ONDEXPO ~~2020~~, ~~2021~~, 2022

Météorologie de l'espace et propagation HF

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Météorologie de l’espace

Le Soleil : Une grosse boule de plasma

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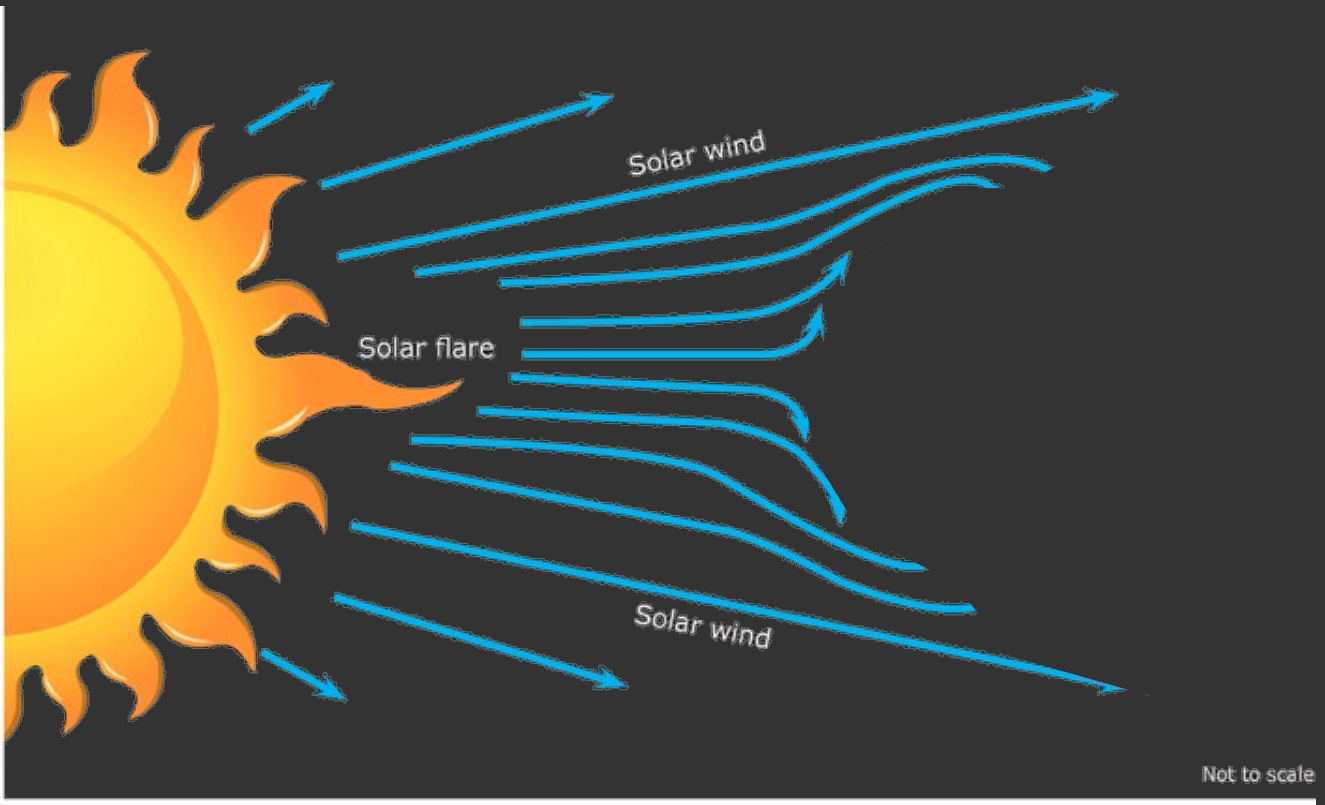
Météorologie de l’espace



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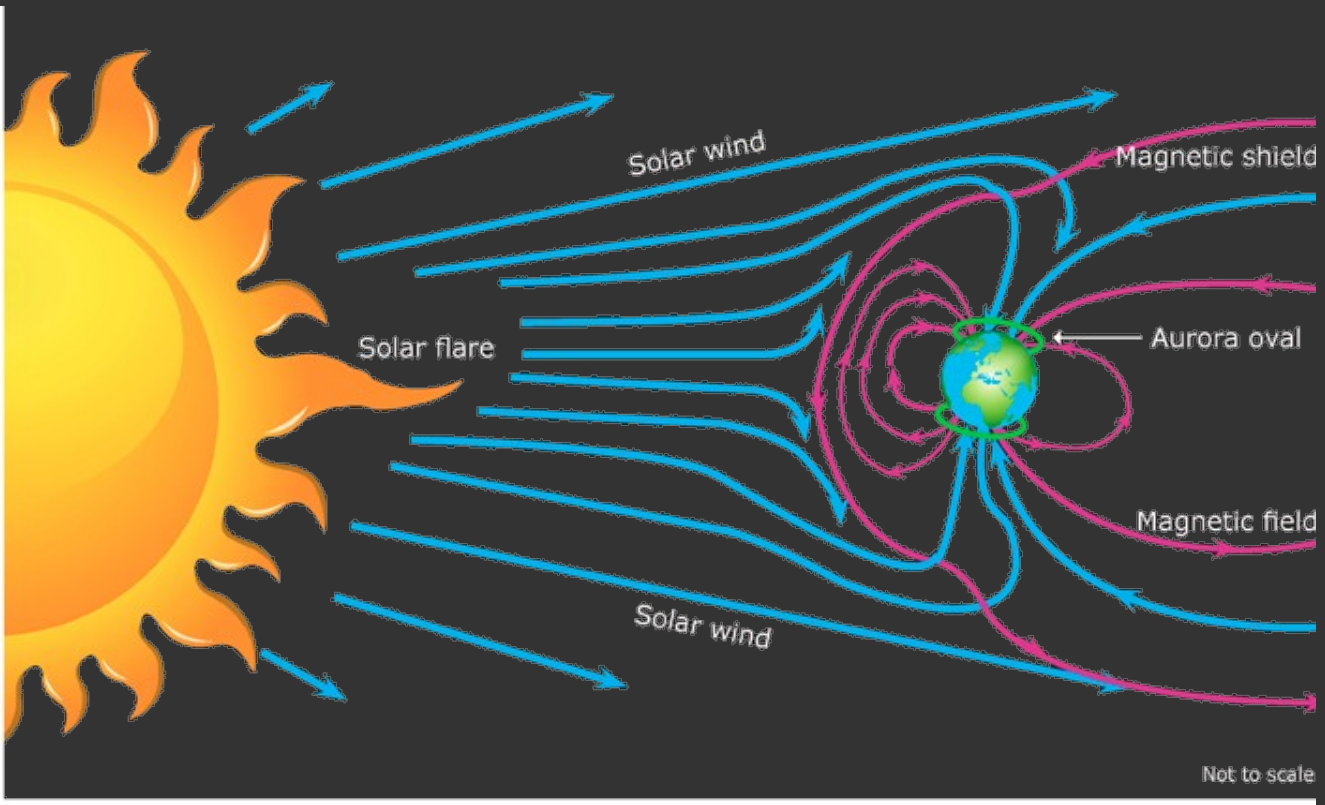
Le vent solaire :

Un flux de plasma

Météorologie de l’espace



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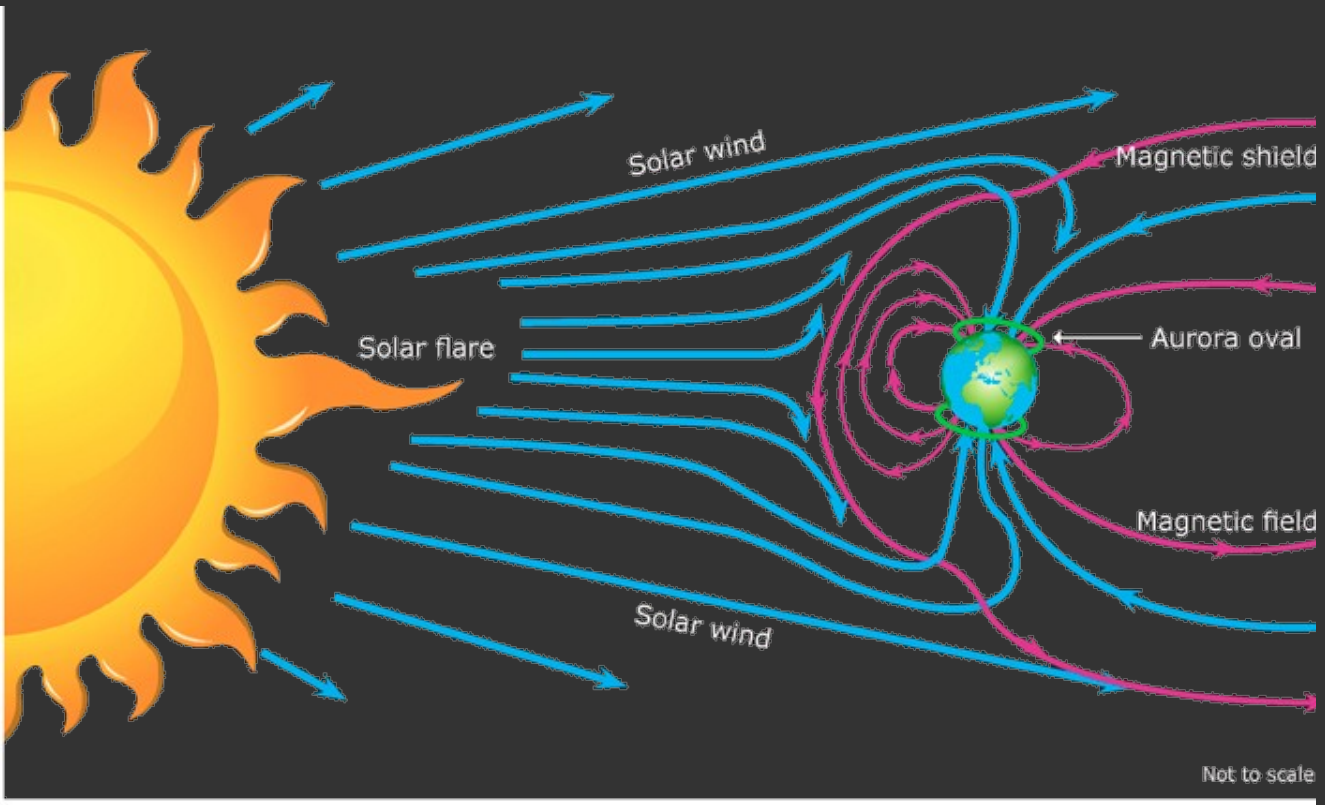
Le champ magnétique :

Des rails à plasma

Météorologie de l'espace



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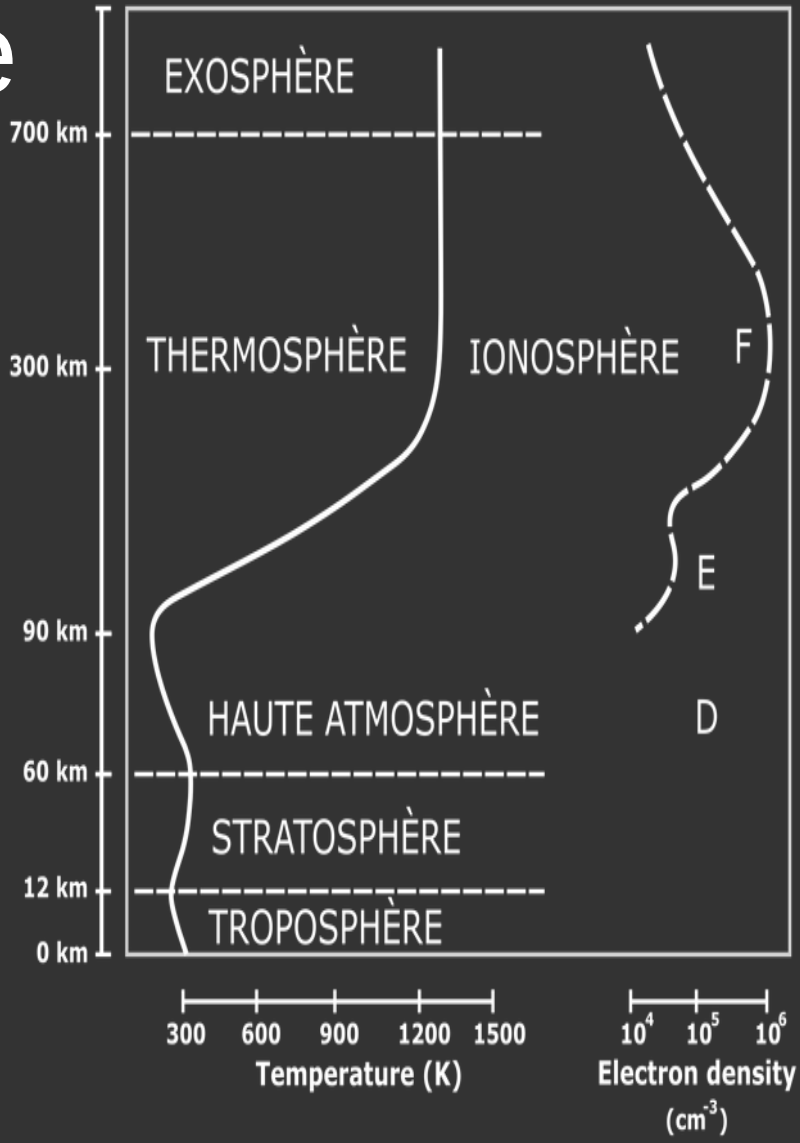
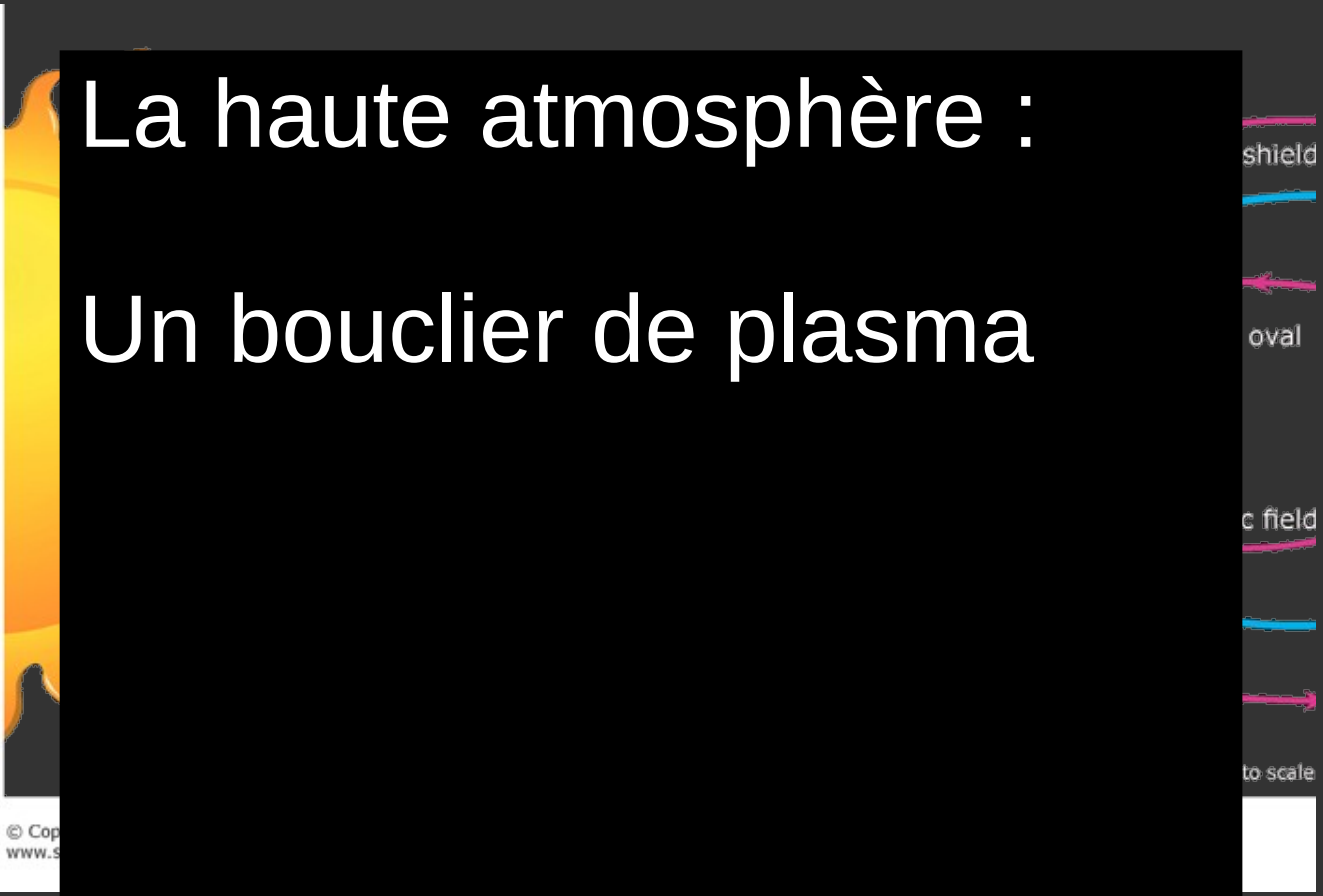
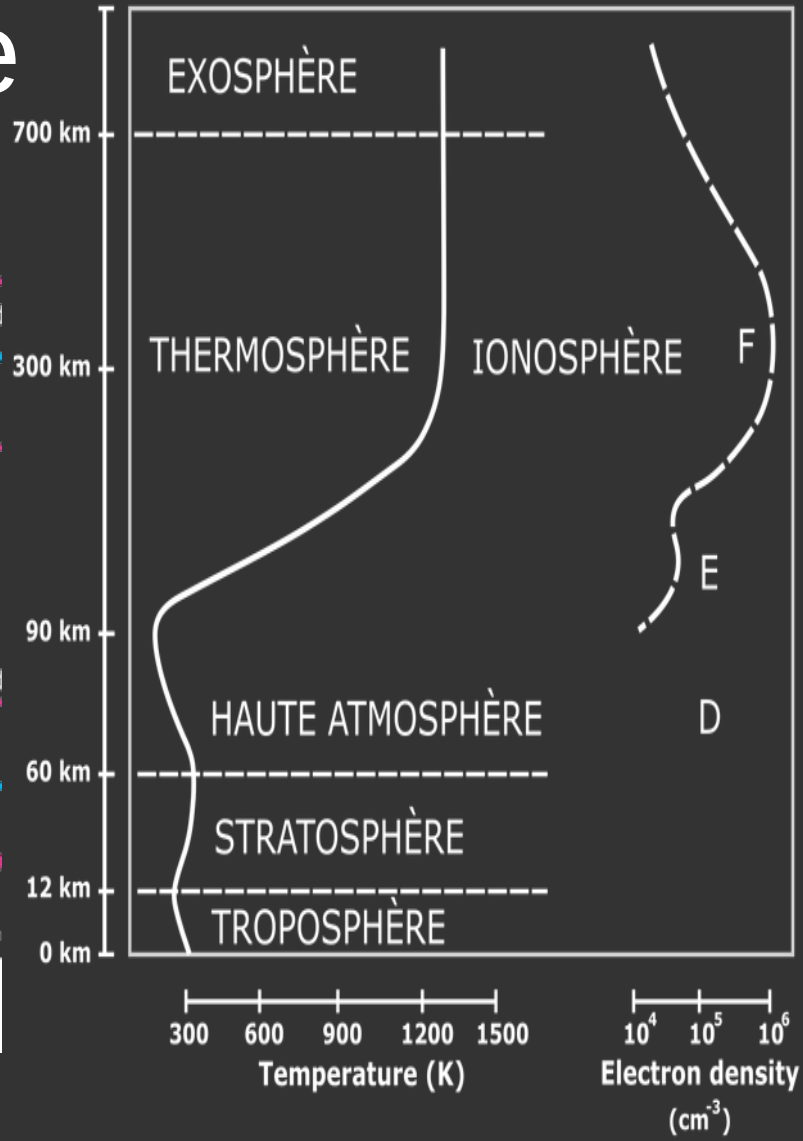


