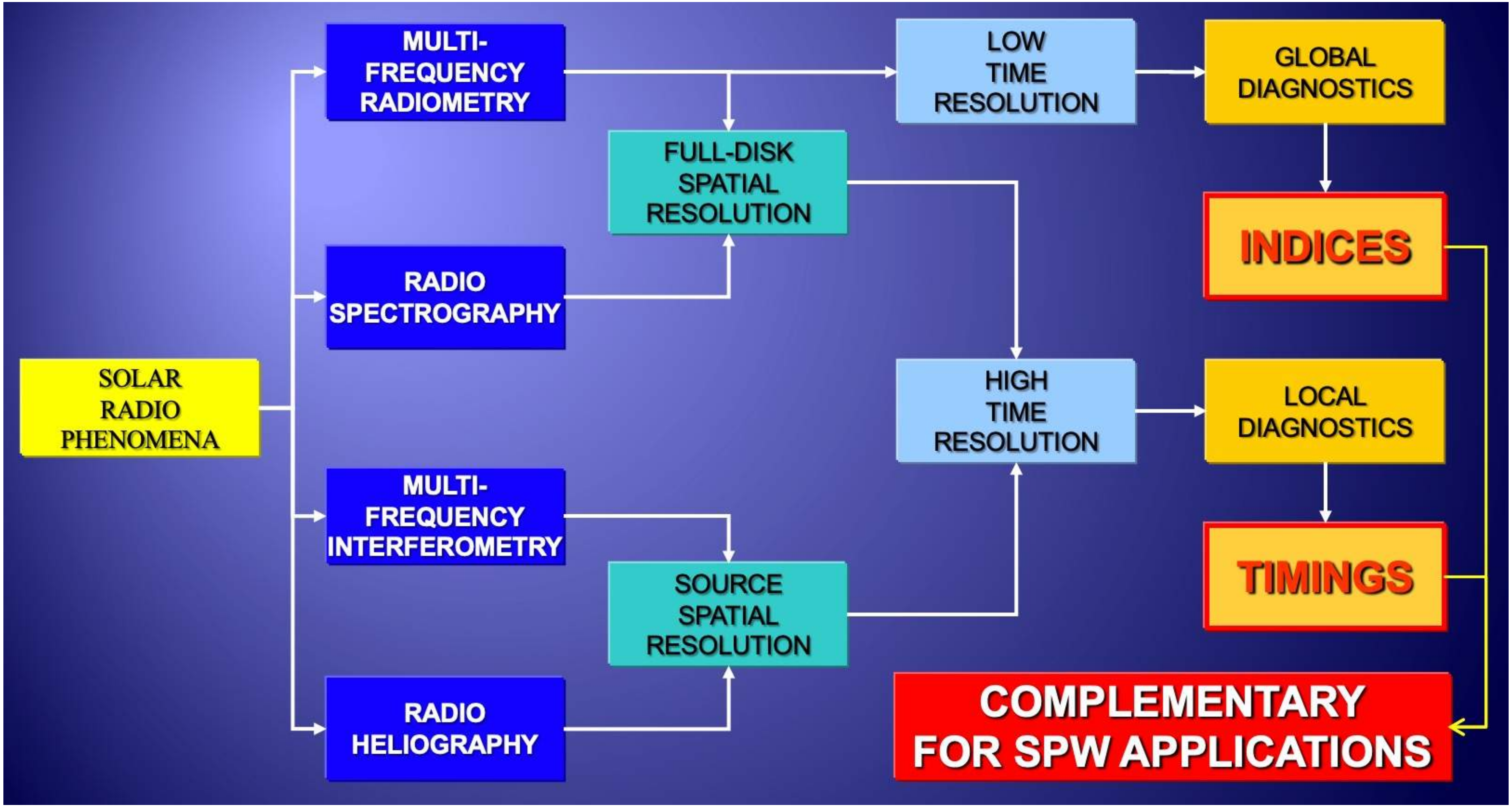
Convolutional Neural Network

CONSIDERATIONS

- REQUIRE VERY EXTENSIVE DATA BASES FOR SUCCESSFUL LEARNING
- PROVIDE ACCEPTABLE BUT NOT YET OPTIMAL RESULTS
- CONFIDENCE LEVEL BELOW 95% IS INADEQUATE AS UNREALISTIC
- ARE USED DUE TO LIMITED KNOWLEDGE OF THE PHYSICS
- ARE A VALUABLE HELP BUT NOT THE ULTIMATE SOLUTION

