Space Weather: Caratterizzazione delle Emissioni ad Alta Energia

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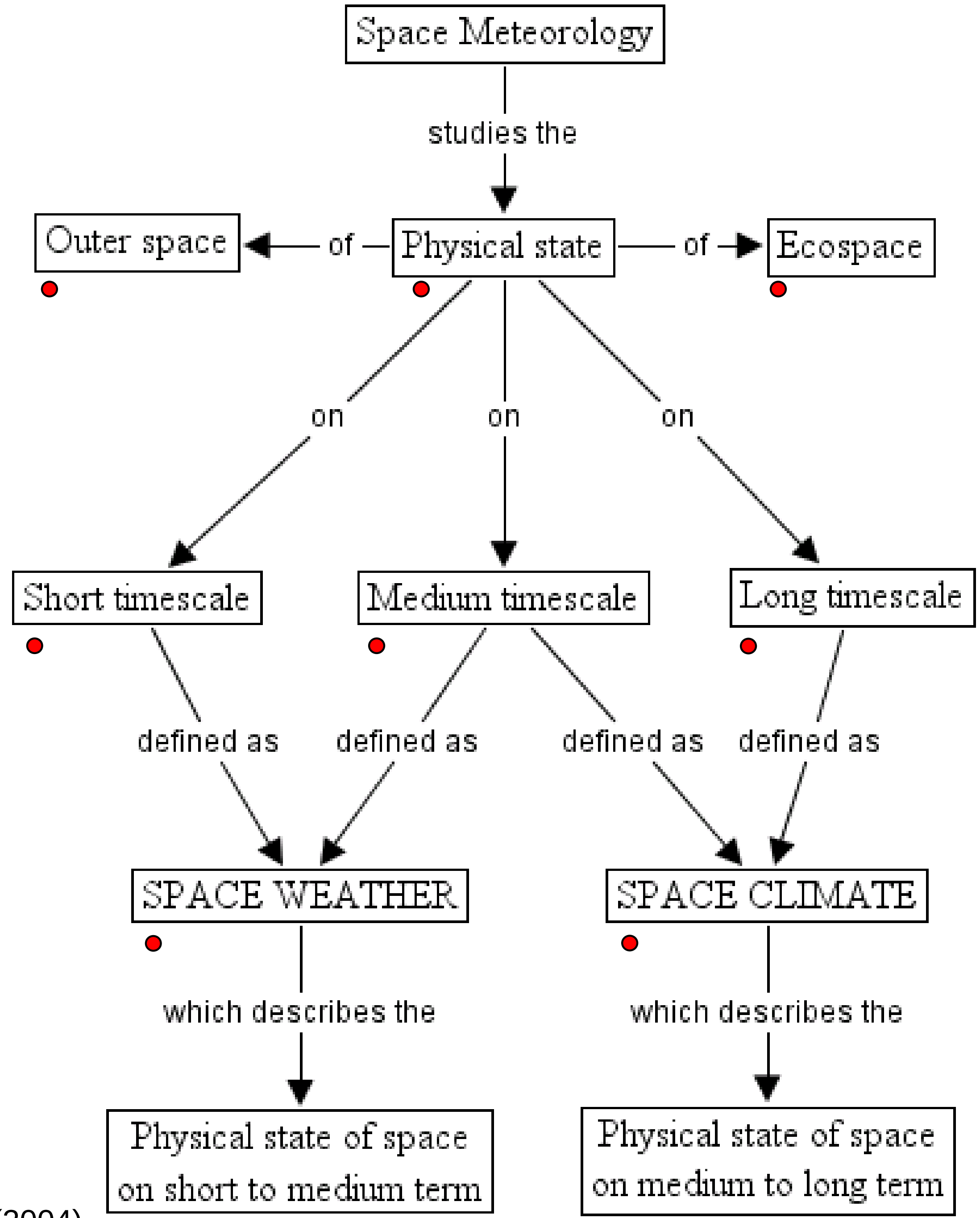
INFN-Laboratori Nazionali di Legnaro – 8 Aprile 2005

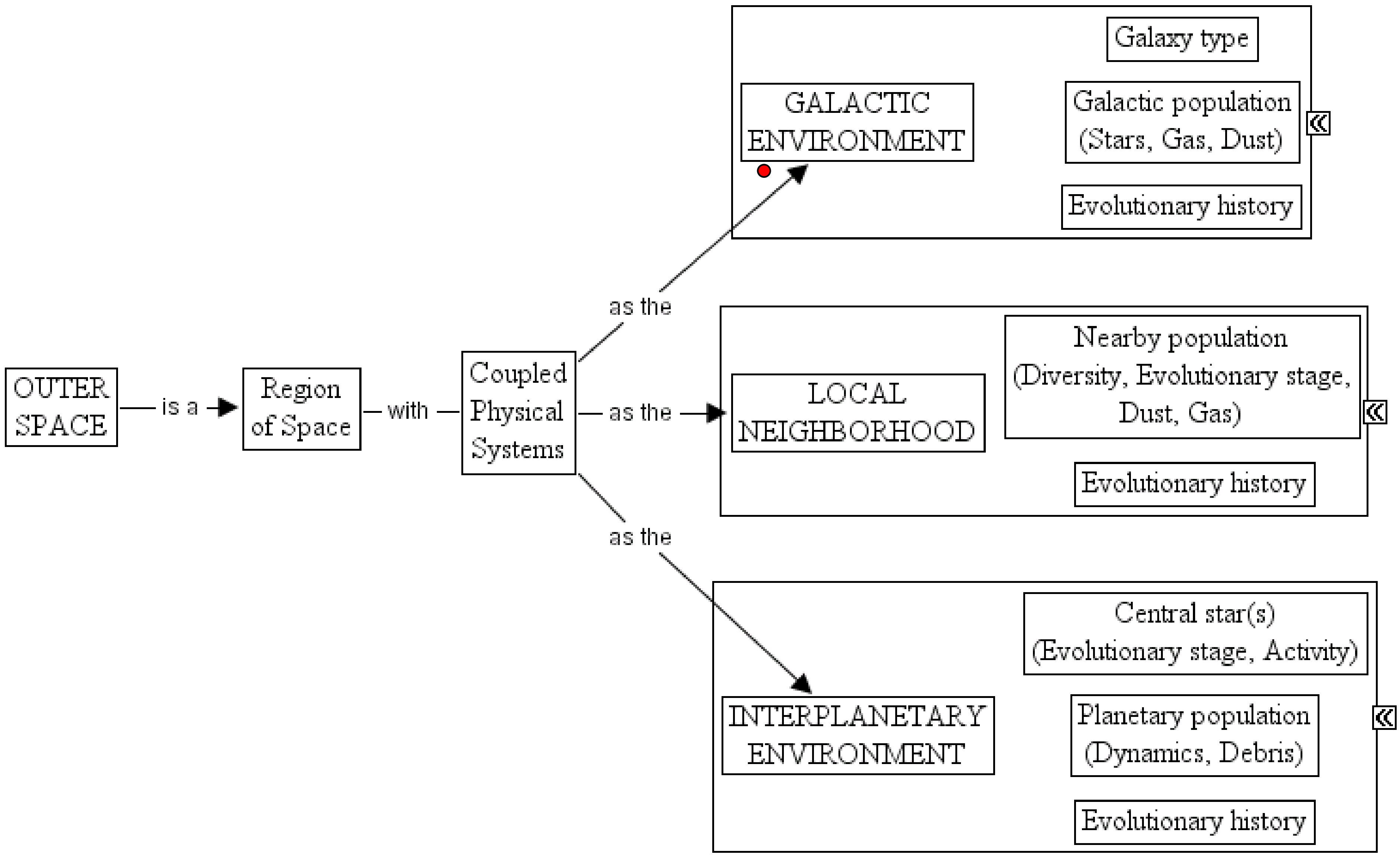
Ontology of Space Meteorology



Messerotti & Lundstedt (2004)

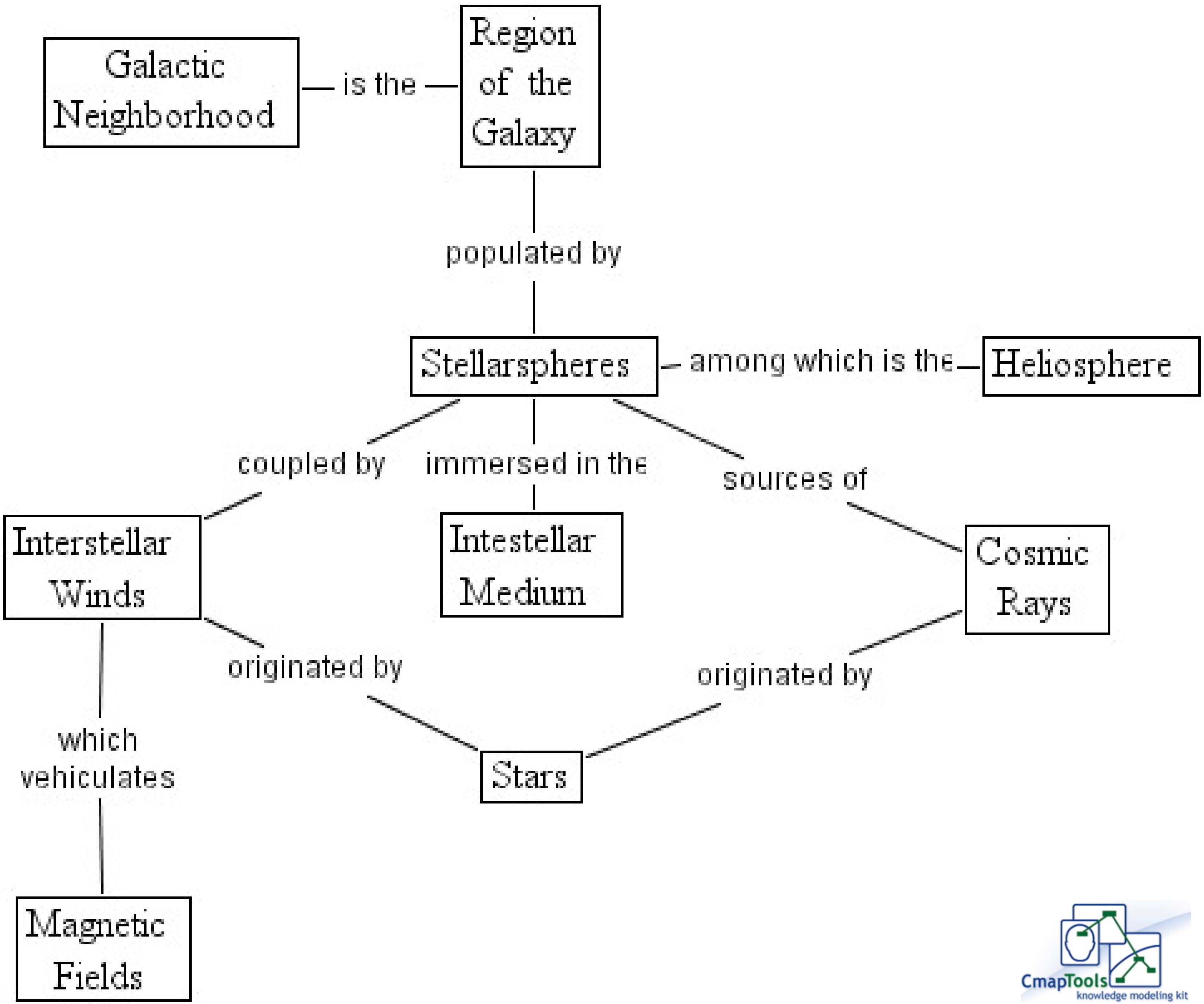
CmapTools knowledge modeling kit

The Outer Space Environment



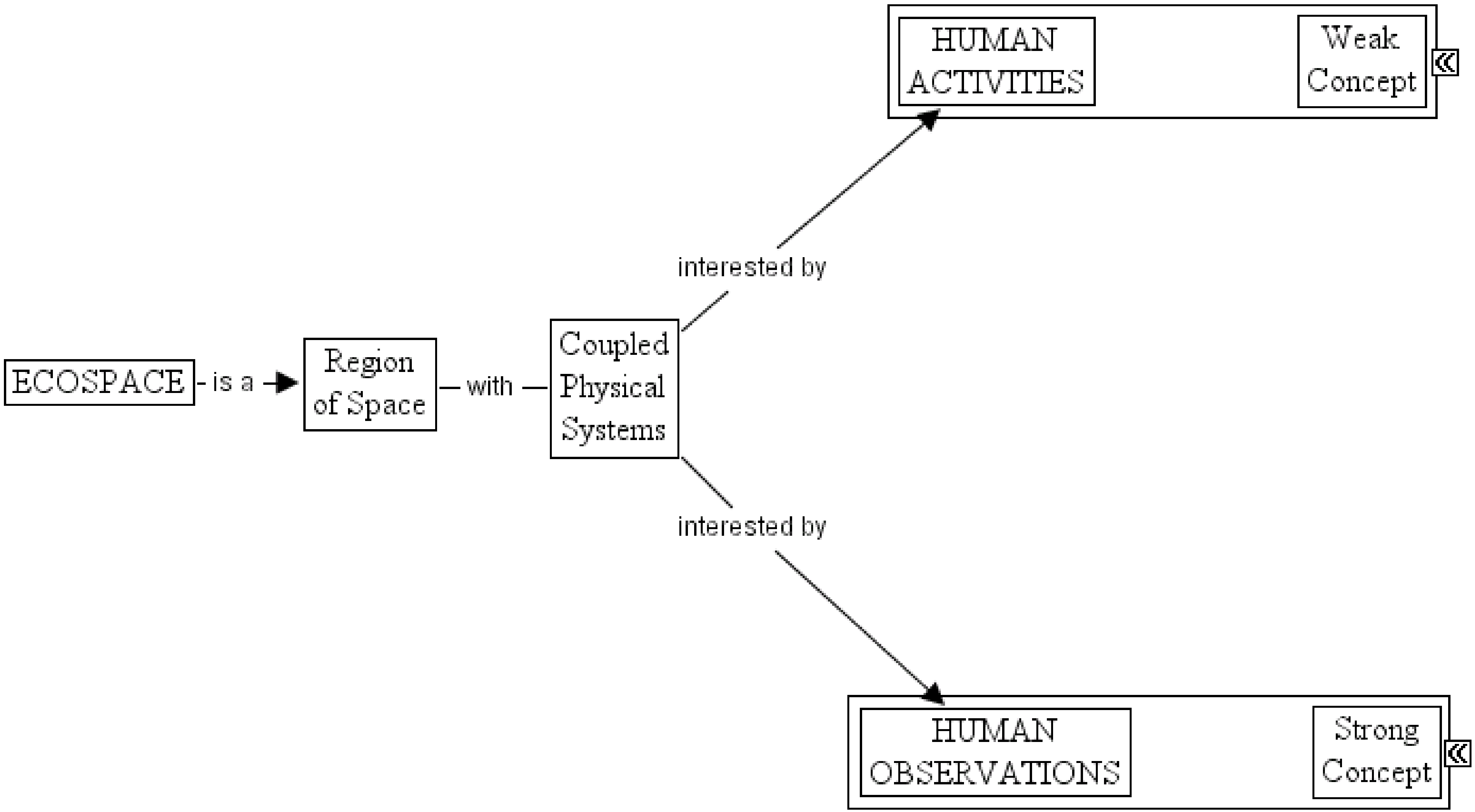
Messerotti & Lundstedt (2004)

The Galactic Neighborhood



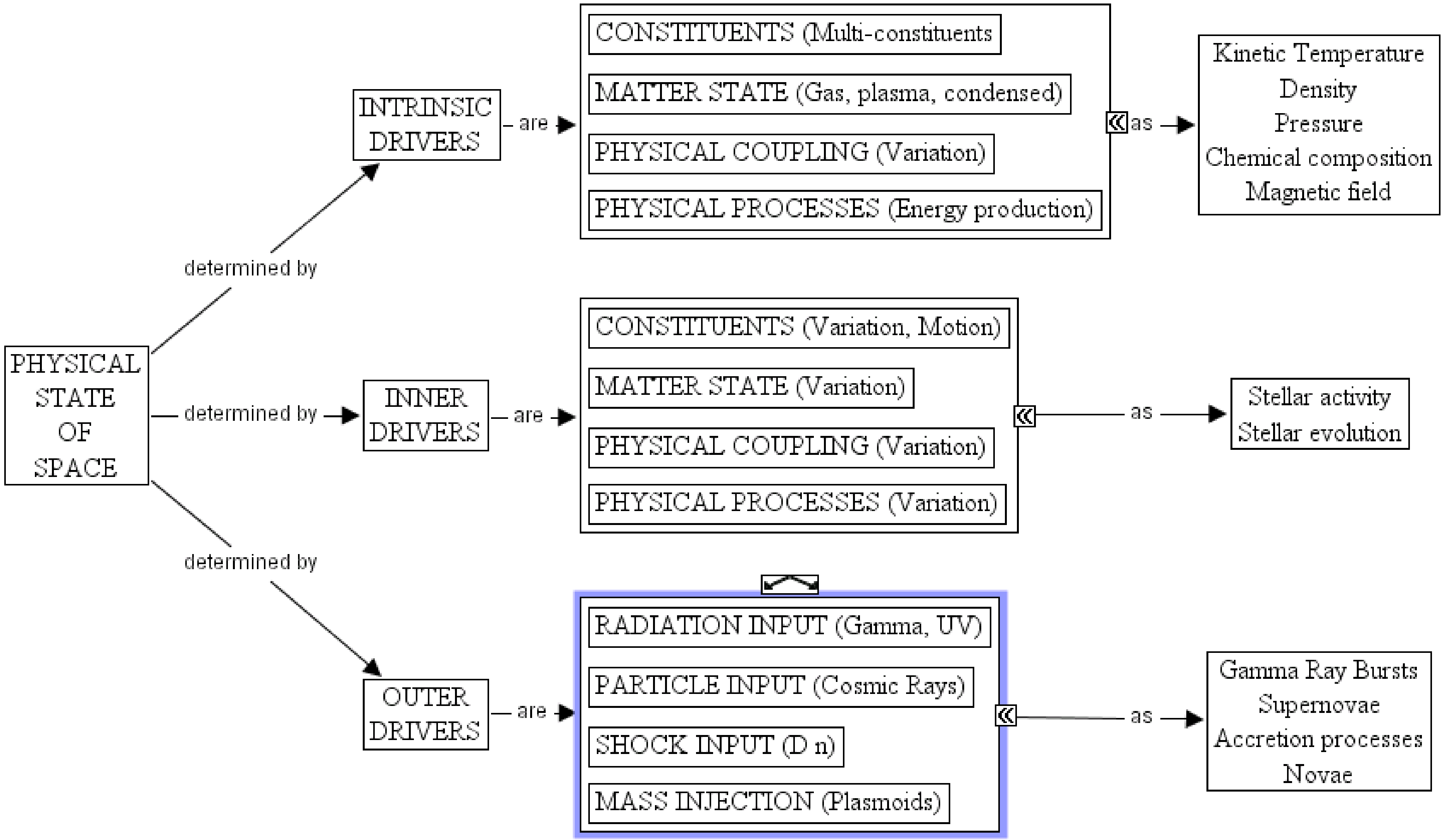
Messerotti & Lundstedt (2004)

The Ecospace



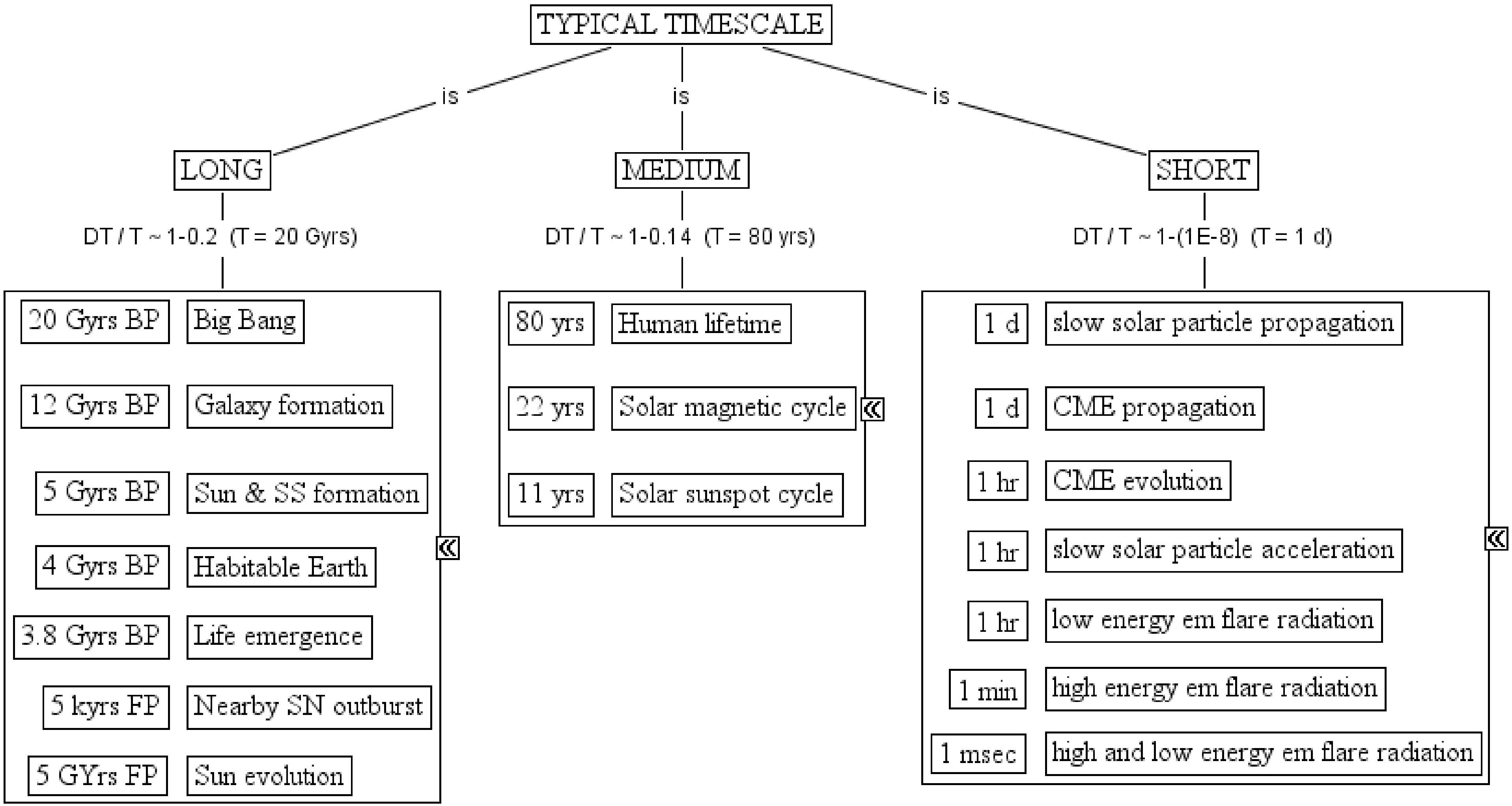
Messerotti & Lundstedt (2004)

Physical State of Space



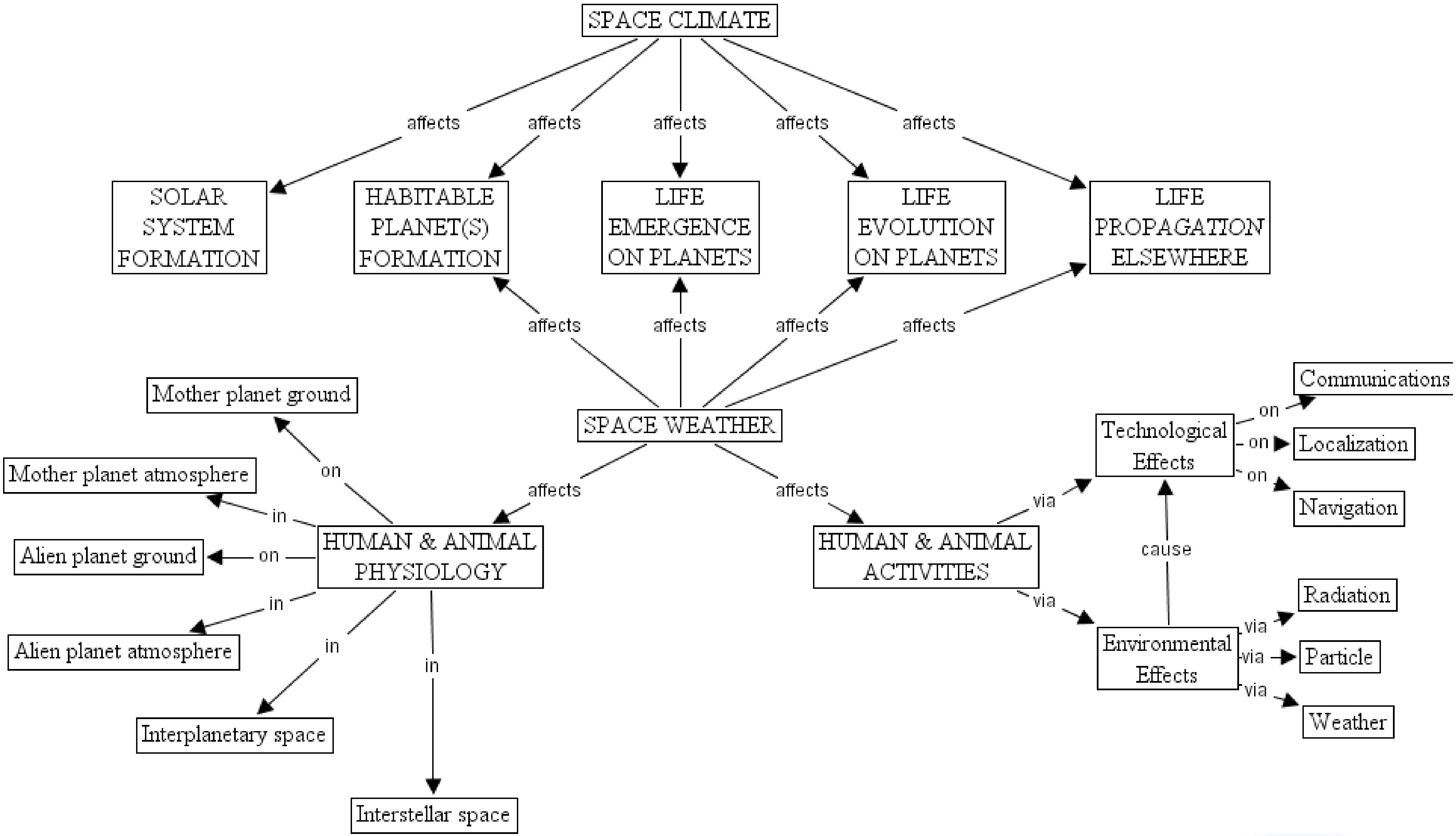
Messerotti & Lundstedt (2004)

