Solar Irridiance: Measurement, Modeling and Connection to the Ionosphere -Thermosphere Dynamics

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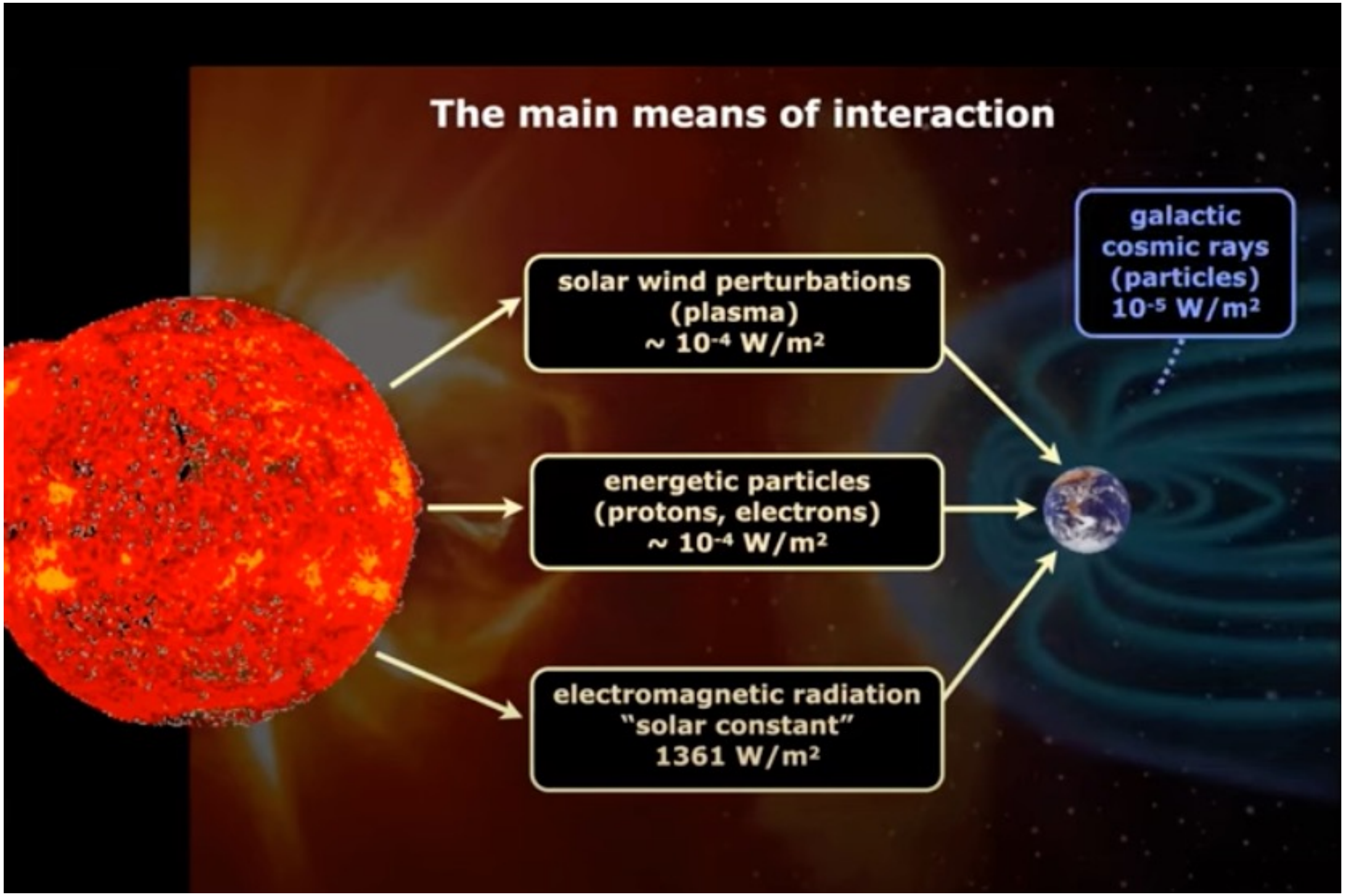
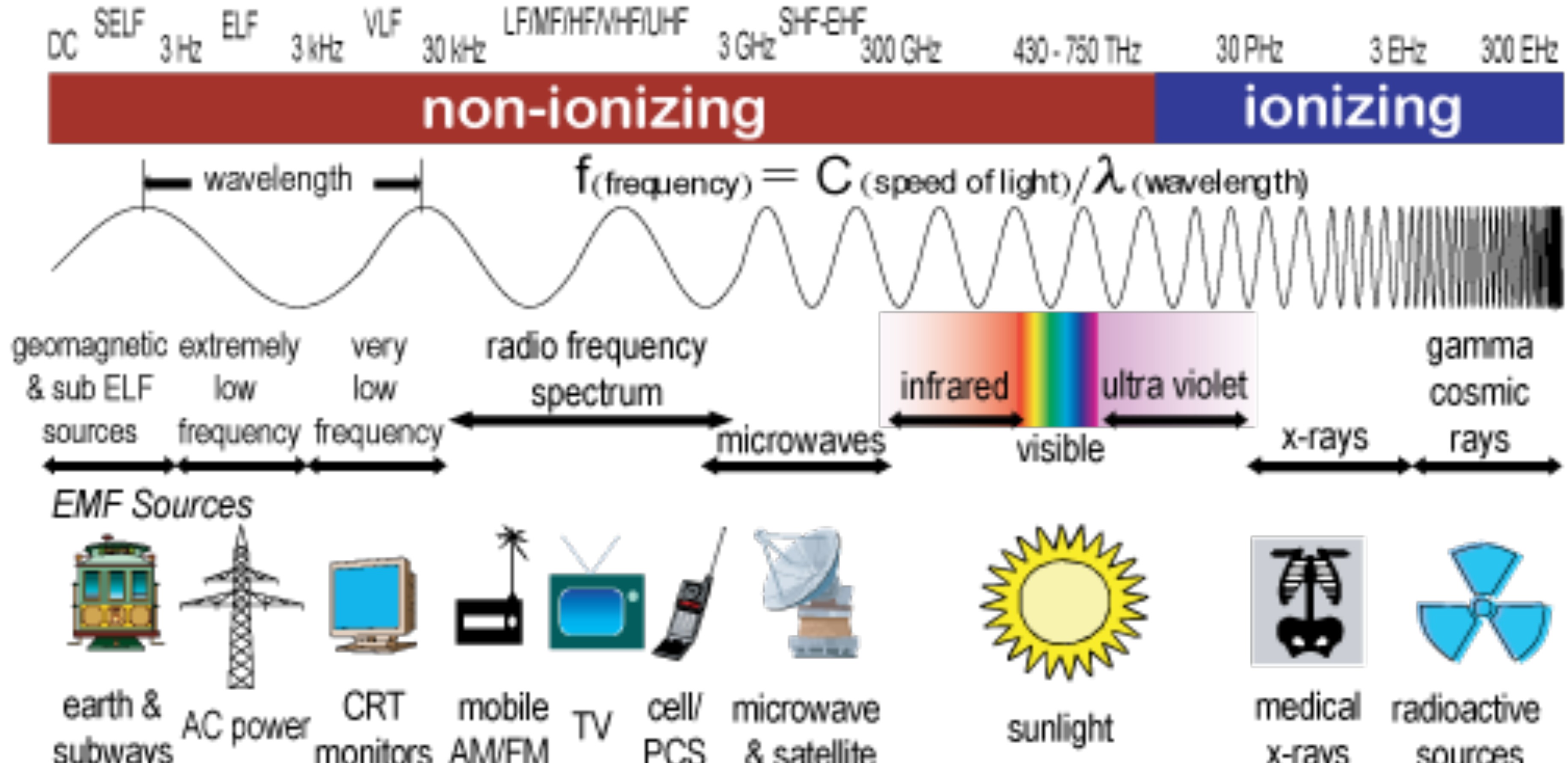
- **Solar Irridiance:** the output of light energy from the the Sun (radiative forcing).
- **Total Solar Irridiance (TSI):** the spatially and spectrally integrated solar radiation incident at the top of the Earth's atmosphere (space climate)
- The Solar Spectral Irradiance (SSI): a measure of the brightness of the entire Sun at a particular wavelength of light. Important spectral irradiance variations are seen in many wavelengths, from the visible and IR, through the UV, to EUV and X-ray. (space weather)
- Solar Spectral Irradiance in Solar EUV and X-ray: important for ionosphere-thermosphere dynamics and satellite drag effects