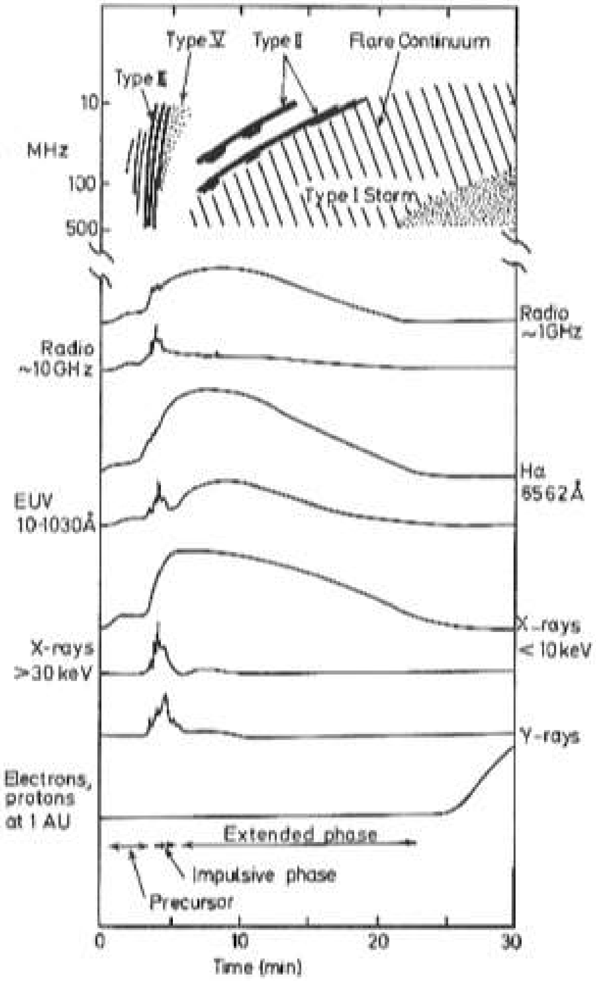
Synopsis of Solar Radio Bursts

Monitoring Solar Radio Bursts for Space Weather

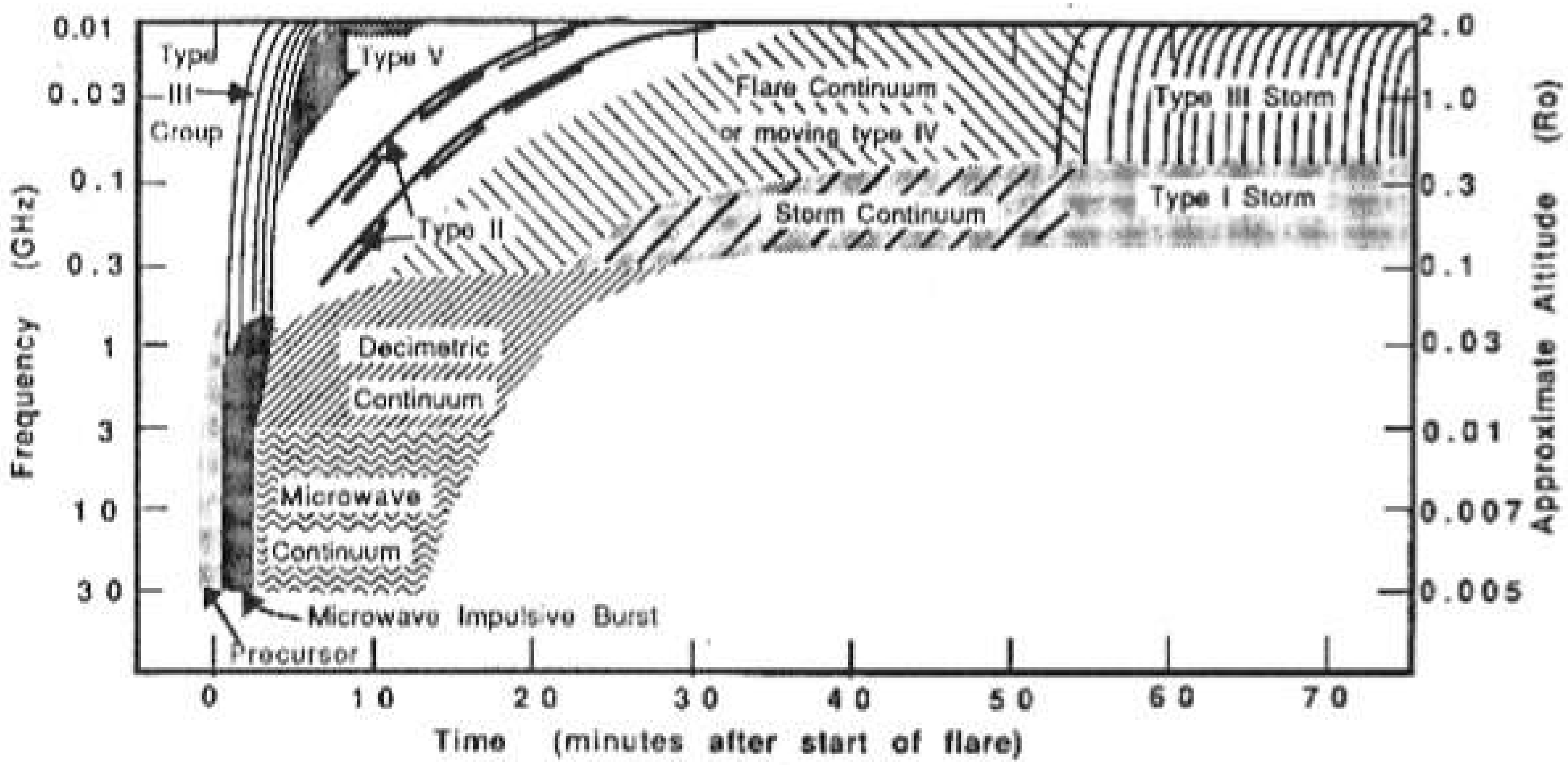


Typology of Solar Radio Bursts

Timing of Flare-Related Events
(MCLean and Labrum, 1985)



Flare-Related Solar Radio Bursts
(Dulk, 1994)



Solar Radio Burst Classifications

TYPE	CHARACTERISTICS	DURATION	FREQUENCY RANGE	ASSOCIATED PHENOMENA
I	Short, narrow-band bursts Usually in large numbers with underlying continuum.	Burst: 1 second. Storm: hrs.- days	80-200 MHz	Active regions eruptive prominences.
II	Slow drifting bursts. Often accompanied by second harmonic	5-30 minutes	Fundamental: 20-150 MHz.	Flares, proton emission, mag-netonetohydro-dynamic shock waves
III	Fast drifting bursts. Can occur singularly, in groups,or storms. Can be accompanied by second harmonic.	Burst: 1-3 seconds. Group: 1-5 min.	10 kHz-1 GHz	Active regions, flares.
IV	Stationary Type IV Broad-band continua emission with fine structure.	Hours - days.	20 - >1000 MHz.	Flares, proton
	Moving Type IV Broad-band, slow drifting, smooth continua.	30 min.-2 hrs.	20-400 MHz.	Eruptive prominences Magnetohydro-dynamic shock waves
	Flare Continua: Broad-band, smooth continua.	3-45 min.	25-200 MHz	Flares, proton Emission
V	Smooth, short lived continua Follow some type III bursts. Never occur in isolation.	1-3 min.	10-200 MHz.	Same as type III bursts.