Phenomenological Timescales



Messerotti & Lundstedt (2004)

Space Conditions Impacts



Messerotti & Lundstedt (2004)

THE STELLAR ENVIRONMENT

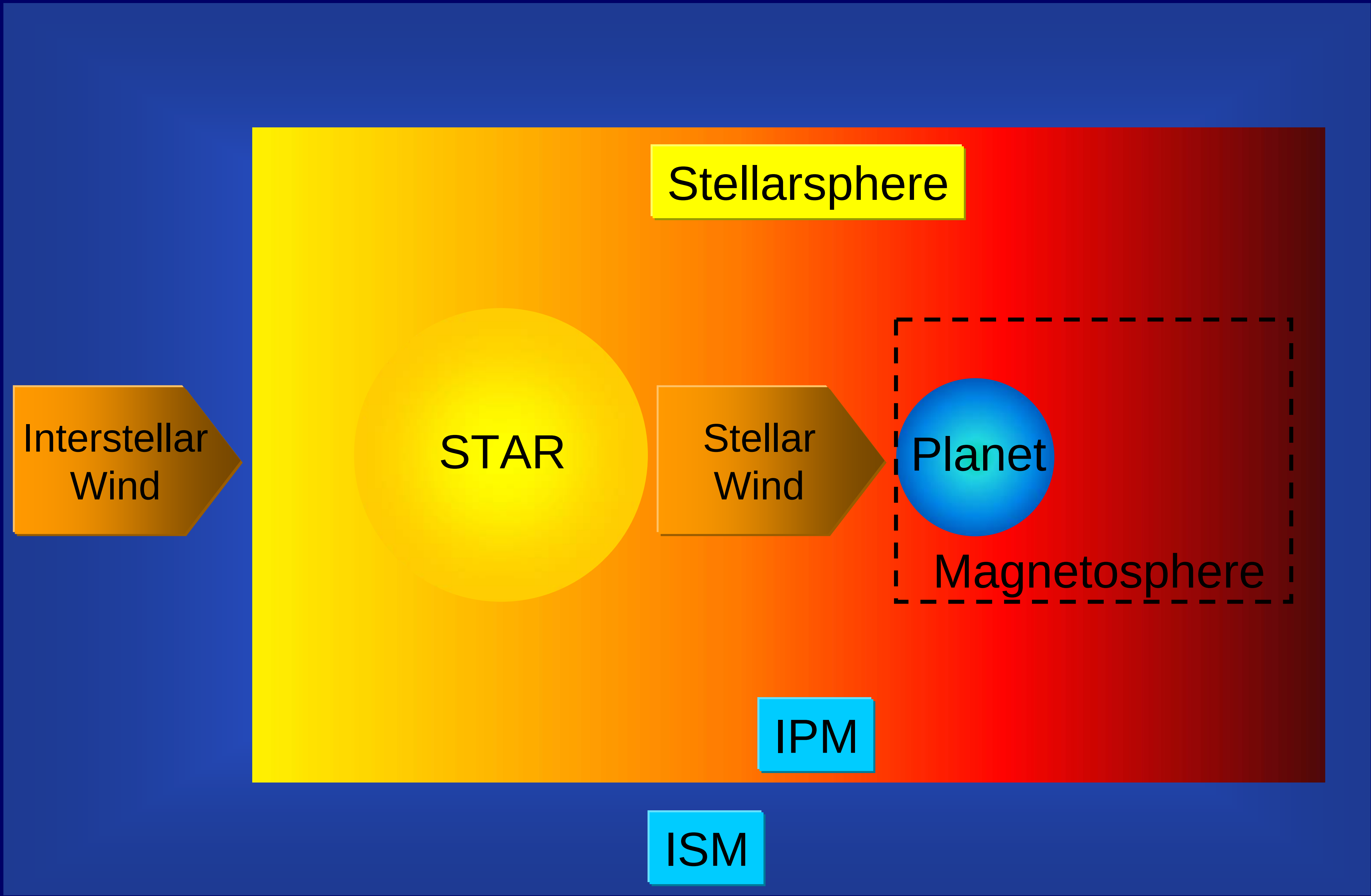
- COMPLEX PHYSICAL SYSTEM composed of

- COUPLED PHYSICAL SYSTEMS as
  - Interstellar Wind (diluted magnetized plasma)
  - STAR (magnetized plasma in organized state)
  - Stellar Wind (diluted magnetized plasma)
  - PLANET (gaseous or condensed organized matter)

- at DIFFERENT PHYSICAL CONDITIONS defined by
  - Temperature
  - Density
  - Gravity
  - Magnetic Field
  - Chemical Composition

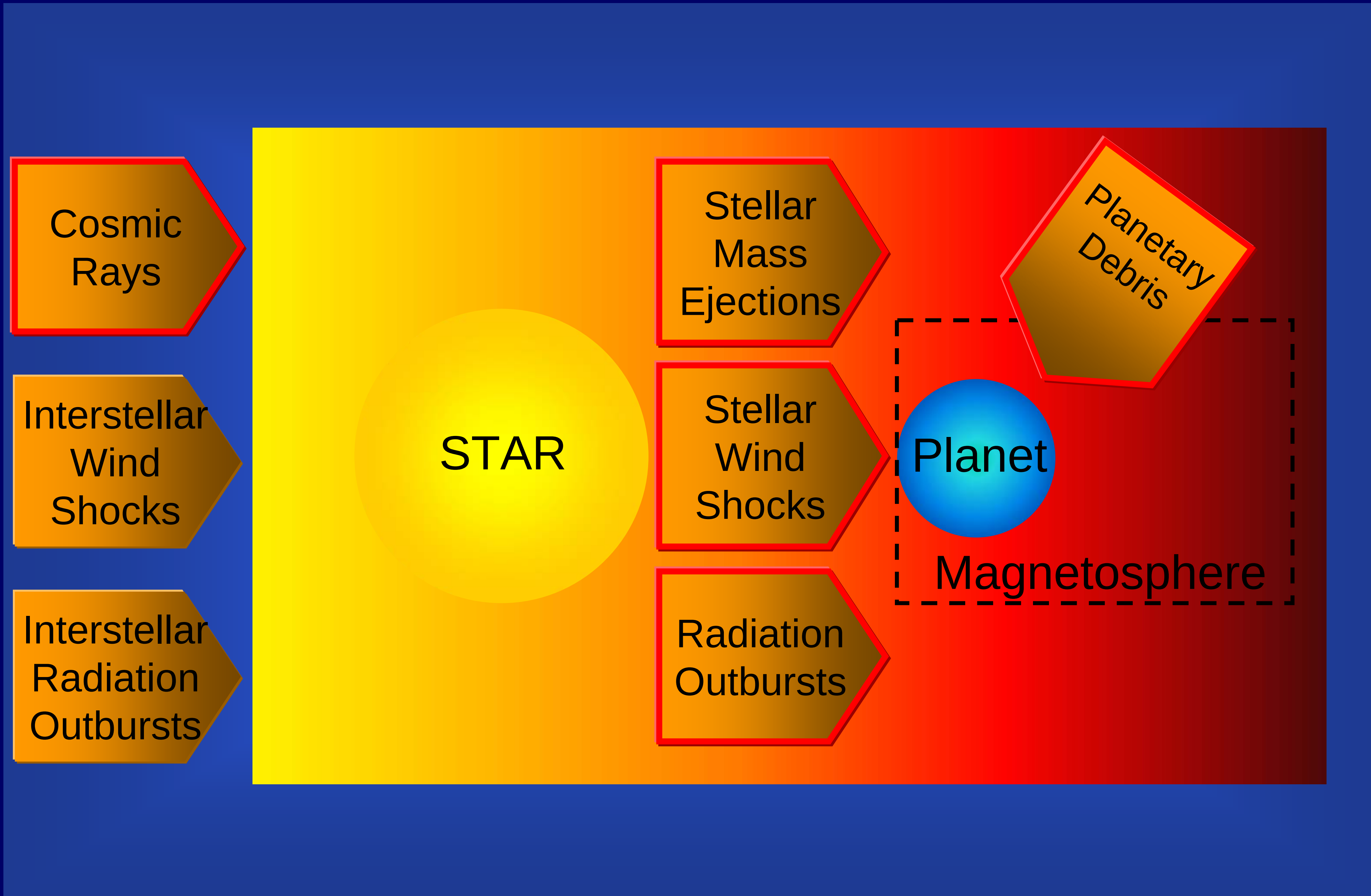
Messerotti (2003, 2005)

SCHEME OF A STELLAR ENVIRONMENT



Messerotti (2003, 2005)

PERTURBATIONS IN THE STELLAR ENVIRONMENT



Messerotti (2003, 2005)

Components of the ISM

Phase	f	n	kT	nkT
		(cm^{-3})	(eV)	$(\mathrm{eV\ cm}^{-3})$
Molecular Clouds	10^{-3}	> 100	$< 10^{-2}$	-
Cold Neutral Medium	0.025	40	$\approx 10^{-2}$	≈ 0.4
Warm Neutral Medium	≈ 0.5	≈ 0.5	≈ 1	≈ 0.5
Warm Ionized Medium	≈ 0.25	≈ 0.2	≈ 1	≈ 0.2
Hot Ionized Medium	≈ 0.2	$\approx 3 \times 10^{-3}$	$\approx 10^{2}$	≈ 0.3
Cosmic Rays	≈ 1	$\approx 10^{-9}$	$\approx 10^{9}$	≈ 1

COLLISIONLESS, NON-THERMAL GAS

From Cohen (2004)

Global Measurements of Cosmic Rays

Components	Tracer	Related ISM	CR Energy	Quantity
		Component	Range	Measured
Electrons	Radio Synchrotron	B	0.2-10 GeV	$\int n_{\mathrm{CR}} B^{1.8}\, dr$
Electrons	Radio Bremsstrahlung	Thermal ISM	100-300 MeV	$\int n_{\mathrm{H}} n_{\mathrm{CR}}\, dr$
Electrons	γ-ray Inverse Compton	Photons	$<$ 100 MeV	$\int n_{*} n_{\mathrm{CR}}\, dr$
Protons	γ-ray π^0 Decay	Thermal ISM	0.3-10 GeV	$\int n_{\mathrm{H}} n_{\mathrm{CR}}\, dr$

From Cohen (2004)

MODEL DIFFERENTIAL SPECTRA OF CRI

$$D(E) = K(0.939 + E)^{-\gamma}\left(1 + \frac{\alpha}{E}\right)^{-\beta} f_3 + x\left(1 + \frac{y}{E^z}\right) f_4$$

Here the first term presents the galactic CR, and the last term takes into account the recently discovered anomalous CR from interval IV (Cummings and Stone, 1987). K, α, β, γ, x, y and z are parameters of the spectrum, which must be determined.

$$f_3 = 0.5\{1 + \tanh[\lambda\,(E - \mu)]\} \qquad f_4 = 0.5\{1 - \tanh[\lambda\,(E - \mu)]\}$$

We will express tanh function through the exponential functions. Then the expression for primary CR spectrum (2) will be:

$$D(E) = \frac{K(0.939 + E)^{-\gamma}}{1 + e^{-2X}}\left(1 + \frac{\alpha}{E}\right)^{-\beta} f_3 + \frac{x}{1 + e^{-2X}}\left(1 + \frac{y}{E^Z}\right) f_4$$

The coefficients K, α, β, γ, x, y, z and μ are solutions of the interpolation problem of the function.

From Velinov (2004)

DIFFERENTIAL SPECTRA OF CRI

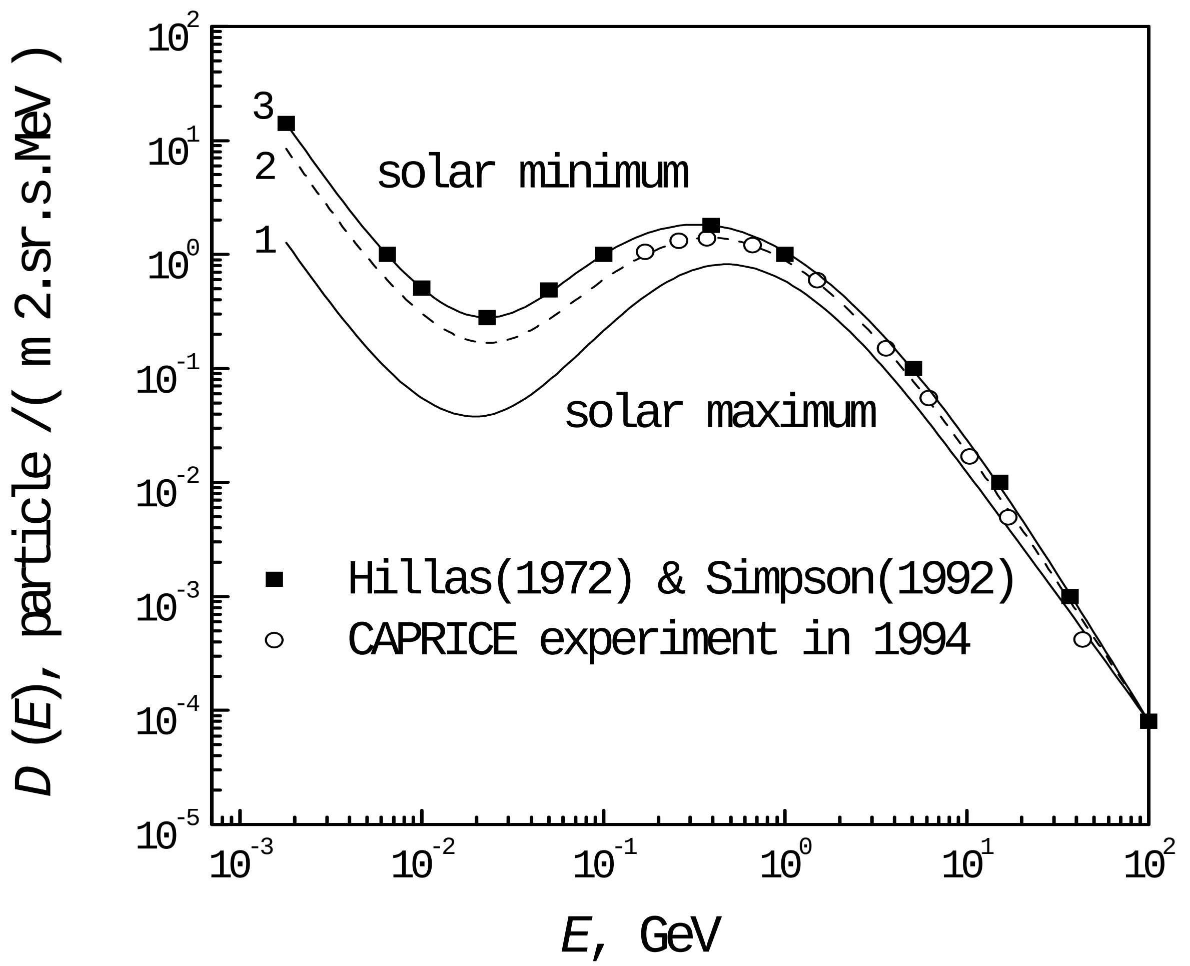


Figure 1. The modeled spectrum *D(E)* of galactic CR proton for three levels of solar activity and measurements: ■ and ○, [1,8] and [13], respectively.

Curve 1 relates to solar maximum 1989, 3 – to solar minimum 1995 and 2 – to 1994, when is made the CAPRICE experiment ○ [13].

From Velinov (2004)

INTEGRAL SPECTRA OF CRI

$$D(>E) = \int^{\infty} D(E)\, dE$$

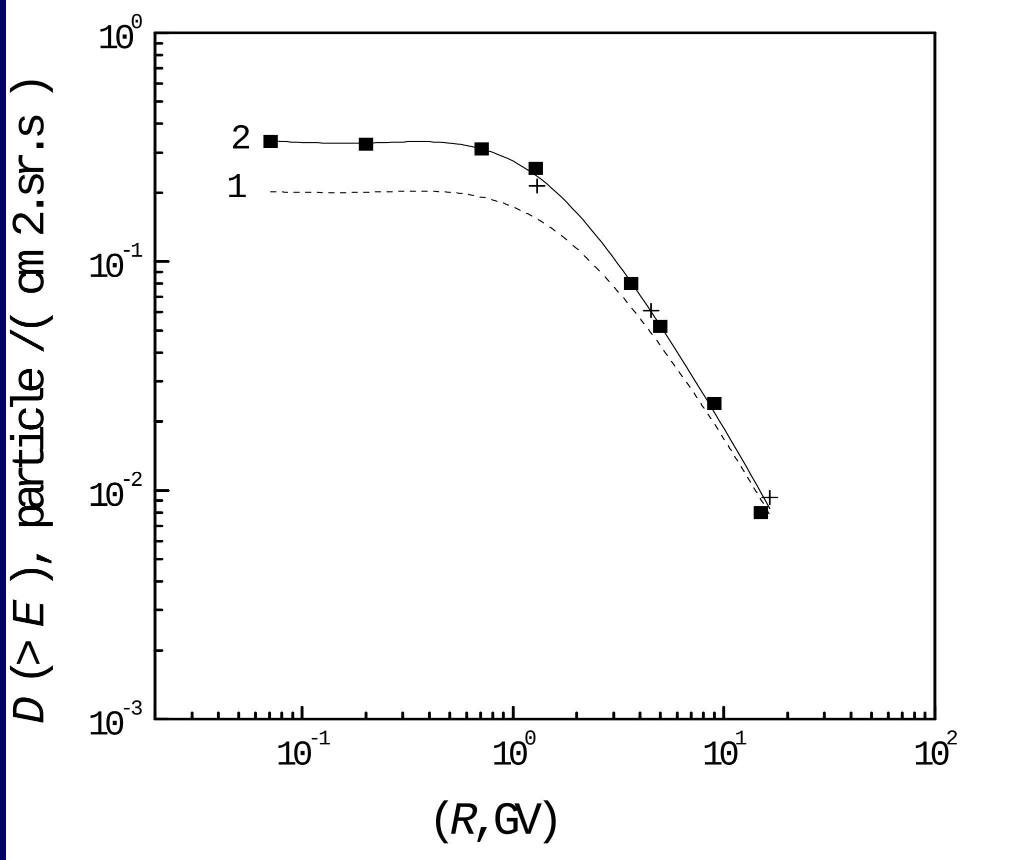


Figure 4. The modeled integral spectrum *D(>E)* of CR protons for maximum (curve 1) and minimum (curve 2) levels of solar activity in comparison with experiments: ■ CREME96 [14] and + Shopper [20].

From Velinov (2004)

STELLAR SPACE METEOROLOGY

The Stellar Space Meteorology observes

- the physical state of the stellarsphere
- the perturbative phenomenology which affects it

on a

- short time scale → STELLAR SPACE WEATHER
- long time scale → STELLAR SPACE CLIMATE

and tries to predict the potential perturbations on a

- short time scale → SSpW NOWCASTING
- long time scale → SSpW FORECASTING

Messerotti (2003, 2005)

STELLAR SPACE METEOROLOGY DRIVERS

- STAR
  - L, M, R, Te, cc
  - Magneticity
  - Variability
  - Wind
- PLANETARY SYSTEM
  - Orbital dynamics
  - Population diversity

Messerotti (2003, 2005)

PLANETARY RESPONSE DRIVERS

- Mass
- Radius
- Density
- Orbital dynamics
- Surface morphology
- Atmosphere
- Magnetosphere

Messerotti (2003, 2005)

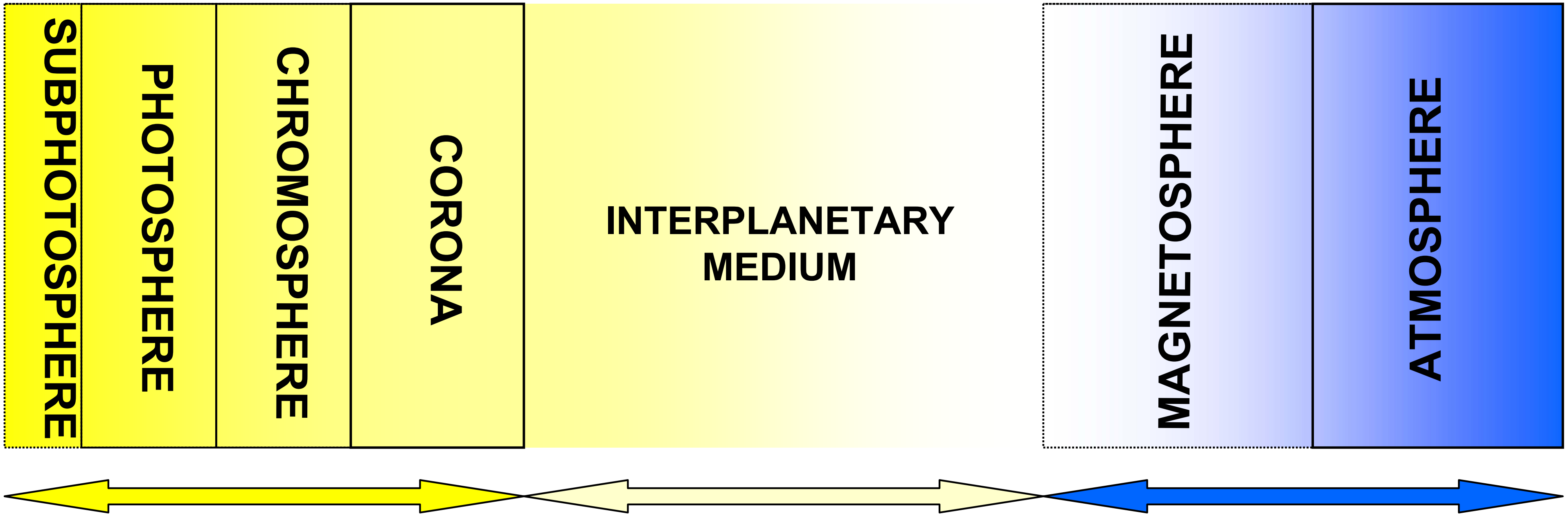
Solar-Terrestrial Environment

PHYSICAL CONDITIONS

- defined as SPACE WEATHER
- strongly affected by SOLAR ACTIVITY but
- HIGHLY NONLINEARLY COUPLED with it
- QUITE COMPLEX TO FORECAST

Messerotti (1999, 2001)

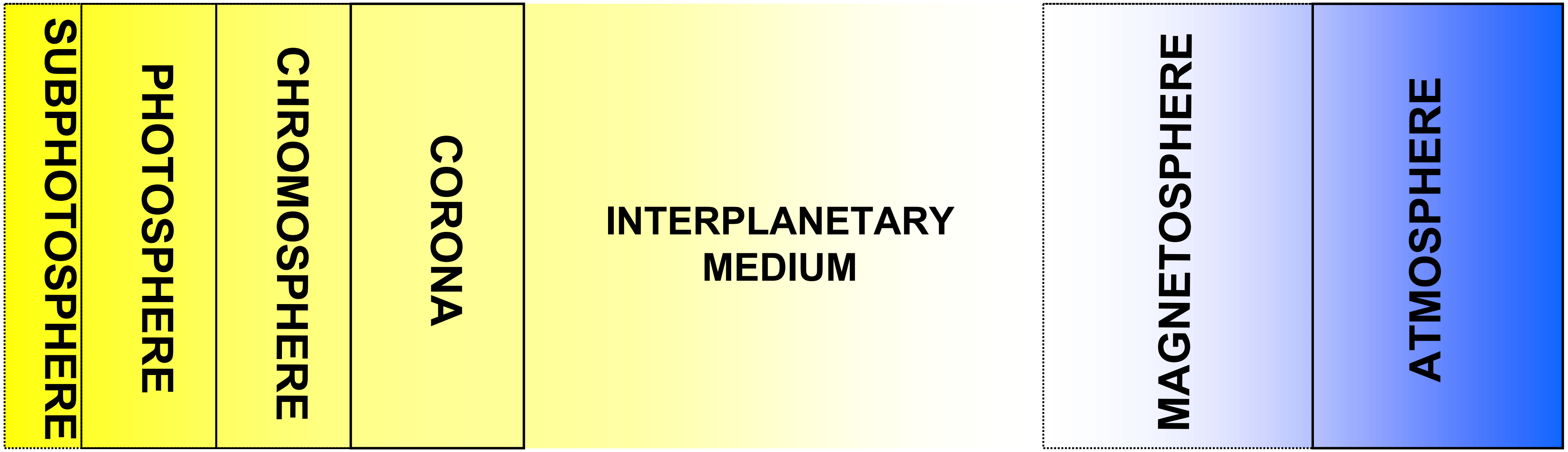
COUPLING IN THE SUN-EARTH SYSTEM



SUN	INTERPLANETARY SPACE	EARTH ENVIRONMENT
Radiated Power 3.82 10^{23} kW		1.36 kW/m^2
Total SW Mass Flow 10^6 tons/s		
Energy in SW 4.1 10^{20} W		10^{13} W / 30 R_E
Energy in CME 7 10^{18} W		1.73 10^{17} W