Météorologie de l’espace

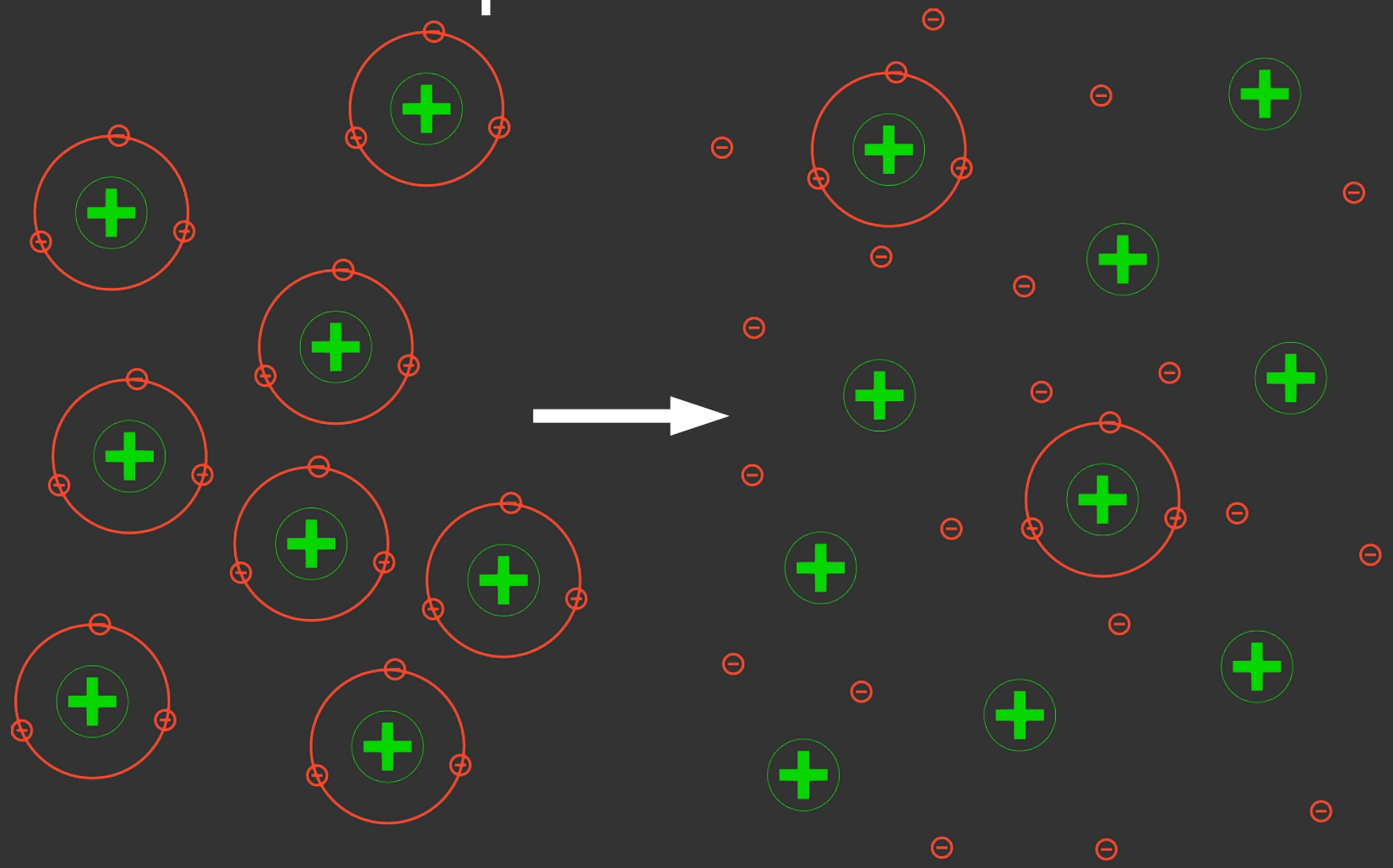
La haute atmosphère :

Un bouclier de plasma





Vous avez dit plasma ?



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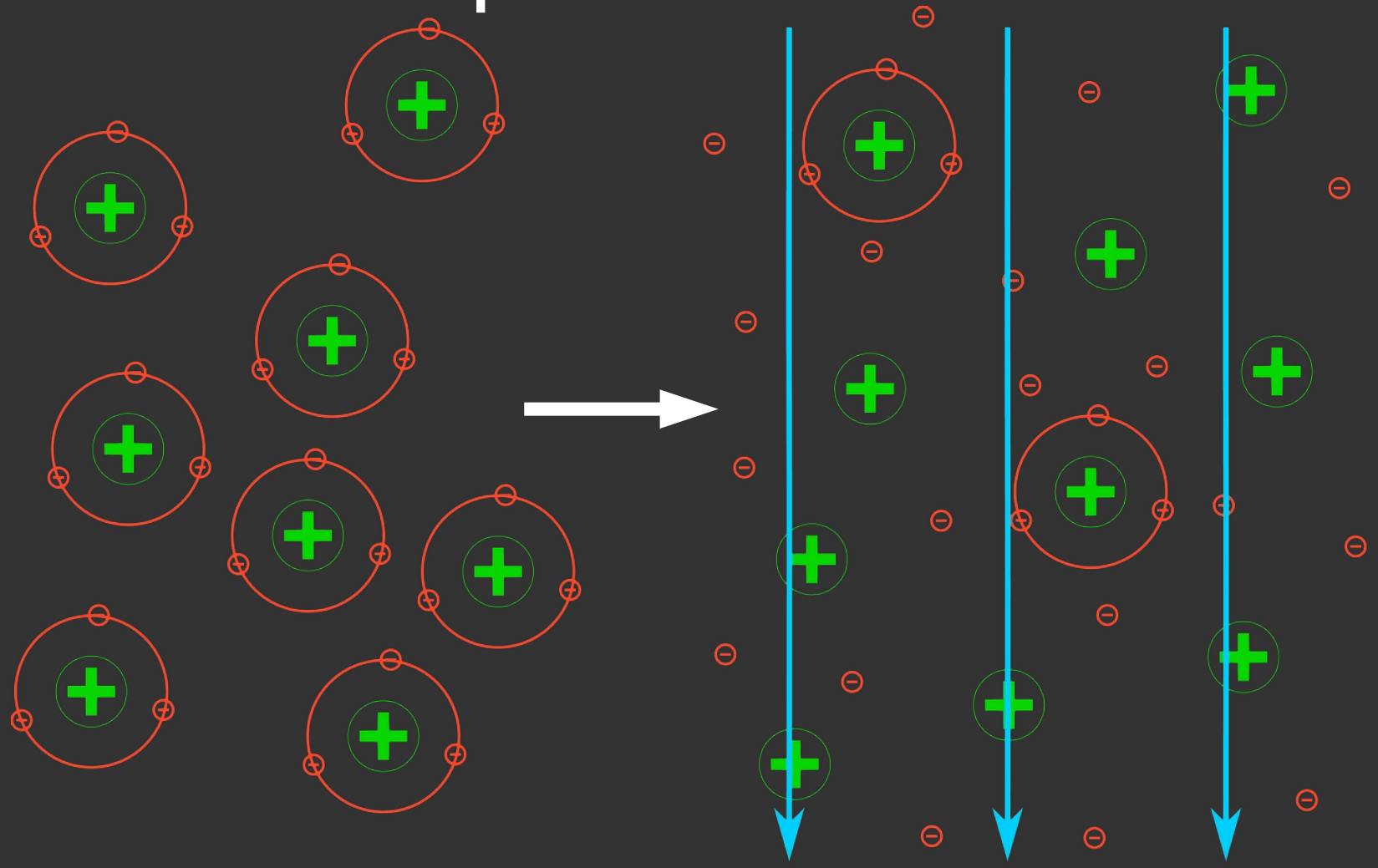
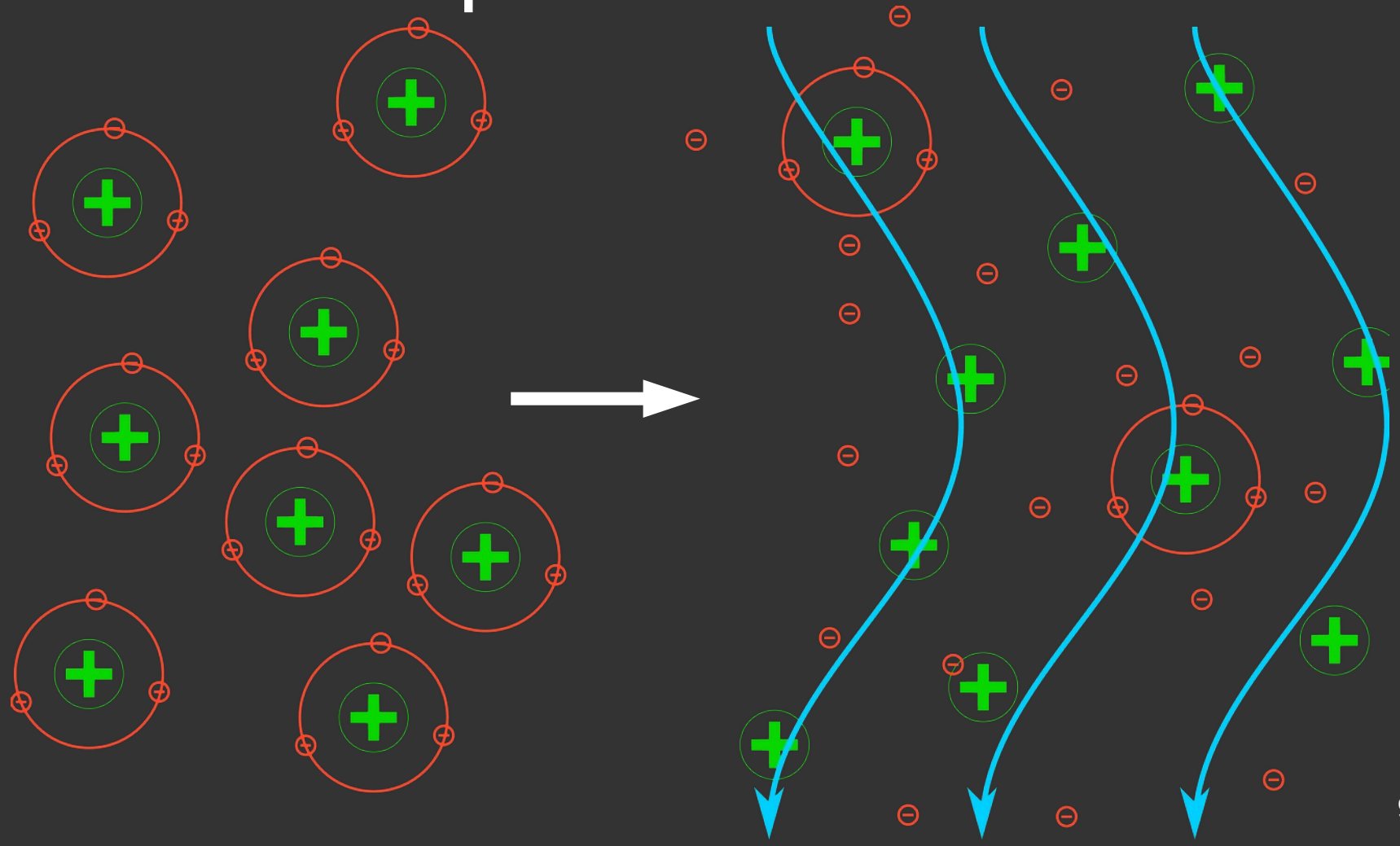
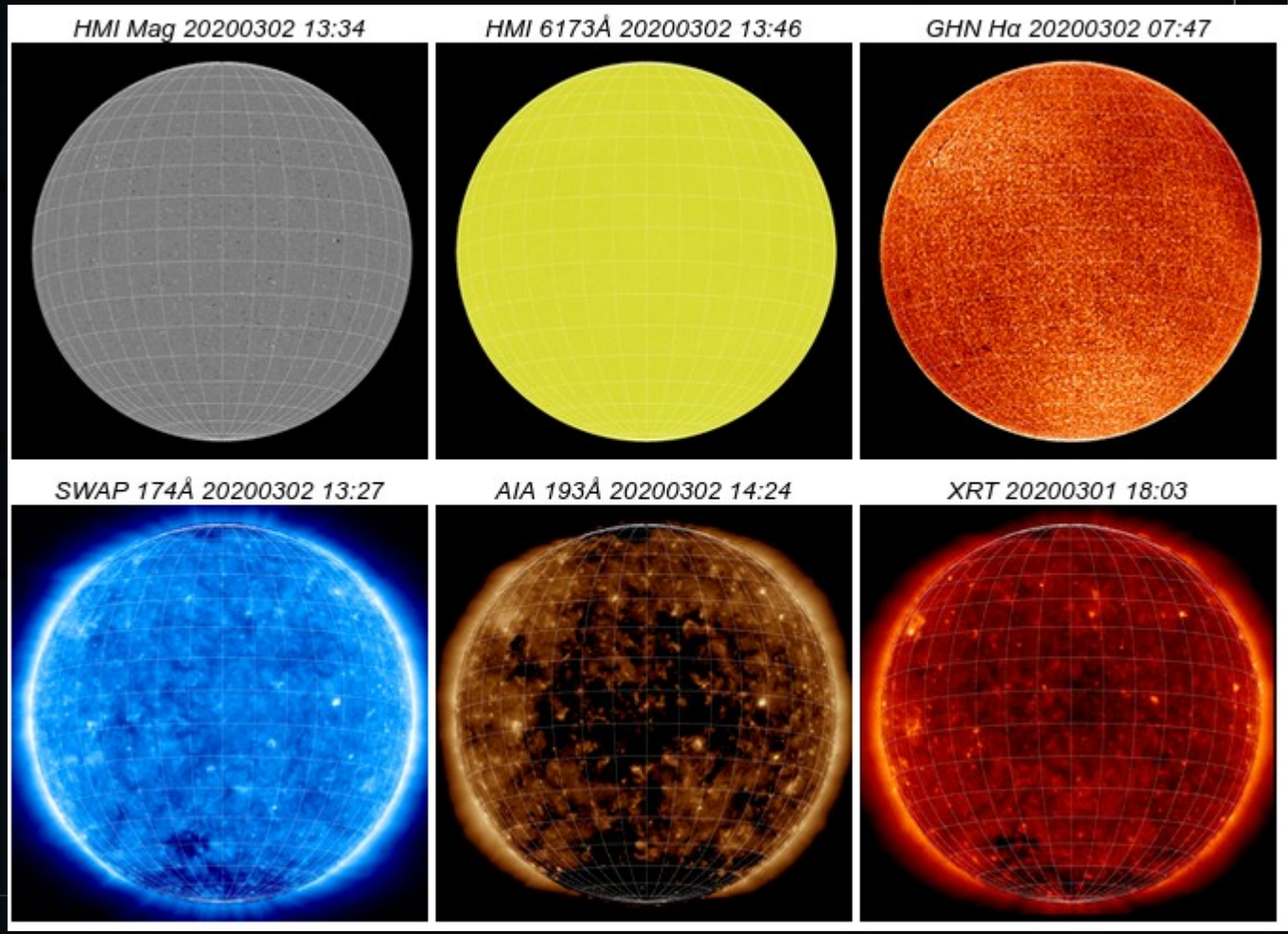


Vous avez dit plasma ?



Le Soleil - Général

- Distance : 150 Mkm
- Diamètre : 1.4 Mkm
- Masse : 2 * 10^{30} kg
- Température
  - Centre 15,1 MK
  - Surface 5 750 K
  - Couronne 5 MK
- Composition
  - Hydrogène 73.5 %
  - Hélium 25 %
  - O, C, Fe, Ne, N, Si, Mg, S