Solar Radio Emissions Considered by NOAA/SWPC

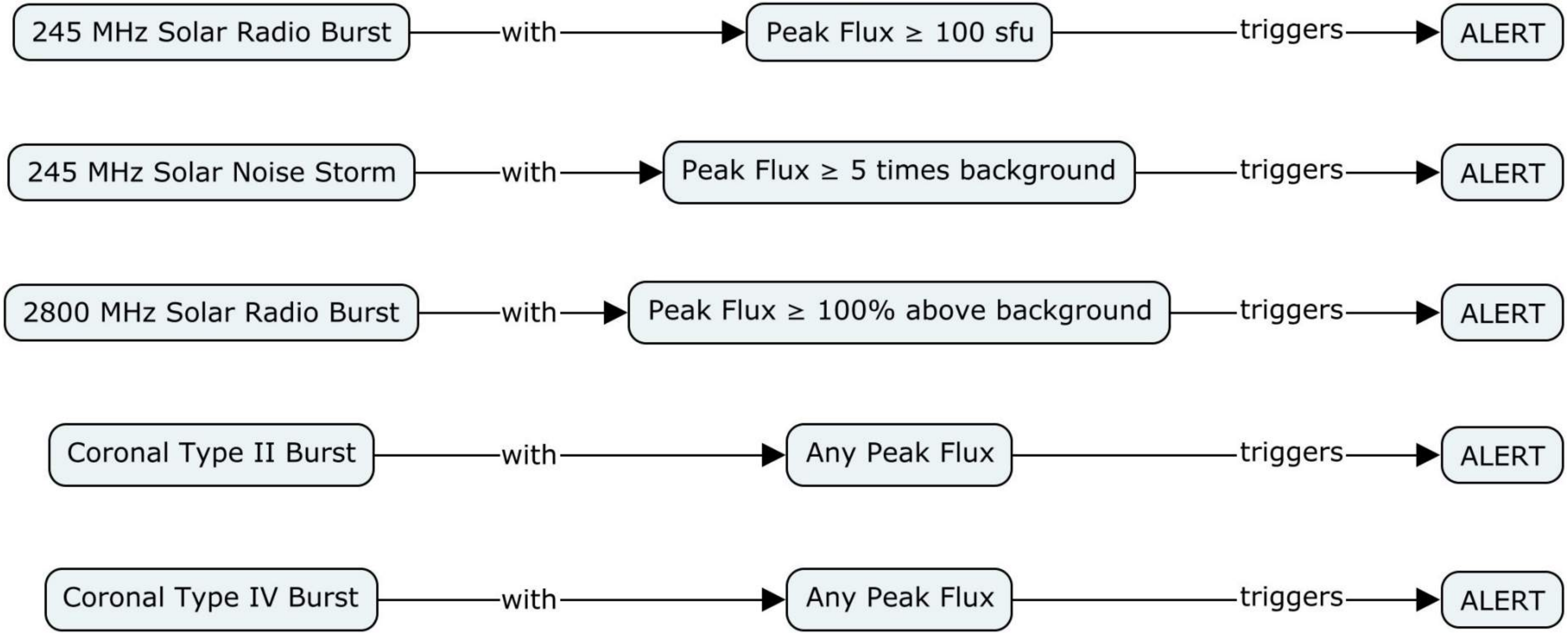
Solar Radio Emissions	Description
☑ SUMMARY: 245 MHz Radio Emission	Daily summary of radio interference which can affect critical search and rescue frequencies.
☑ ALERT: Type II Radio Emission	Occur in loose association with major solar flares and are indicative of a shock wave moving through the solar atmosphere.
☑ ALERT: Type IV Radio Emission	Associated with some major solar flare events beginning 10 to 20 minutes after the flare maximum, and can last for hours.
☑ SUMMARY: 10 cm Radio Burst	Proxy of solar EUV emission, important for satellite drag.

NOAA/SWPC Solar Radio Bursts Alerts

CATEGORY TYPE	THRESHOLD	ALERT	WARNING
Radio			
245 MHz burst	peak flux $\geq$ 100 s.f.u.	*	
245 MHz noise storm	peak flux > 5 times background	*	
10 cm burst	peak flux $\geq$ 100% above background	*	
Type II event	any	*	
Type IV event	any	*	
Particle			
Electron Event	peak flux 10^3 pfu @ > 2 MeV	*	
Suspected Proton Flare	peak flux 10 p.f.u. @ > 10 MeV	*	
P10 Proton event	peak flux 10 p.f.u. @ > 10 MeV	*	*
P100 Proton event	peak flux 100 p.f.u. @ >100 MeV	*	*
SST Radiation Alert	$\geq 0.1^{-4}$ sievert/hour ($\geq$ 10 millirems/hour)	*	*
X-ray			
M5	peak flux $\geq 5 \cdot 10^{-5}$ W m^{-2}	*	
X1	peak flux $\geq 1 \cdot 10^{-4}$ W m^{-2}	*	
Geomagnetic			
A Index $\geq$ 20	running $A_B \geq 20$	*	*
A Index $\geq$ 30	running $A_B \geq 30$	*	*
A Index $\geq$ 50	running $A_B \geq 50$	*	*
K Index = 4	$K_B = 4$	*	
K Index = 5	$K_B = 5$	*	
K Index $\geq$ 6	$K_B \geq 6$	*	
Atmospheric disturbance			
Stratwarm	stratospheric warming conditions	*	

- Sievert (Sv): effective (equivalent) dose of radiation received by a living organism 1 Sv = 100 rem
- particle flux unit (p.f.u.) [cm^{-2} s^{-1} sr^{-1}]