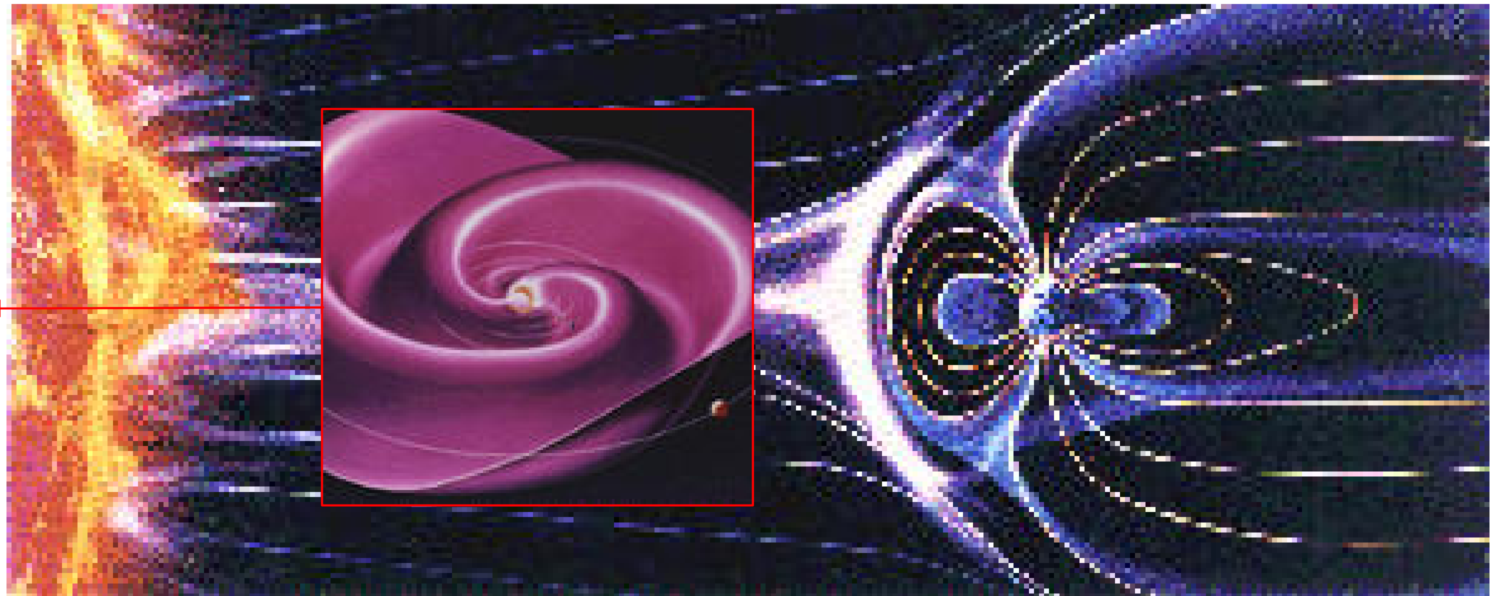
Messerotti (1999, 2001)

CHARACTER OF THE MAGNETIC FIELD



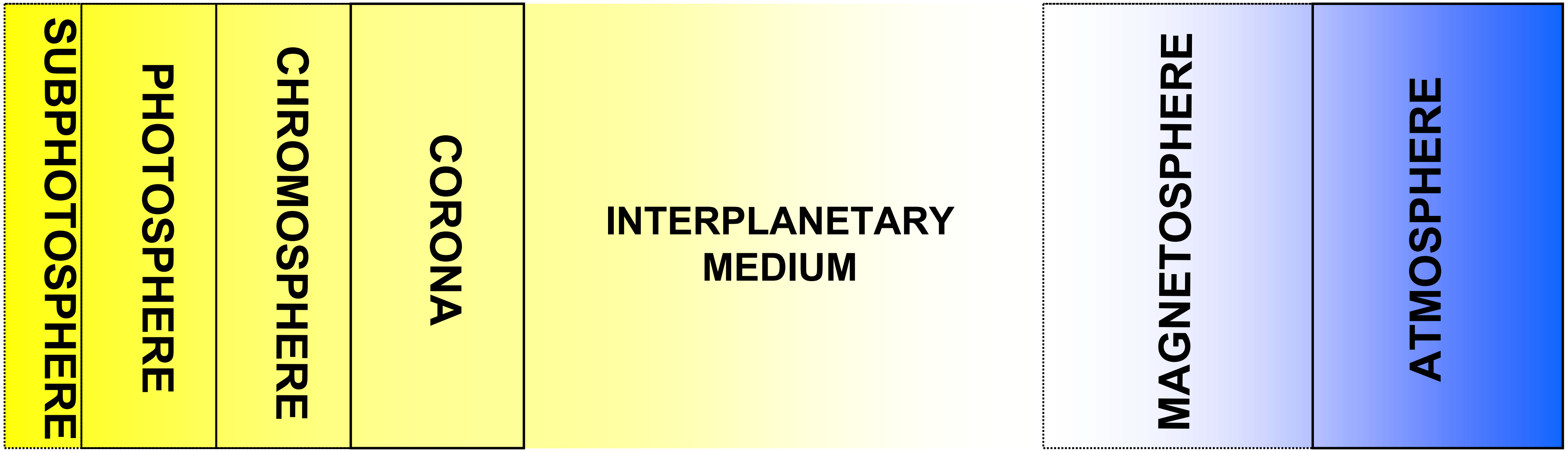
DIPOLAR RADIAL SECTORED DIPOLAR
AZIMUTHAL WARPED ASYMMETRIC
MAGNETIC FIELD

- Arch. spiral
- 0.1-80 nT
- 4 SSBs
- +/- 7.25° lat
- 45° cross angle



Messerotti (1999, 2001)

SOLAR DRIVERS OF IPM & EARTH PERTURBATIONS



Fluid motions

Sunspots

e.g.

Flares — γ, X, UV; p, e — SID, PCA

Prominences, Filaments — CME

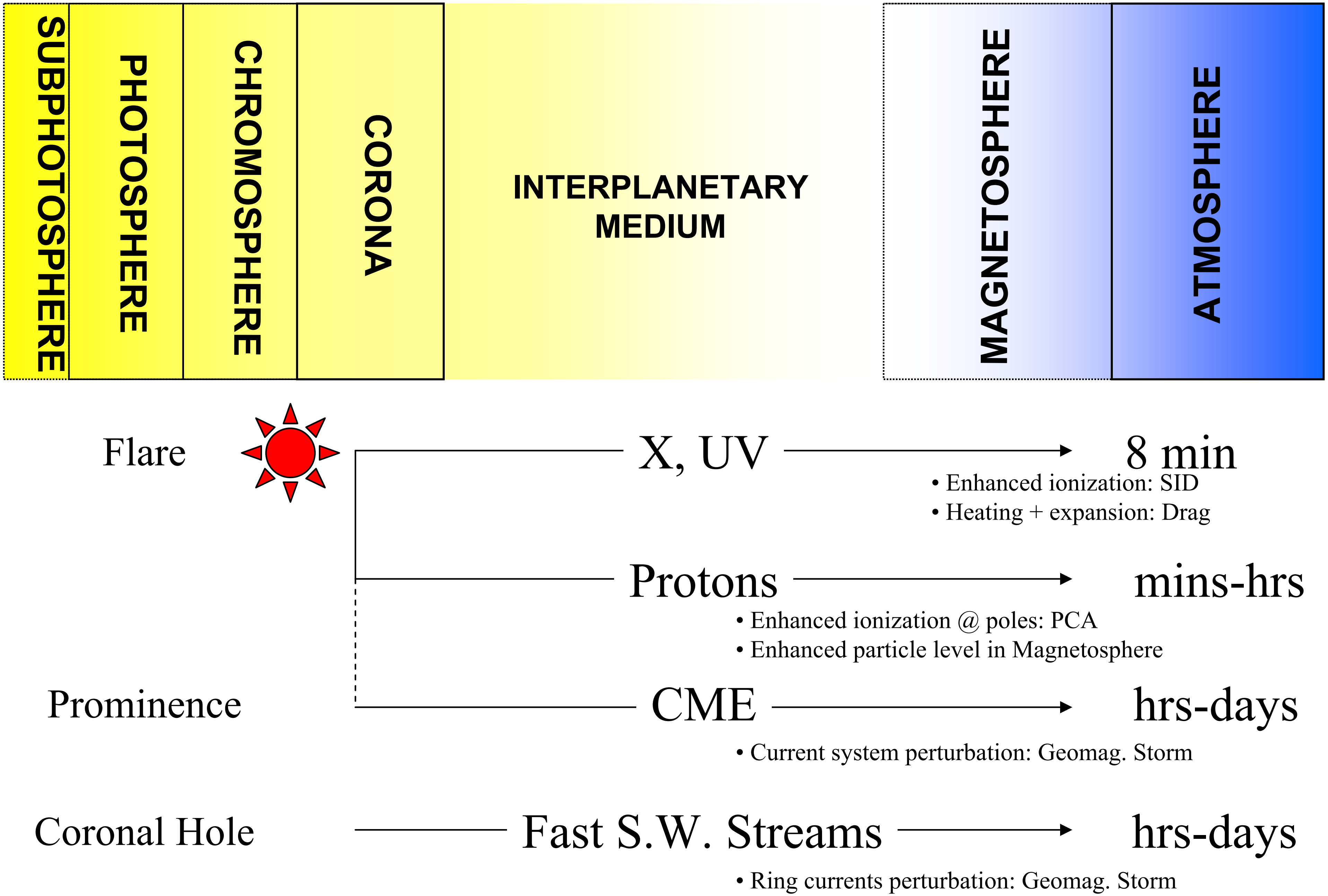
Condensations

Streamers — Slow SW

Coronal Holes — Fast SW — Recurrent & n.-rec. Geomagnetic Storms

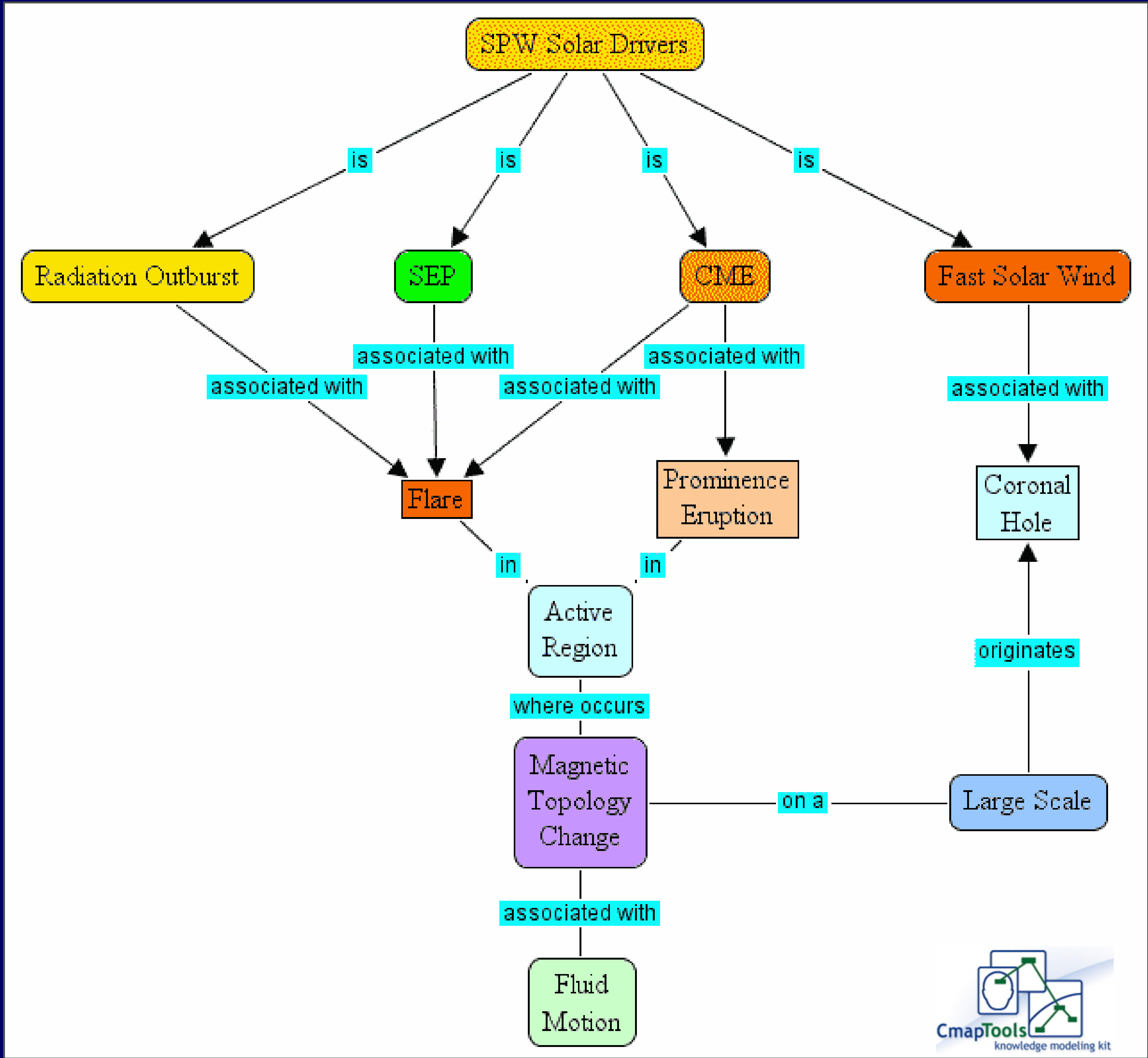
Messerotti (1999, 2001)

INDICATIVE TIMING OF S-T PERTURBATIONS



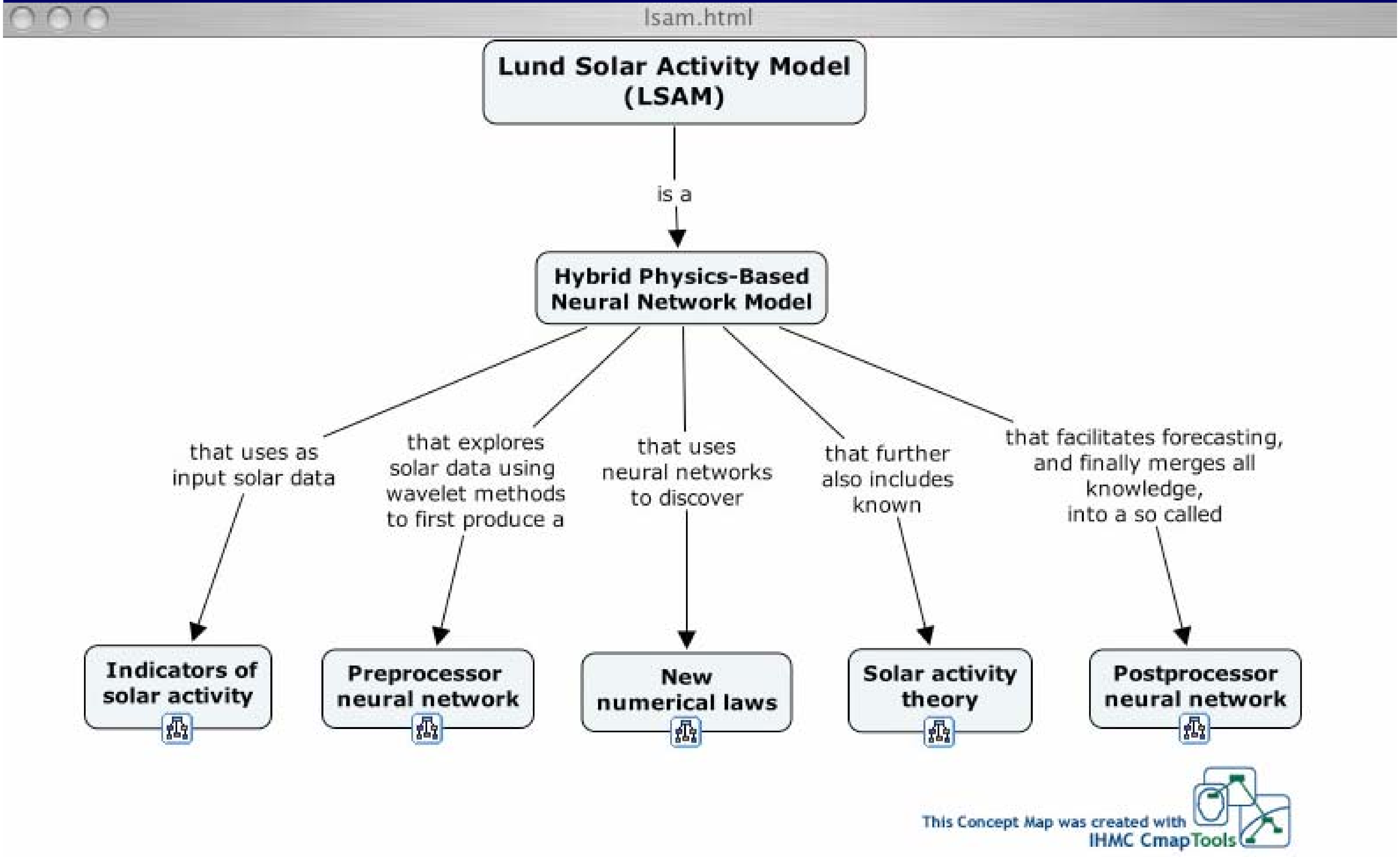
Messerotti (1999, 2001)

Space Weather Solar Drivers



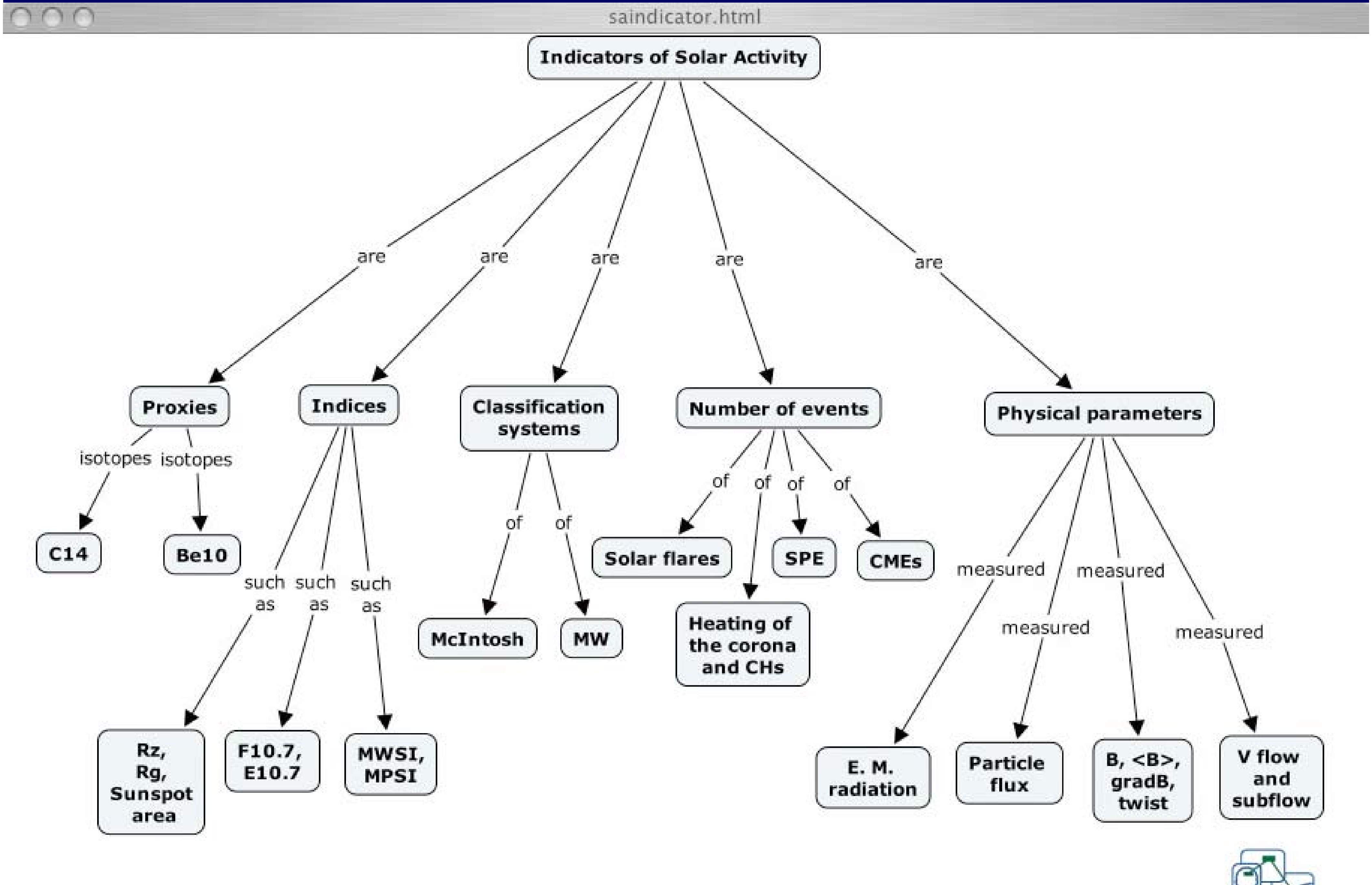
Messerotti (2004)

SOLAR ACTIVITY MODELLING



From Lundstedt (2004)

INDICATORS OF SOLAR ACTIVITY



From Lundstedt (2004)

THE SUN
AS
AN ACTIVE STAR

The Sun as a Star

MAIN SEQUENCE YELLOW DWARF

• L	$3.9\ 10^{26}$ W
• M	$1.99\ 10^{30}$ kg
• R	$6.96\ 10^{5}$ km
• T_e	5785 K
• Sp. type	G2V
• Age	$5\ 10^{9}$ years
• Phase	stable H burning
• Variability	on a second order scale
• Magneticity	on a second order scale

Messerotti (1999, 2001)

The Sun as Physical System

COMPLEX SYSTEM made of
COUPLED MAGNETIZED PLASMAS
at different spatial scales and physical status

	T_e [K]	N_e [cm^{-3}]
• CORE	10^7	10^{19}
• RADIATIVE ZONE	10^6	10^{16}
• CONVECTIVE ZONE	10^5	10^{14}
• PHOTOSPHERE	10^3	10^{12}
• CHROMOSPHERE	10^4	10^{11}
• TRANSITION REGION	10^5	10^{10}
• CORONA	10^6	10^{09}
• SOLAR WIND	10^5	10^{01}

Messerotti (1999, 2001)

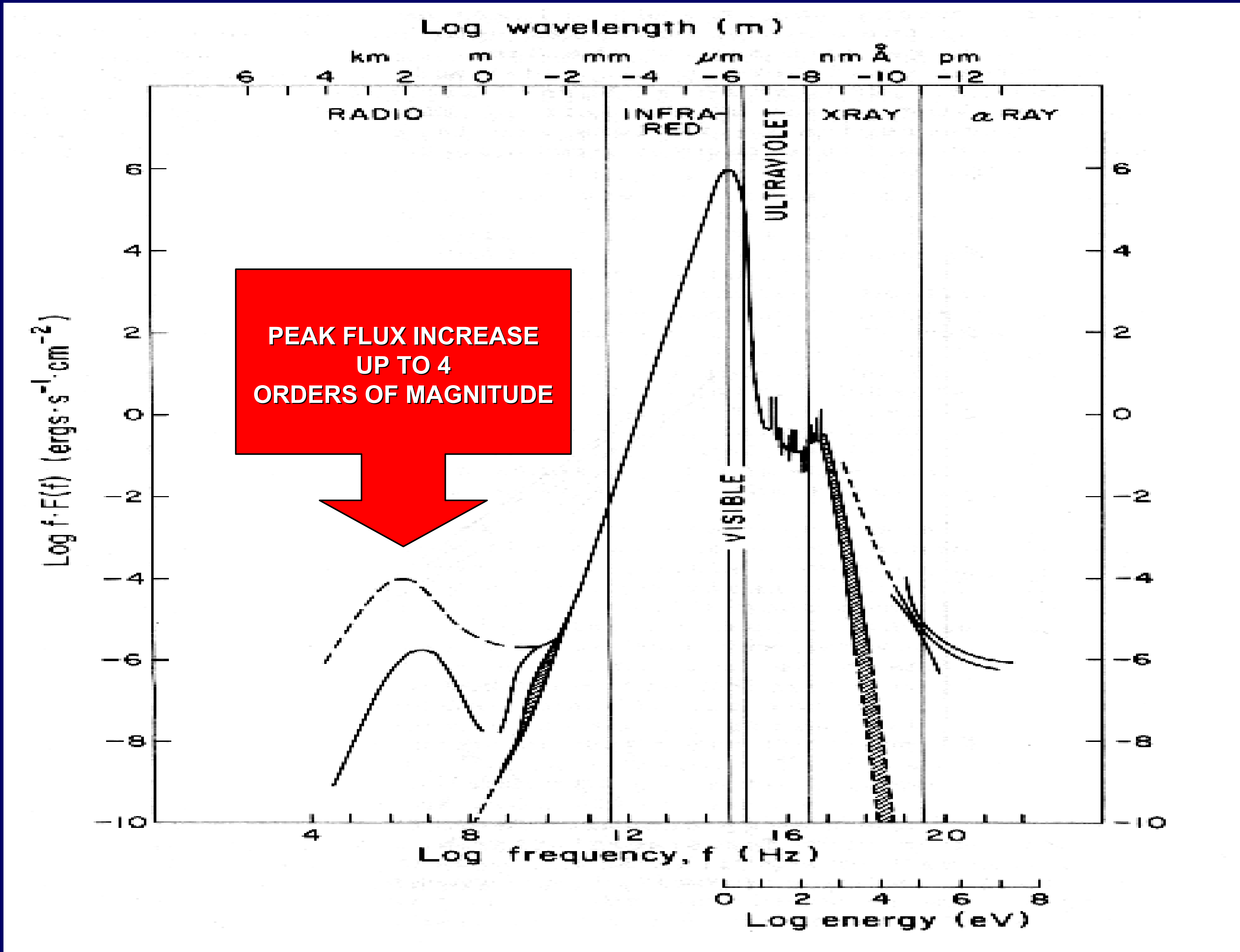
Solar Activity

COMPLEX of PHENOMENA

- **VARIABLE on**
  - spatial scale
  - time scale
  - energy scale
- **OCCURRING in**
  - photosphere — SUNSPOTS
  - chromosphere — FLARES
  - corona — CMEs
  - solar wind — FAST STREAMs
- **AS**
  - heating
  - particle acceleration
  - waves and shocks
  - emission of radiation
  - plasmoid formation
- **TRIGGERED by**
  - fluid motions
  - interacting magnetic fields
    at different spatial scales