Le Soleil - Composition

Gaz

Couche convective

Couche radiative

Source de chaleur

Le Soleil - Composition

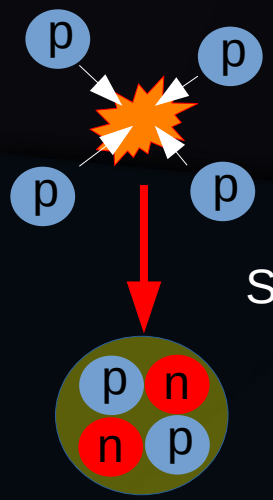
Atmosphère / Couronne

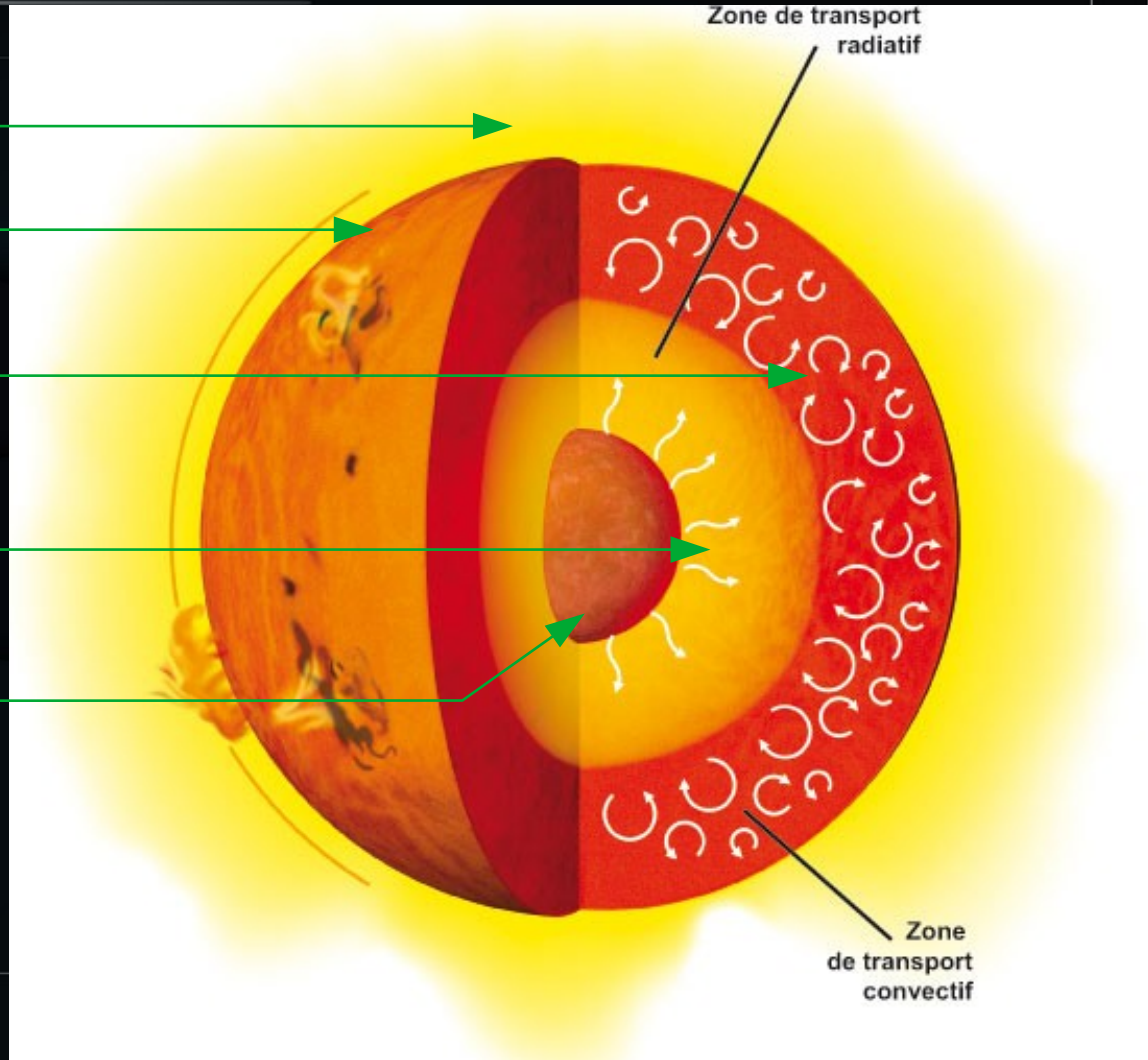
Photosphère

Couche convective

Couche radiative

Source de chaleur
Fusion nucléaire :
4 protons → Hélium

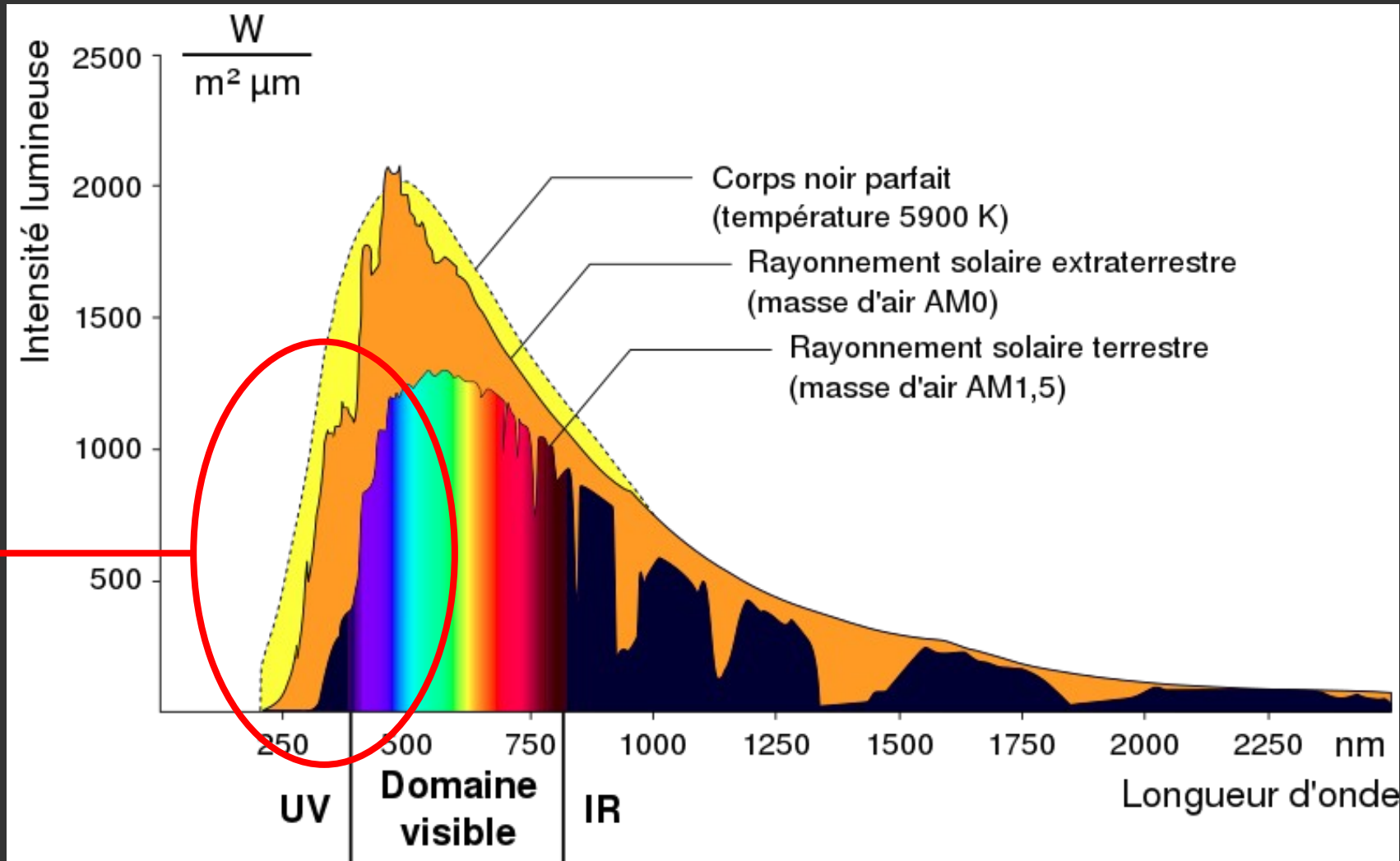




2 types d’émissions

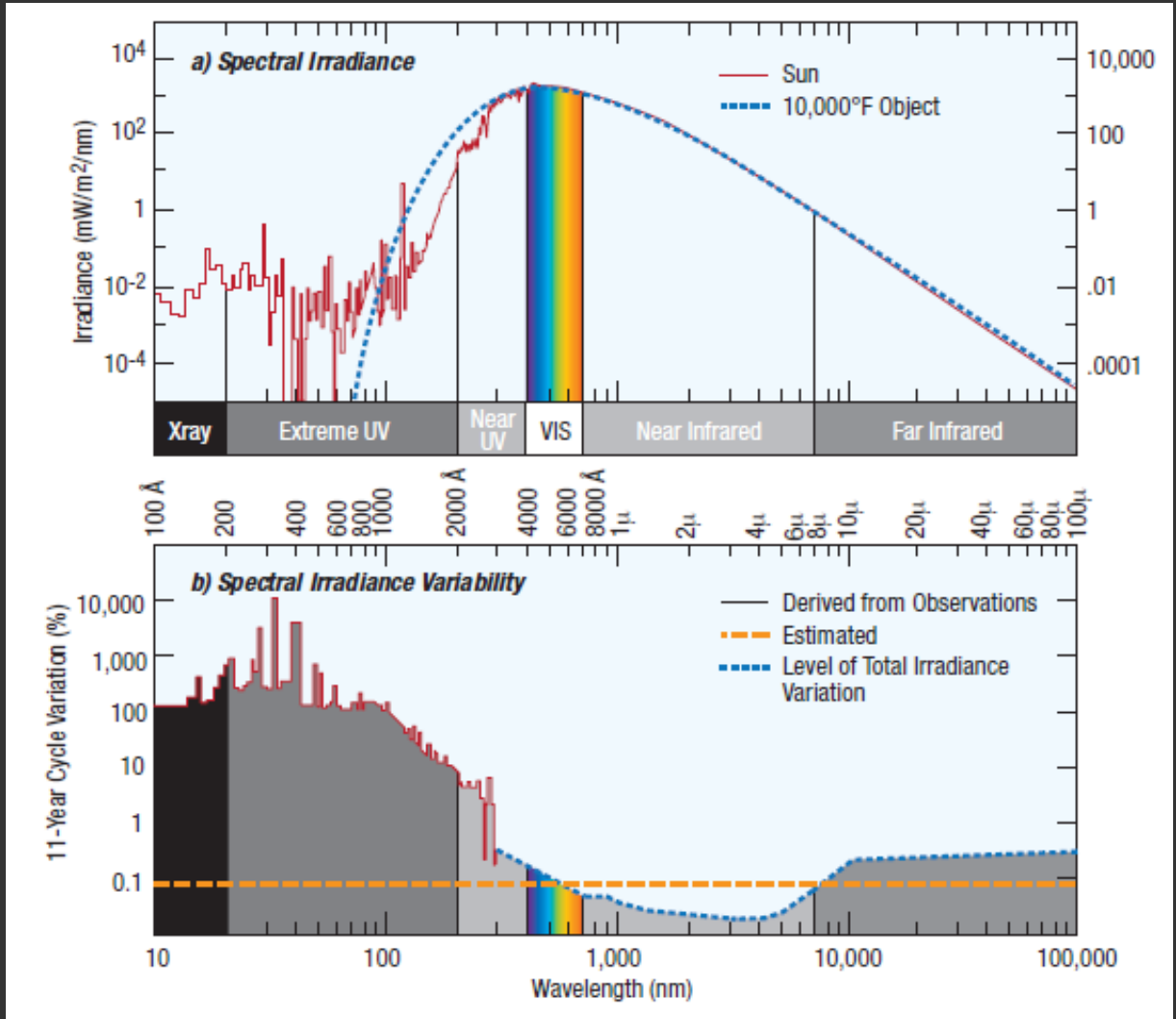
- Lumière
  - Rayonnement électromagnétique (lumière visible, radio, UV, infr-rouge, rayons X, Gamma...)
- Matière
  - Atomes, électrons, protons...

La lumière du Soleil



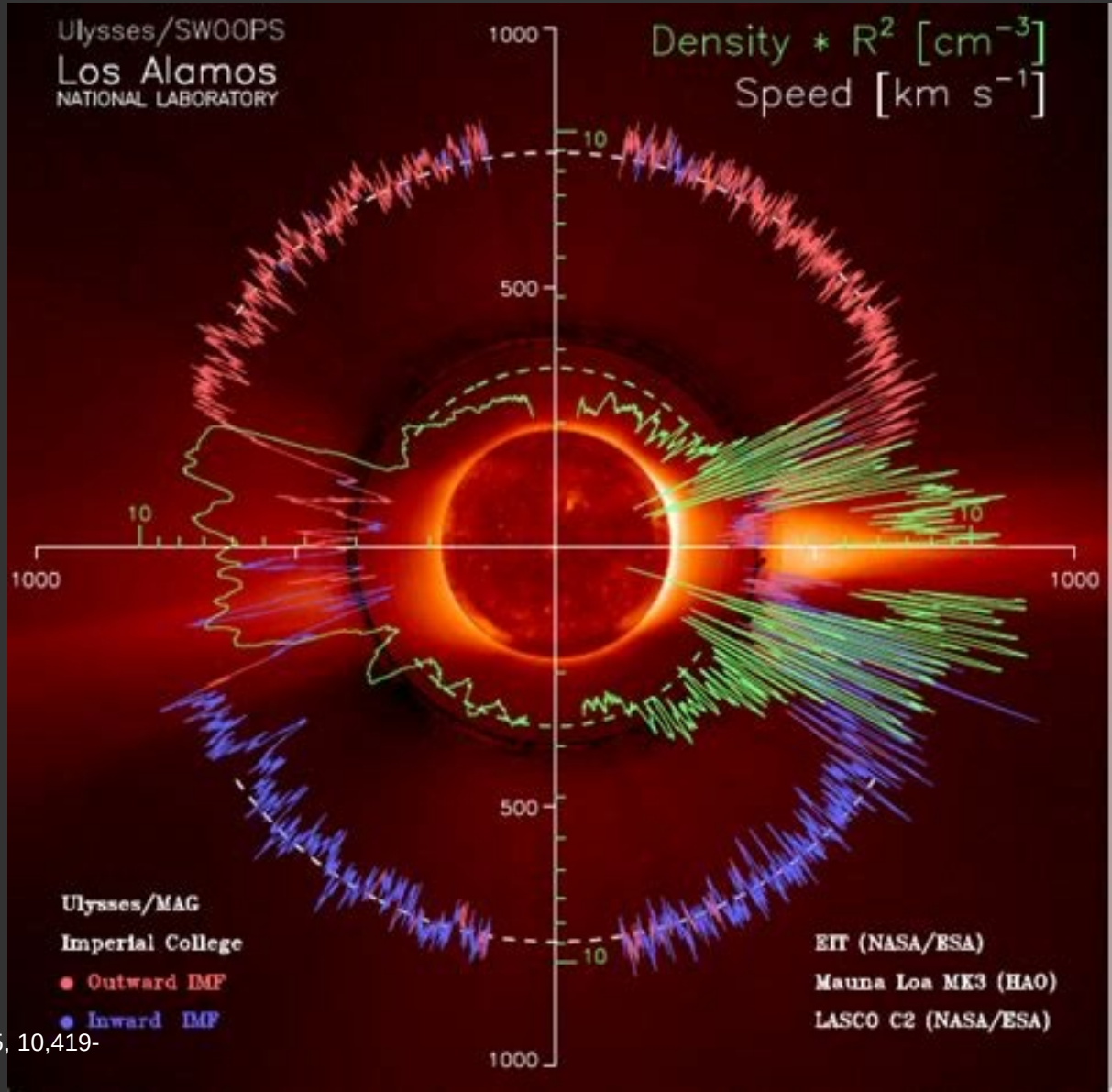
Absorption de l'UV par l'atmosphère

La lumière du Soleil



Le Vent Solaire

- Electrons
- Protons
- Noyaux lourds
- Équateur :
  - VS rapide (+ 600 km/s)
  - Peu dense
- Poles :
  - VS lent (~ 400 km/s)
  - Dense

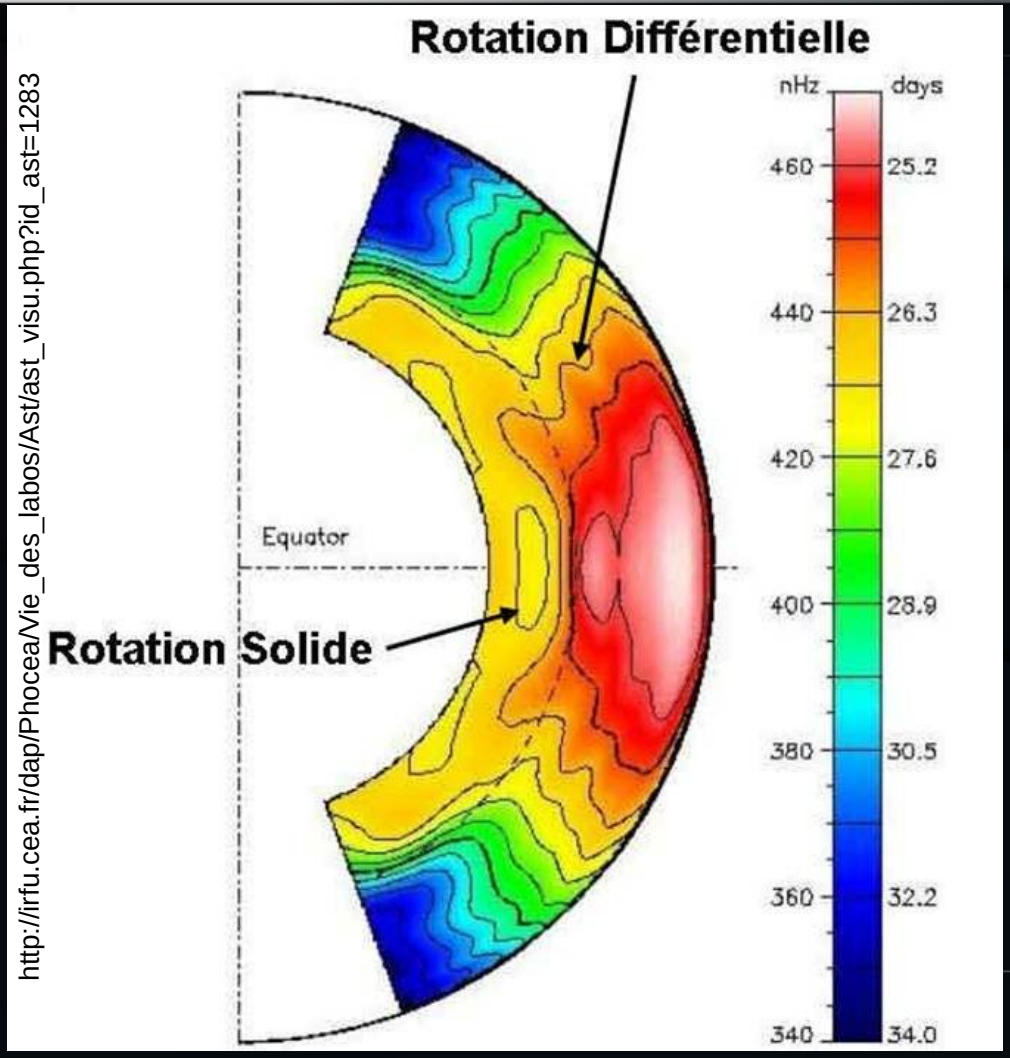


SWOOPS observations of the solar wind during Ulysses' first full polar orbit around the Sun. Credit: McComas, D. J., et al. (2000), J. Geophys. Res., 105, 10,419-10,433.