Details of SWPC Solar Radio Bursts Alert Levels

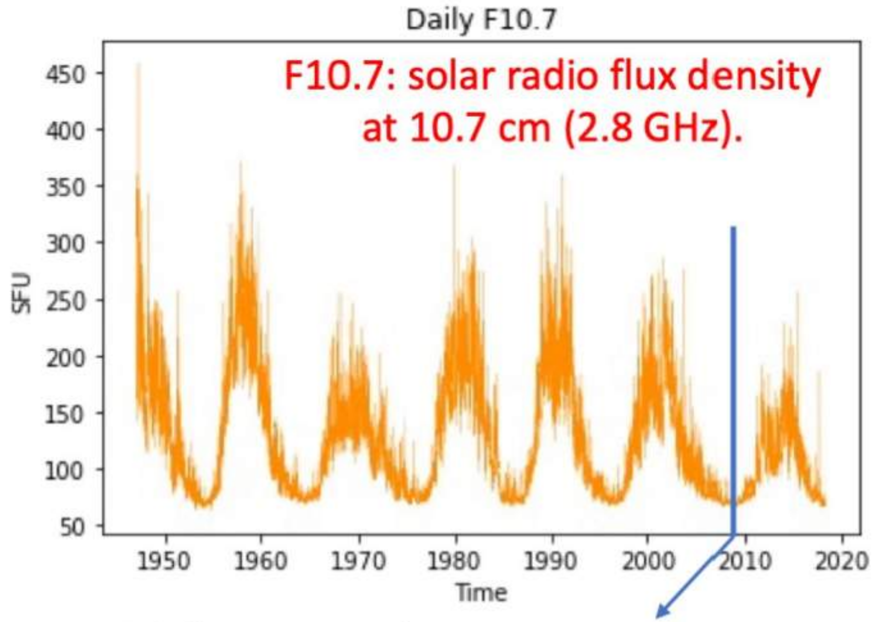


A Neural Network Approach to the Forecast of the 10.7 cm Solar Radio Index

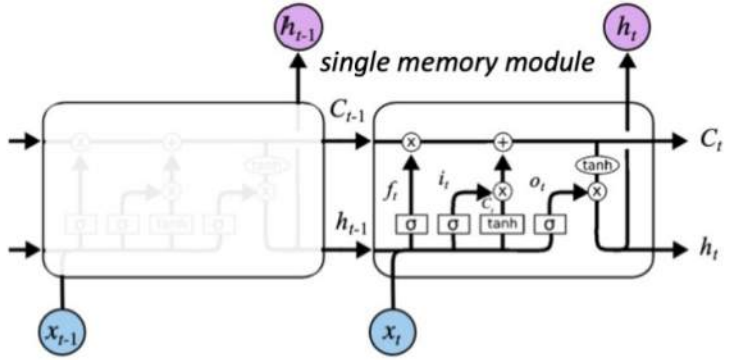
BY MY PHD STUDENT A. MARCUCCI AND MY COLLABORATORS G. JERSE AND V. ALBERTI AKA THEY HAVE DONE THE WORK AND I TAKE THE CREDIT AS USUALLY OCCURS WHEN YOU ARE A SENIOR

Time Series Analysis: F10.7 Forecasting

Comparison of Univariate NN-based Models (1)



20% dataset used as test-set
80% dataset used as training-set



- Index of Solar Activity Level *(S-component)*
- Proxy for solar UV/EUV radiation.
- Input for atmospheric density model in low-Earth orbit → spacecraft orbit determination, re-entry, orbital debris predictions…

CLASSIC LSTM: Model Baseline

Long Short Time Memory (LSTM) belongs to the family of *Recurrent Neural Networks* (RNNs) and emphasizes the sequence structure, thus particularly suited for timeseries forecasting applications.

LSTM model has a chain-like structure of repeating memory modules with specific features to evaluate whether the information provided to the network is useful or not.

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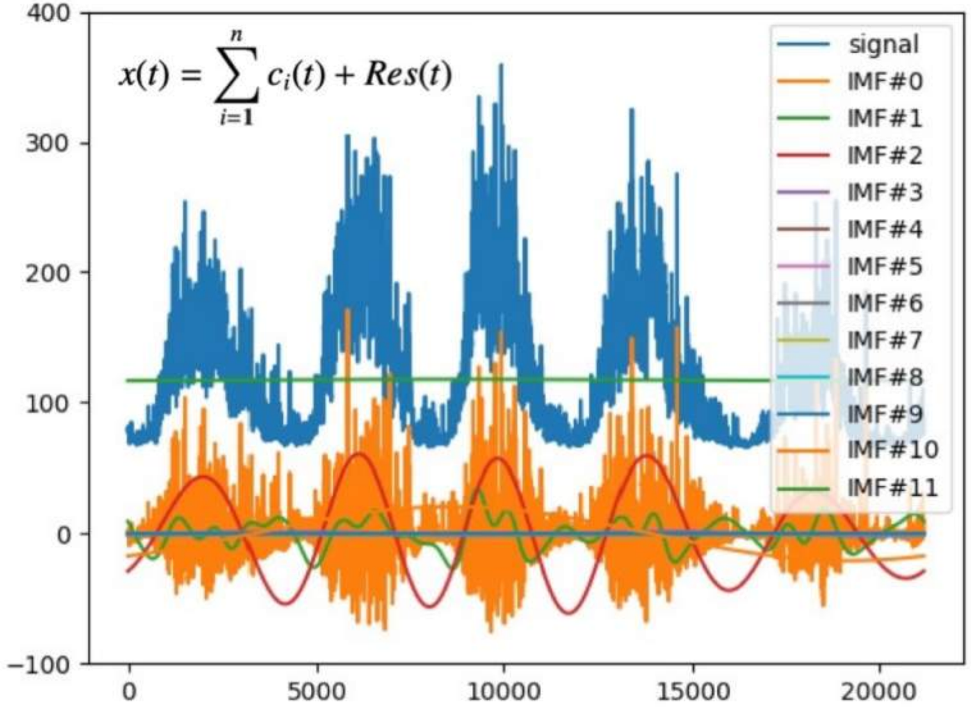
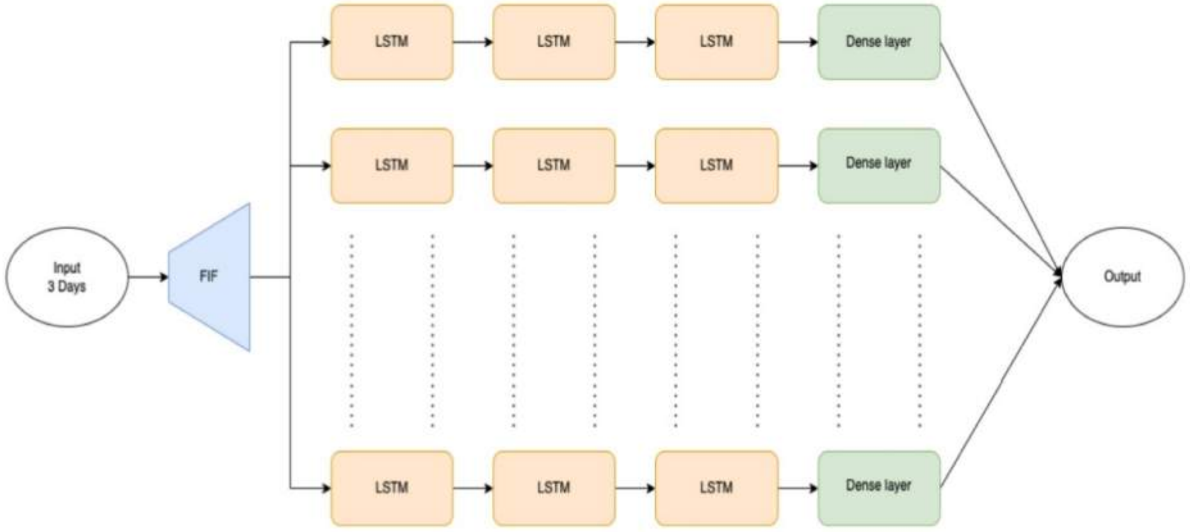
Time Series Analysis: F10.7 Forecasting