The Main Means of Interactions between the Sun and Earth



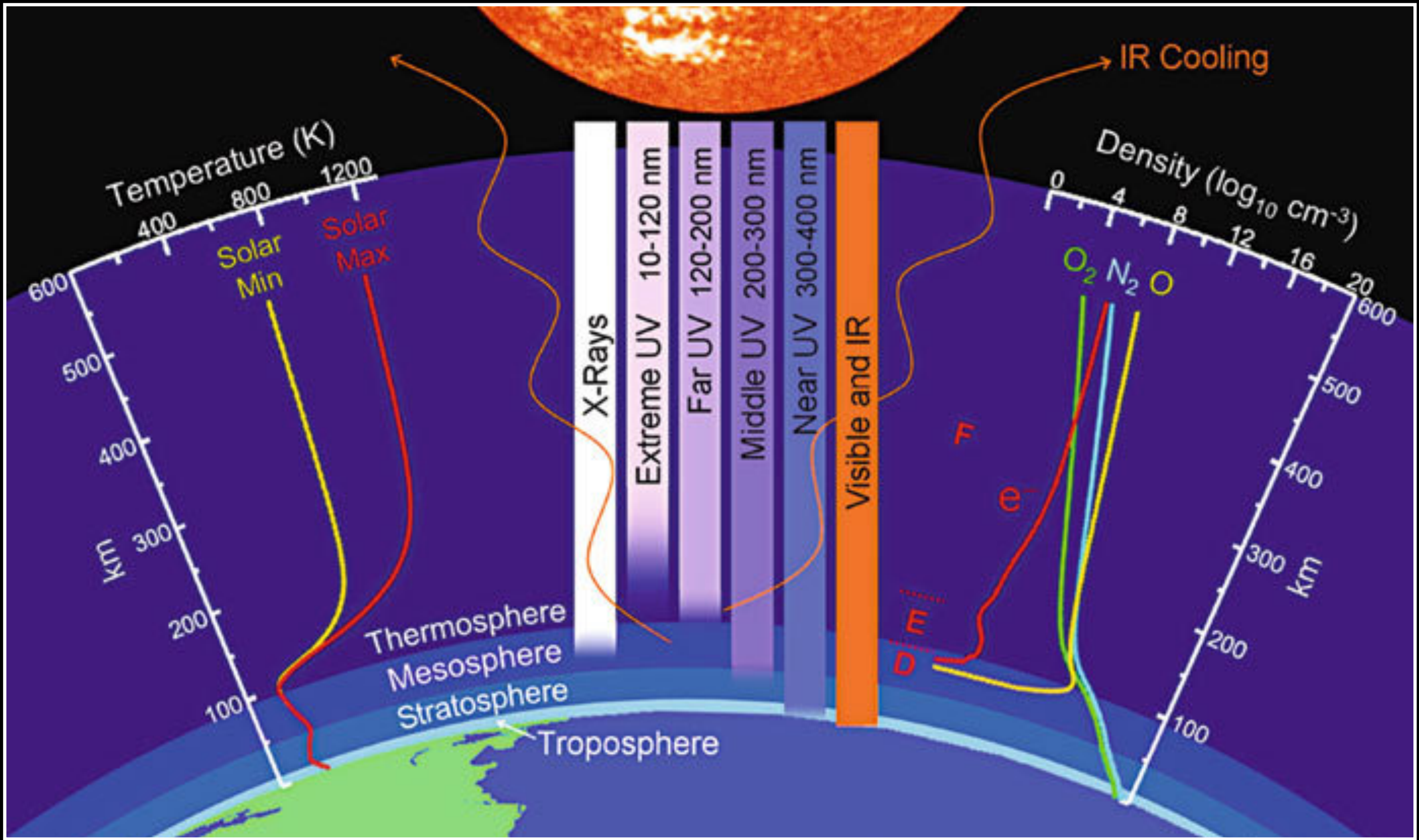
Space Weather, Space Climate and Habitability on Earth, Thierry Dudok de Wit