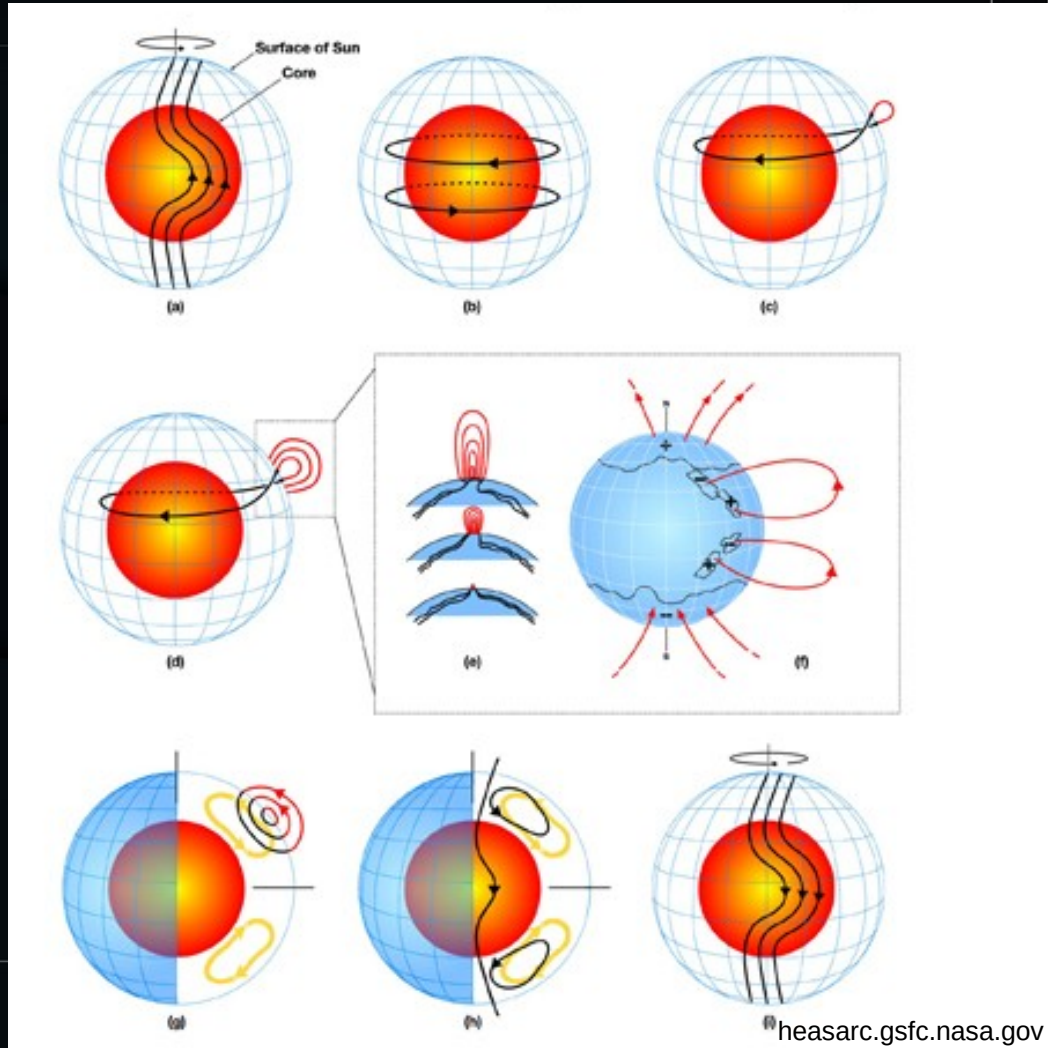
Le Soleil – Champ Magnétique

Crédits photo : Solar Wind Sherpas

Le Soleil – Rotation Différentielle

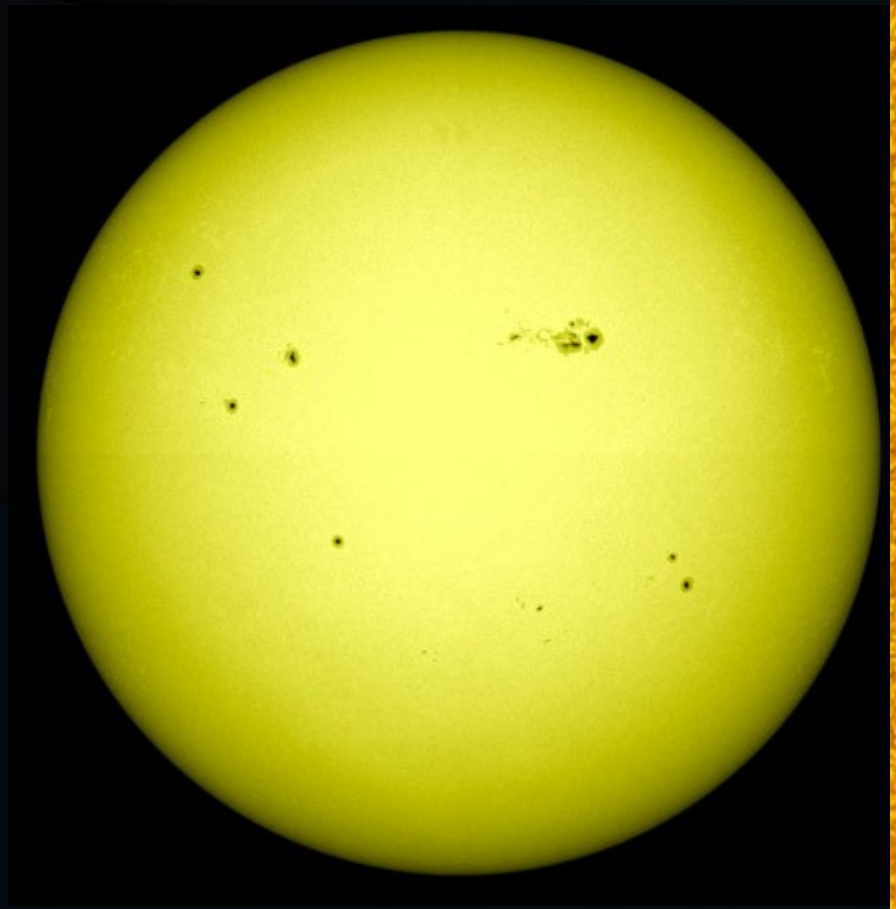


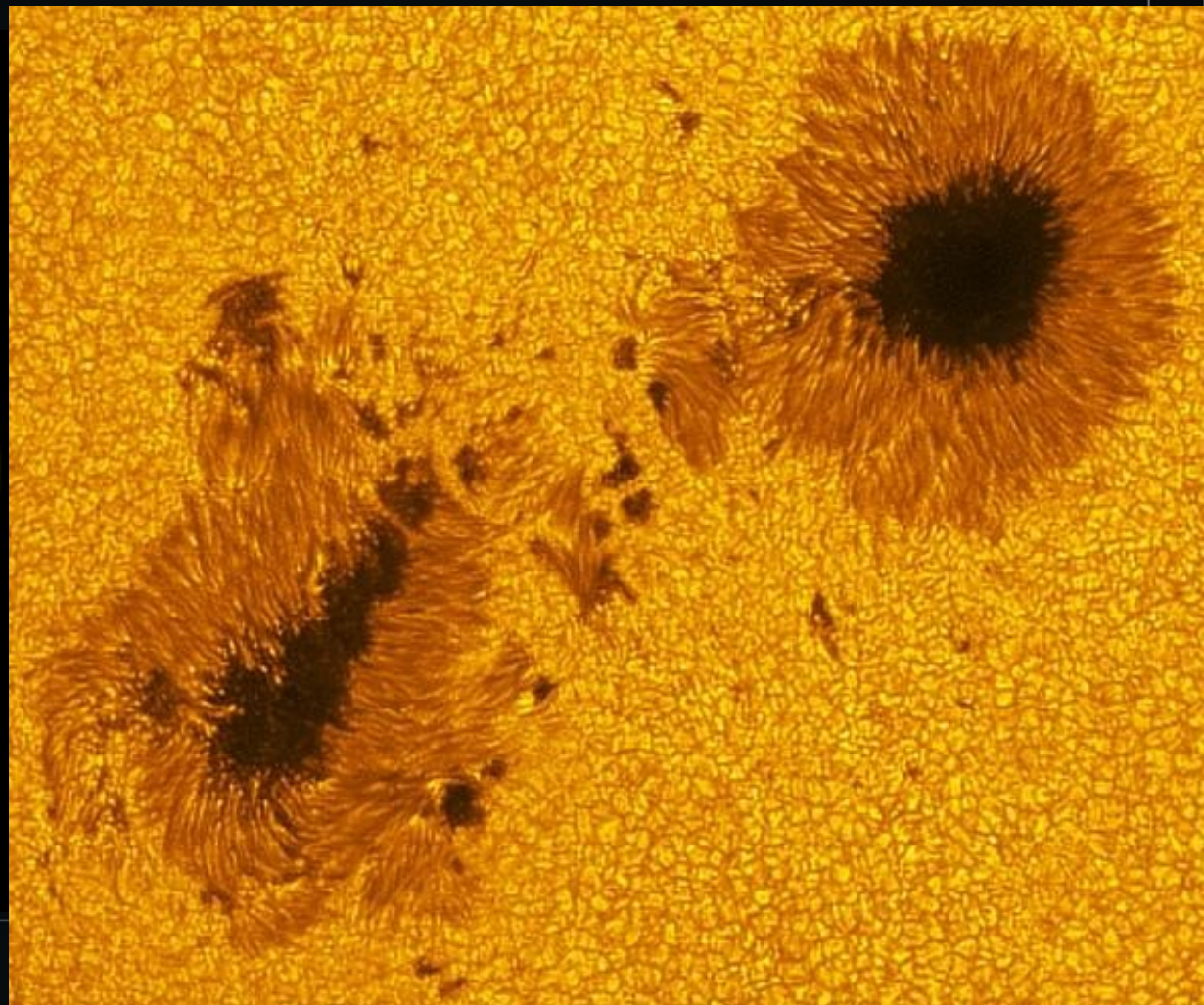
http://irfu.cea.fr/dap/Phocea/Vie_des_labos/Ast/ast_visu.php?id_ast=1283