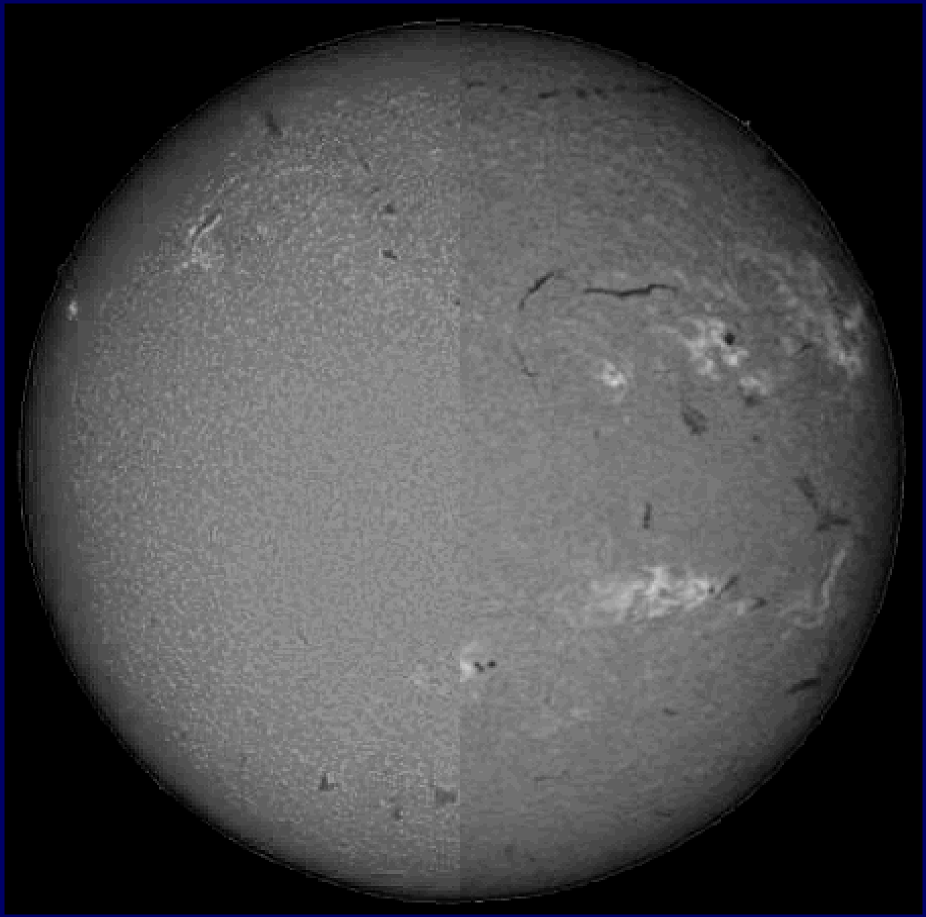
Messerotti (1999, 2001)

THE SOLAR RADIATION SPECTRUM

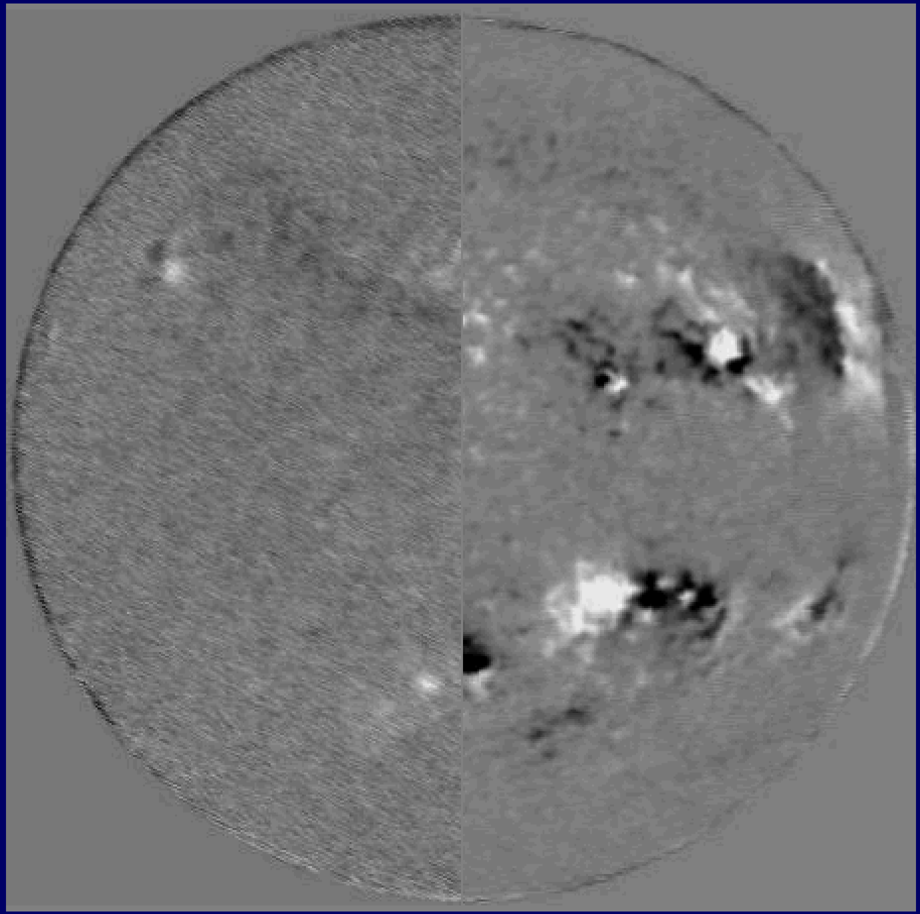


Messerotti (1999, 2001)

LOW AND HIGH SOLAR ACTIVITY



L H
H-alpha

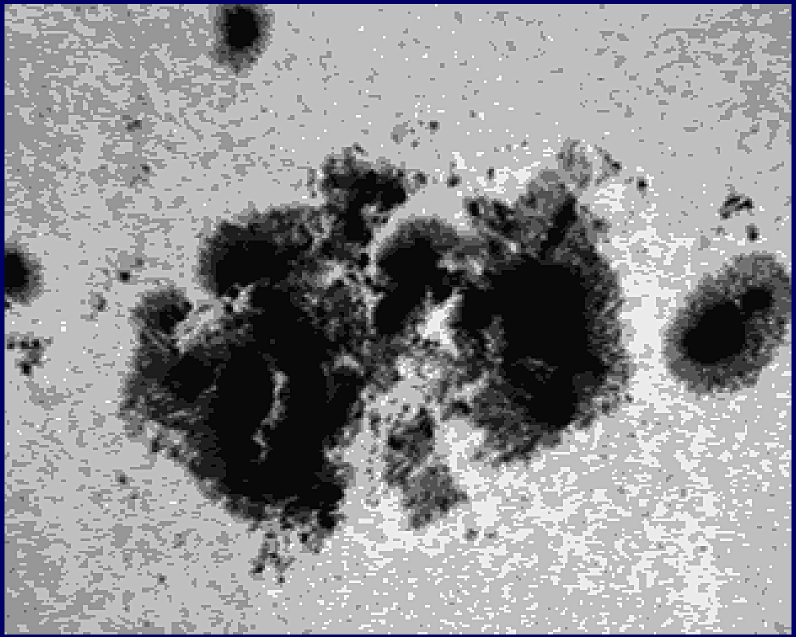


L H
M.F.

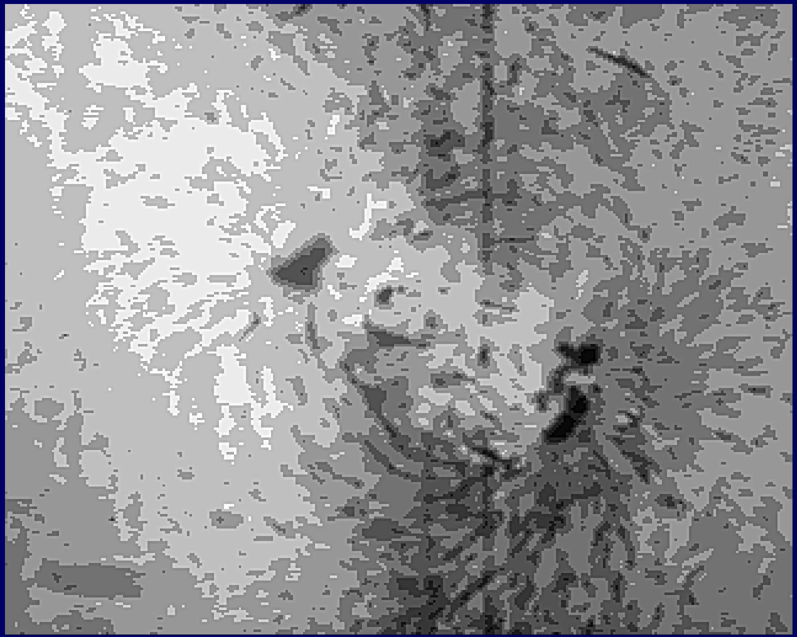
Messerotti (1999, 2001)

Images courtesy Kanzelhoehe Solar Observatory

ACTIVE REGION



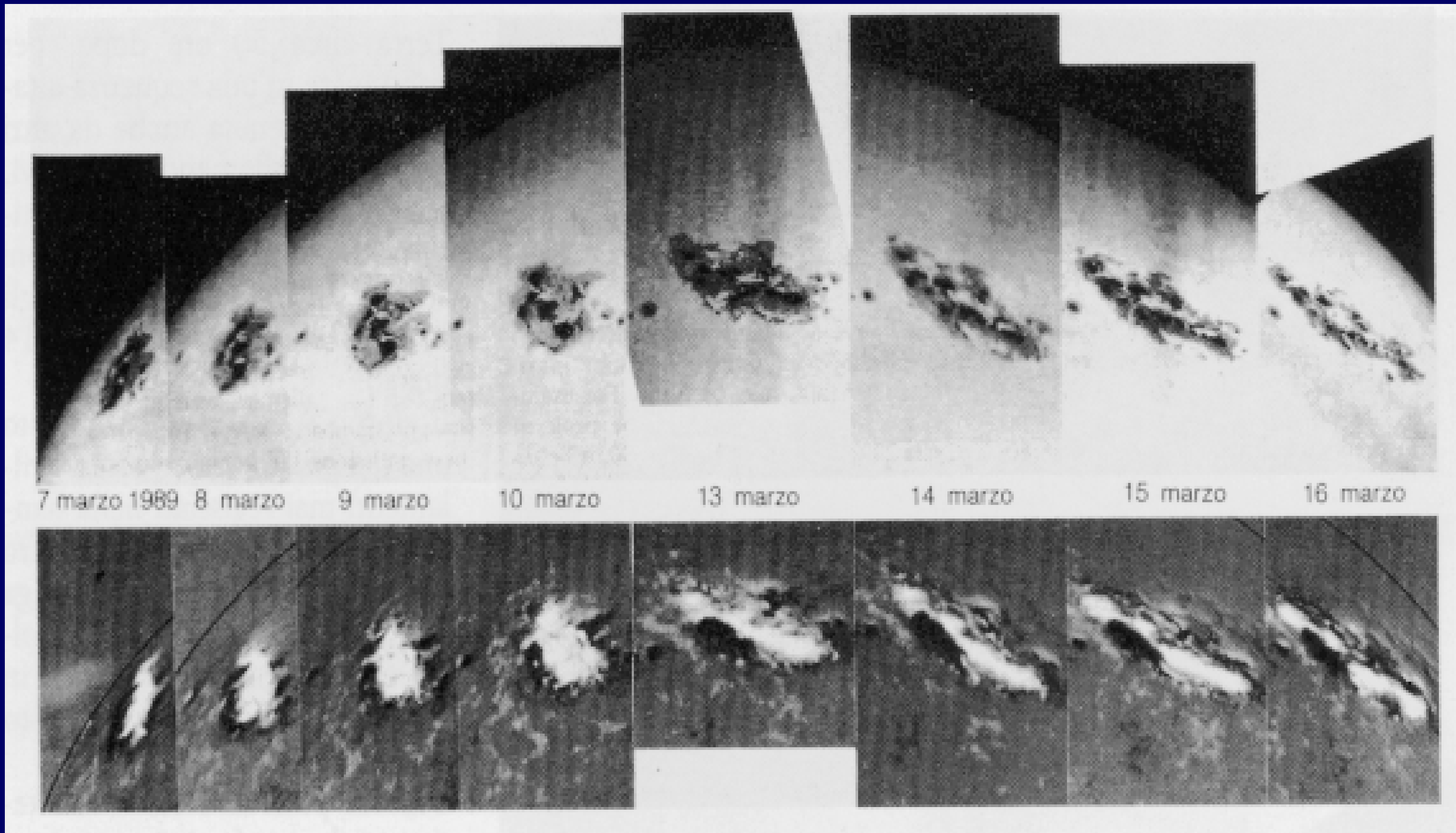
SUNSPOT GROUP



MAGNETIC FIELD

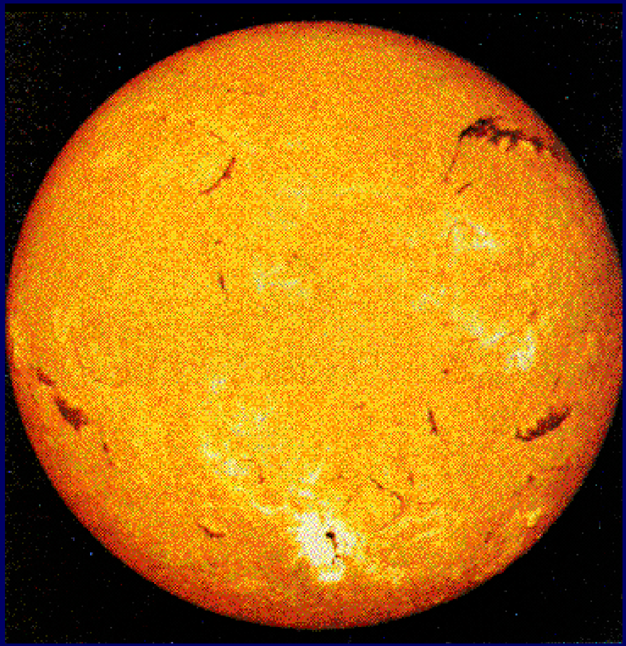
Messerotti (1999, 2001)

AR5395 - MARCH 1989

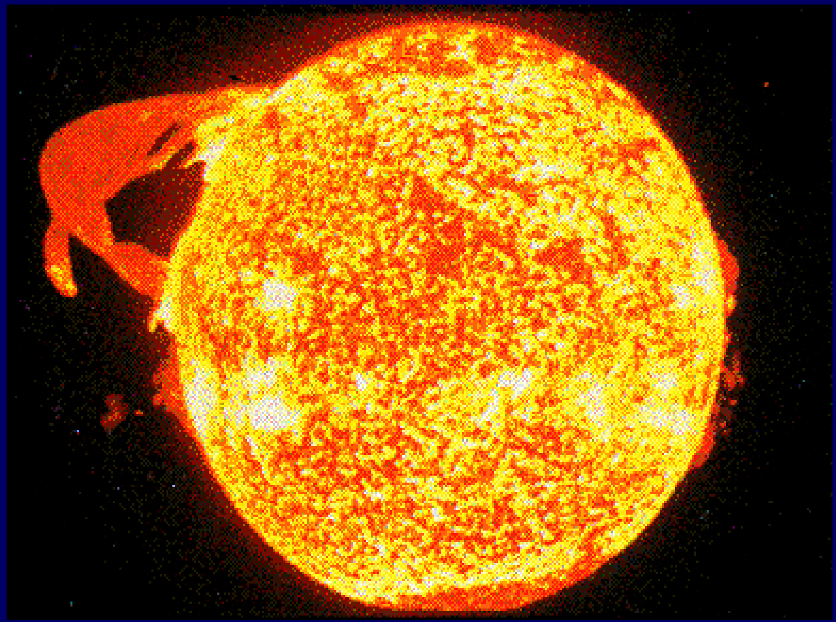


Messerotti (1999, 2001)

CHROMOSPHERE



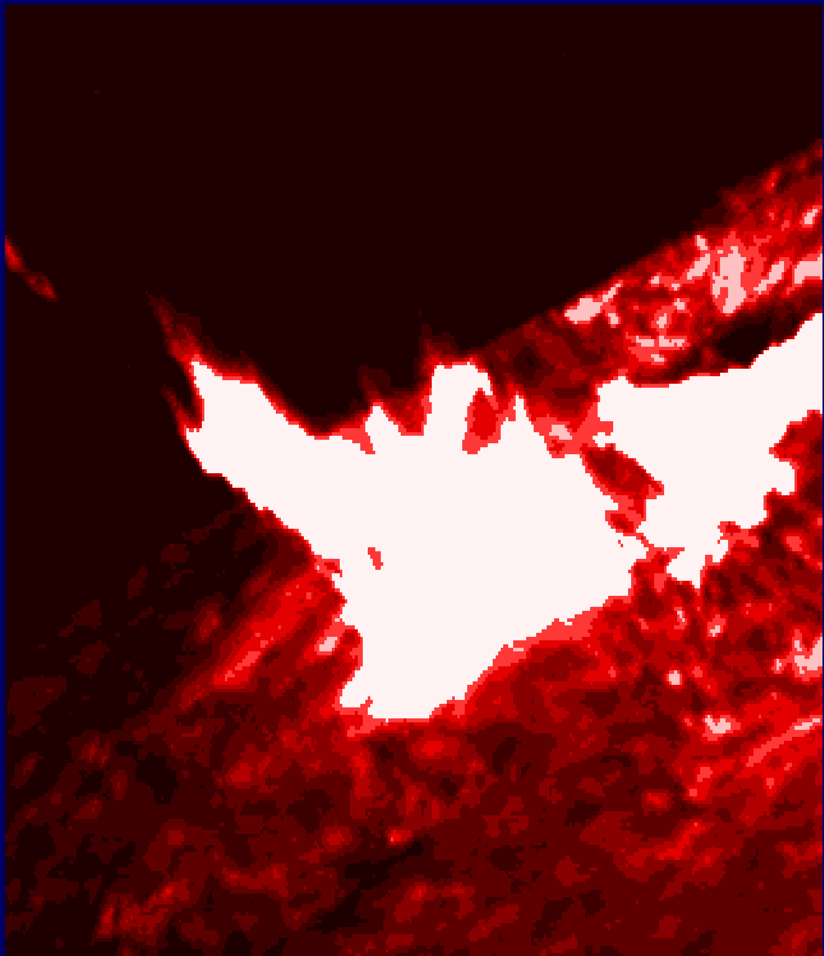
H-alpha



HeII

Messerotti (1999, 2001)

FLARE



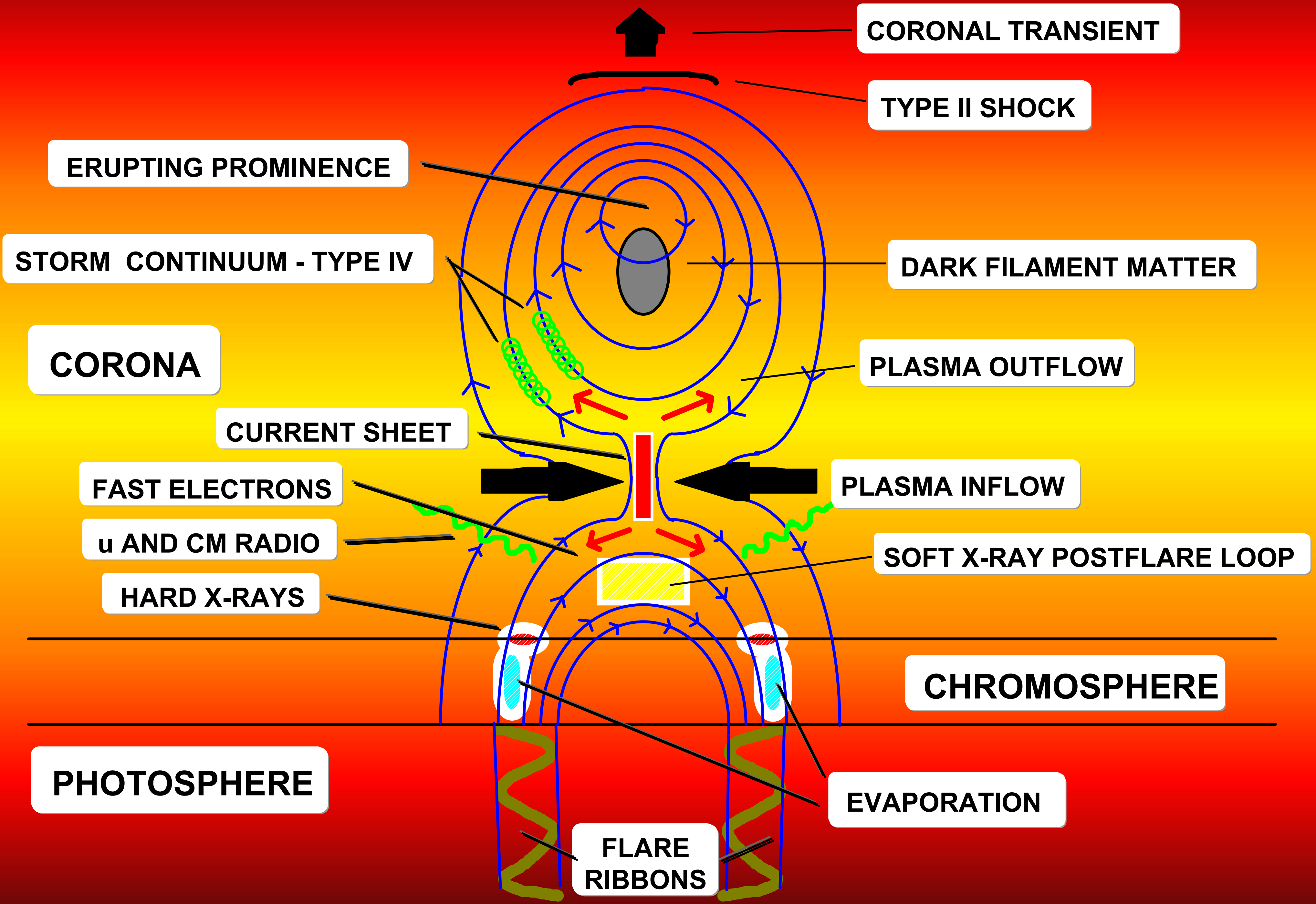
Messerotti (1999, 2001)

SOLAR FLARE

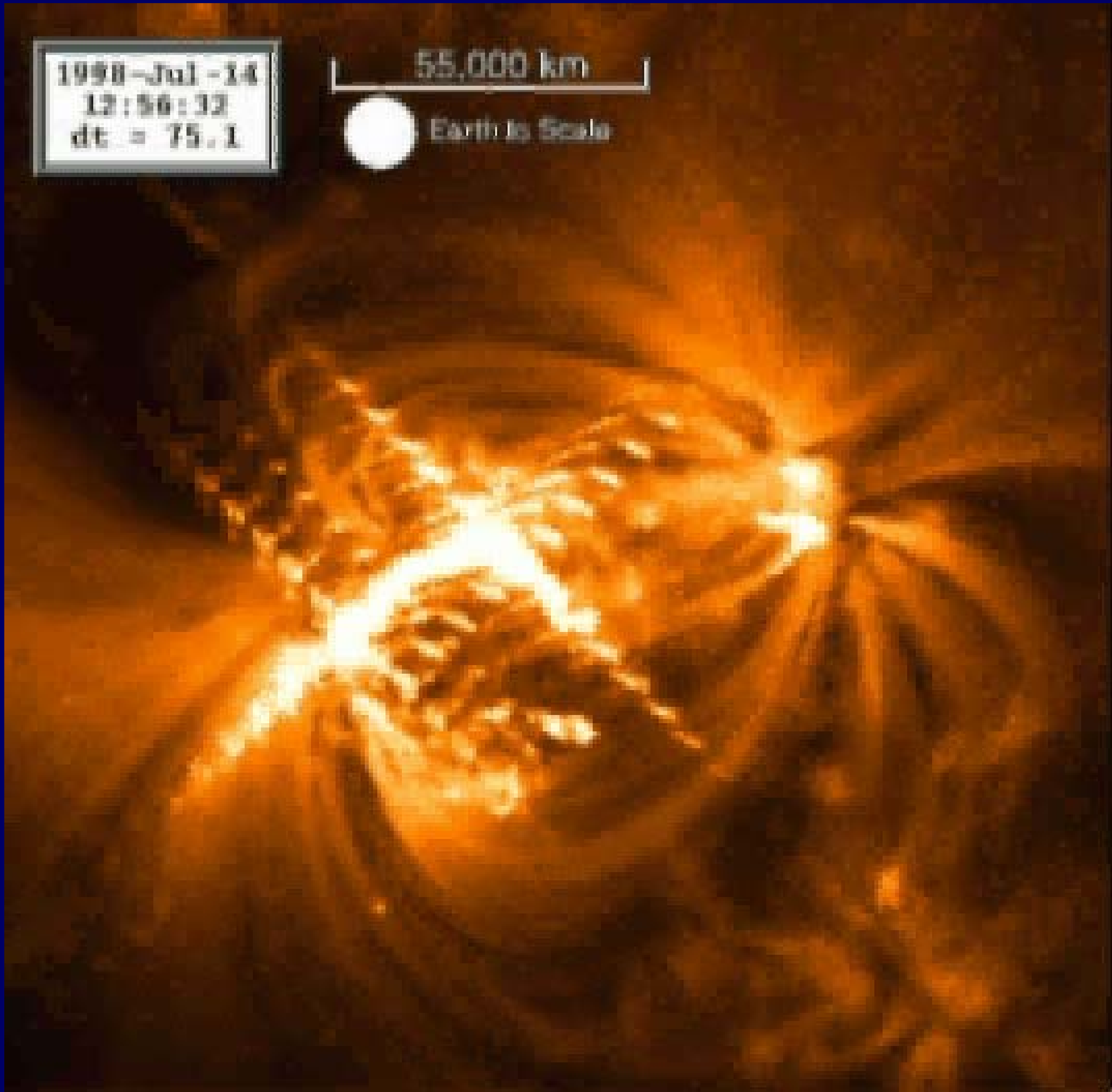
- **Magnetic reconnection** occurs and result in:
  - **Plasma heating**
    - T~10^4 K in chromosphere
    - T~10^7 K in corona
  - **Particle acceleration** (20 keV - 1 GeV)
  - **Total energy** in largest events ~10^{25} J
  - **Transient e.m. radiation**
    - from γ to Radio (thermal)
    - HXR (< 0.1 nm) (non-thermal)
    - Radio by en. Particles (non-thermal)

Messerotti (1999, 2001)