THE ELECTROMAGNETIC SPECTRUM



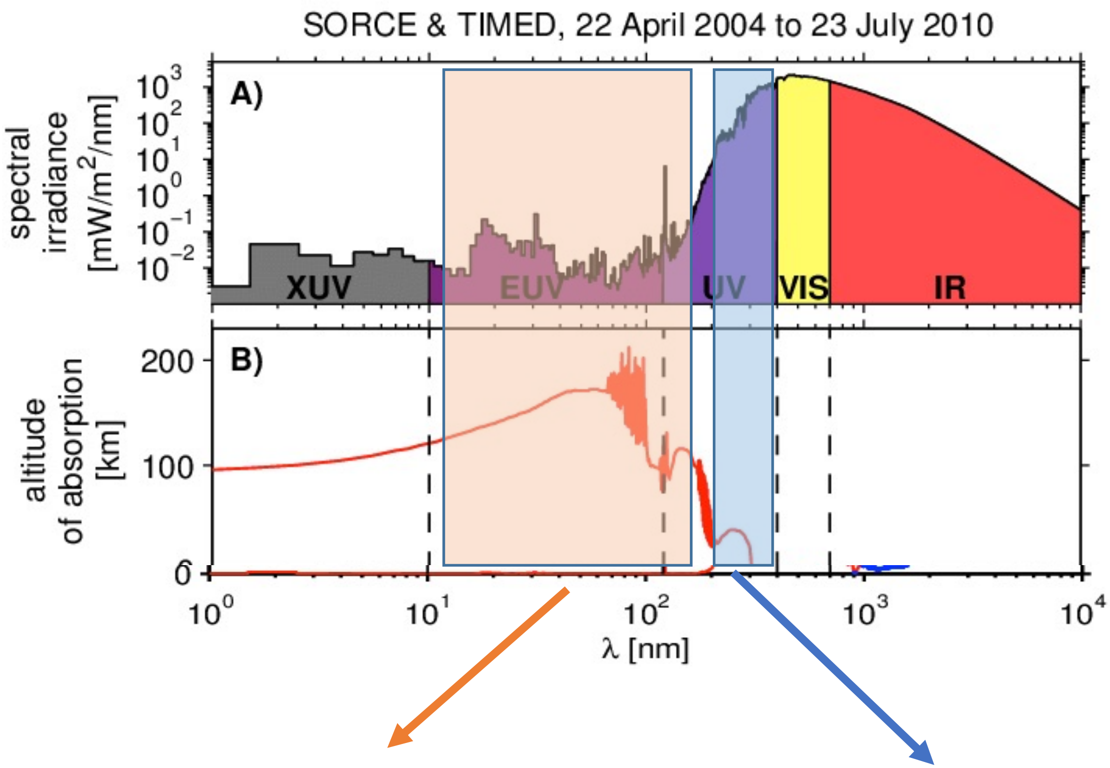
Gigahertz (GHz) 10-9 Terahertz (THz) 10-12 Petahertz (PHz) 10-15 Exahertz (EHz) 10-18 Zettahertz (ZHz) 10-21 Yottahertz (YHz) 10-24

Solar Irridiance and its Influence on Earth's Atmosphere



Solar radiation of different wavelengths is absorbed at different levels in the atmosphere (*M. Rycroft, 2013*)

Solar Irridiance and its Influence on Earth's Atmosphere



The spectral composition of solar irradiance is important in determining at what altitudes it is absorbed and produces local heating.