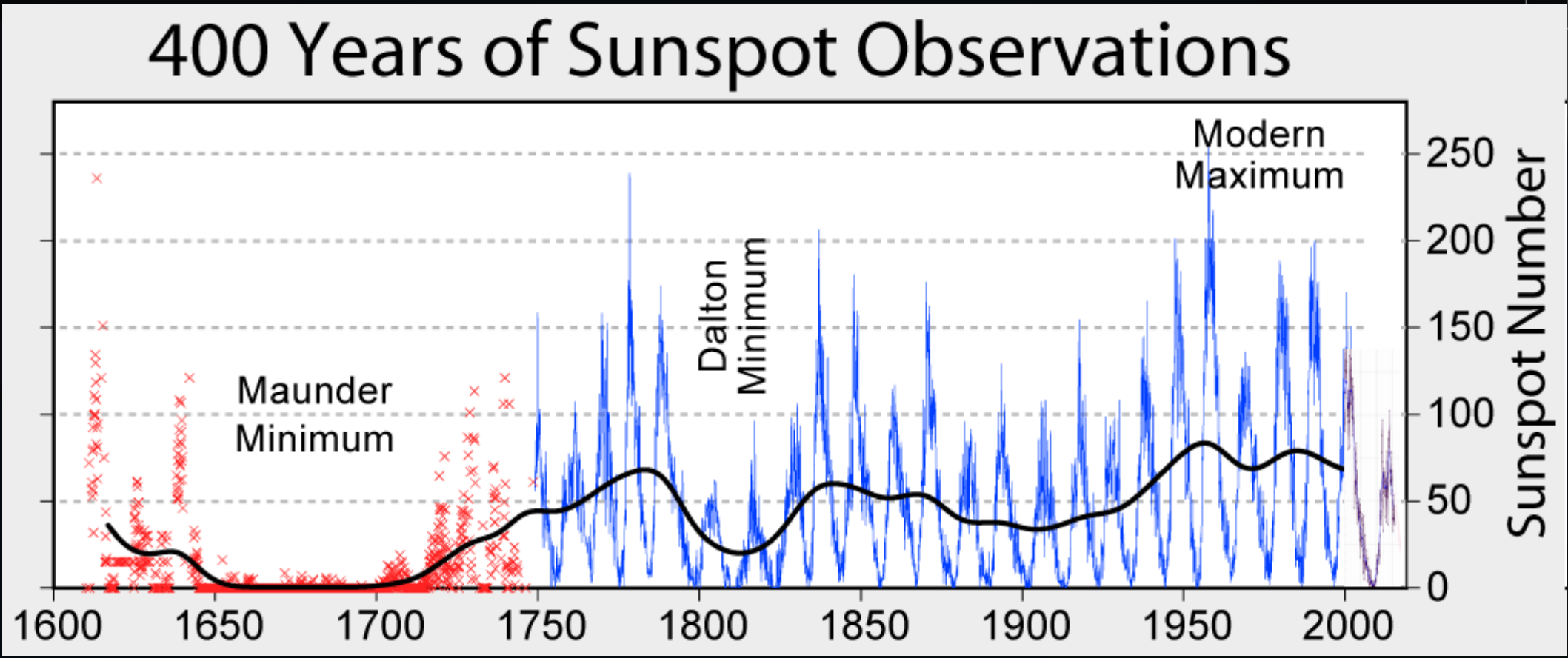
heasarc.gsfc.nasa.gov

Le Soleil – Taches Solaires

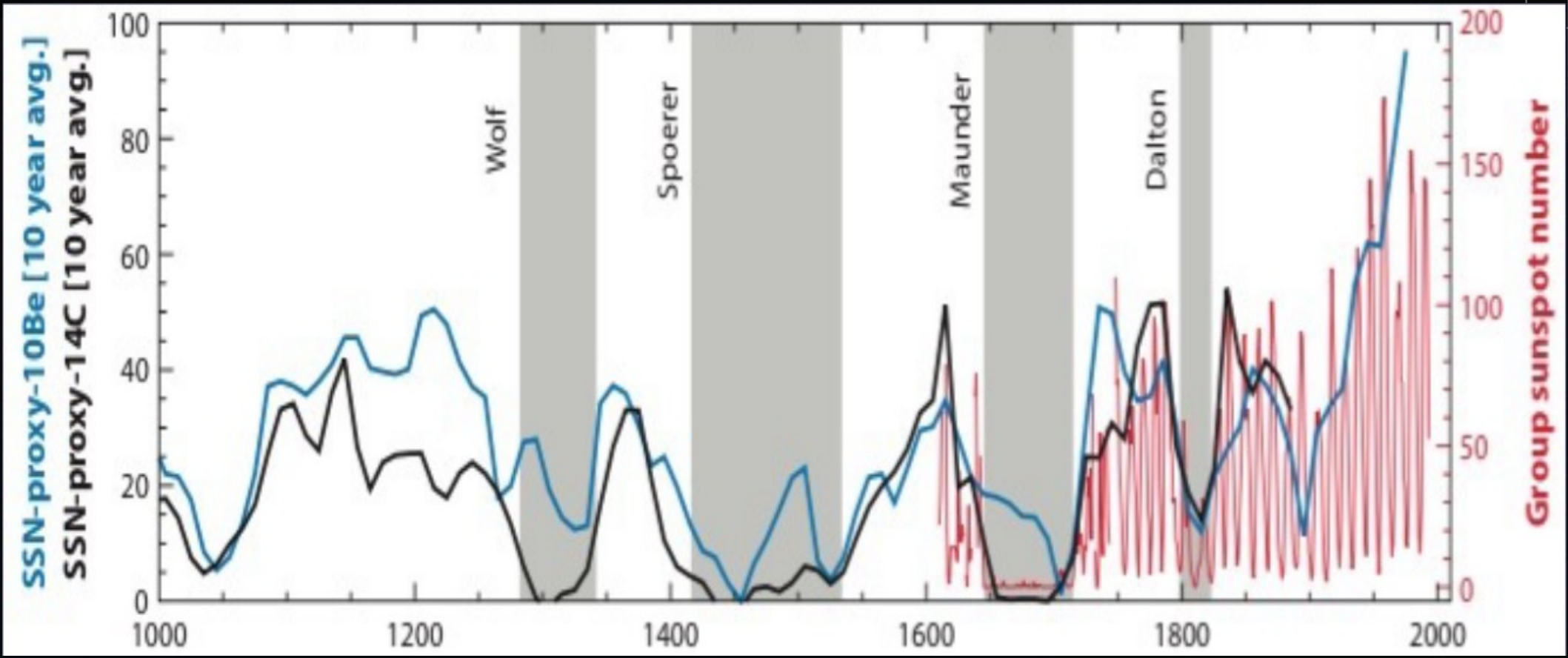




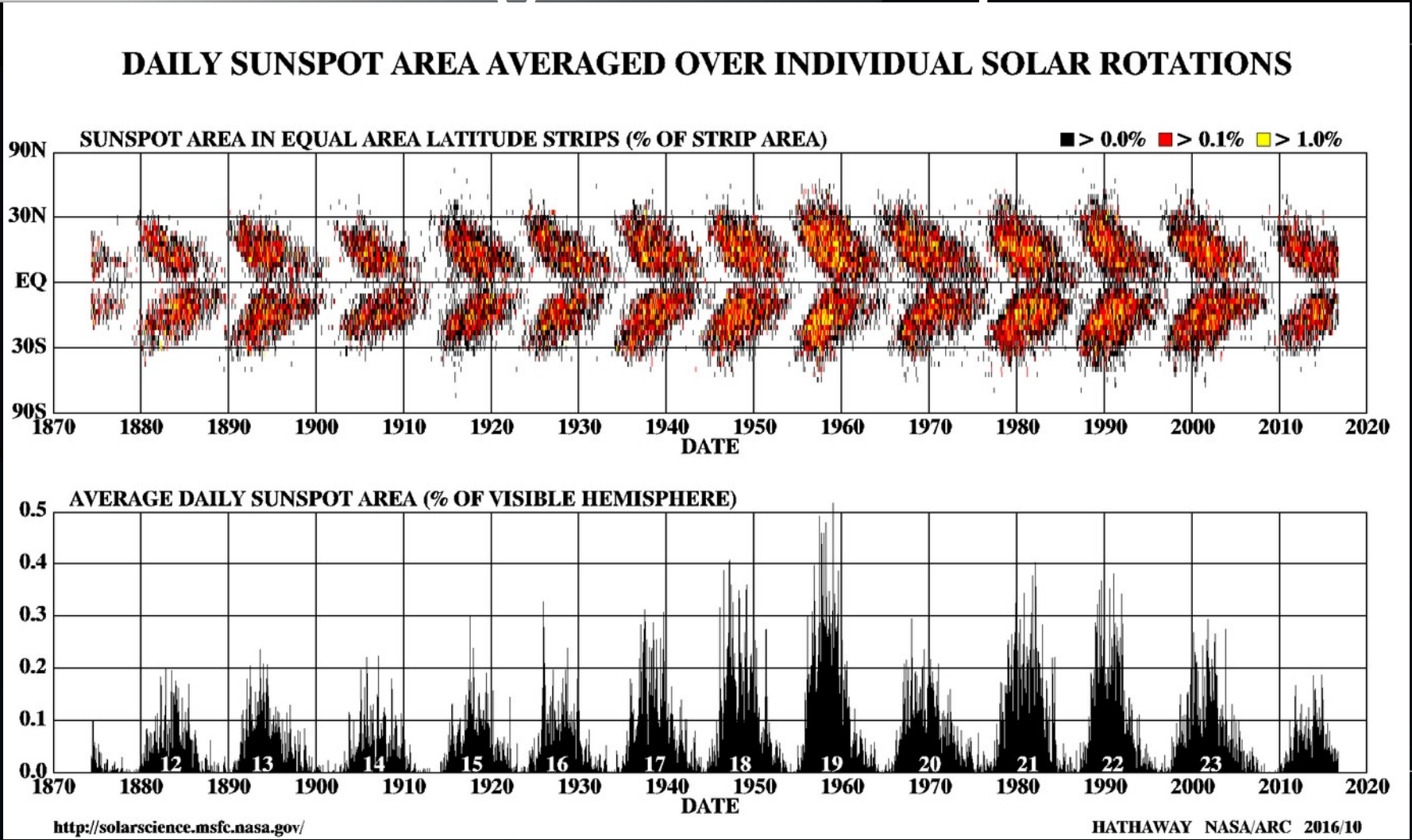
Le Soleil - Activité



Le Soleil - Activité

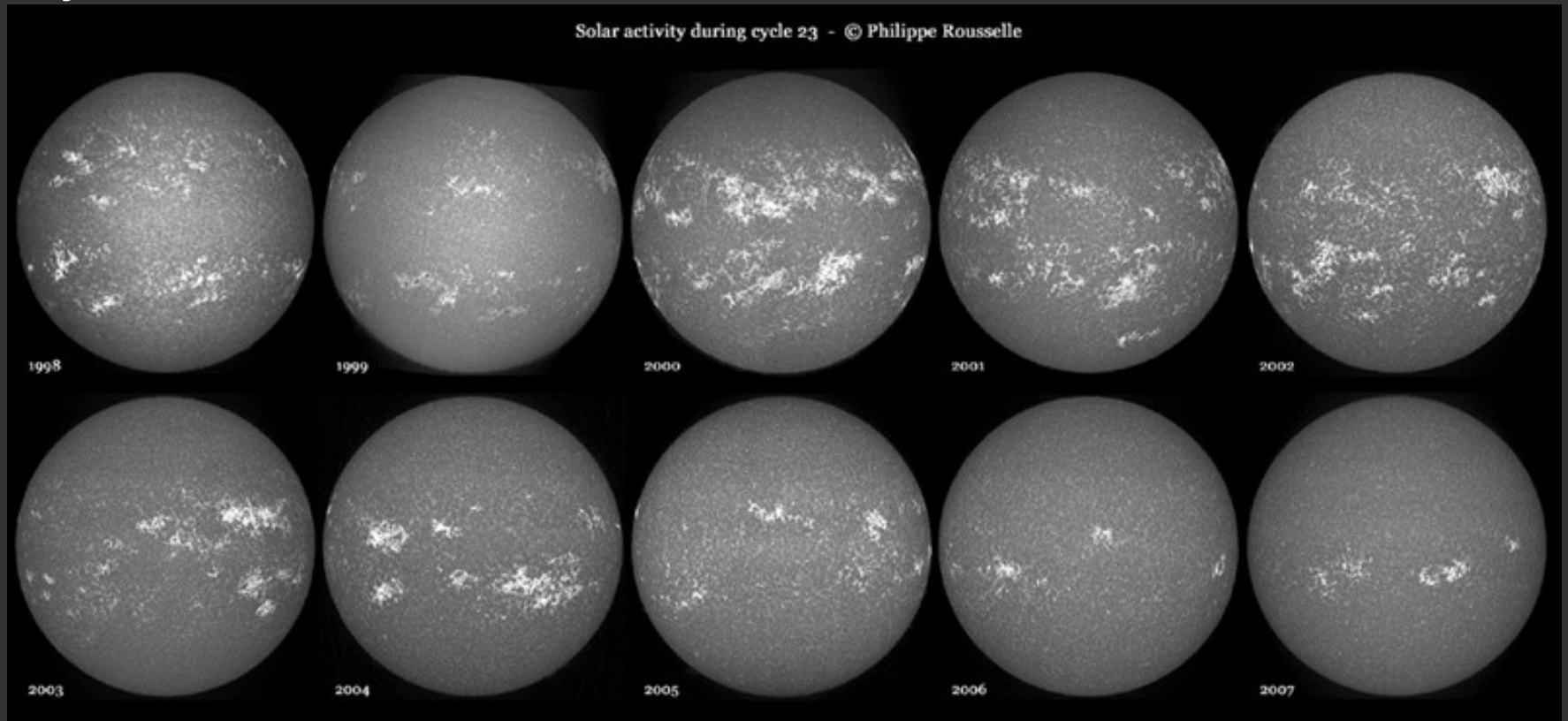


Le Soleil – Diagramme Papillon



Le Soleil

- Emissions fortement variables !
- Cycle d’activité de ~11 ans

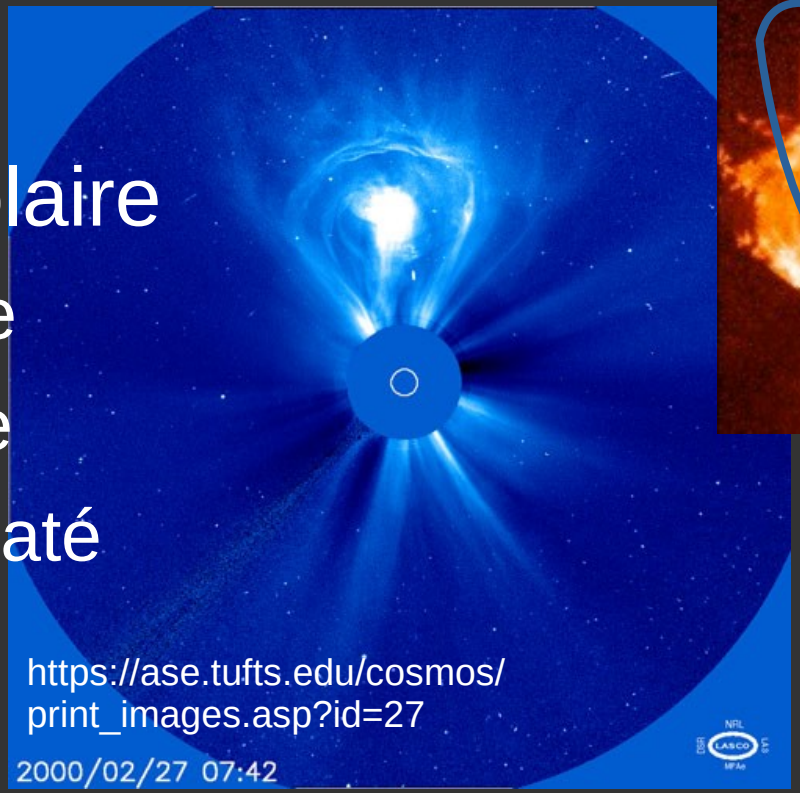


Phénomènes violents

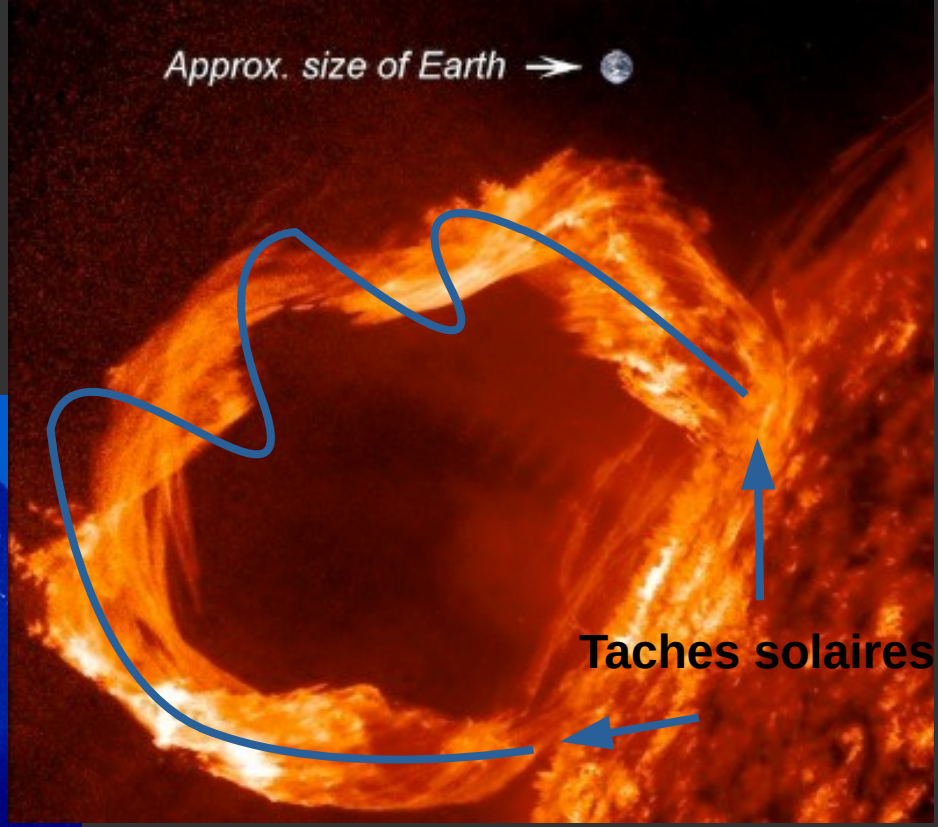
- Éjections coronales de masse (CME)
- Éruptions solaires (solar flares)
- Orages magnétiques

Éjections (CME)

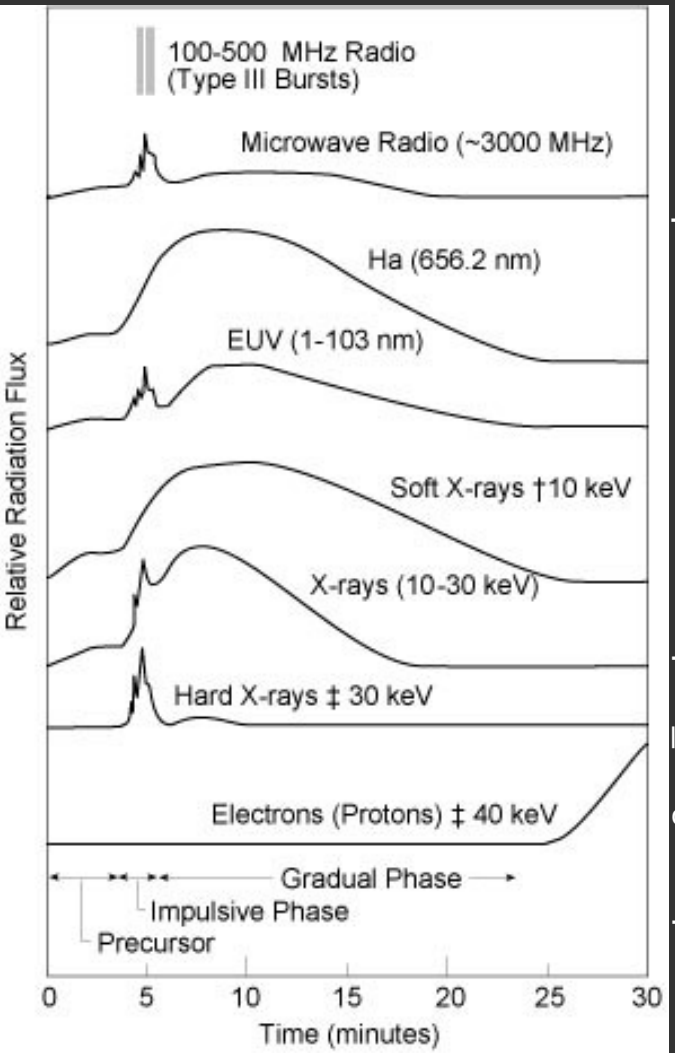
- Coronal Mass Ejection
- lien
- Vent solaire
  - rapide
  - dense
  - collimaté



https://ase.tufts.edu/cosmos/print_images.asp?id=27



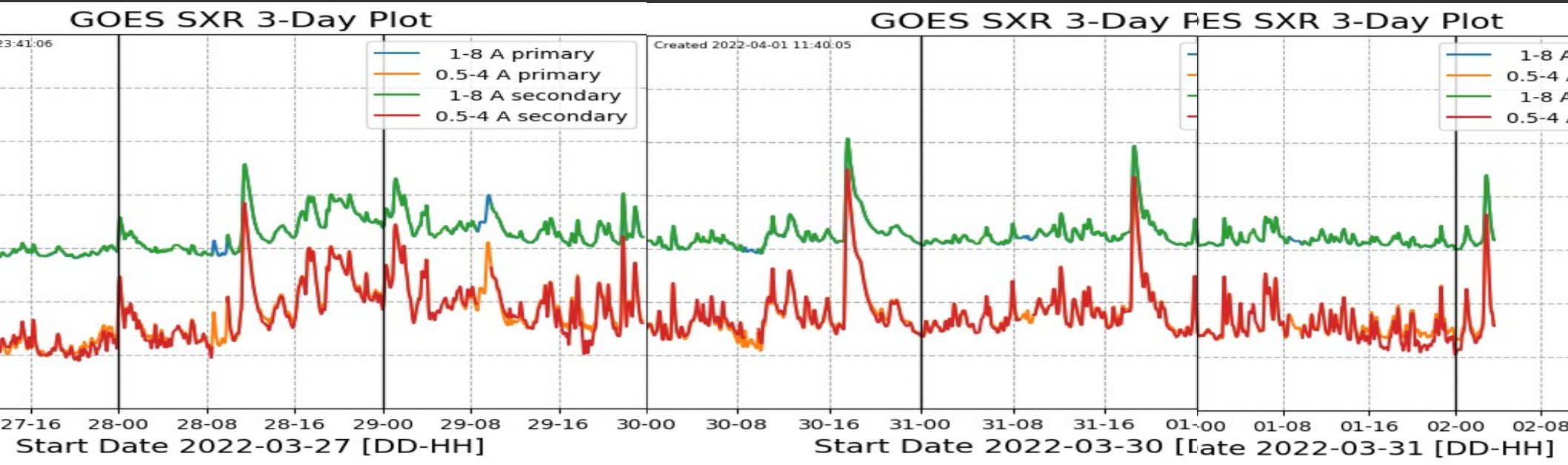
Émissions électromagnétiques

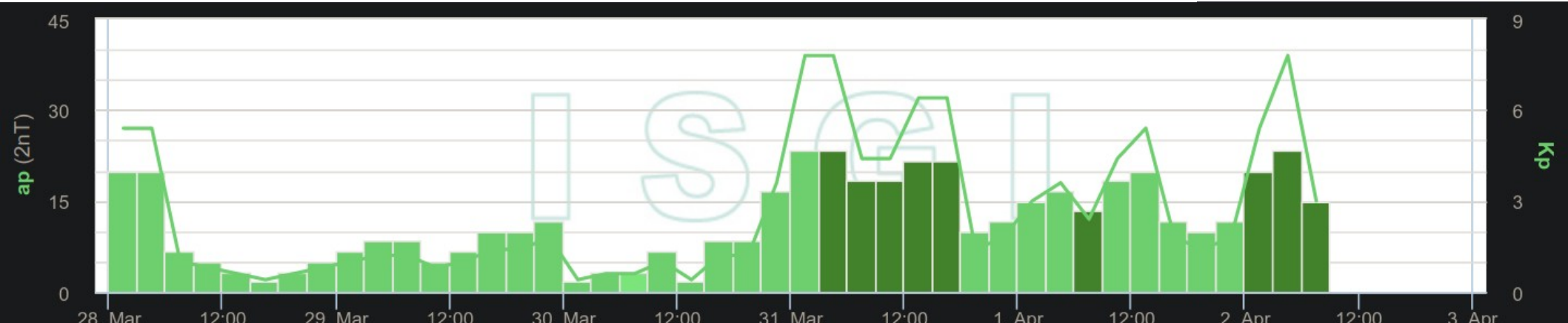


https://ase.tufts.edu/cosmos/print_images.asp?id=27

- Rayons X
- Micro ondes
- UV
- Radio (100 – 500 MHz)

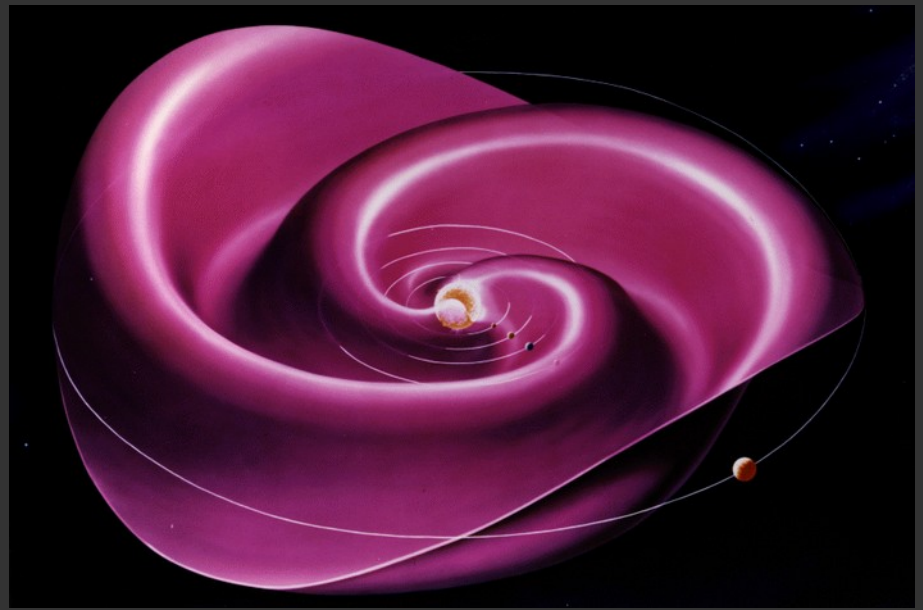
Cette semaine !

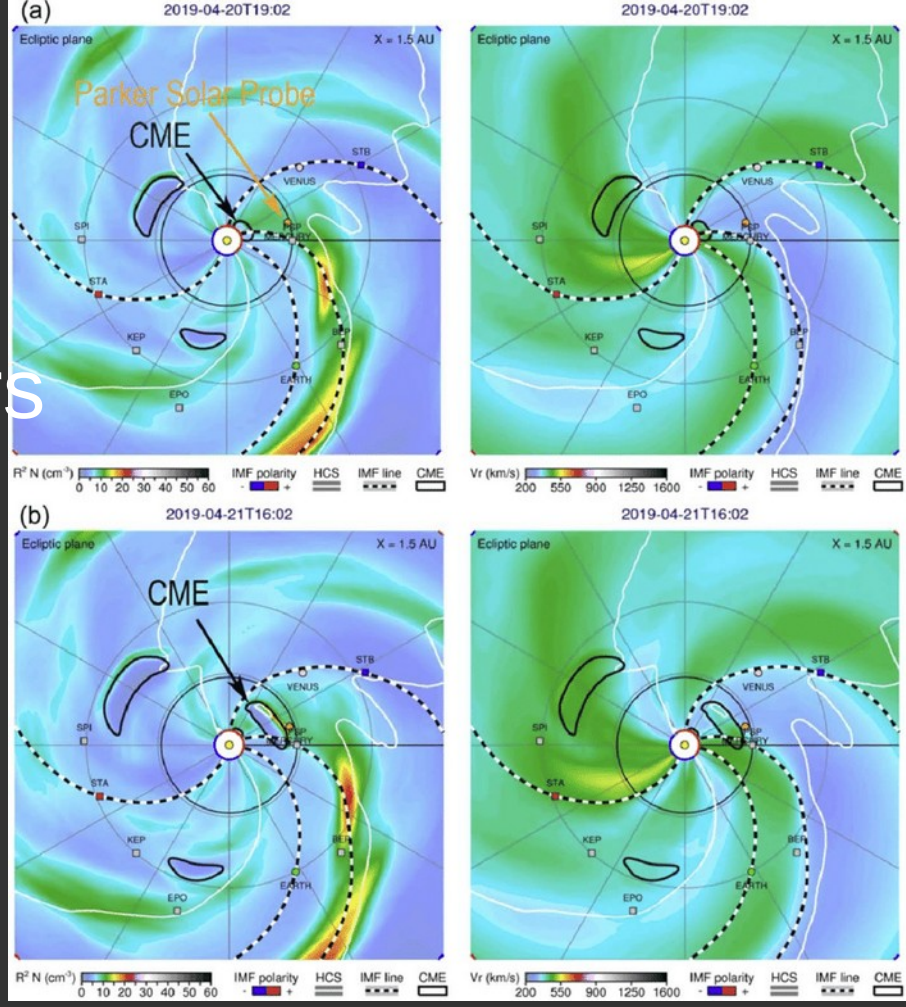




Trajet Soleil-Terre

- Lumière ~ 8 min
- Vent solaire ~ quelques jours
- Spirale de Parker



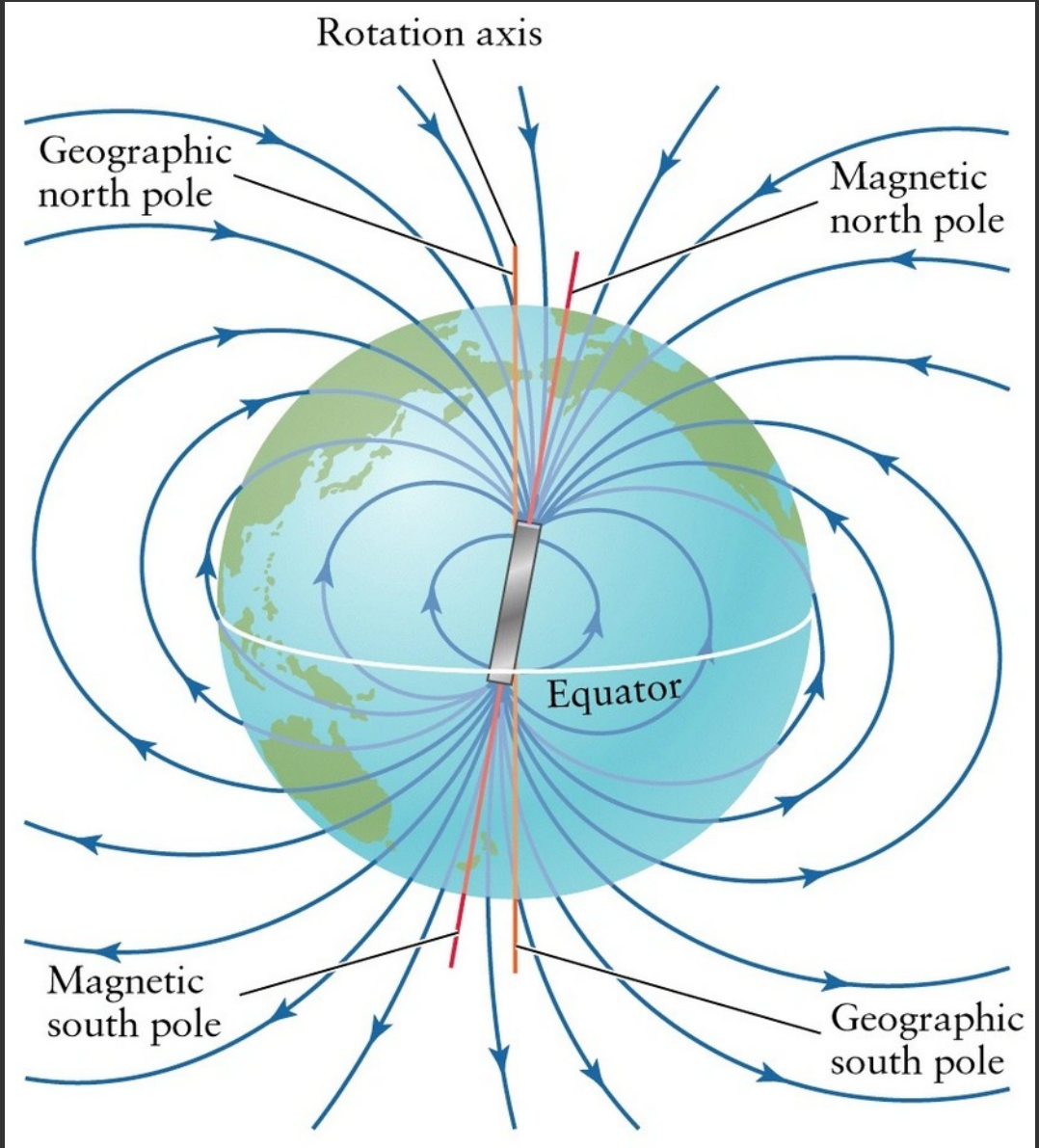


Schwadron, N., et al. (2020). 10.3847/1538-4365/ab5527.