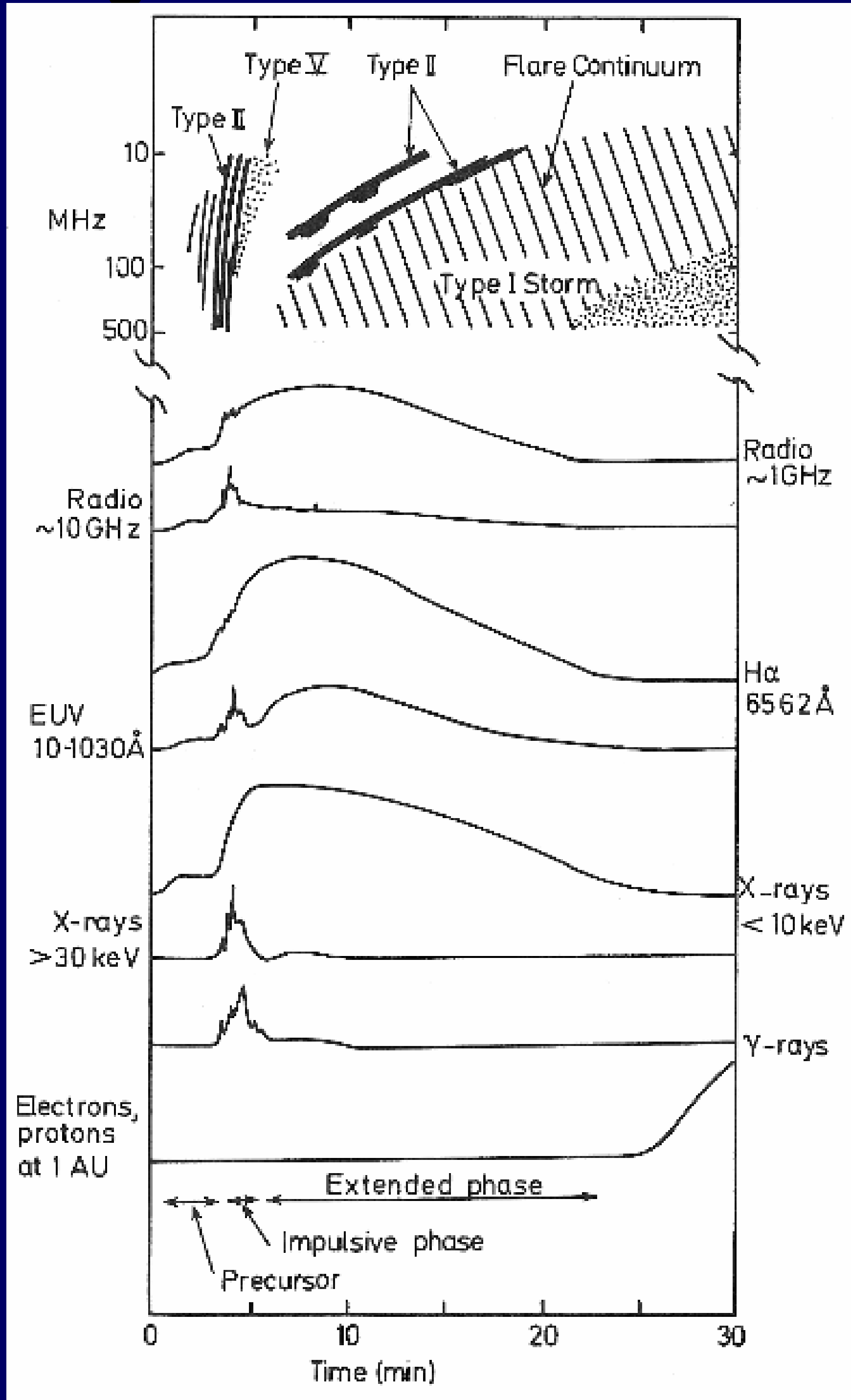
FLARE MODEL


CORONAL TRANSIENT
TYPE II SHOCK
ERUPTING PROMINENCE
STORM CONTINUUM - TYPE IV
DARK FILAMENT MATTER
CORONA
PLASMA OUTFLOW
CURRENT SHEET
FAST ELECTRONS
PLASMA INFLOW
u AND CM RADIO
SOFT X-RAY POSTFLARE LOOP
HARD X-RAYS
CHROMOSPHERE
PHOTOSPHERE
EVAPORATION
FLARE
RIBBONS

FLARE



Timing of Flare-Related Events



McLean & Labrum (1985)

SOLAR FLARE CHARACTERISTICS

IMPULSIVE

- Electron rich
- $^3He/^4He$ =1
- Fe/O = 1
- H/He = 10
- Q_{Fe} = 20
- Duration = hours
- Longitude = 40-70
- Radio Type = III,V(II)
- X-rays = Impulsive
- Events/year = about 1000

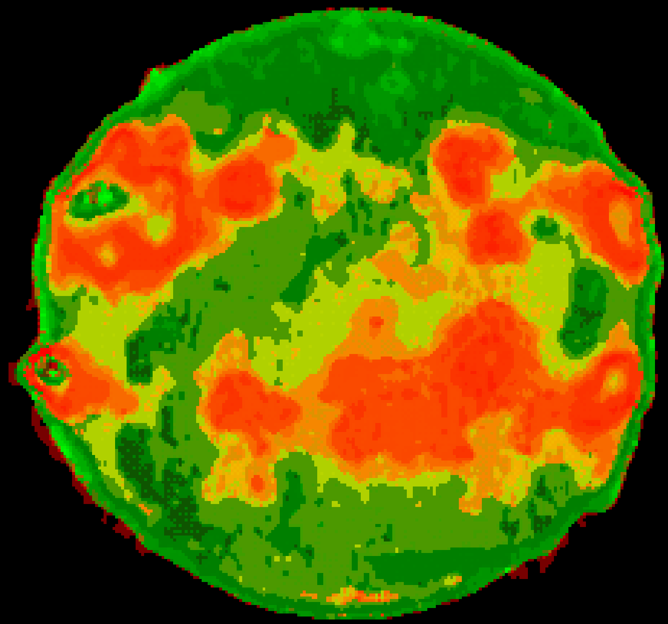
GRADUAL (CMEs)

- Proton rich
- $^3He/^4He$ =0.0005
- Fe/O = 0.1
- H/He = 100
- Q_{Fe} = 14
- Duration = days
- Longitude = more flat
- Radio Type = II,IV
- X-rays = Gradual
- Events/year = about 10

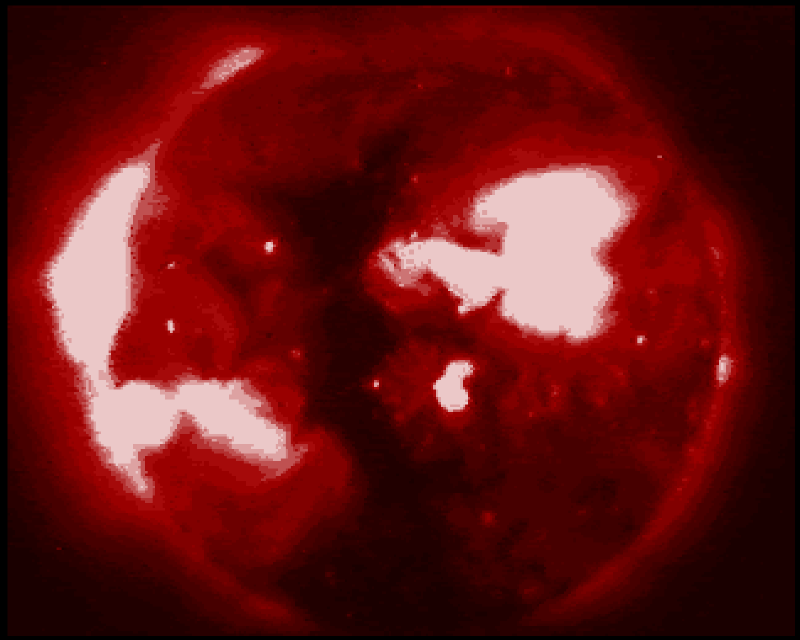
ONLY 1-2% of CMEs produce Solar Energetic Particles

From Grimani & Vocca (2004)

RADIO AND X CORONA



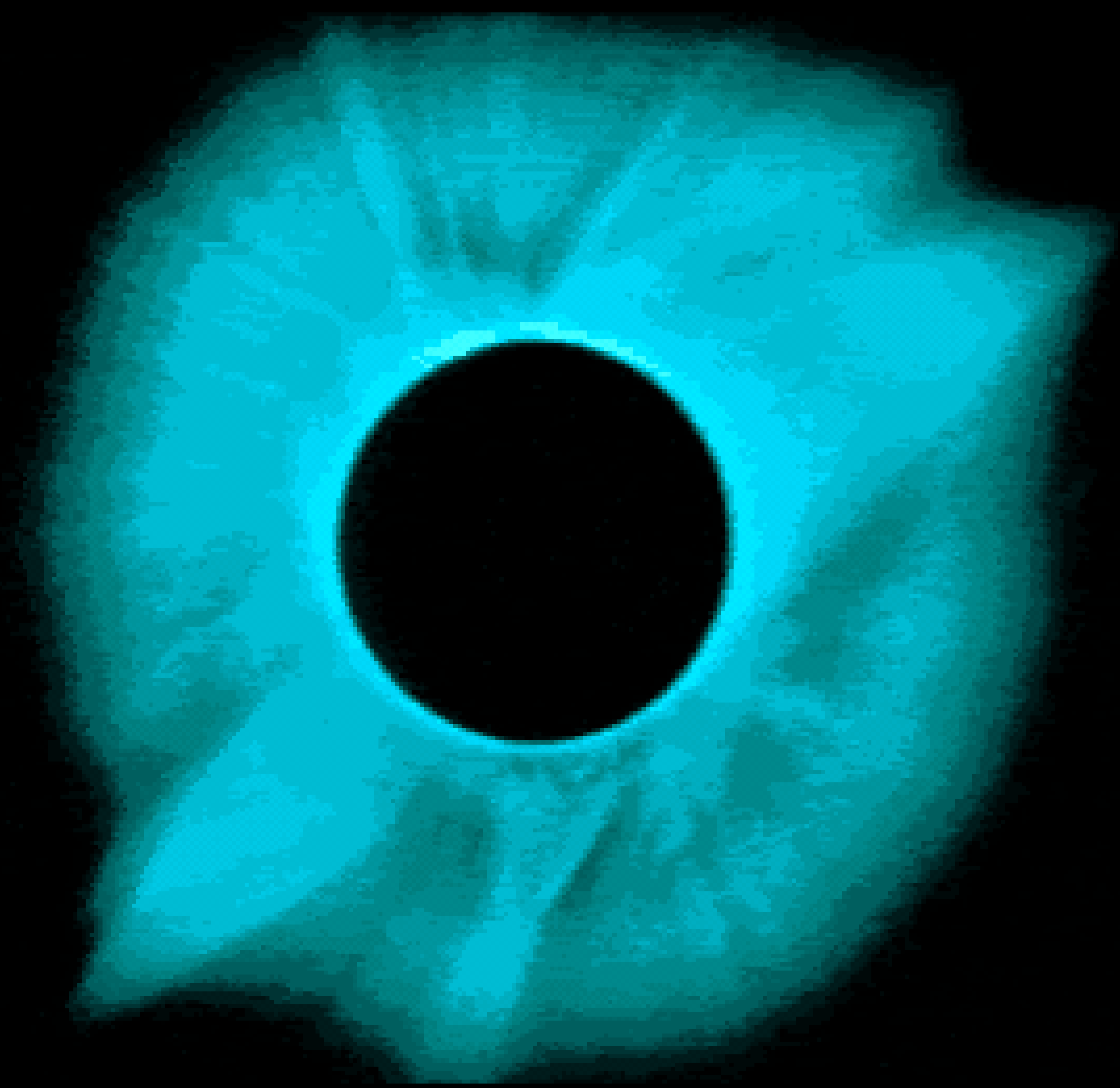
RADIO



X

Messerotti (1999, 2001)

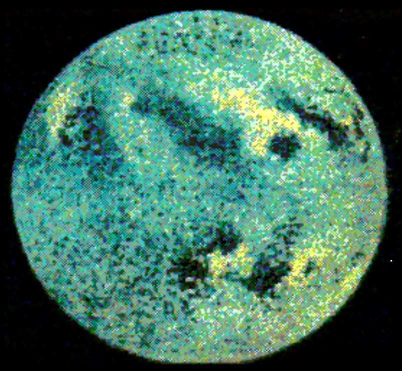
WHITE-LIGHT CORONA



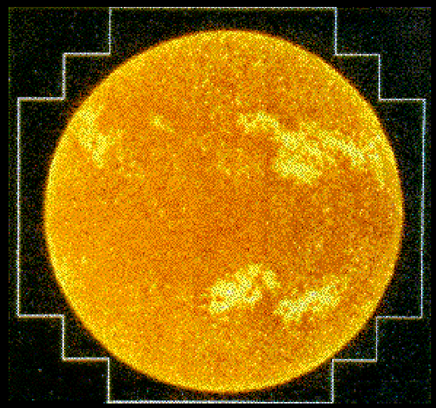
Messerotti (1999, 2001)

THE SOLAR WIND

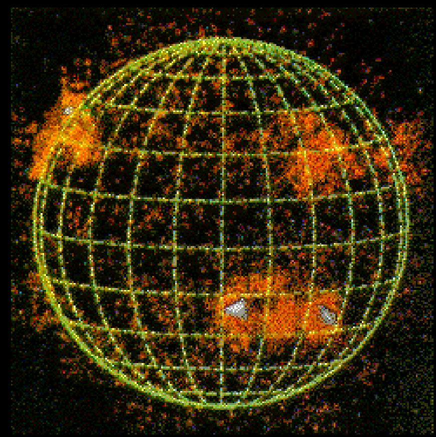
MULTIBAND OBSERVATIONS



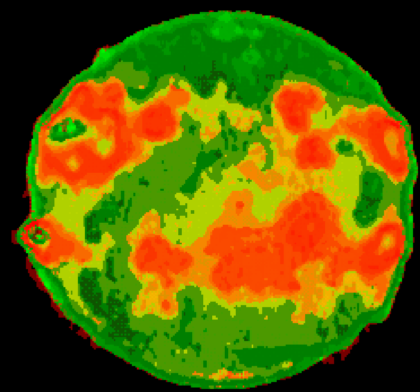
Magnetic Field



UV



X

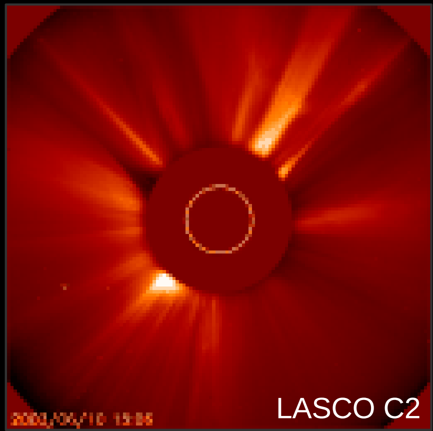


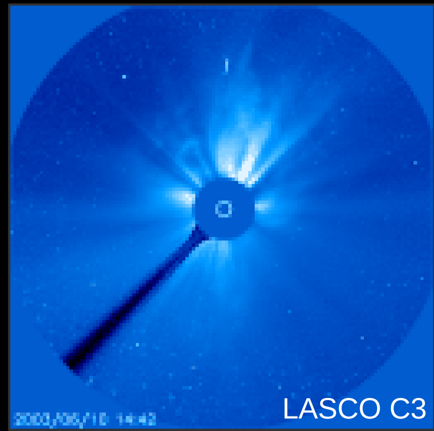
Radio

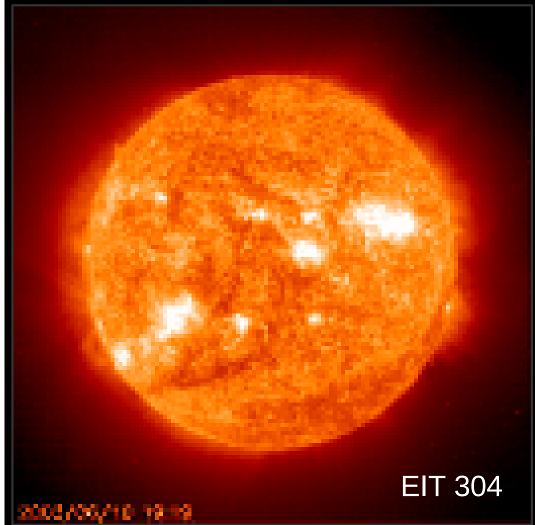
$\delta s < 1$ arcsec
$\delta t < 1$ msec

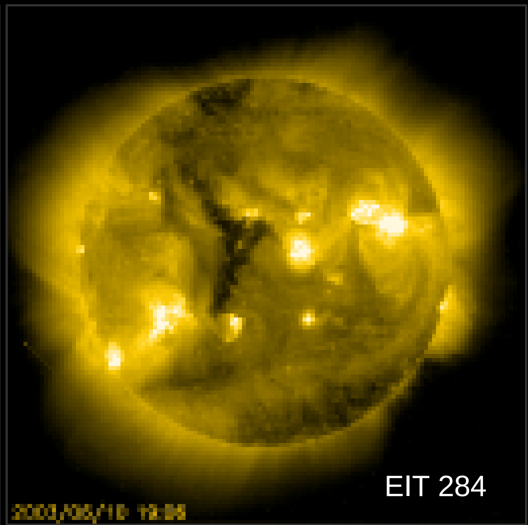
Messerotti (1999, 2001)

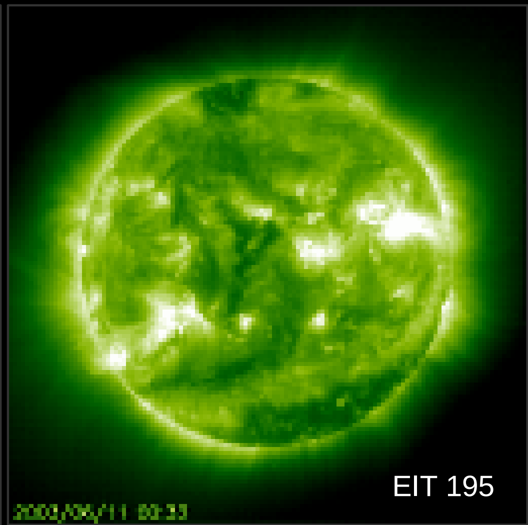
SPACE-BASED MULTIBAND OBSERVATIONS FROM SOHO

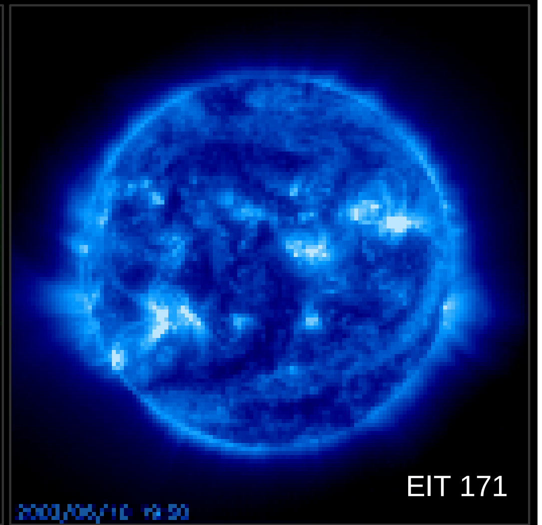


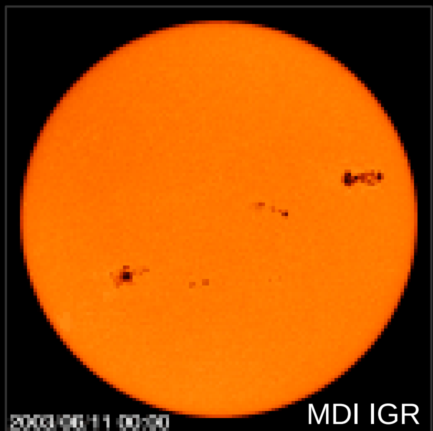






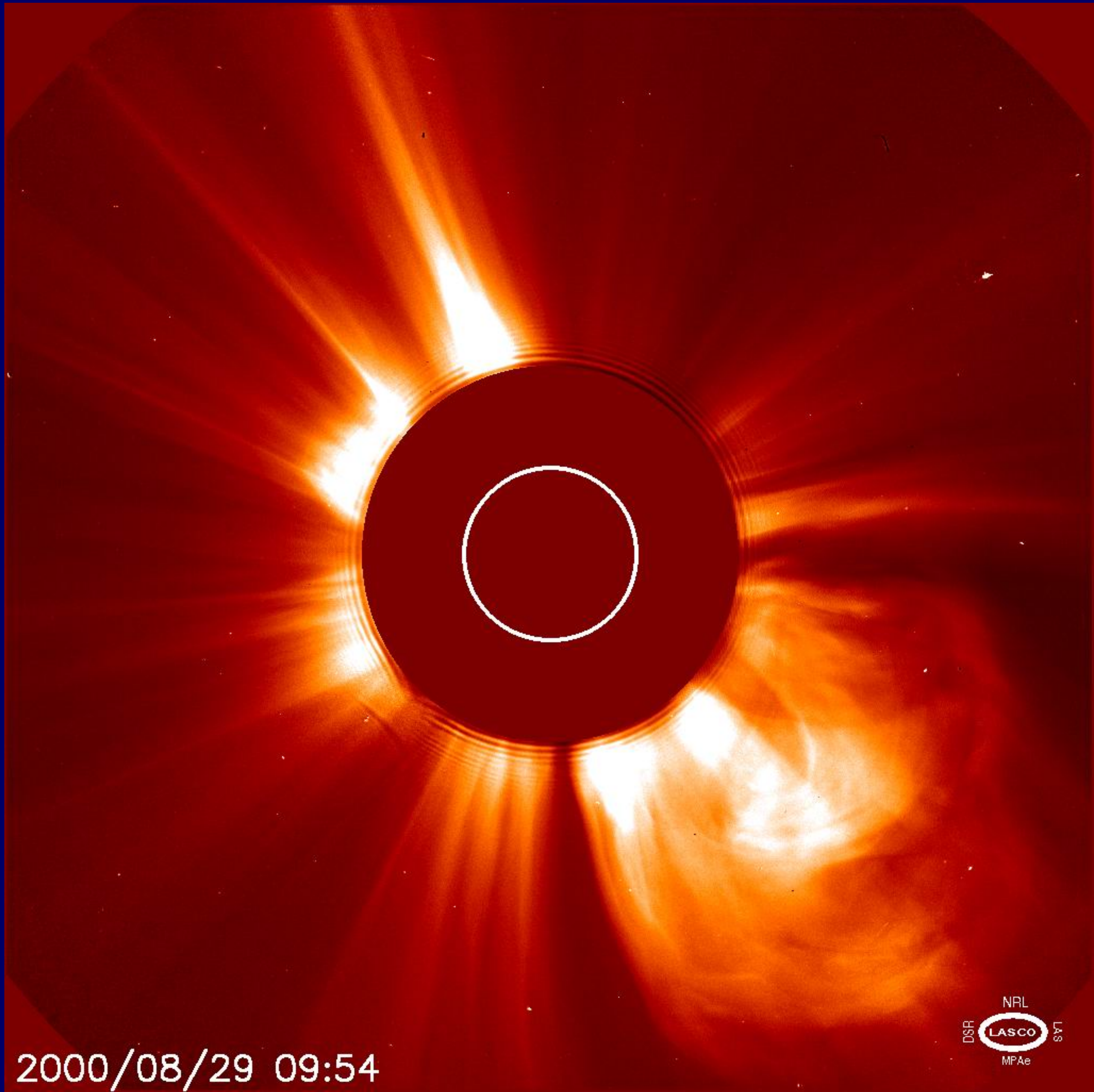






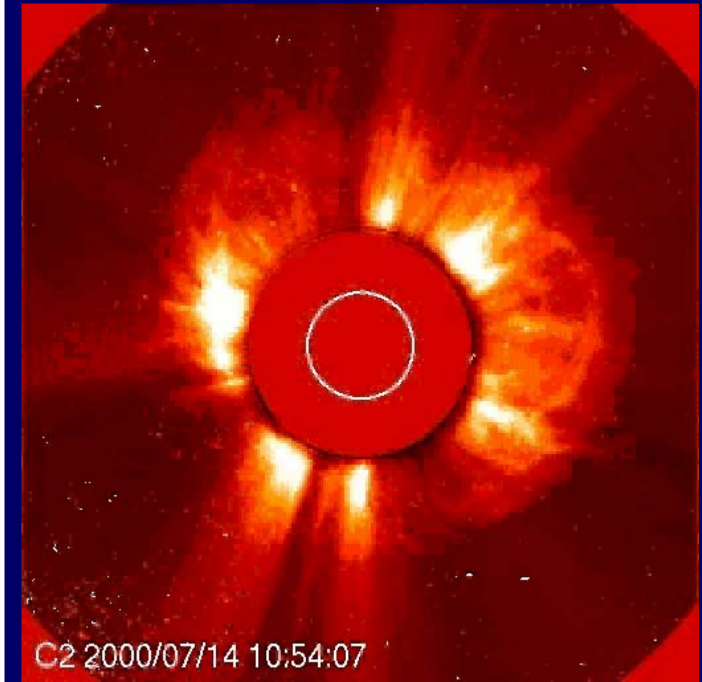
Messerotti (1999, 2001)

A Coronal Mass Ejection (CME)



Messerotti (1999, 2001)

CME Evolution and Particle Storm



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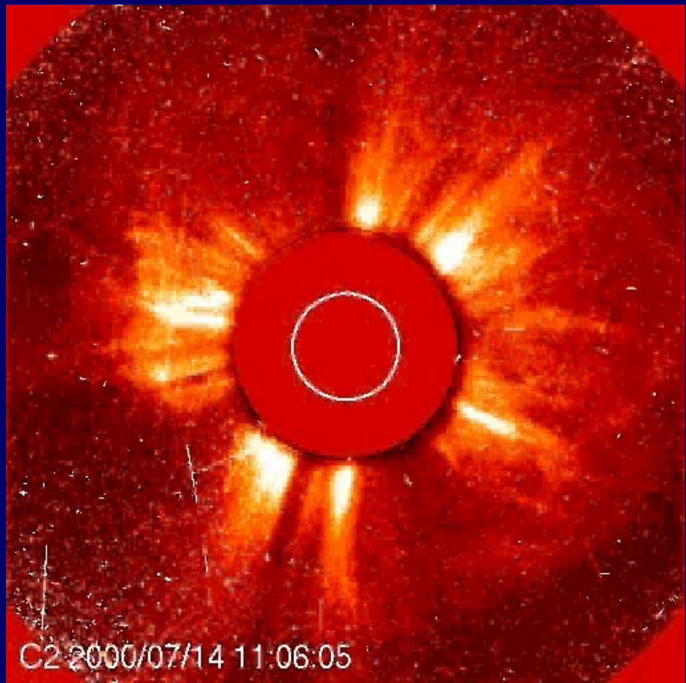