Comparison of Univariate NN-based Models (2)

LSTM-FIF Model

Fast Iterative Filtering method is a technique for the analysis of non-stationary and non-linear signals with its decomposition into simple oscillatory functions, **Intrinsic Mode Functions** (IMFs) without leaving the time domain and with variable phases and amplitudes.





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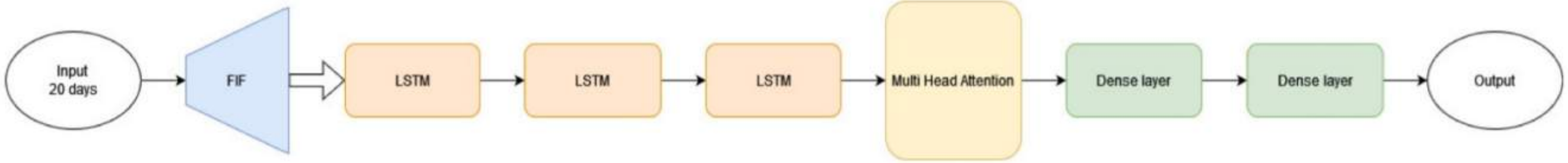
Solar Radio Index Time Series Forecasting

Comparison of Univariate NN-based Models (3)

LSTM-FIF-MHA Model

Attention architecture mimics human cognitive attention adaptively selecting the most critical input to the current goal, giving higher weights to the corresponding original feature sequence, and suppressing other useless information.

This mechanism allows for attending to parts of the sequence differently (e.g. longer-term dependencies versus shorter-term dependencies).



3 LSTM layers of 40 nodes each
6 heads in the attention layer
20 days as lookback window

While in the FIF+LSTM each IMF is considered as a single univariate timeseries which is fed to each LSTM network, in this model each IMF is considered as one component of a multivariate timeseries, with the output directly predicting the final value.

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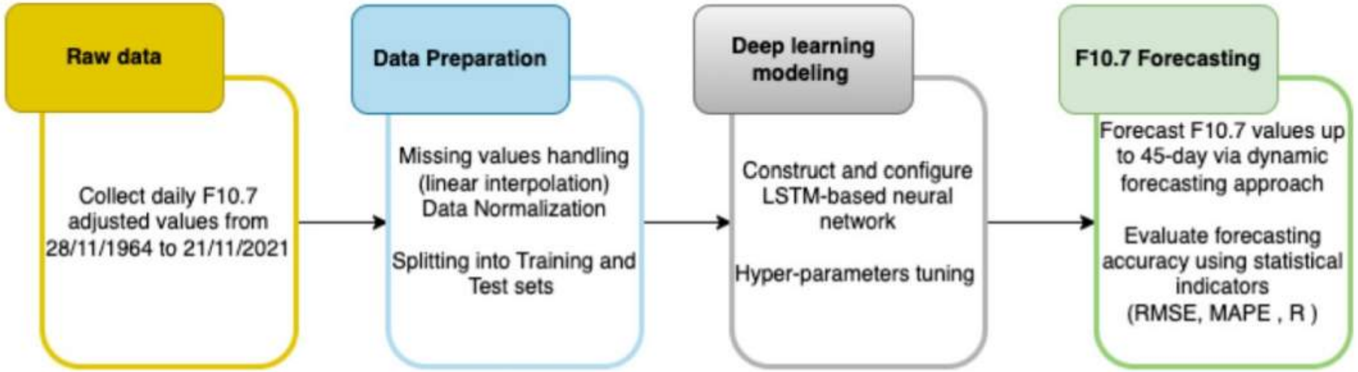
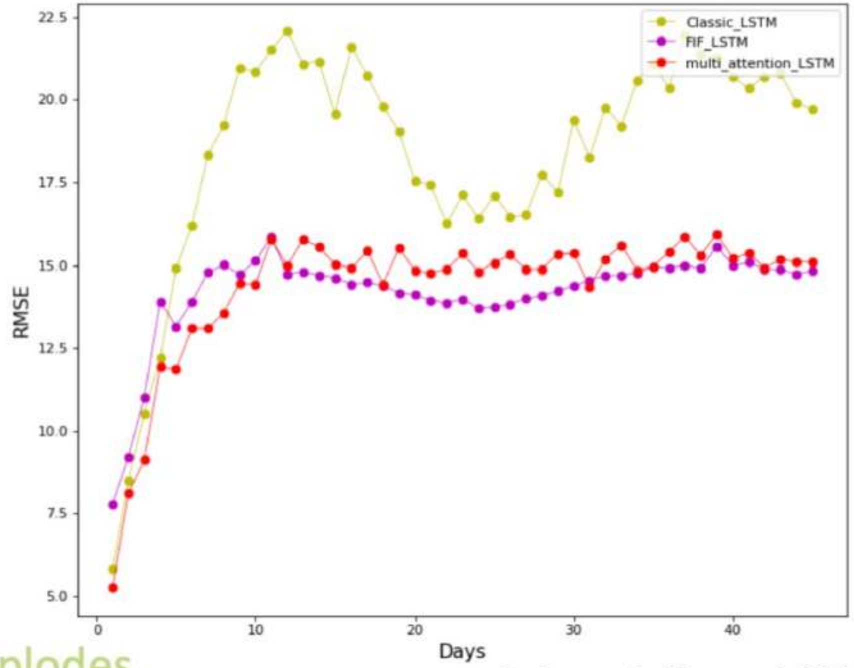
Solar Radio Index Time Series Forecasting
Comparison of Univariate NN-based Models