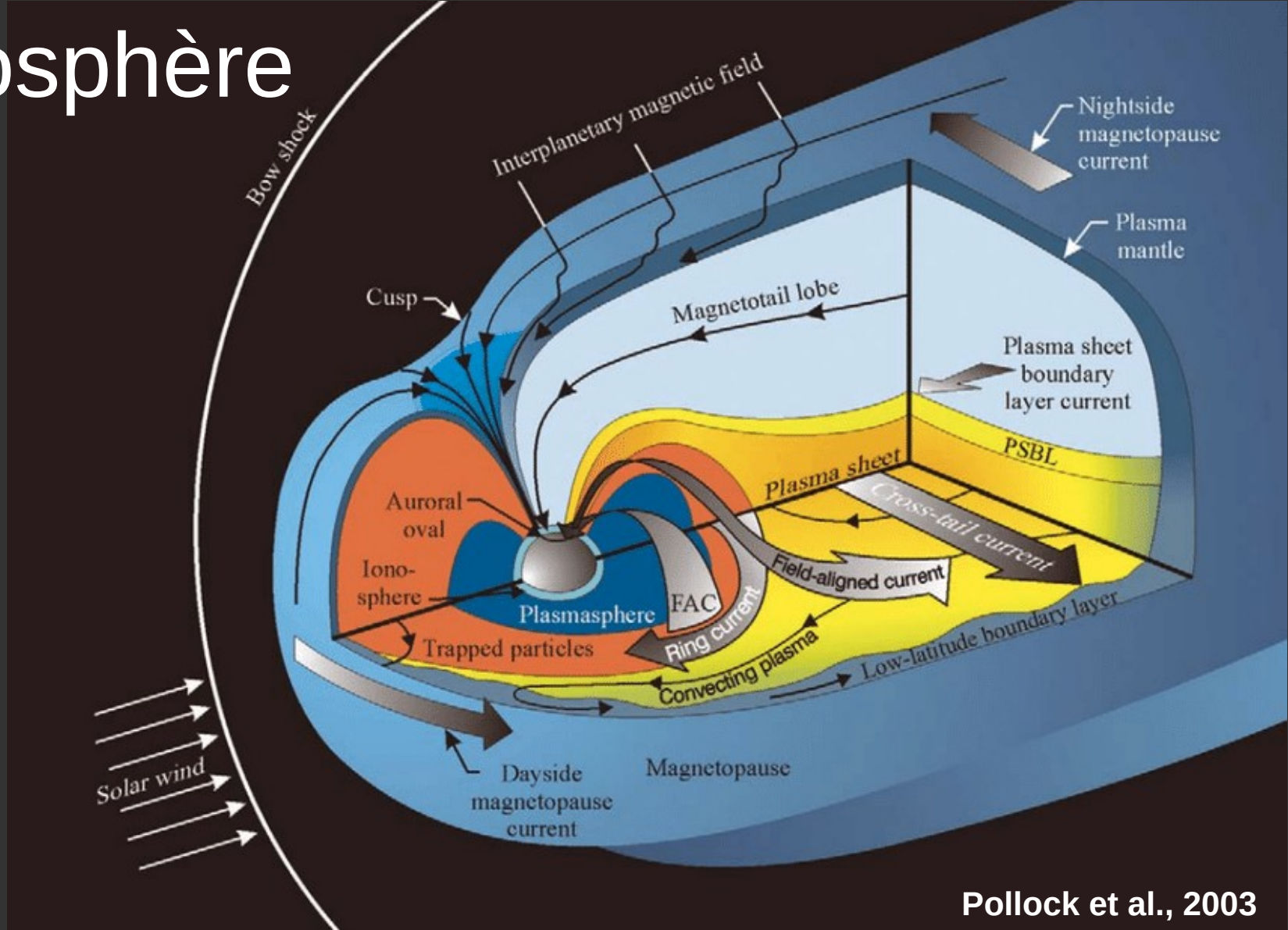
La Terre

- Effet Dynamo
  - Noyau liquide
  - Conducteur (Fe, Ni)
  - Rotation

- Champ magnétique

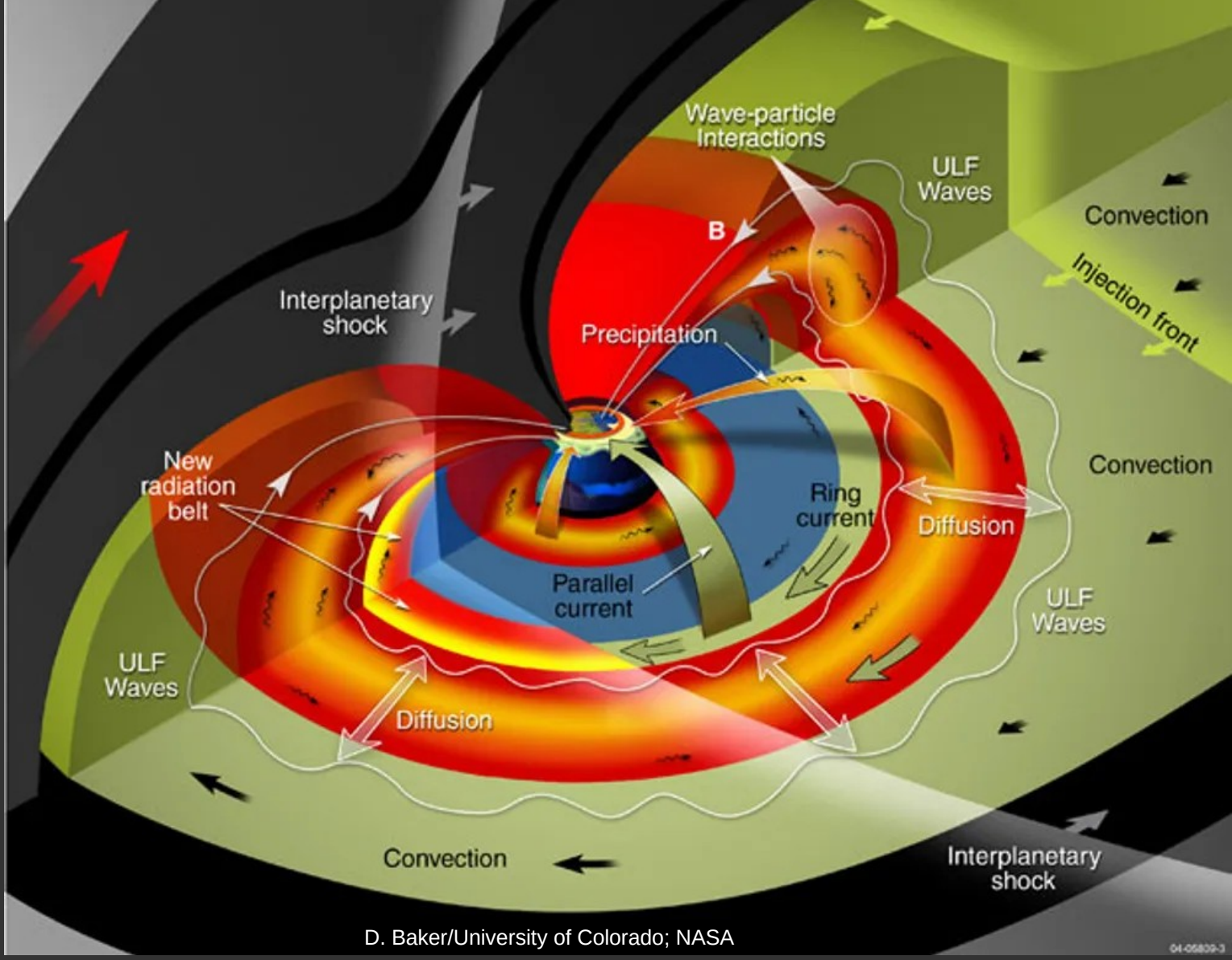


Magnétosphère

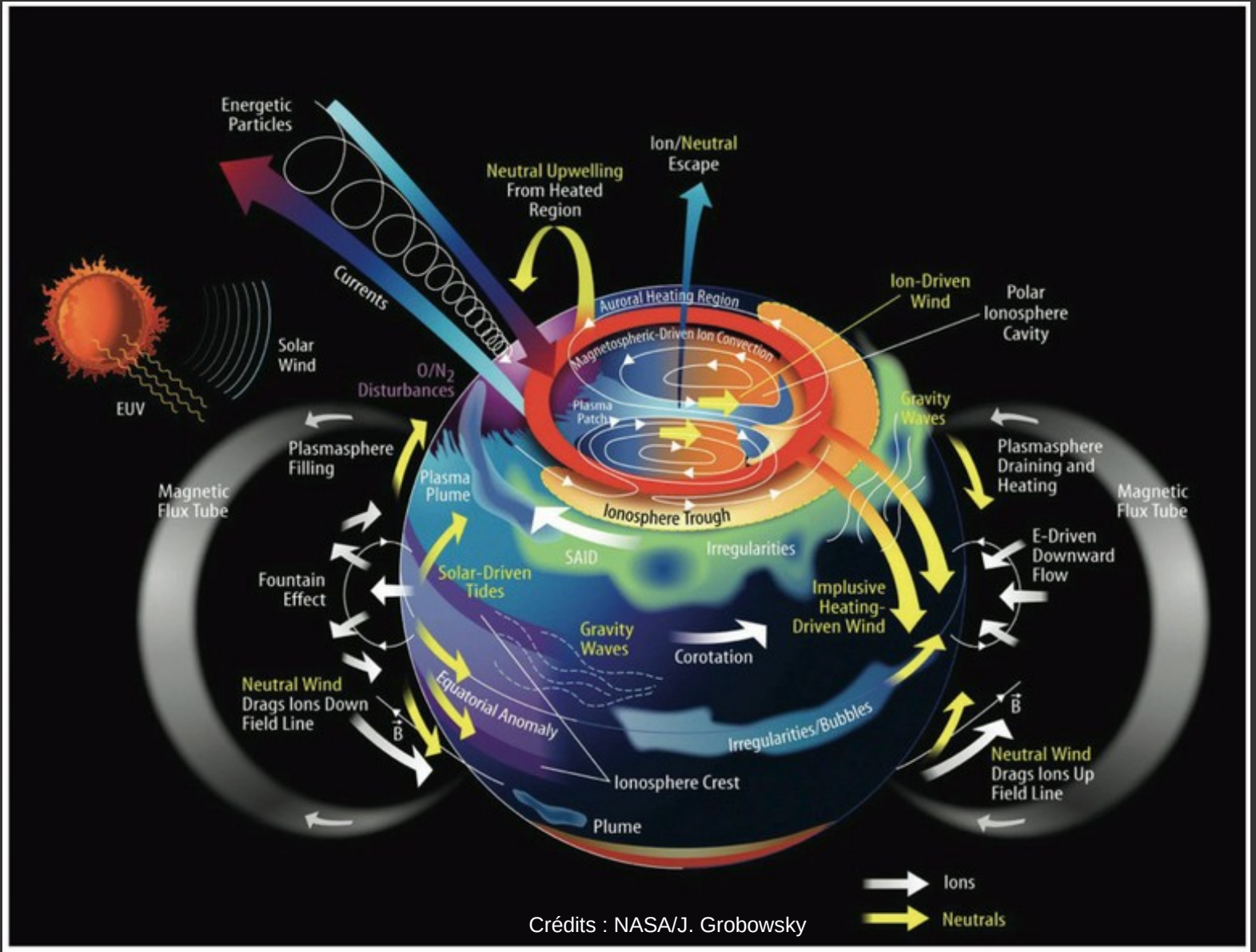


Pollock et al., 2003

Ceinture de Van Allen

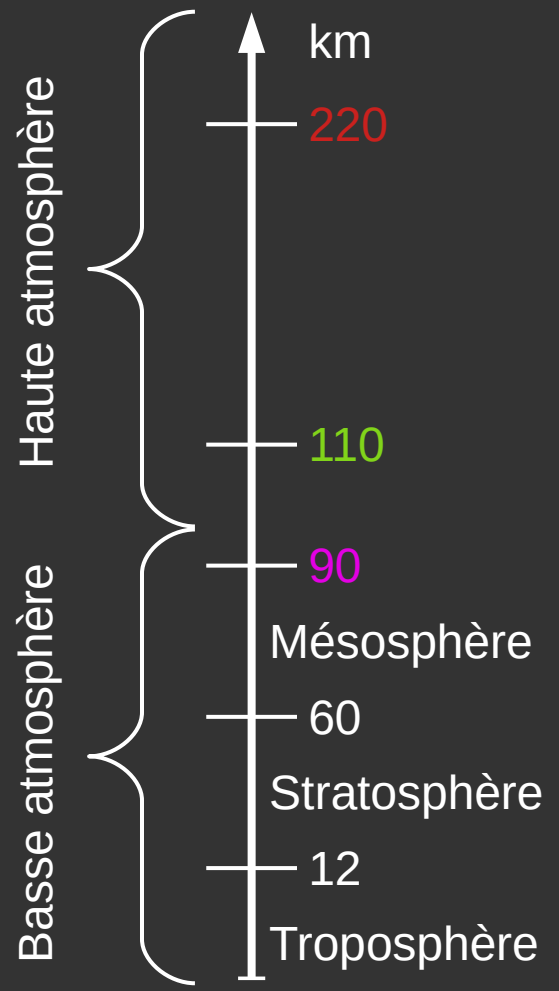


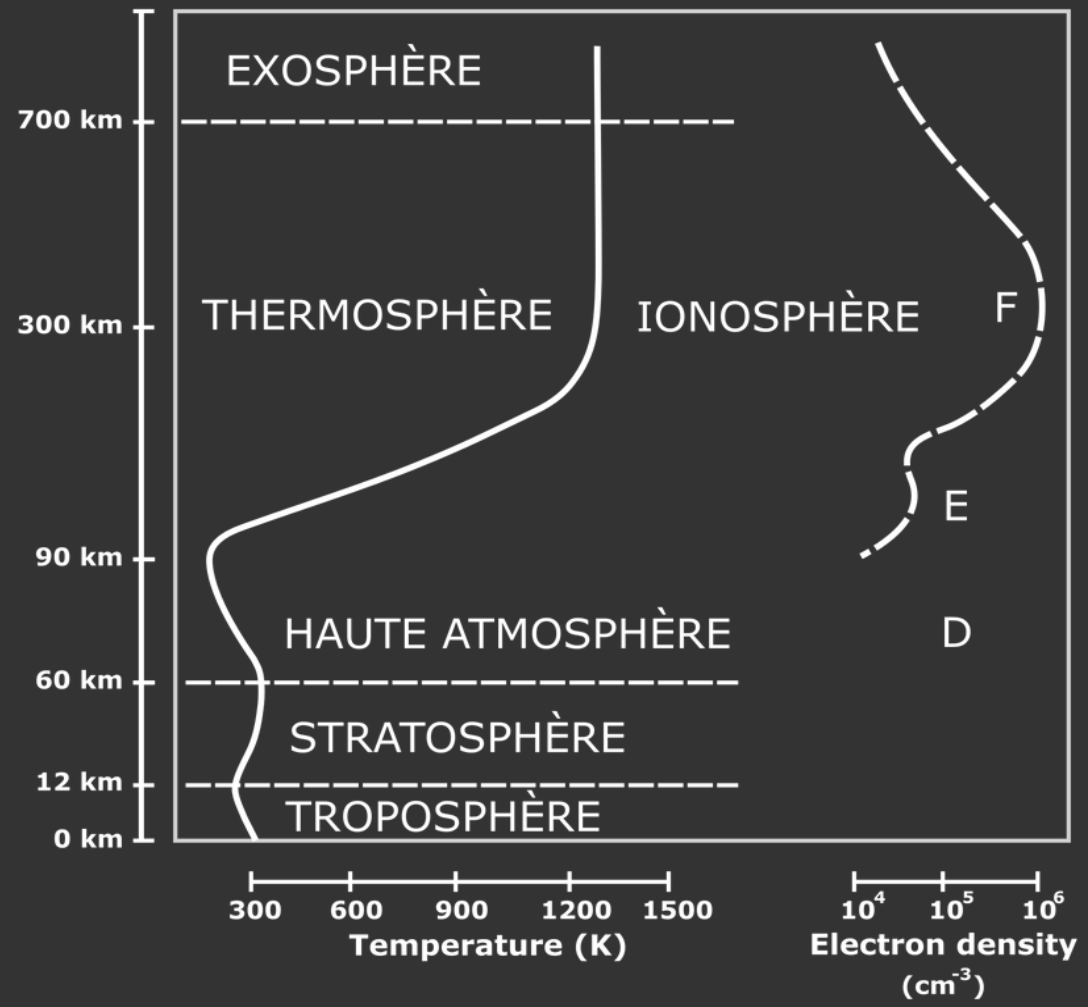
D. Baker/University of Colorado; NASA



Crédits : NASA/J. Grobowsky

L’atmosphère :





Couleurs aurorales :

Oxygène atomique O :

- Rouge (630.0 nm)
- Vert (557.7 nm)

Azote N_2^+ :

- Bleu (427.8 nm)
- Mauve (391.4 nm)

Crédit : Quentin de Meur

Haute atmosphère

- 60 km et +
- Hautement variable dans le temps et l’espace
- Décomposée en :
  - Ionosphère = ions + électrons
  - Thermosphère = neutres