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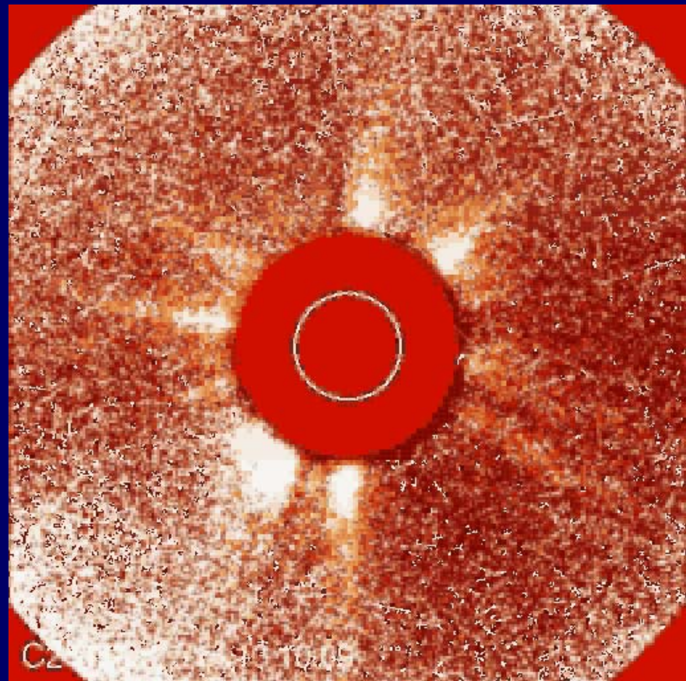
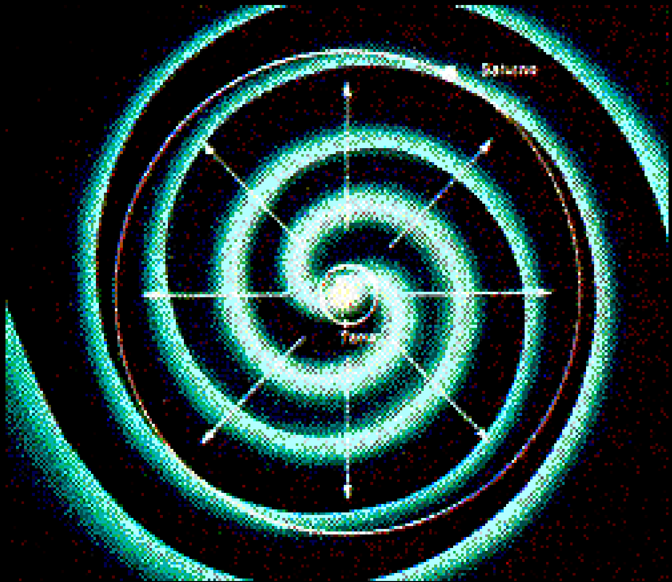


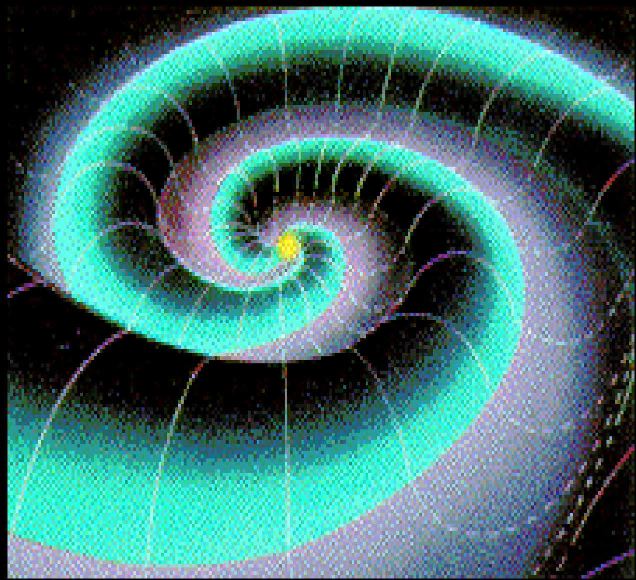
3

Messerotti (1999, 2001)

SOLAR WIND STRUCTURE



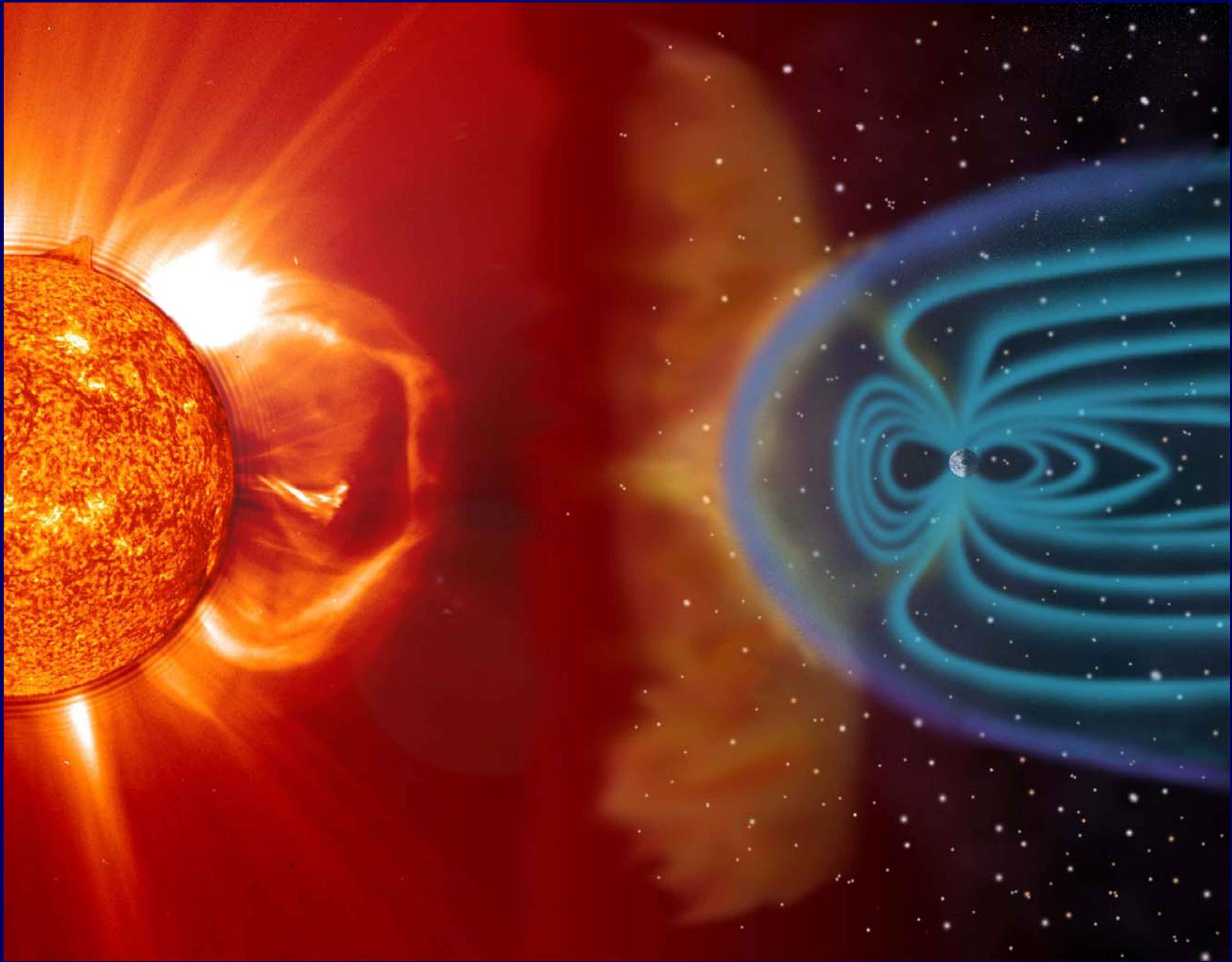
2-D



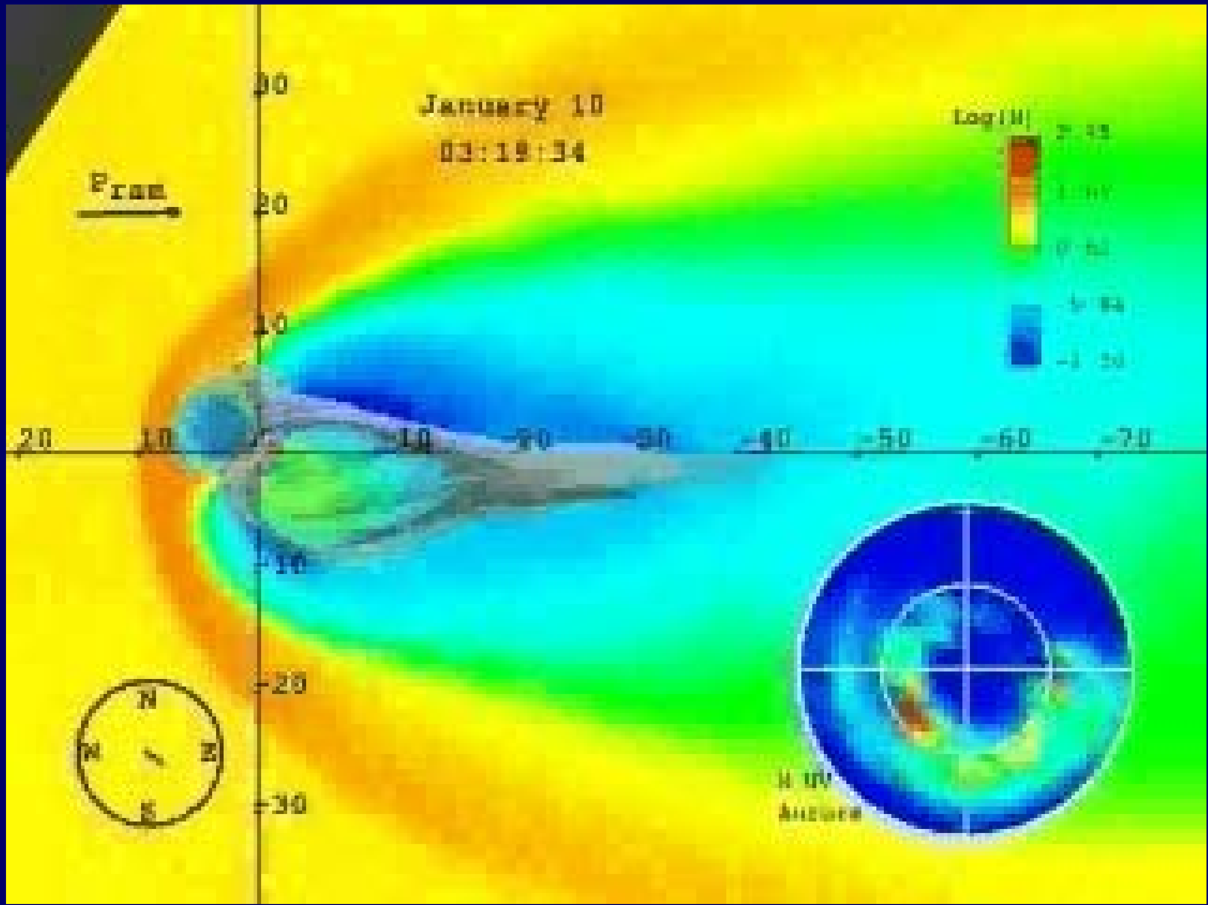
3-D

Messerotti (1999, 2001)

A CME HITS THE EARTH MAGNETOSPHERE

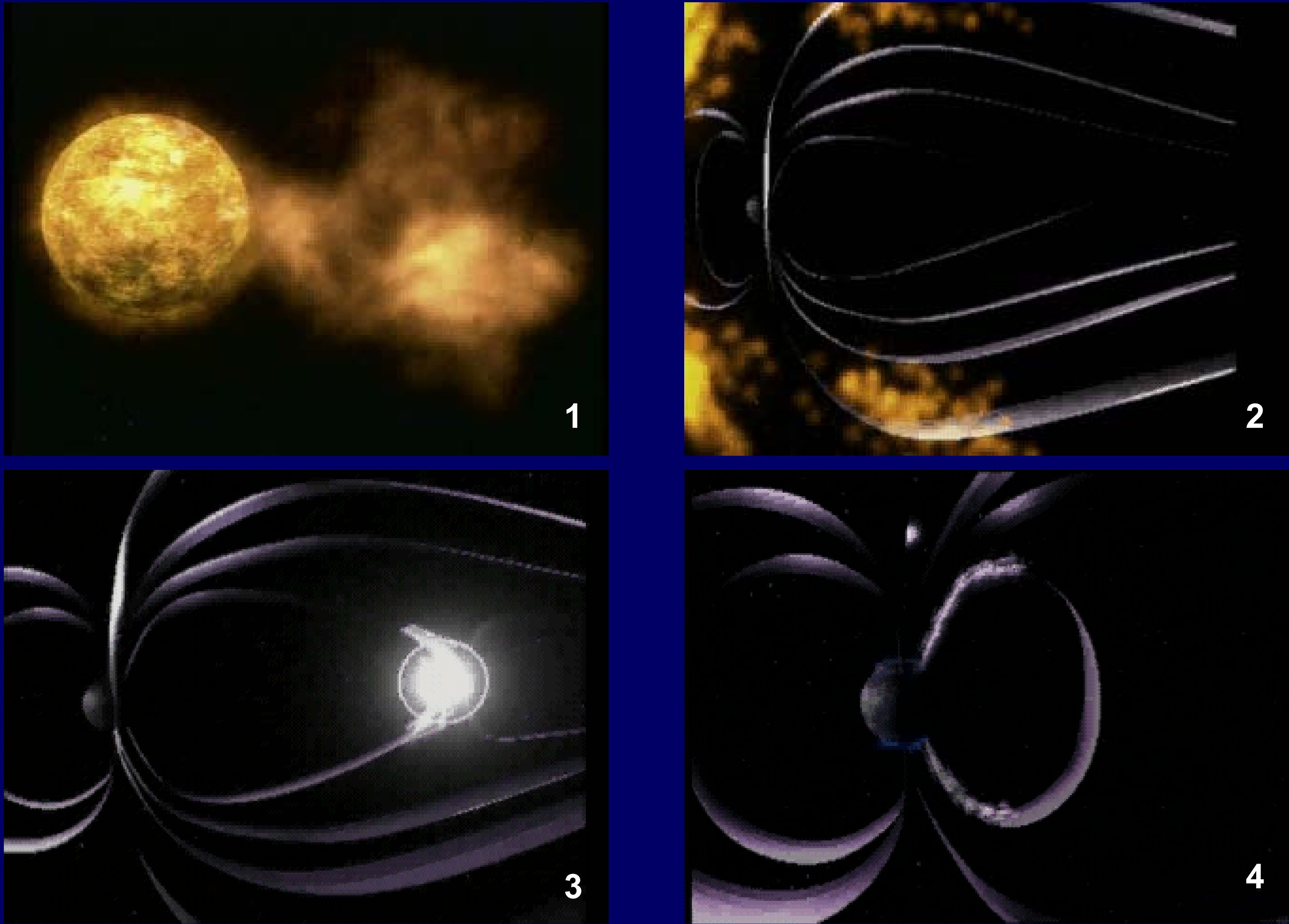


MAGNETOSPHERE COMPRESSION

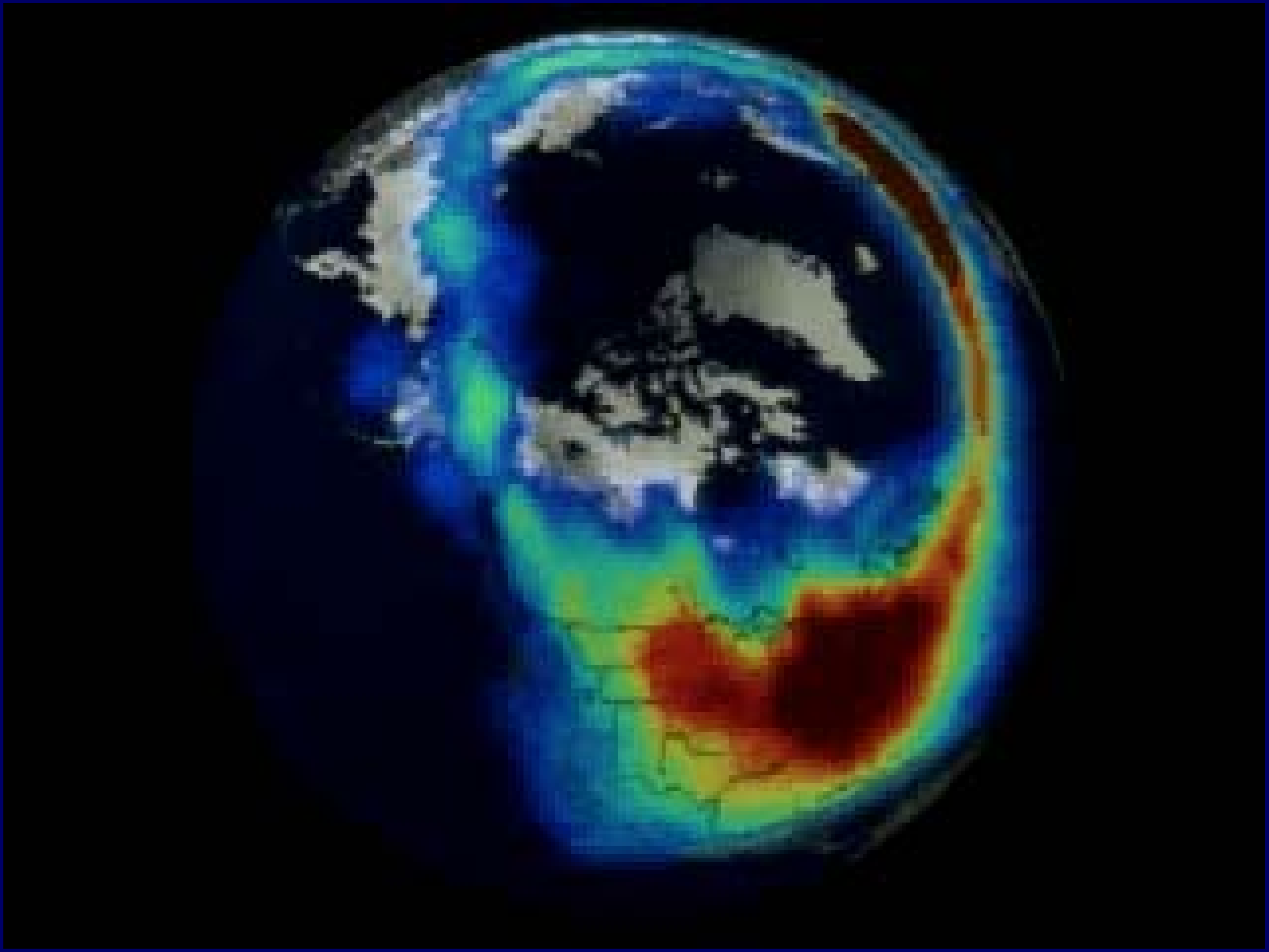


From Goodrich modelling

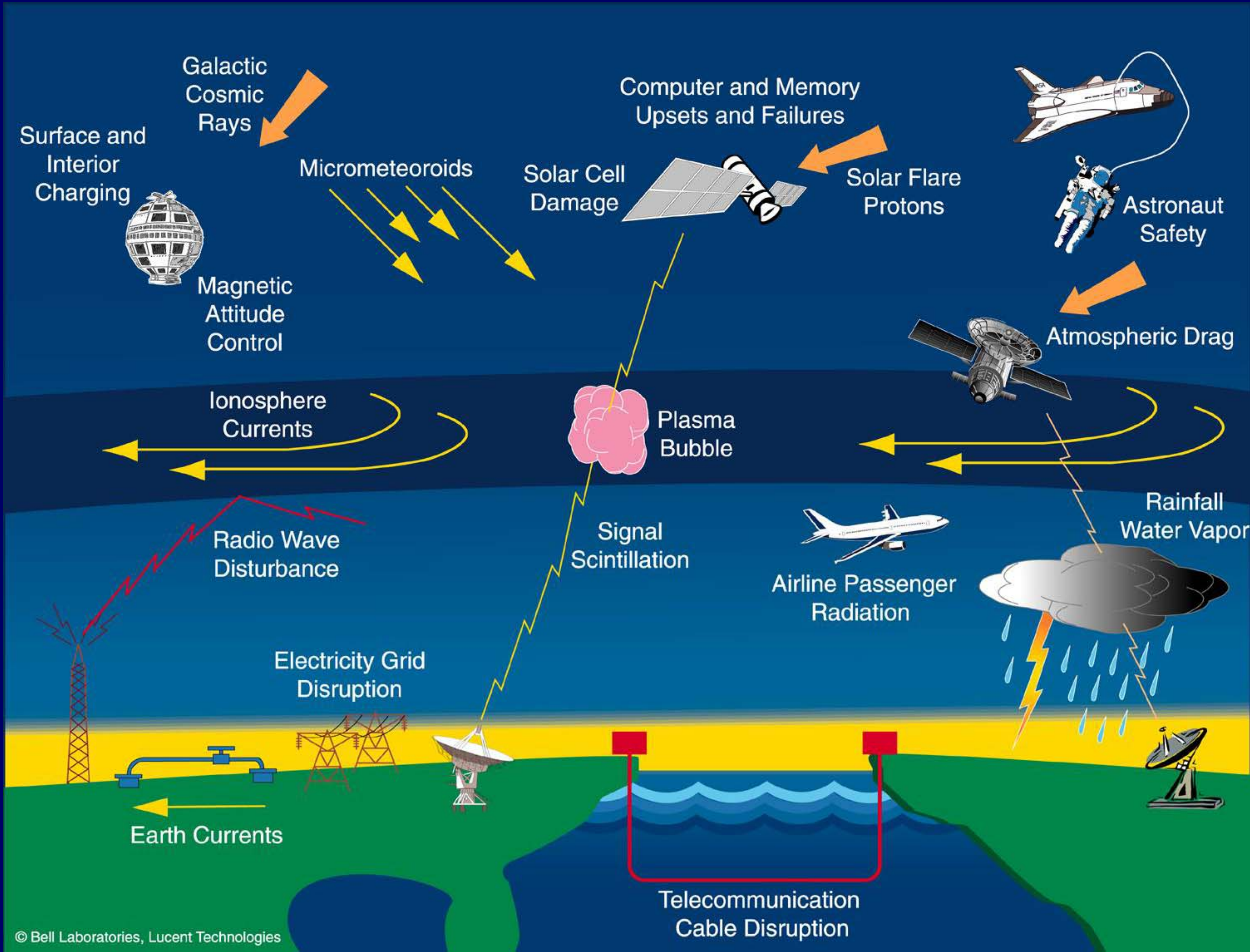
CME-MAGNETOSPHERE INTERACTION



AURORAL OVAL

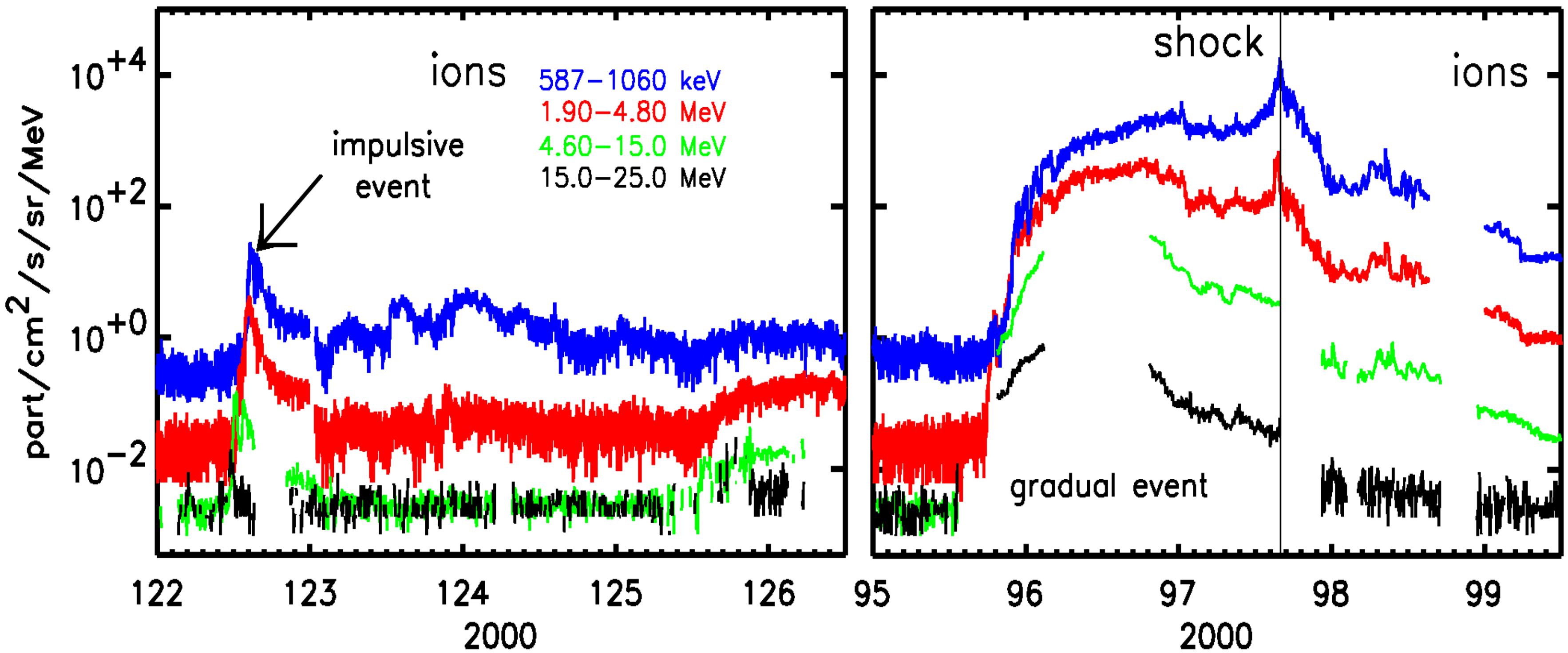


SPACE WEATHER EFFECTS AT THE EARTH



Solar Energetic Particle (SEP) Events

- Impulsive
- Gradual (interplanetary shock-accelerated particles)