G. Jerse, A. Marcucci, 2024

- Classic LSTM shows good results in 1-day forecast but then rapidly explodes
- FIF+LSTM and FIF+LSTM+MHA algorithms overperform for long term prediction with a very stable performance in lag size

The proposed neural networks have been trained on the training set using a partition of the HOTCAT computing infrastructure at the Astronomical Observatory of Trieste (OATS, INAF) and is composed by 15 Hewlet-Packard computing nodes, equipped each with 48 (Intel(R) Xeon(R) Gold 5118 CPU @ 2.30GHz) core and 10 GB Ram running on CentOS 7.

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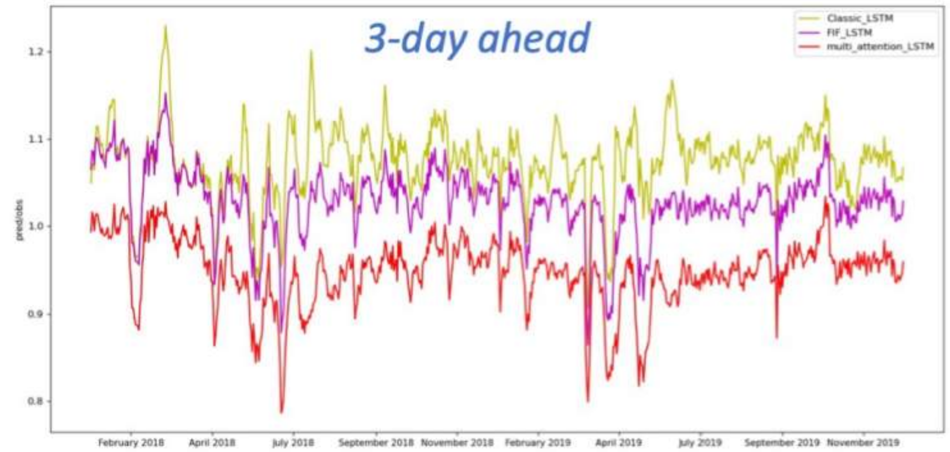
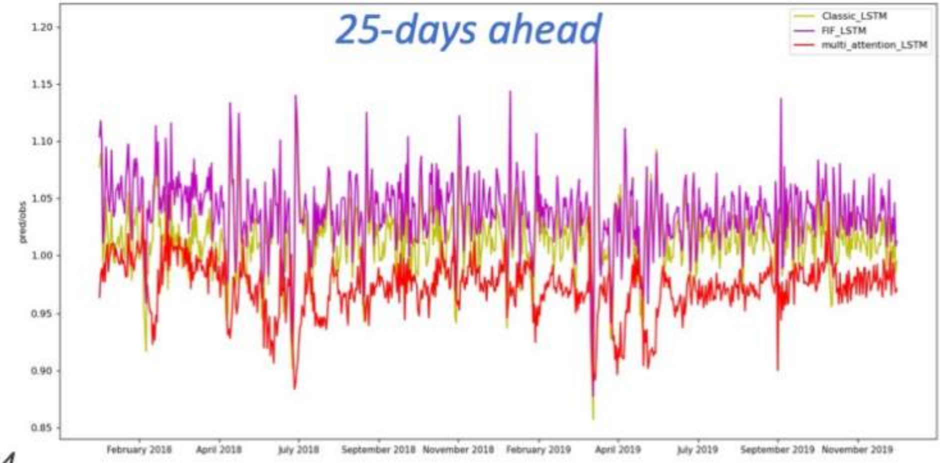
Solar Radio Index Time Series Forecasting

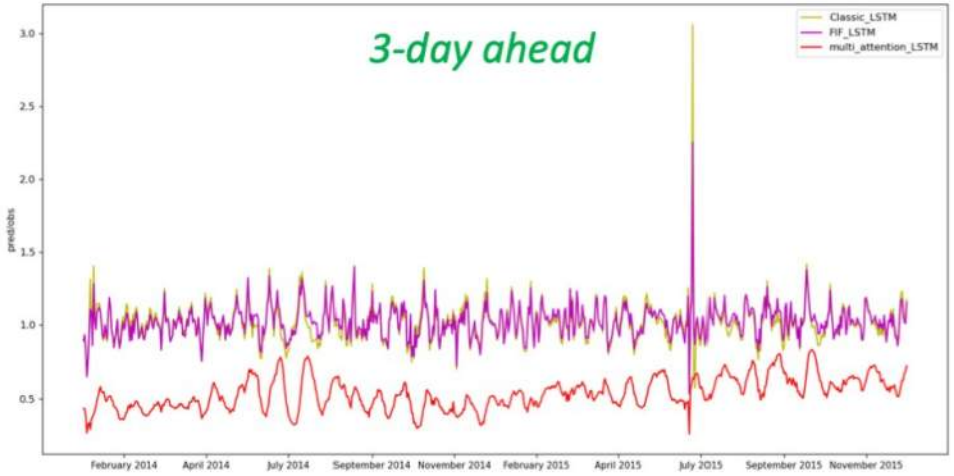
Comparison of Univariate NN-based Models