Variations spatiales : Latitude

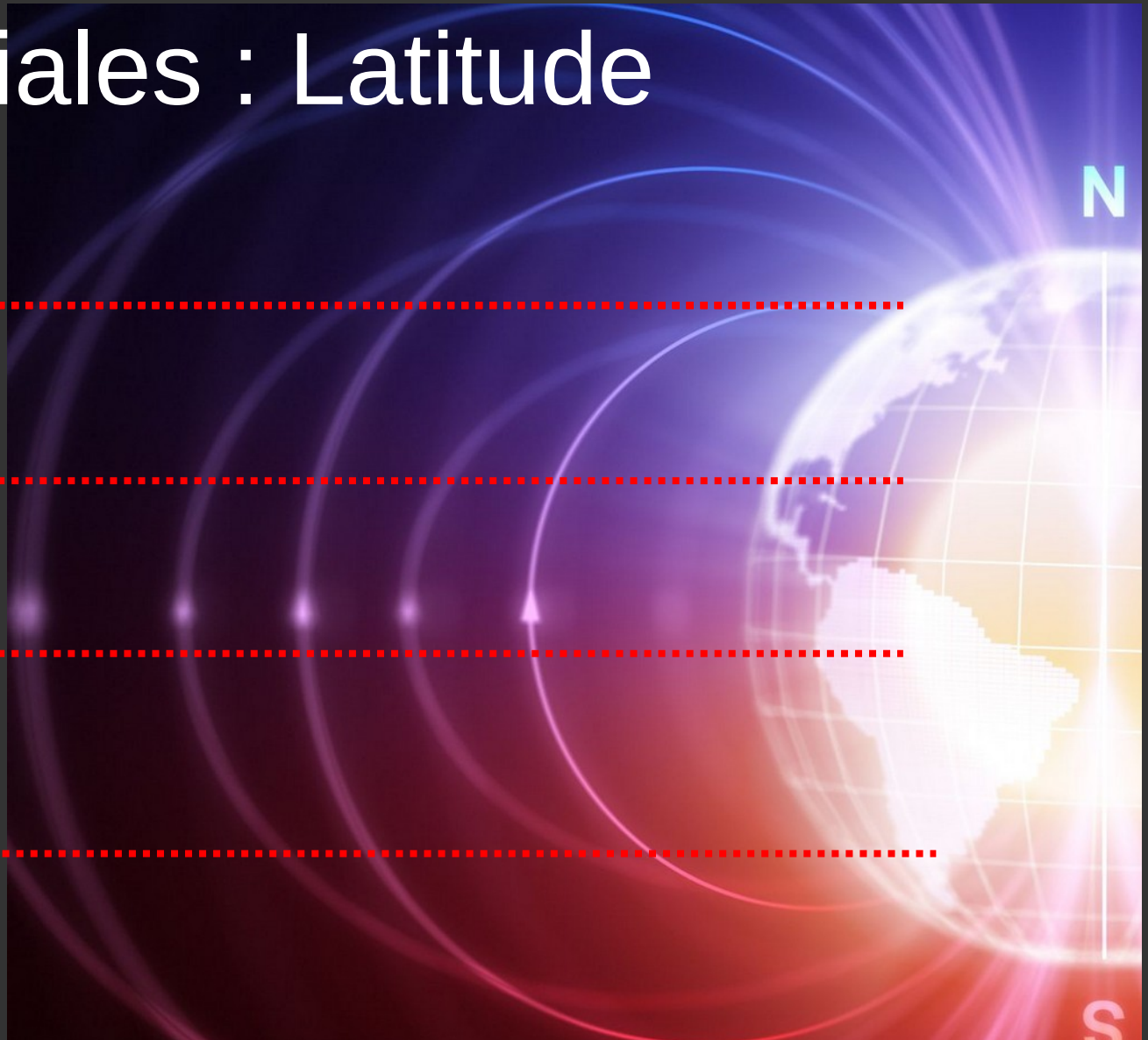
Zone aurorale

Moyennes latitudes

Zone équatoriale

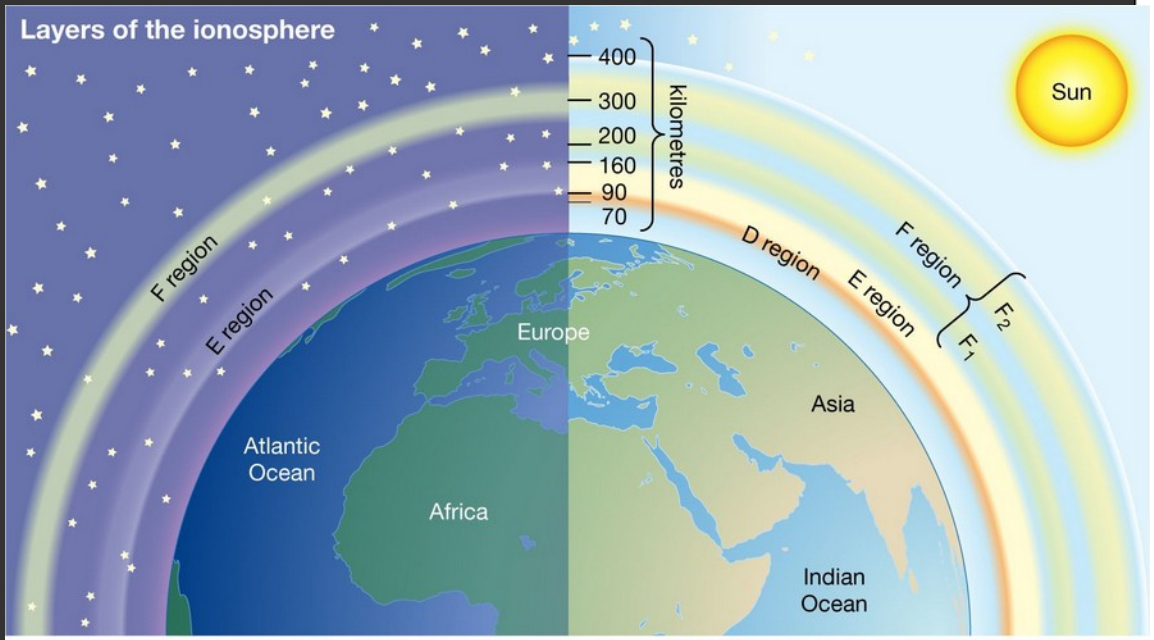
Moyennes latitudes

Zone aurorale



Variations spatiales : Altitude

- Découpe en couches D, E, F historique



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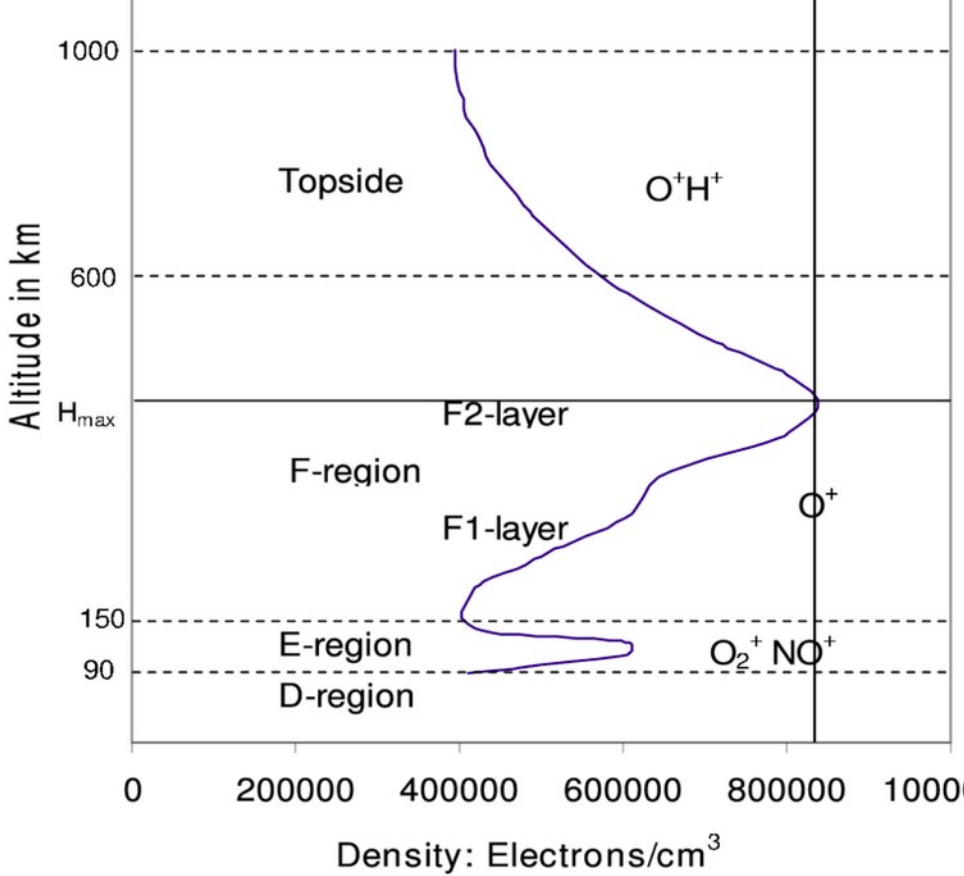
Sibanda, Patrick. (2022). Particle precipitation effects on the South African ionosphere.



Variations temporelles

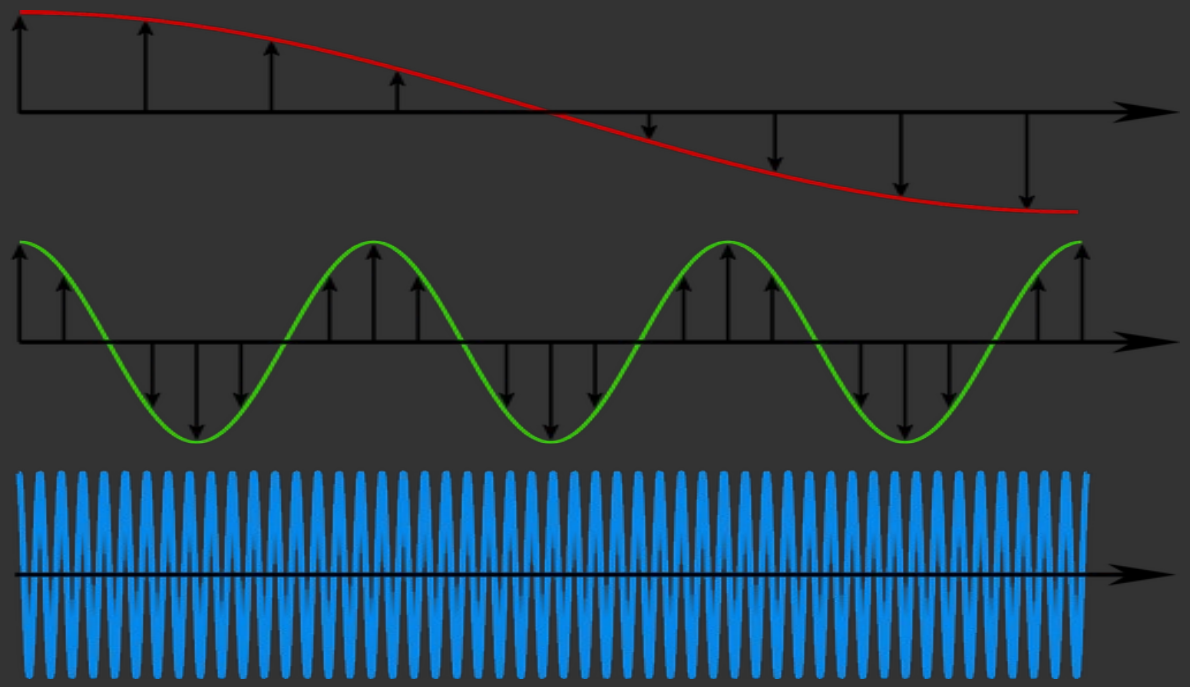
- Sec/min : zone aurorale, météore,
- Heures : zone E sporadique, tempètes magnétiques, solar flares, ondes de gravités
- Jours / Nuit : Partout
- Mois : Rotation solaire (27 j)
- Années : Cycle solaire

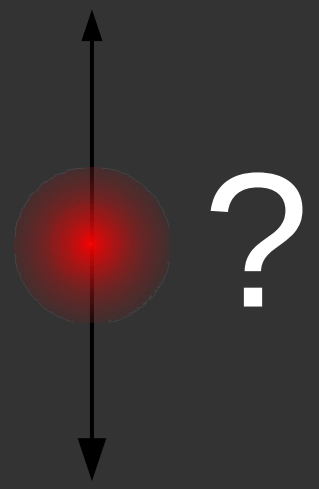
En quoi ces variations sont-elles importantes pour les communication HF ?

- Ionosphère = plasma
- HF = onde électromagnétique

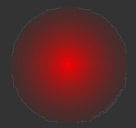
- Plasma et champ magnétique sont étroitements liés.

Combien de fois un électron peut-il réagir à un changement électro-magnétique ?

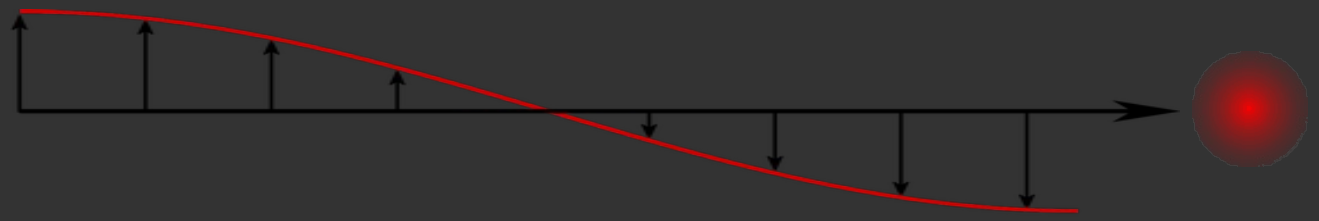




Combien de fois un électron peut-il réagir à un changement électro-magnétique ?

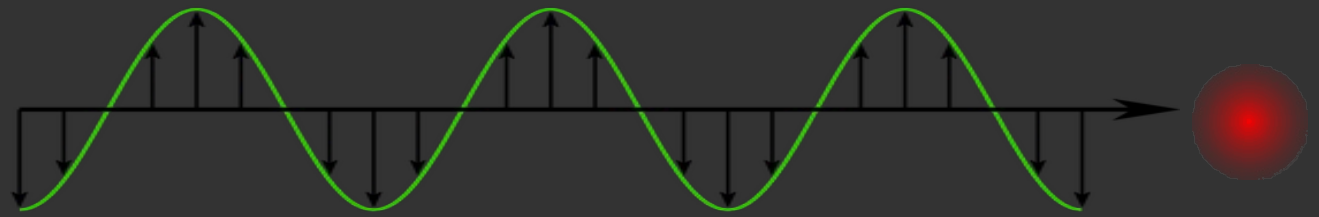


Combien de fois un électron peut-il réagir à un changement électro-magnétique ?



Combien de fois un électron peut-il réagir à un changement électro-magnétique ?

Combien de fois un électron peut-il réagir à un changement électro-magnétique ?



Fréquence plasma

$$\omega_p = \sqrt{\frac{n_e e^2}{\varepsilon_0 m}}$$

- Charge et masse d’un électron
- Permittivité du vide

Concentration électronique VARIABLE

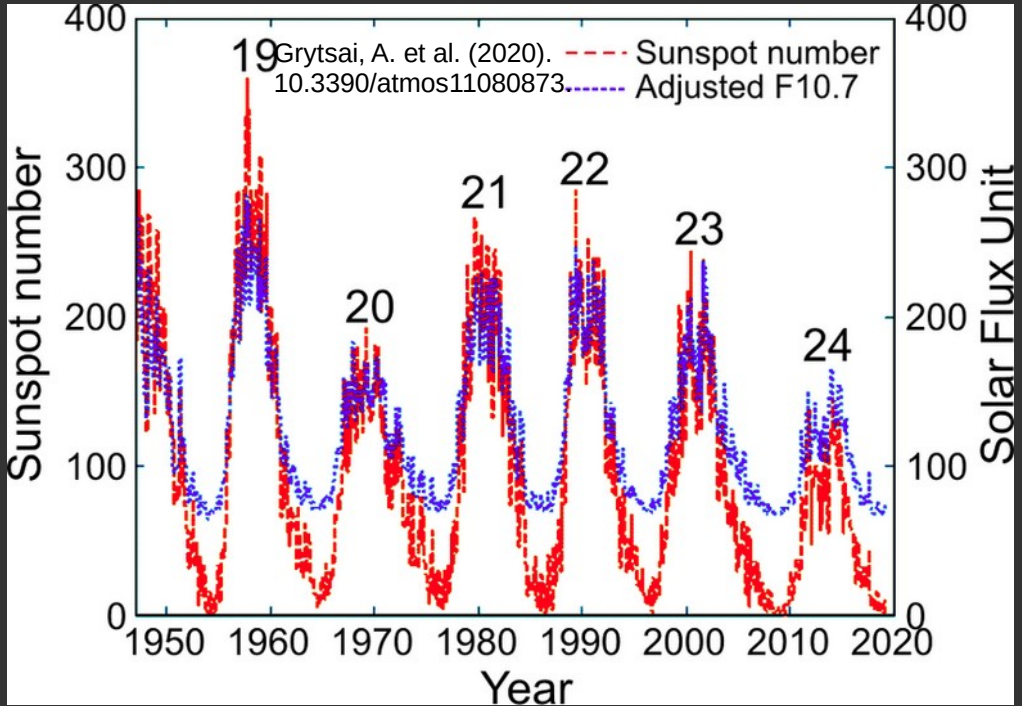
Mesures de météo de l’espace

- Observations solaires
- Magnétomètres
- Satellites

INDICES (proxies)

Mesures de météo de l’espace

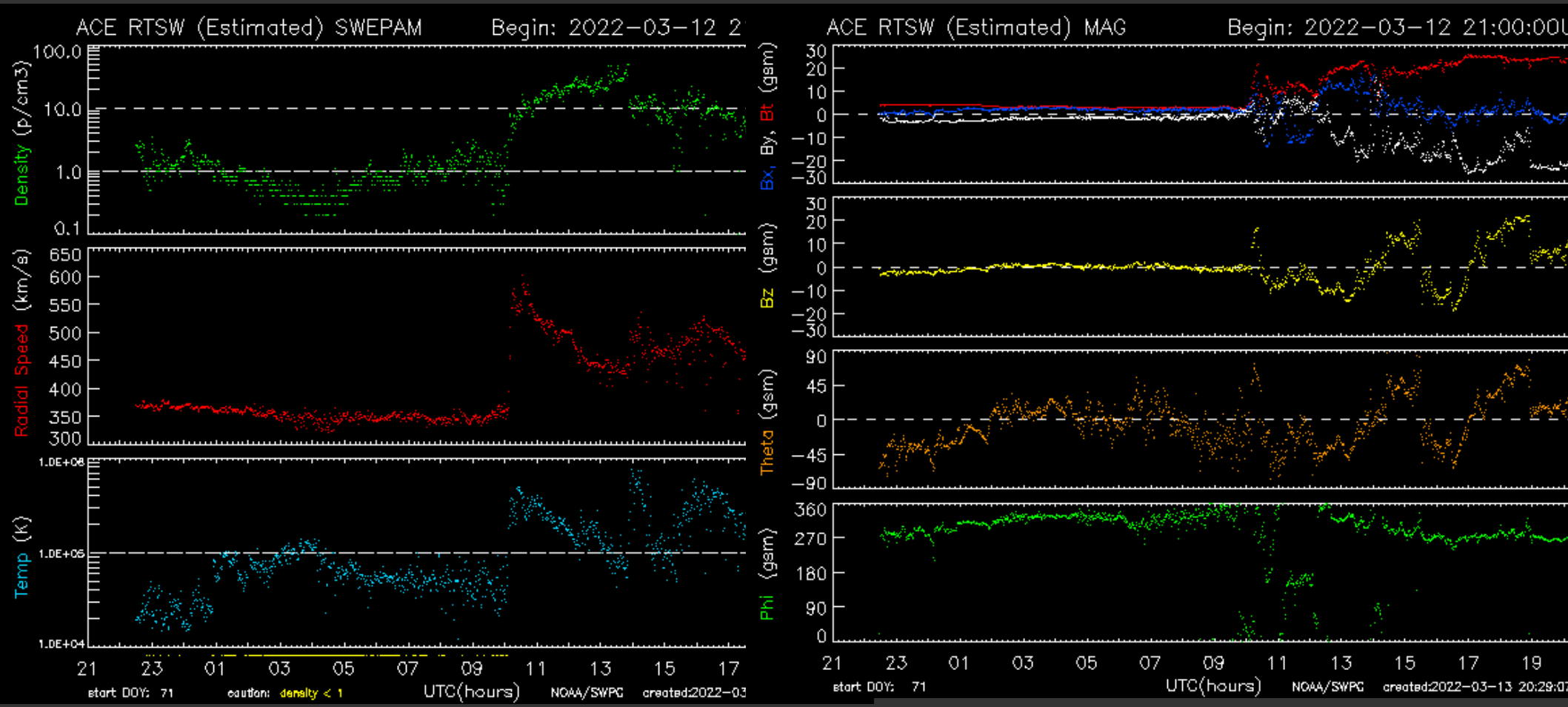
- Observations solaires (https://www.solarmonitor.org/)
  - Nombre & surface des taches solaires
  - F10.7 cm
  - X-rays, (GOES)
  - Proton, Electrons