Time profiles of protons for an impulsive (left) and a gradual (right) SEP event as measured by ACE/EPAM (two lower energy channels) andIMP-8/CPME. (two high energy channels)

From Sanahuja et al. (2004)

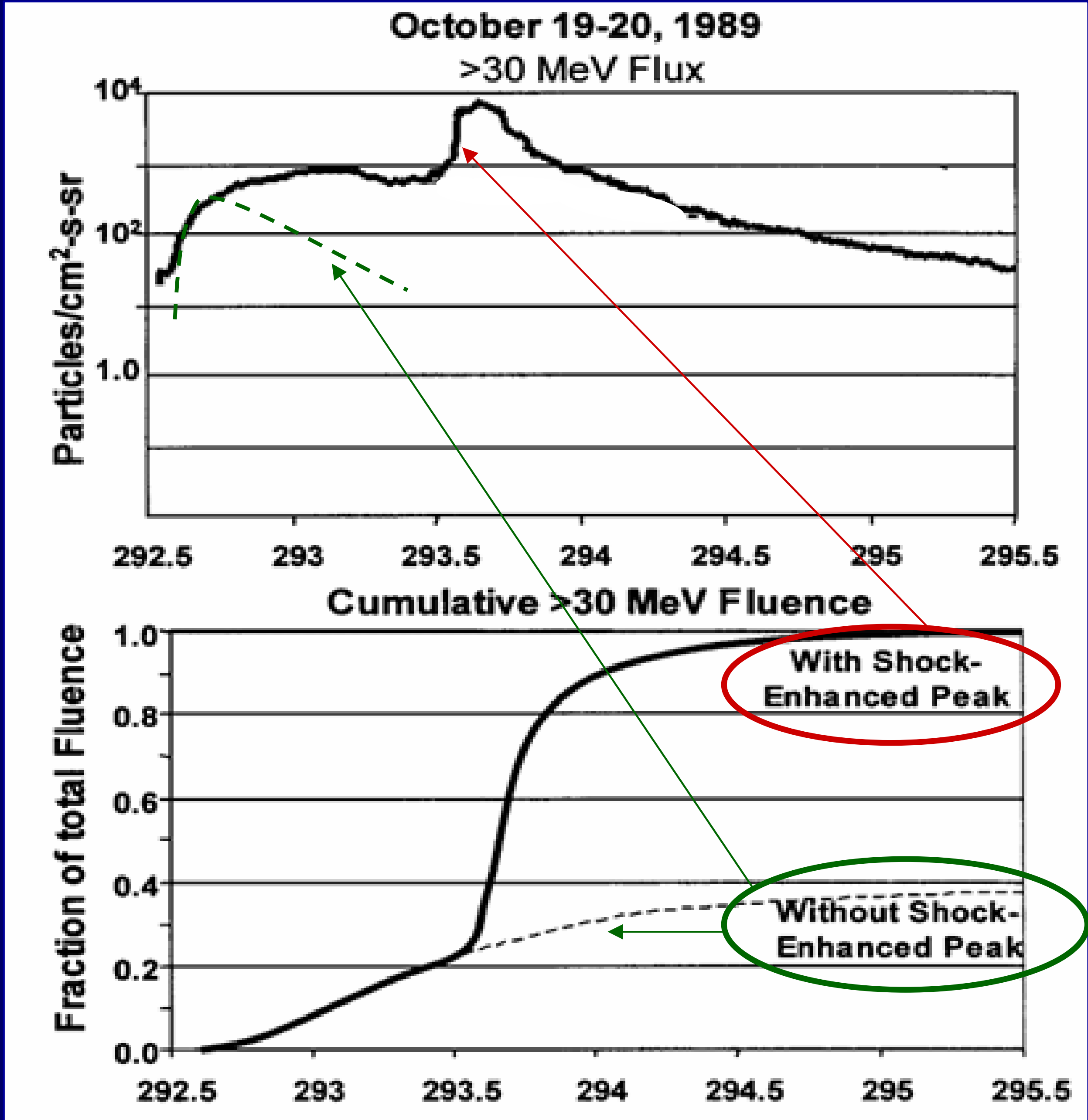
The Problem

Gradual SEP events

- Possible impulsive (solar) component
- Contribution to flux and fluence of particles accelerated at the front of the interplanetary shock

Without an IP shock …

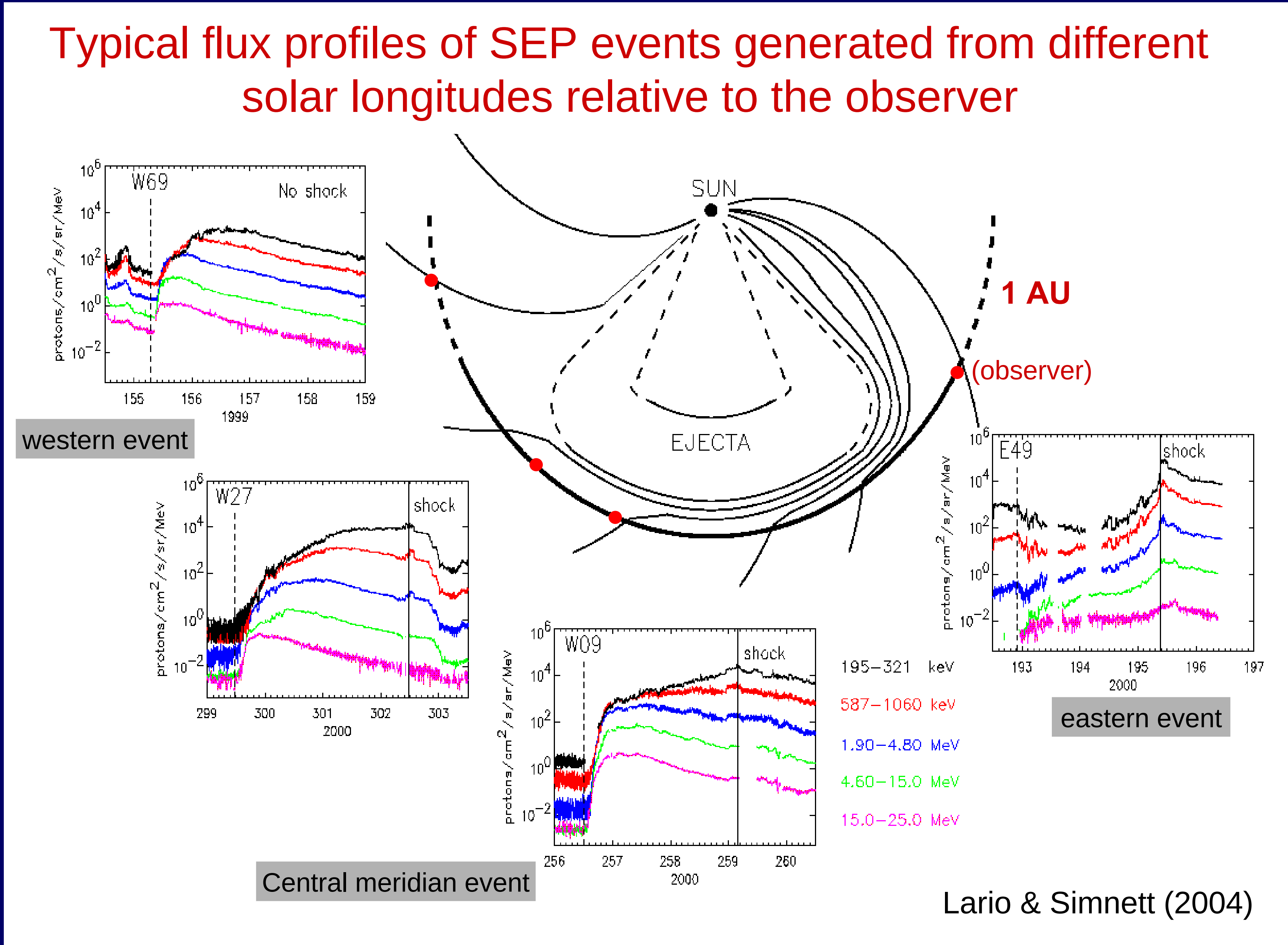
- How to explain the observed fluence?
- How to explain the peak flux?



Data from GOES spacecraft (Turner, 2001)

From Sanahuja et al. (2004)

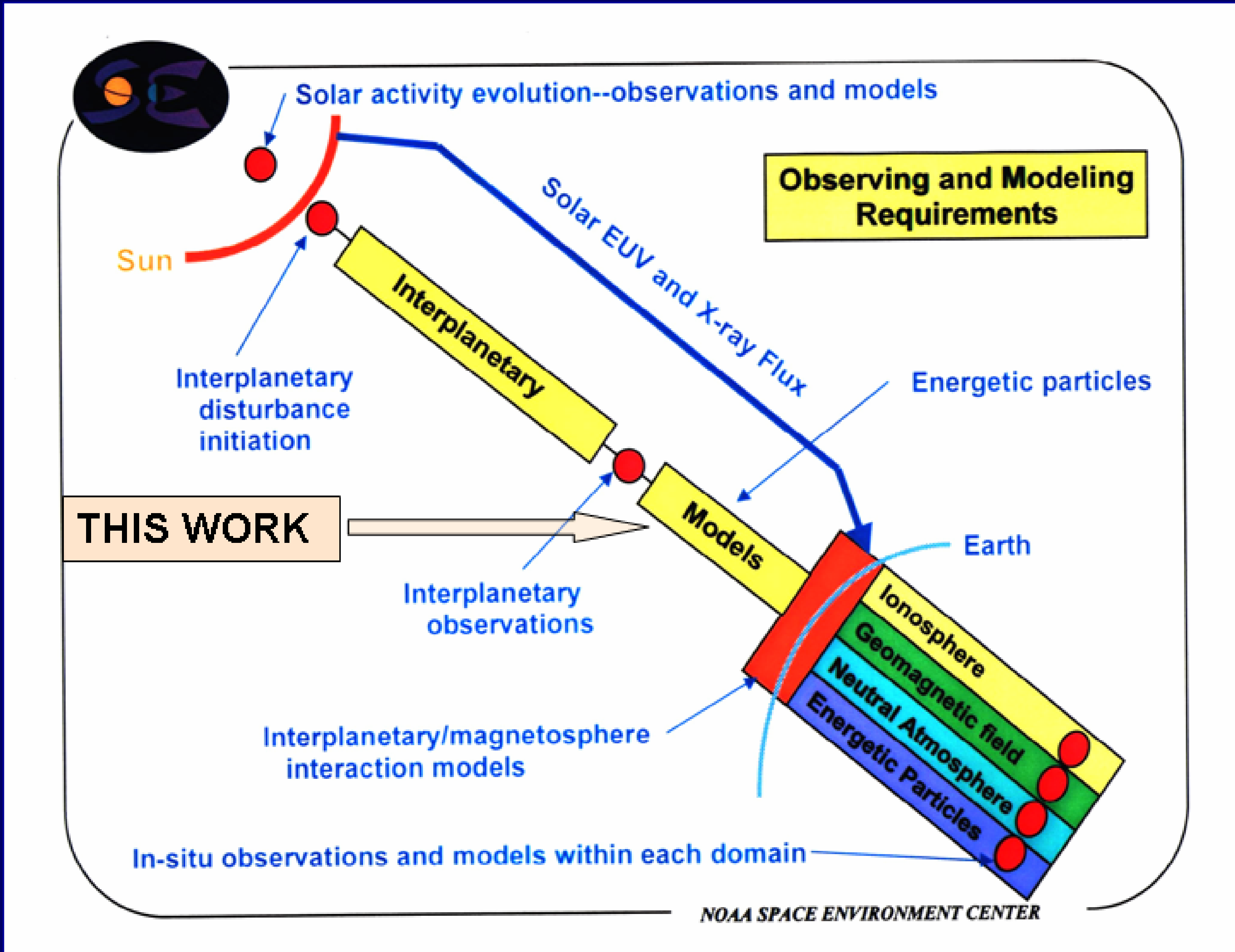
Typical Flux Profiles of SEPE generated at different longitudes



ACE/EPAM and IMP-8/CME data. Dashed vertical lines: occurrence of the parent solar event. Solid vertical lines: arrival of the interplanetary shock

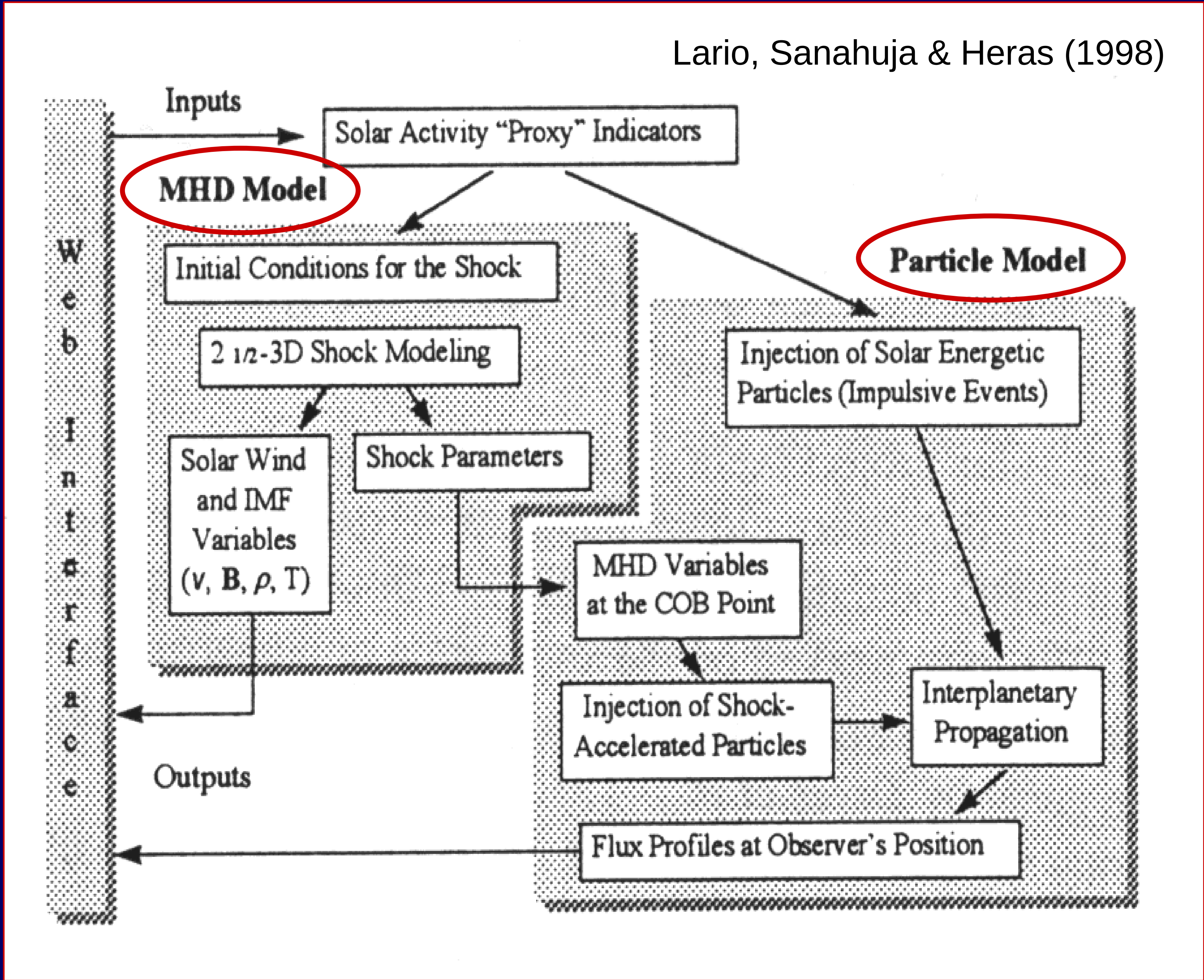
From Sanahuja et al. (2004)

Solar Energetic Particle (SPE) Events: The Scenario



From Sanahuja et al. (2004)

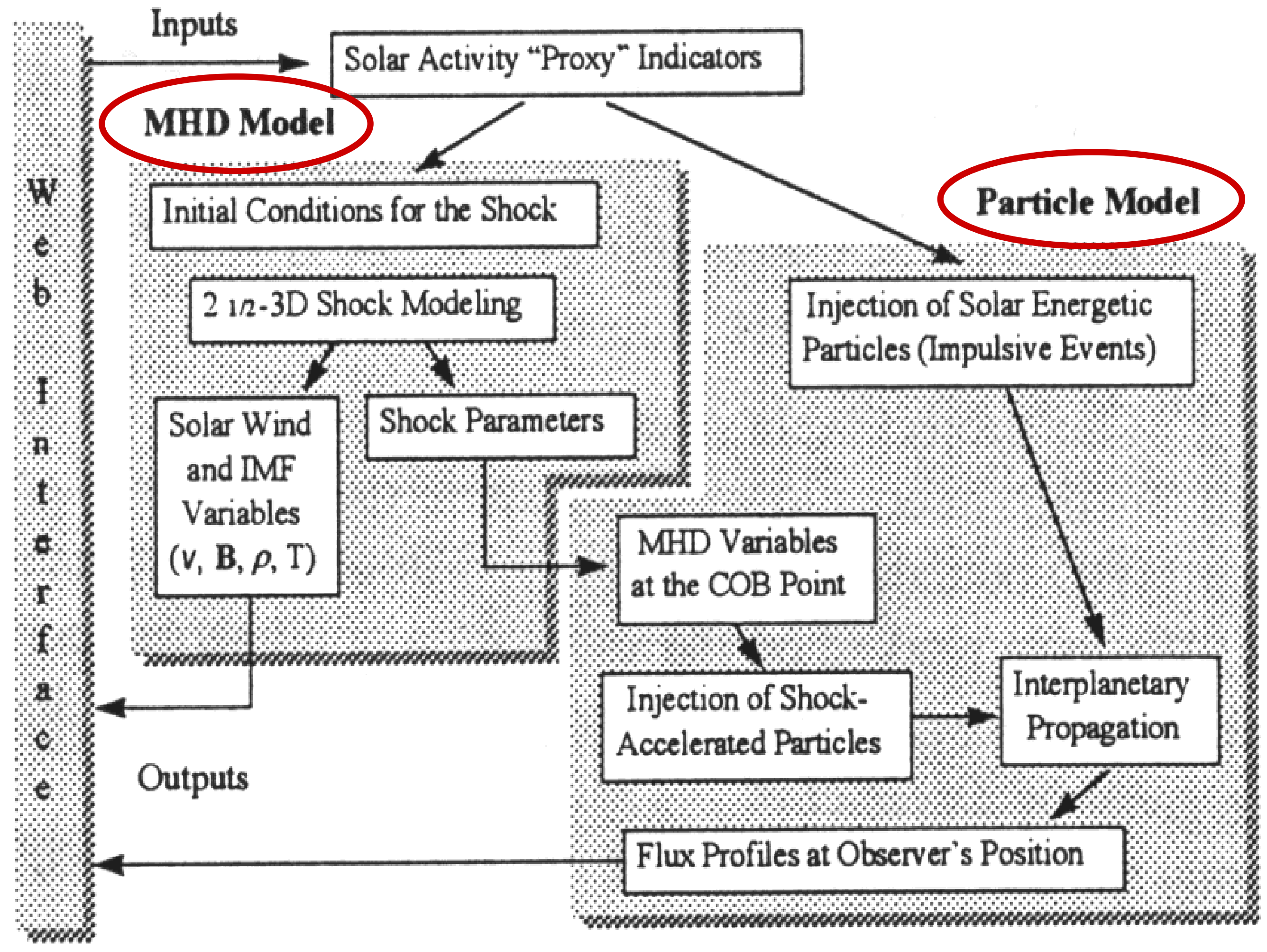
IP Shock-plus-Particle Propagation Model



From Sanahuja et al. (2004)

IP Shock-plus-Particle Propagation Model

Lario, Sanahuja & Heras (1998)



Synthetic proton flux and anisotropy profiles by:

1. Running the MHD model
2. Calculating the injection rate through Q(VR)
3. Running the particle transport code

From Sanahuja et al. (2004)

SOLPENCO

Main purpose ⇨ Provide the capability to quantitatively and rapidly predict SEP upstream fluxes and fluences generated by CME-driven shocks

For:

- **Proton energies between 88 keV and 90 MeV**
- **Shock initial velocities (at 18 $R_{\odot}$) ranging from 750 km s^{-1} to 1800 km s^{-1}**
- **Observers located at 1 AU and 0.4 AU with heliolongitudes ranging from W90 to E75**

From Sanahuja et al. (2004)

Modelling the Interaction of GCR and SCR

Computer simulation of

- particle trajectories in the Earth‘s magnetosphere by using a mathematical model of the Earth‘s magnetic field

and of

- interactions with the Earth‘s atmosphere, taking into account relevant nuclear particle physics

From Flueckiger & Desorgher (2004)

Tools

Two Geant4 applications

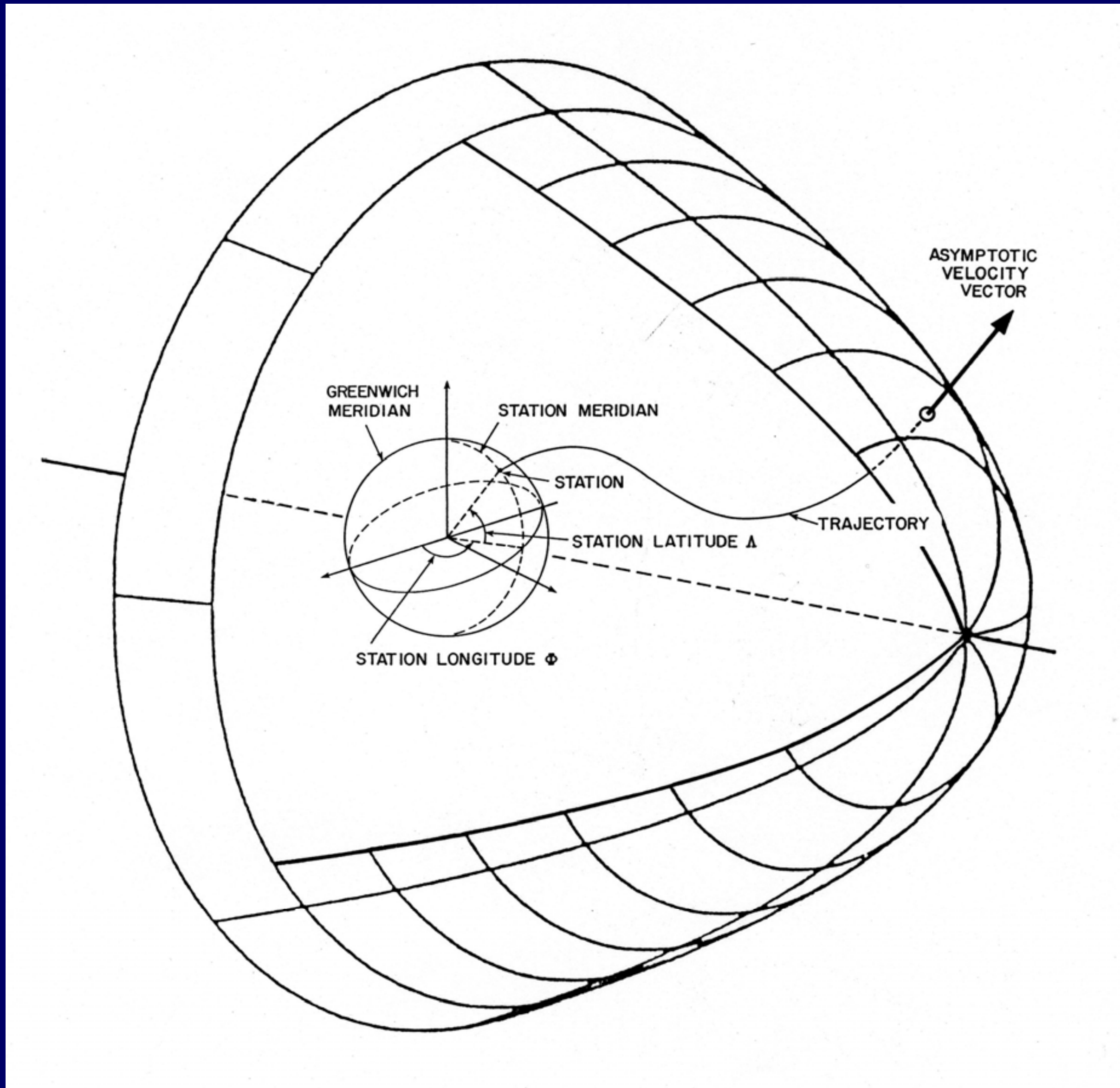
- Magnetocosmics

and

- Atmocosmics

From Flueckiger & Desorgher (2004)