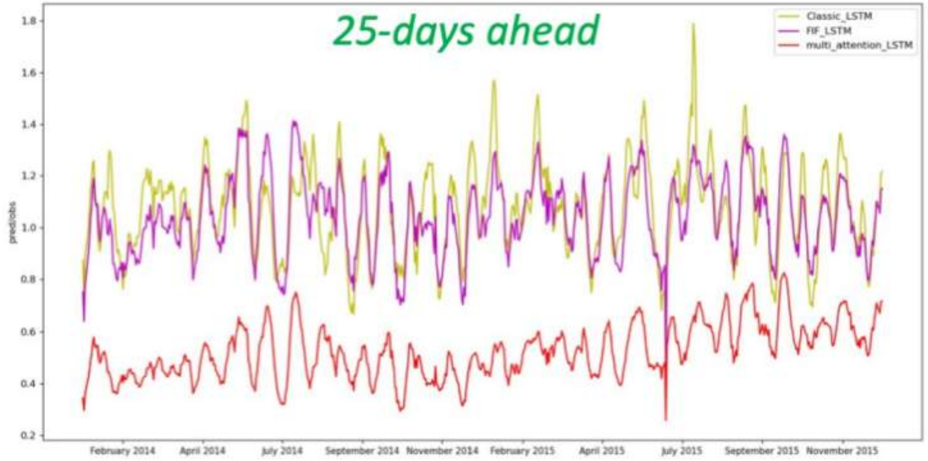
Solar Minimum



G. Jerse, A. Marcucci, 2024



Solar Maximum



During high level of solar activity statistical errors increase due to extremely complex physical processes difficult to forecast. FIF+LSTM+MHA can globally handle information respect to different regimes of time scales.

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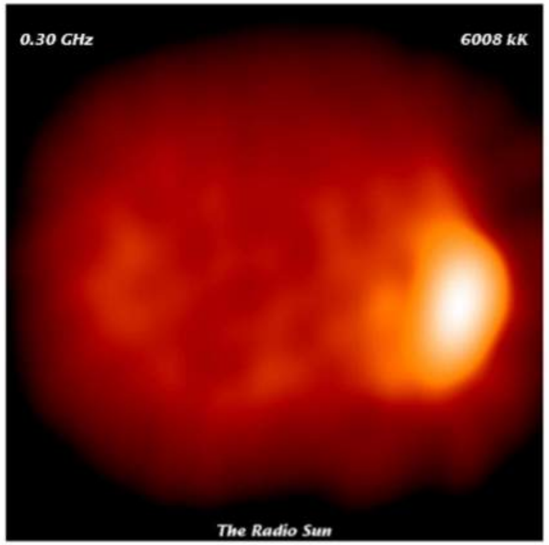
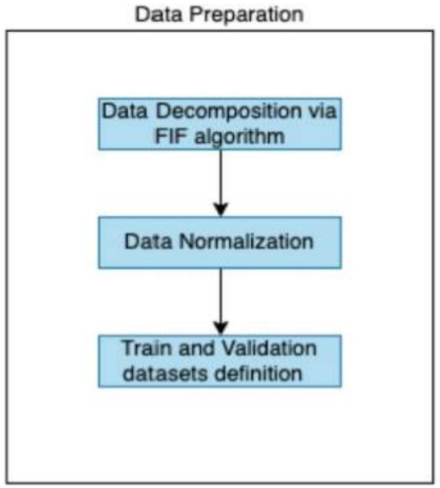
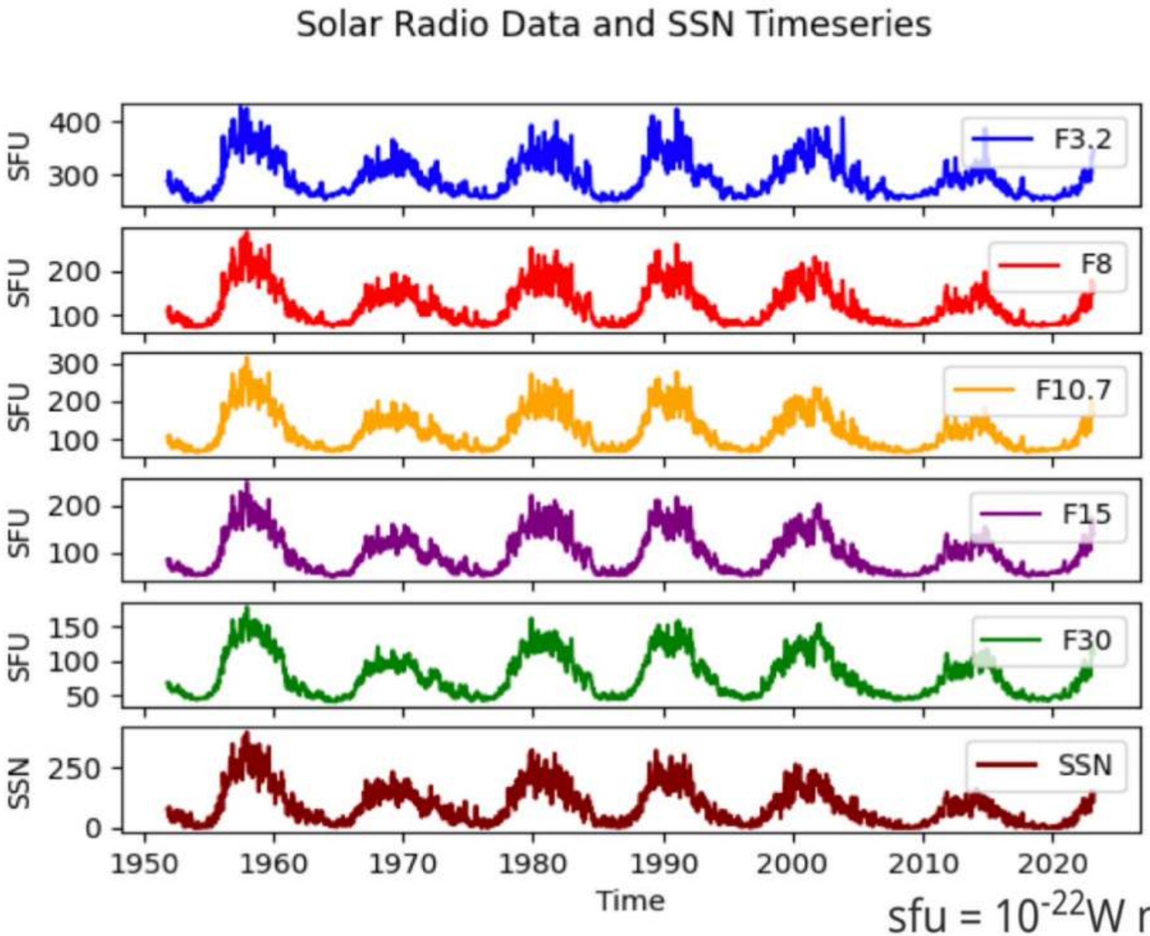
Solar Radio Index Time Series Forecasting