Mesures de météo de l’espace

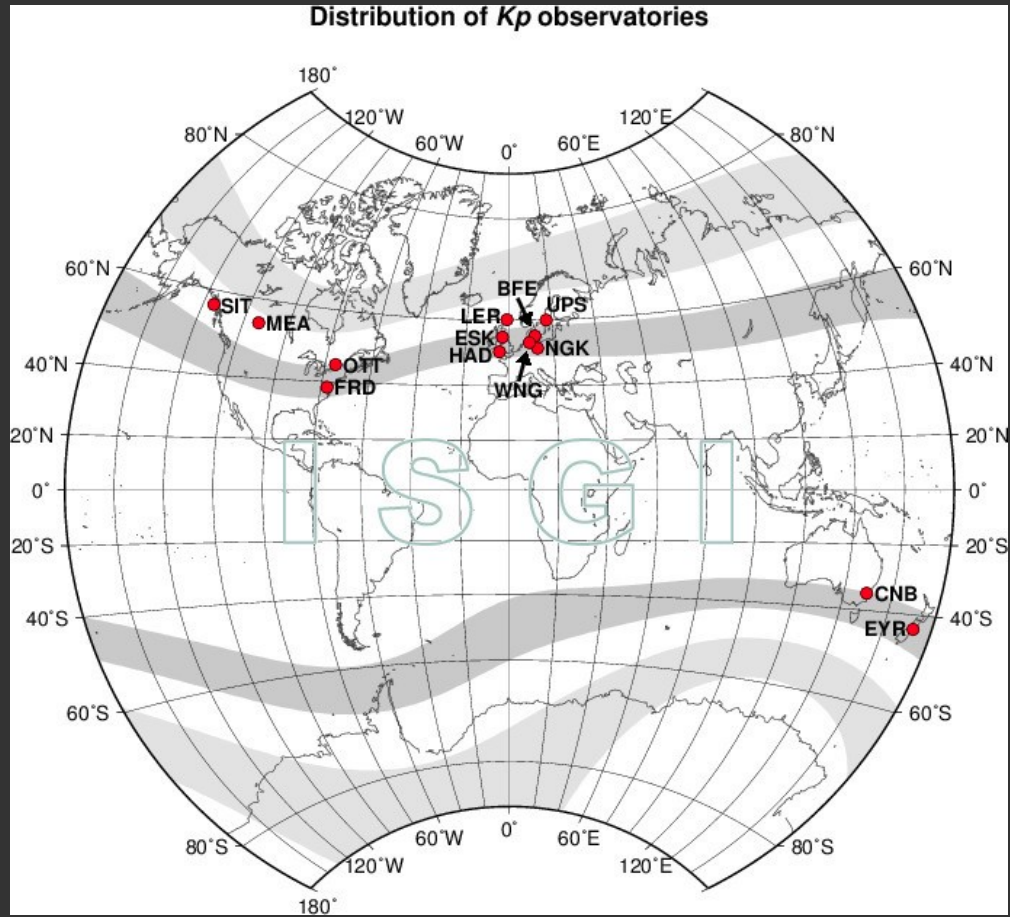
- Vent solaire (https://www.solarmonitor.org/) (ACE)
  - Concentration
  - Vitesse
  - Température
- Champ magnétique
  - Magnitude
  - Orientation

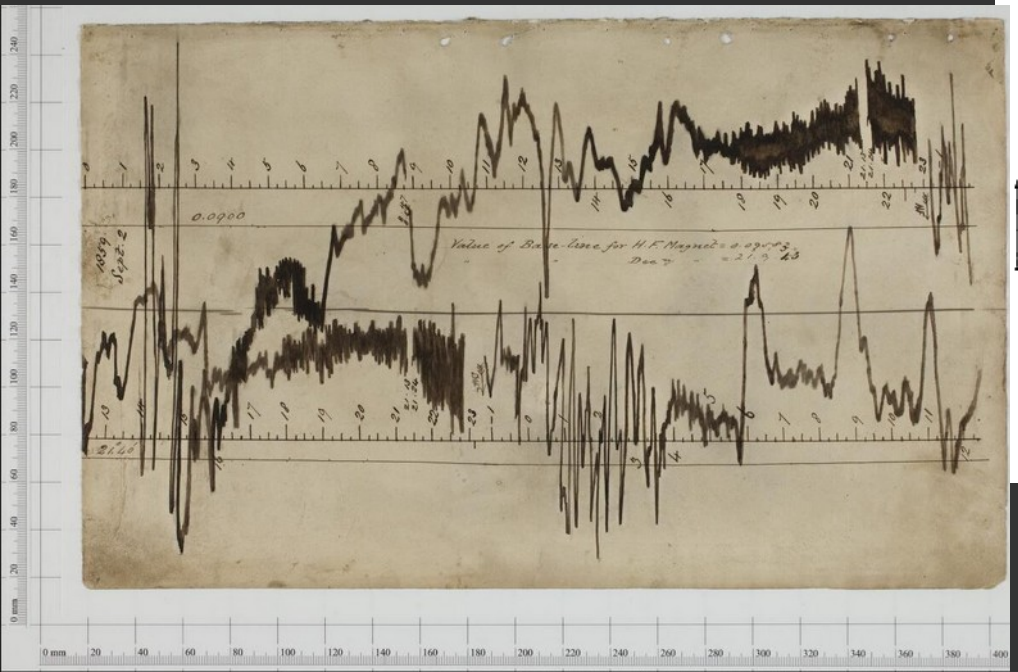
Mesures de météo de l’espace



Mesures de météo de l’espace

- Magnétomètres
  - Sol / Spatial
  - Indices (isgi.unistra.fr)
    - K, Kp
    - aa, am, ap
    - Dst





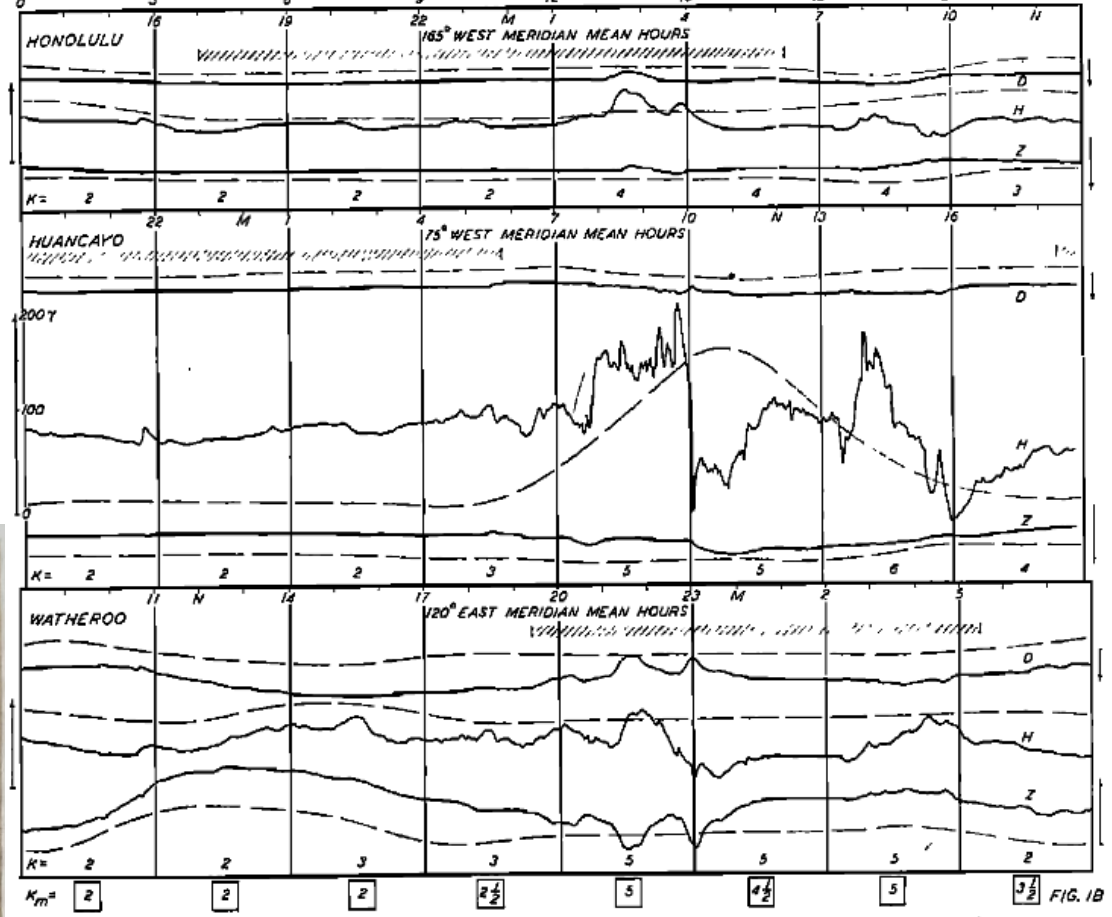
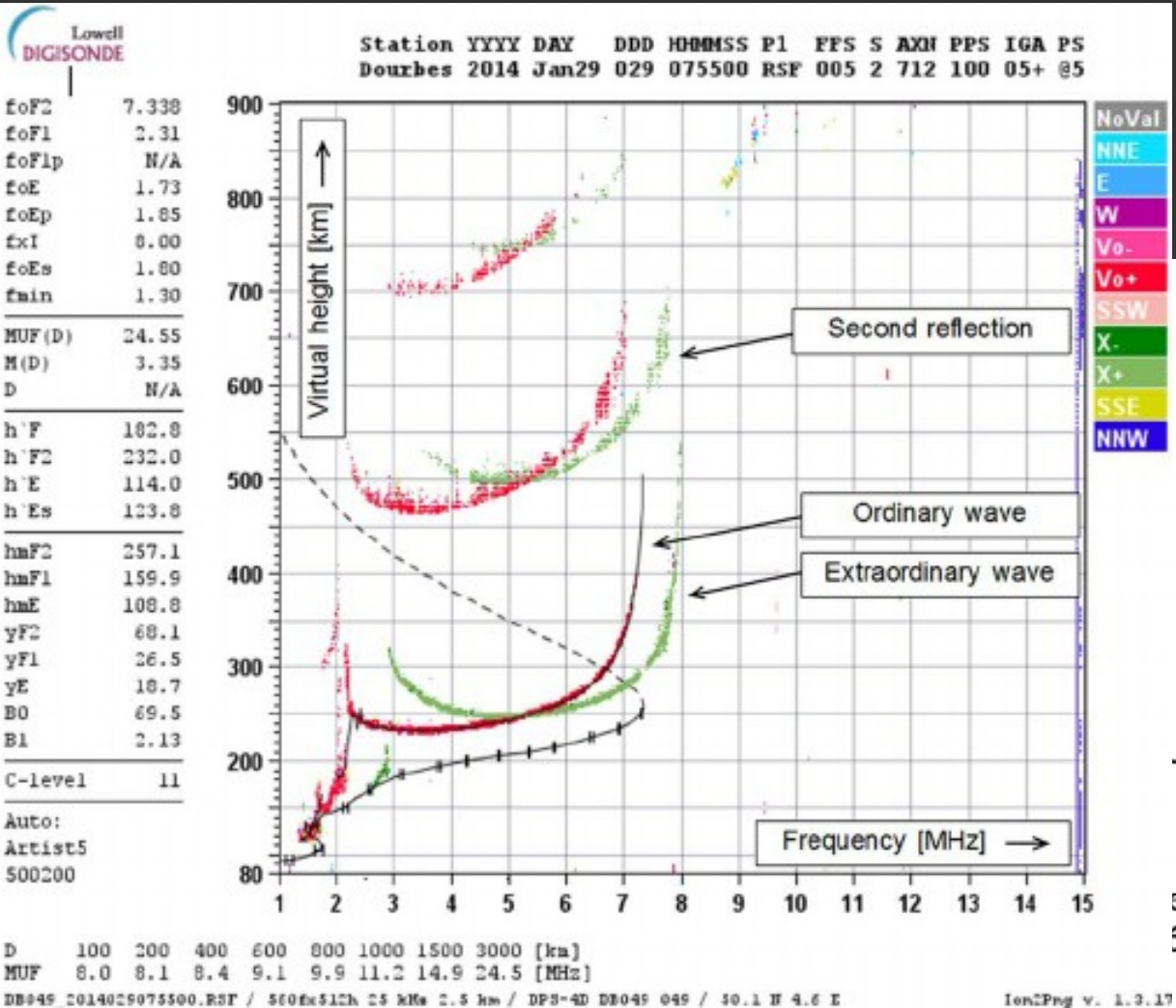


FIG. 1—SIMULTANEOUS MAGNETOGRAMS (ACTUAL RECORDS, FULL, NON-K-VARIATION, BROKEN)

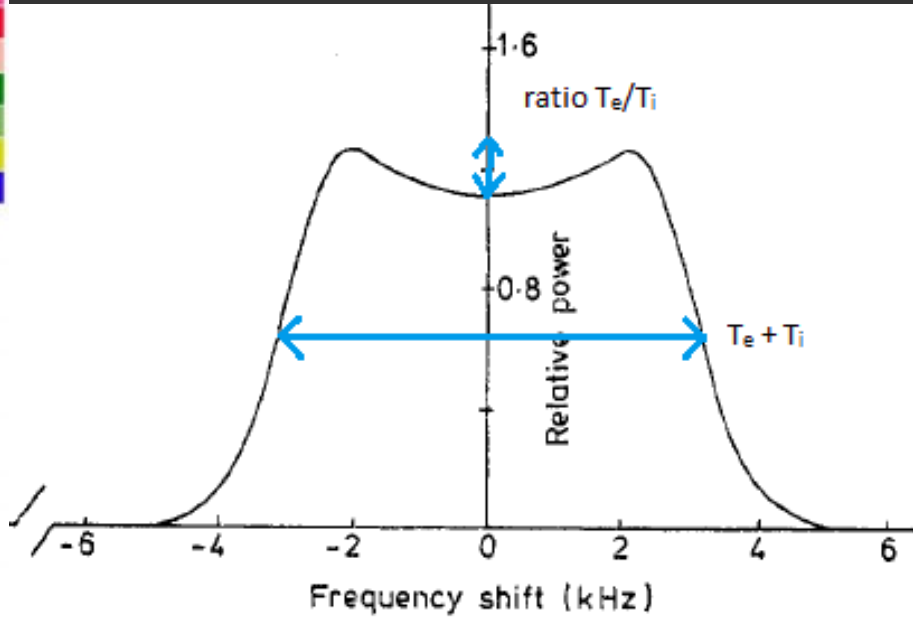
LEGEND

////// = NIGHT HOURS AT GROUND-LEVEL; ↑ OR ↓ = 100γ (UNLESS OTHERWISE MARKED) INDICATING DIRECTIONS INCREASING COMPONENTS TOWARD NORTH, EAST, AND NADIR; K = 3-HOUR INDICES; K_m = AVERAGE K

Ionosonde et EISCAT



Witvliet, B. et al. (2015)
10.1109/MAP.2015.2397071



ectrum and plasma lines. $N = 10^{12}$ m^{-3}, $T_e = 1000$ K,
5.

Source : Vickers, Hannah. (2011)

Autres conséquences et applications

- Sécurité des satellites et astronautes
- Grille électrique à grande échelle
  - Black outs
- Aviation
- Communication et GNSS
- Mining

Événements marquants

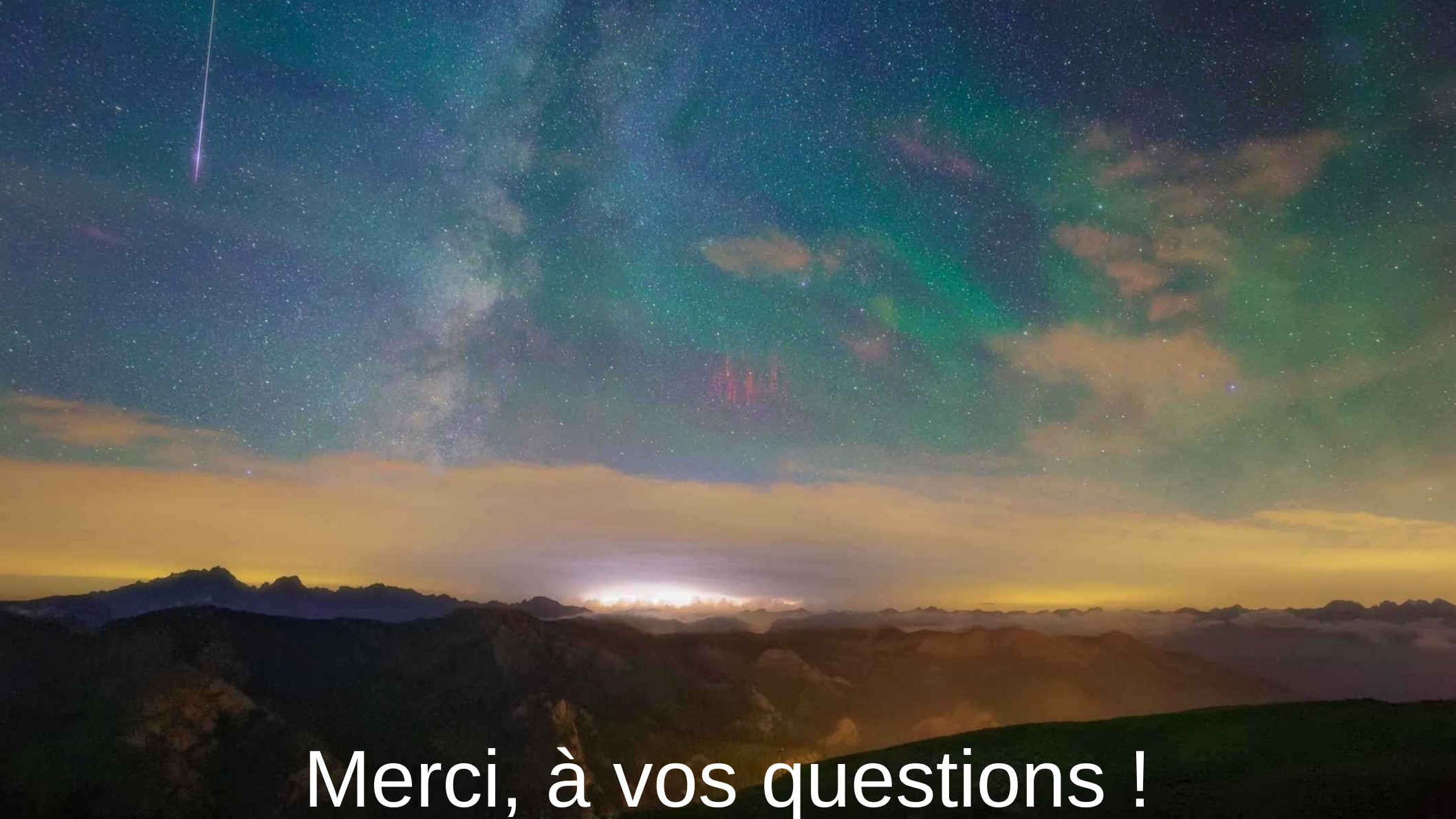
- 1859 : Événement de Carington
  - Télégraphes endommagés (voir même améliorés !)
- 1972 : Réseau électrique et comm. Explosion de mine marines
- 1989 : Québec black out de 9h

Récapitulation

- Soleil à l’origine de toutes les variations
  - UV, rayons X, f10.7
  - Vent solaire (électrons, protons)
- Vent solaire guidé par le champ magnétique terrestre
- Ionisation de la haute atmosphère
- « Miroir » d’onde HF

Récapitulation

- Météorologie de l’espace tout aussi complexe et imprévisible que la météo de surface
- Observations du soleil et du VS en direct
- Indices d’activités (proxy)
  - K_P, a, f10.7, taches solaires…


Merci, à vos questions !