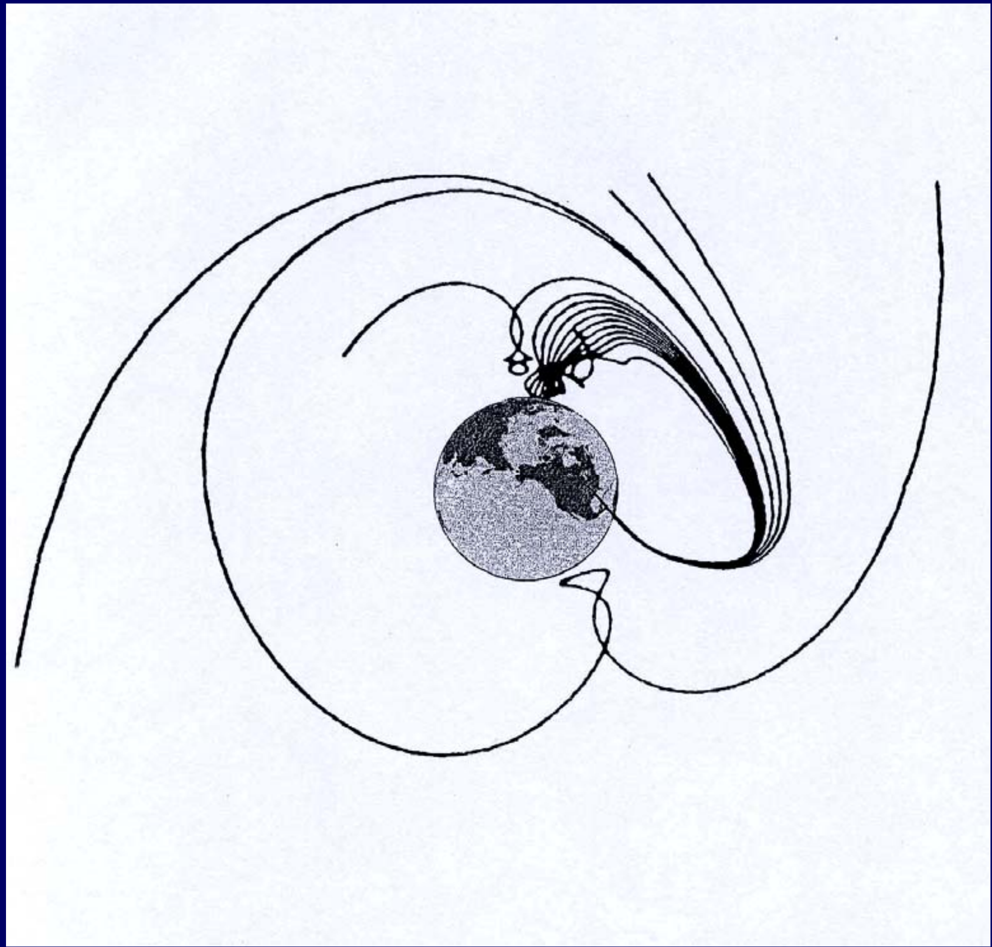
Magnetocosmics I



Cosmic Ray Trajectories

From Flueckiger & Desorgher (2004)

Magnetocosmics II

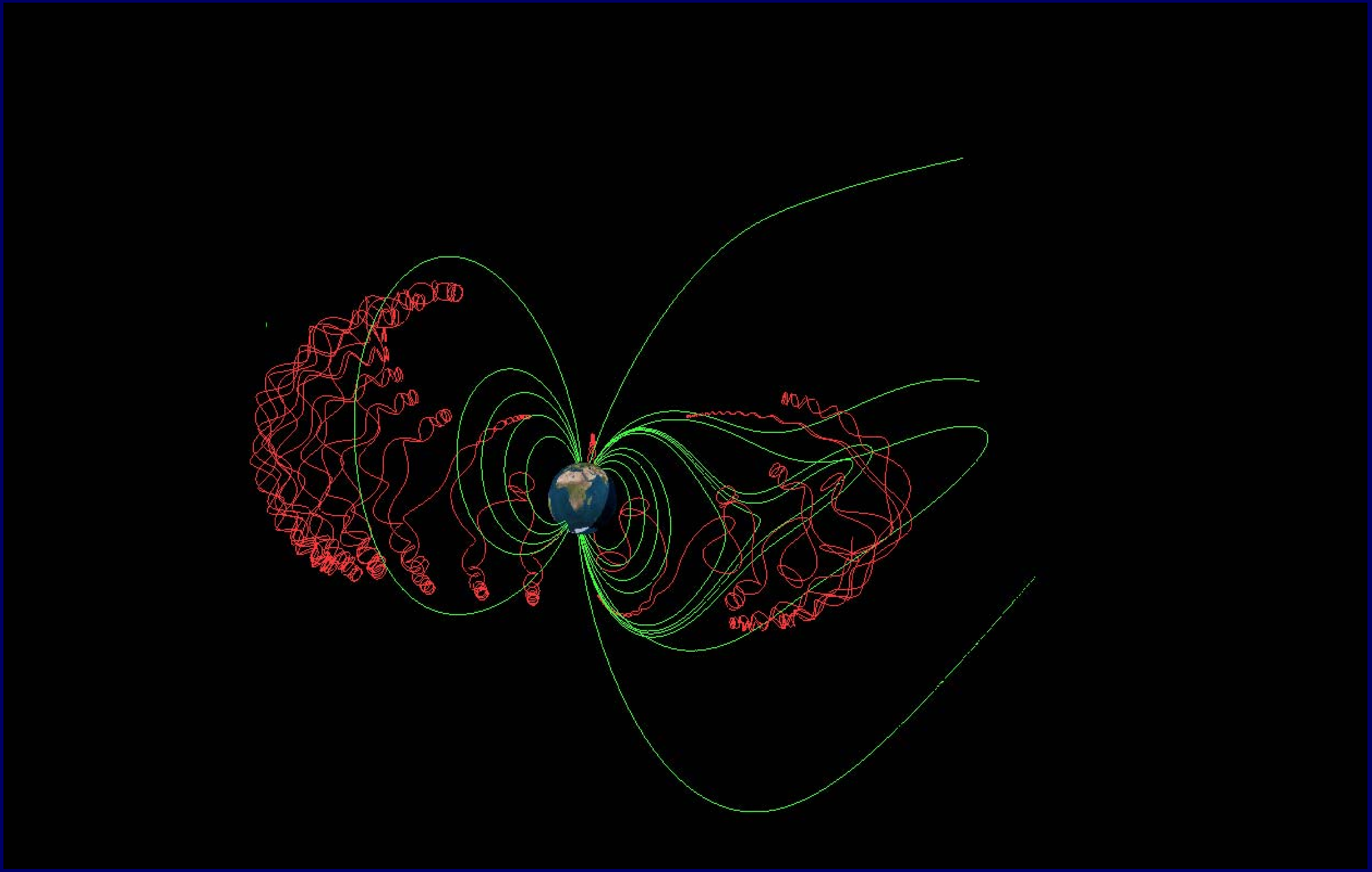


Cosmic Ray Trajectories

Cutoff Energy / Cutoff Rigidity

From Flueckiger & Desorgher (2004)

Magnetocosmics III



Cosmic Ray Trajectories - p – 1 GeV

From Flueckiger & Desorgher (2004)

Magnetocosmics IV

Combined with additional input information the program yields primary particle spectra of

Galactic Cosmic Rays (GCR) and
Solar Cosmic Rays (SCR)

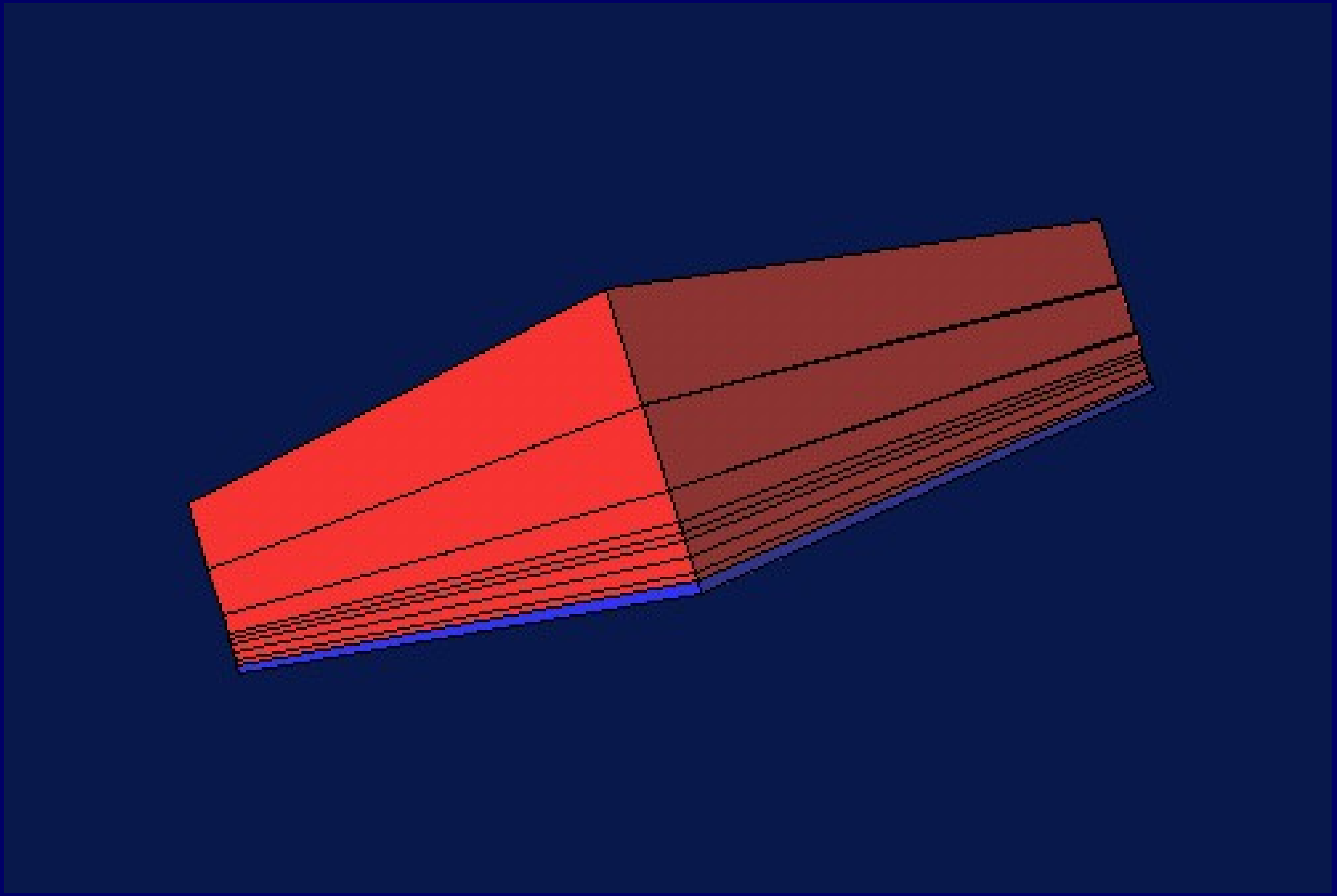
at the top of the atmosphere in dependence of:

- position
- time

including effects of e.g. local time position, geomagnetic activity, modulation

From Flueckiger & Desorgher (2004)

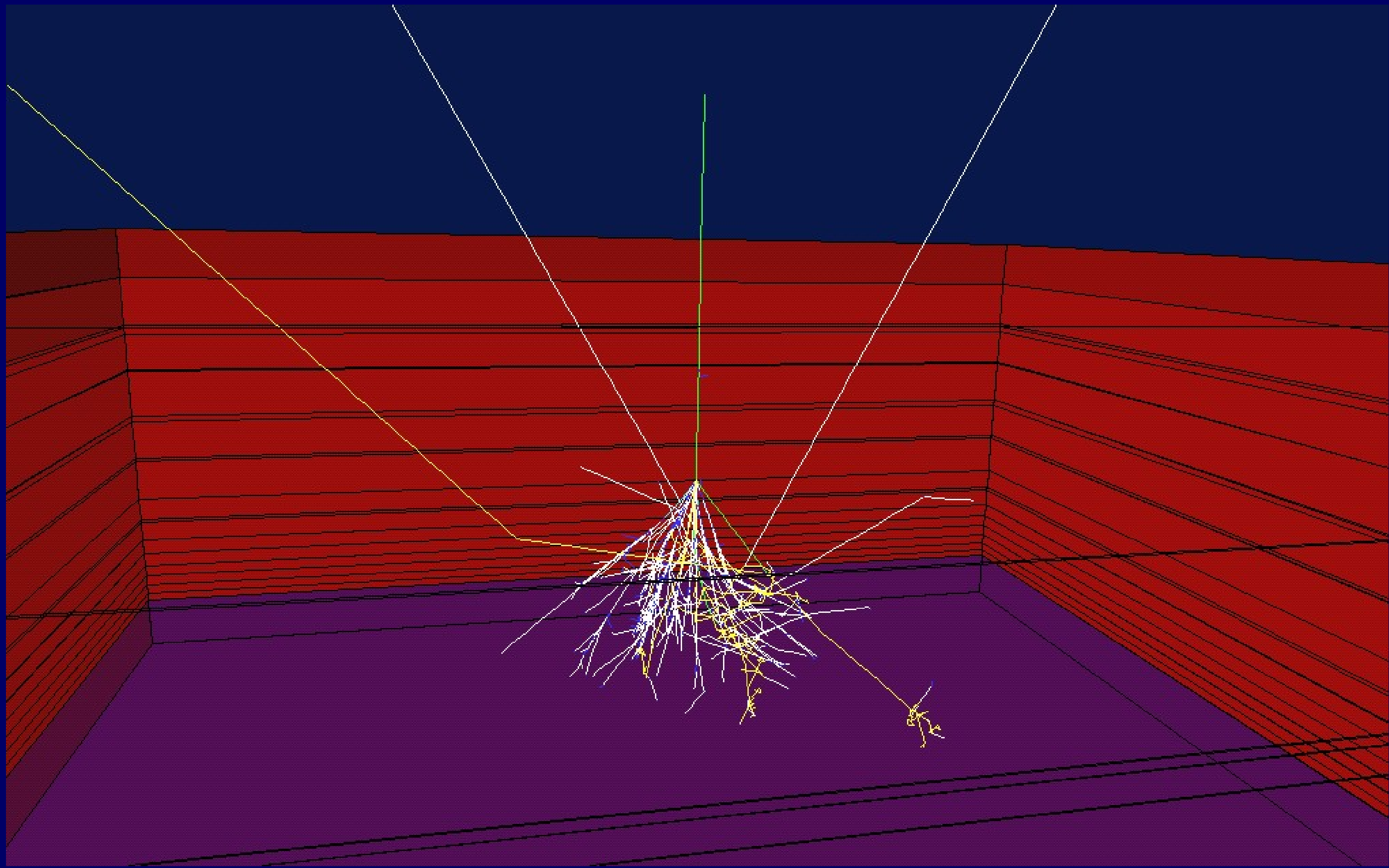
Atmocosmics I



Atmosphere – Layer Structure

From Flueckiger & Desorgher (2004)

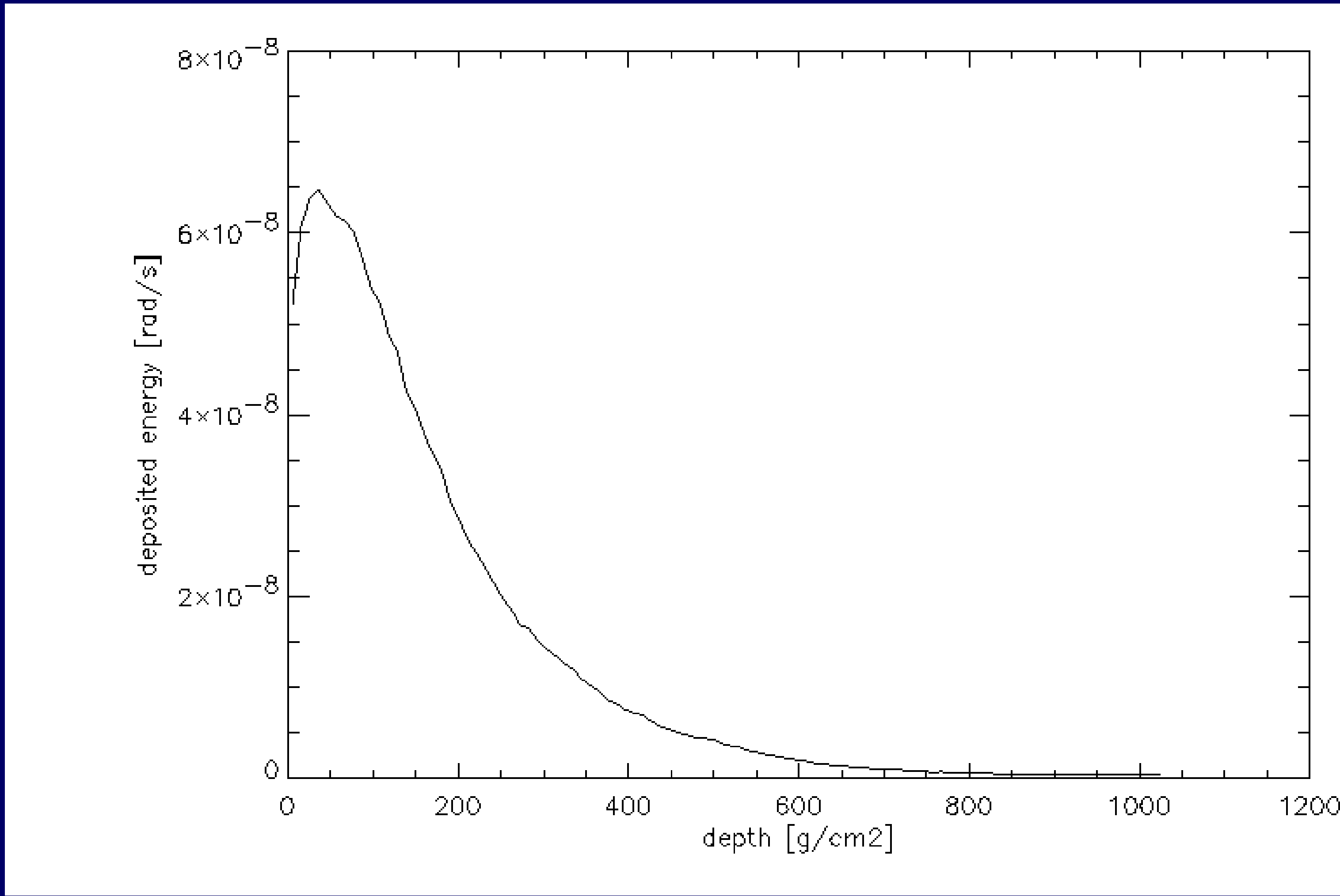
Atmocosmics II



Atmospheric cascade initiated by a 1 GeV proton

From Flueckiger & Desorgher (2004)

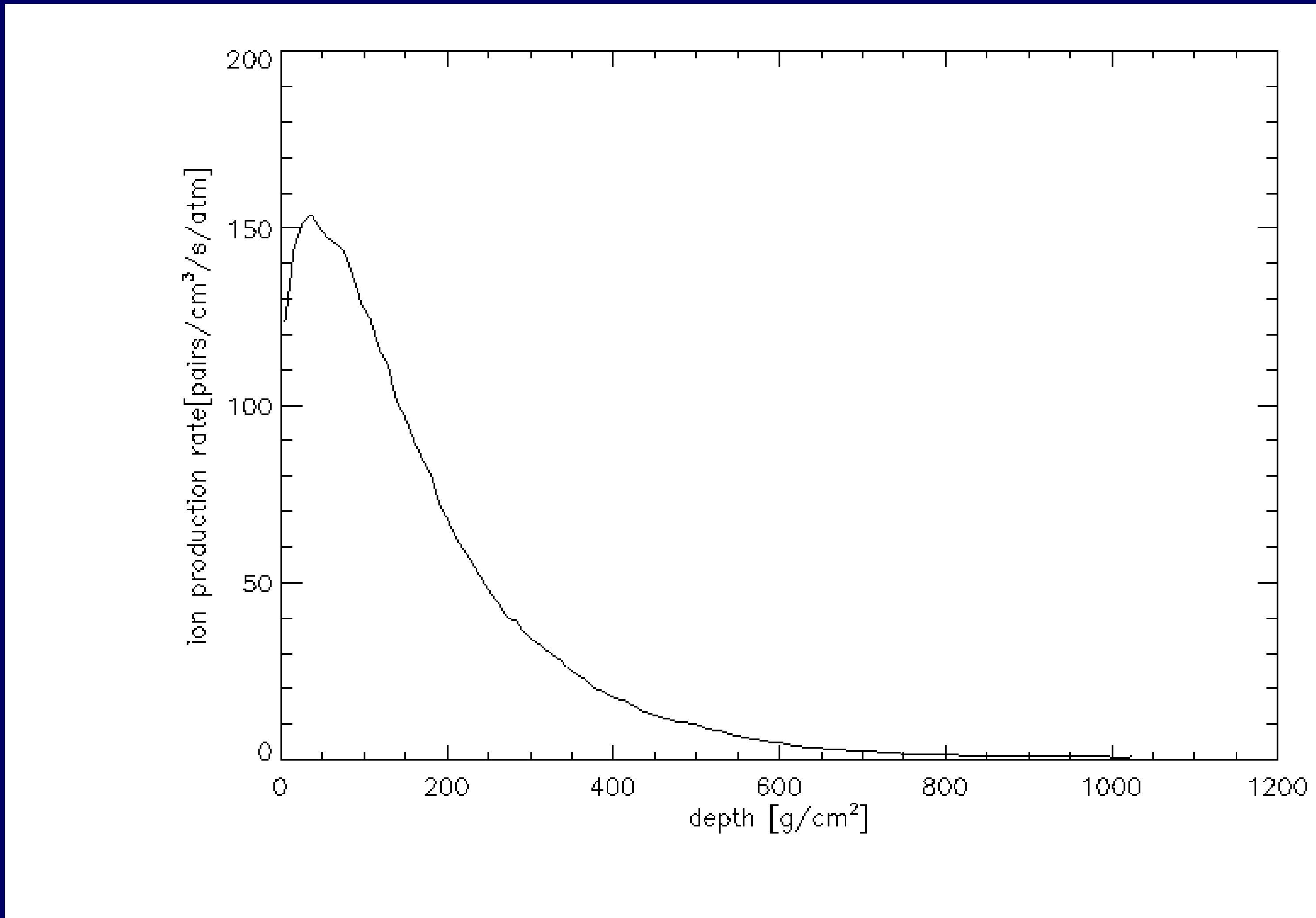
Atmocosmics III



Energy deposit vs. Atmospheric depth
Solar Maximum - 45°N / 0°E - 10‘000 p

From Flueckiger & Desorgher (2004)

Atmocosmics IV



Ion production vs. Atmospheric depth
Solar Maximum - 45°N / 0°E - 10‘000 p

From Flueckiger & Desorgher (2004)

Monitoring Scenario: The Pros

- SOLAR WEATHER MONITORS
  - Radiation & particles
    - Space-based detection (e.g. SOHO)
    - Ground-based detection (many instruments)
  - Monitored phenomenology
    - Inner plasma
    - Photospheric plasma
    - Chromospheric plasma
    - Coronal plasma
    - Extended coronal plasma

Messerotti & Lundstedt (2004)

Monitoring Scenario: The Cons

- SPACE-* and GROUND-BASED MONITORS
  - INCOMPLETENESS in
    - Phenomenology coverage
    - Spatial coverage
    - Temporal coverage
    - Energy coverage
  - MOSTLY NON-REAL-TIME OPERATIONS
  - LIMITATIONS IN TELEMETRY*
  - UNGUARANTEED MISSION*/OPERATION CONTINUITY
  - LIMITED MISSION*/OPERATION DURATION
  - MISSION*/INSTRUMENTATION DESIGN DRIVEN BY “ALCHEMIC POLITICAL” CONSTRAINTS

Messerotti & Lundstedt (2004)

Monitoring Scenario: The Data Issues

- COMMON TO SPACE- AND GROUND-BASED MONITORS:
  - HUGE NUMBER OF DATA SETS
  - LARGE NUMBER OF DATA STANDARDS
  - LIMITED DATA AVAILABILITY
  - NON-REAL-TIME AVAILABILITY
  - LIMITED DATA ACCESSIBILITY
  - NON-USER-FRIENDLY SEARCH AND RETRIEVAL
  - DIFFICULT DATA CALIBRATION
  - COMPLEX DATA ANALYSIS
  - LIMITED CROSS-DATA AN.

- POSSIBLE SOLUTIONS TO MOST ISSUES:
  - NONE: WILL INCREASE TO PBs
  - COORDINATION ON COMMON STANDARDS
  - AGREEMENT ON DATA POLICIES
  - DEVELOPMENT OF VIRTUAL MONITORS
  - IMPROVEMENT IN WEB ACCESSIBILITY
  - ADVANCED DATA HANDLING
  - INCORPORATION OF S/W LIBRARIES
  - DEVELOPMENT OF VIRTUAL OBSERVATORIES

HS NETWORKING, HPC, I-GRID

Messerotti & Lundstedt (2004)

Modelling Scenario: The Cons

- NO SELF-CONSISTENT THEORY for:
  - AR formation & evolution
  - FLARE triggering, acceleration, radiation
  - PROMINENCE fomation & eruption
  - CME generation & propagation
  - CME plasmoid structure and magnetic field
  - SLOW SW generation, evolution & topology
  - FAST SW generation, evolution & topology
  - IP MAGNETIC FIELD topology
  - INTERACTION with GMF

Messerotti & Lundstedt (2004)

Forecasting Scenario: The Cons

- LIMITED RESULTS for:
  - AR formation & evolution
    - Expert Systems based on a posteriori modelling
  - FLARE occurrence & class
    - Statistical methods based on precursors & SOC
    - Mainly nowcasting
  - CME formation & evolution
    - Statistical methods based on precursors
    - Mainly nowcasting

- STATE-OF-THE-ART based on hybrid approach involving AI TECHNIQUES

- MAIN ISSUE is LACK of SCIENTIFIC KNOWLEDGE on the PHYSICS

Messerotti & Lundstedt (2004)

SOLAR WEATHER VISIONS

- Improved knowledge of
  - Physics of solar activity processes
  - Propagation & coupling
  - Precursors, timings & occurrence frequencies

- Comprehensive network of space- & ground-based real-time observatories

- Solar-Terrestrial Virtual Monitor I-Grid

- Geospace models fully incorporate Solar Weather key parameters

⇓

IMPROVED NOWCASTING & FORECASTING

Messerotti & Lundstedt (2004)

The Dream Solar Weather Network

- 3-D solar in situ monitoring (6 RTT spacecrafts)
- 3-D IP in situ monitoring (3 RTT spacecrafts)
- 3-D Earth in situ monitoring (6 RTT spacecrafts)
- Complete ground-based observing network
- Real-time data storage & indexing
- Real-time data availability & analysis
- Real-time modelling & forecasting

Messerotti & Lundstedt (2004)

Glossary

AI	Artificial Intelligence
AR	Active Region
CME	Coronal Mass Ejection
CR	Cosmic Rays
CR-I	Primary Cosmic Rays
GCR	Galactic Cosmic Rays
GMF	GeoMagnetic Field
HPC	High Performance Computing
HS	High Speed
I-Grid	Intelligent Grid
IP	InterPlanetary
PB	PetaByte
RTT	Real-Time Telemetry
SCR	Solar Cosmic Rays
SOC	Self-Organized Criticality
SOHO	Solar and Heliospheric Observatory
SW	Solar Wind
S/W	SoftWare

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