Multivariate LSTM-FIF-MHA

Multifrequency FIF-LSTM-MHA model







9.4 GHz

3.7 GHz

2.8GHz

1.9 GHz

1.0 GHz

$sfu = 10^{-22} W\ m^{-2}\ Hz^{-1}$

from 2/11/1951 to 14/3/2023

Source: LASP Interactive Solar IRradiance Datacenter (LISIRD)

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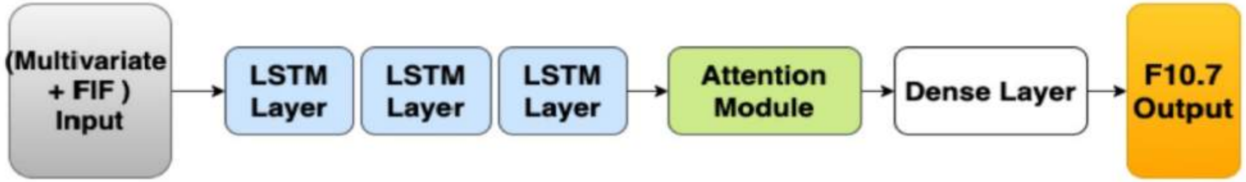
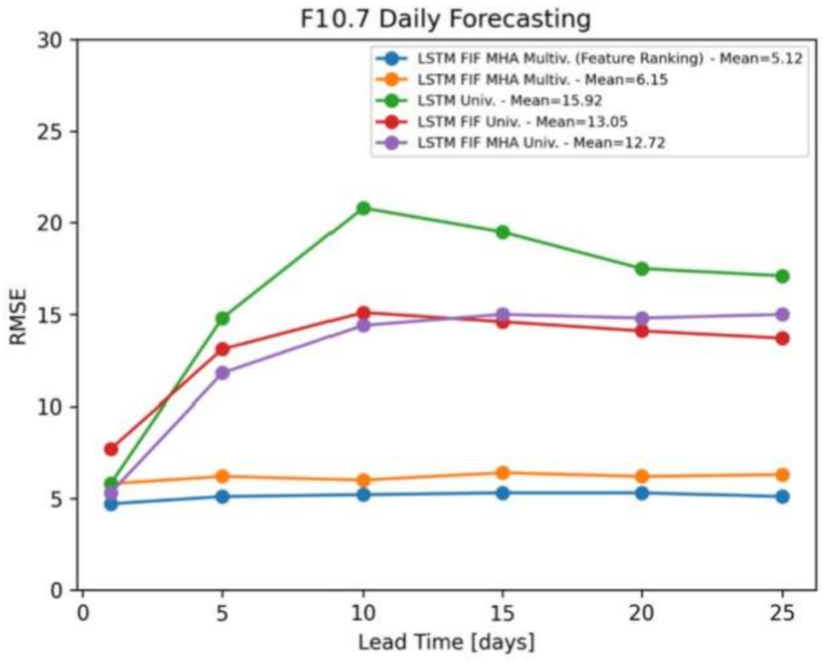
Solar Radio Index Time Series Forecasting

Multivariate LSTM-FIF-MHA

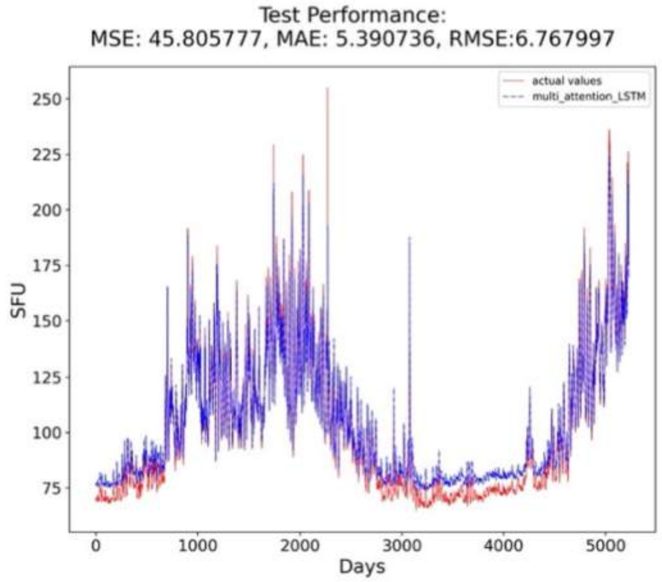
Hyprparameter	Our Tuning
Layers	3
Lookback	50 days
Loss	RMSE
Activ. Func	Sigmoid
Optimizer	Adam
Batch size	48
Hidden Neurons	12
Epochs	Early Stopping

For each solar index we keep only the IMFs with highest importance for F10.7 forecasting, reducing the dimensionality of the data, to train the NN.





Marcucci A. et al., 2024



Relative error under 10% and an RMSE of approximately 5 sfu, across various forecasting horizons ranging from 1 to 25 days, indicating overall effectiveness in predicting the F10.7

MARCUCCI (2024)

Conclusions

- TO DATE, THE COMPLEXITY OF THE PHYSICS UNDERPINNING SOLAR RADIO EMISSIONS AND THEIR TRIGGERING PROCESSES DOES NOT ALLOW ANY RELIABLE FORECAST OF THE OCCURRENCE OF SOLAR RADIO BURSTS

- WE CAN PROVIDE A STATISTICAL ESTIMATE OF SRB OCCURRENCE BY RESORTING ON SOLAR RADIO CLIMATOLOGY, I.E., THE OBSERVATIONS OF SRBs ON A VERY LONG TIME SPAN

- SOLAR RADIO CLIMATOLOGY IS QUITE INCOMPLETE AND THIS AFFECTS THE USE OF MACHINE/DEEP LEARNING APPROACHES

- AN EFFECTIVE APPROACH IN FORECASTING SOLAR RADIO INDICES IS THE USE OF ANN WITH ADVANCED ARCHITECTURES

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TOO PESSIMISTIC?

A PESSIMIST IS A WELL-INFORMED OPTIMIST...

THANK YOU FOR YOUR ATTENTION!
ANY QUESTIONS?