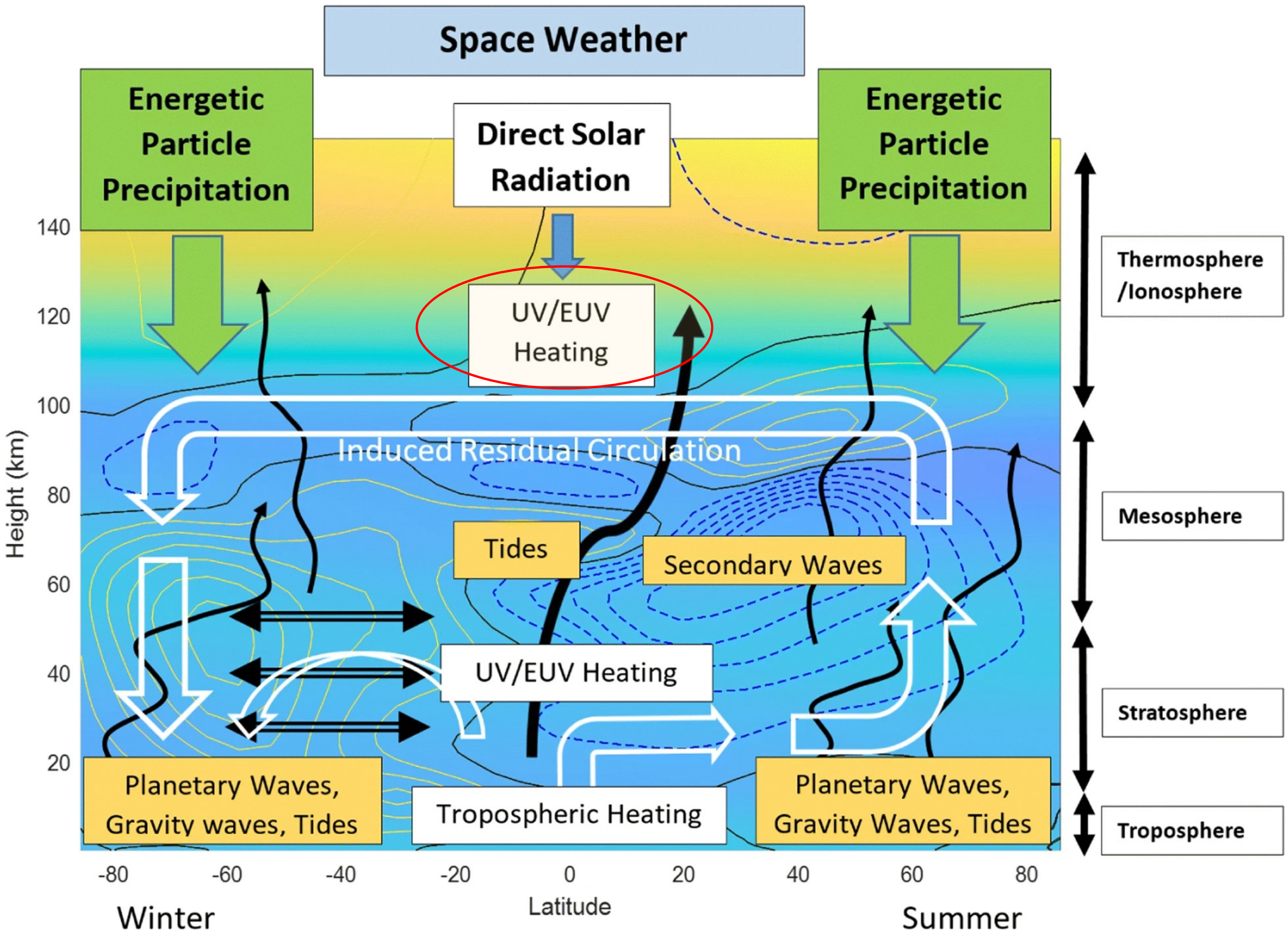
Impact on satellite drag and radio communication (Lilensten et al. 2008)

Impact on the ozone layer (Haigh, 2007)

Solar irradiance variability has different temporal scales

Solar cycle, seasonal, 27-day, daily, eruptive events (minutes ~ hours)

Solar Irradiance and its Influence on Earth’s Atmosphere



Solar Irridiance: Measurements

- Most of it have to be measured in space due to atmospheric absorption
- Continuous solar irradiance measurements across the broad wavelengths are often limited

Solar Irridiance and its Influence on Thermospheric Density (Satellite Drag)

The density and composition of thermosphere is mostly sensitive to variations of the solar irradiance in the EUV (10 —121 nm) spectral range (*T. Dudok de Wit and S. Bruinsma, 2011*)

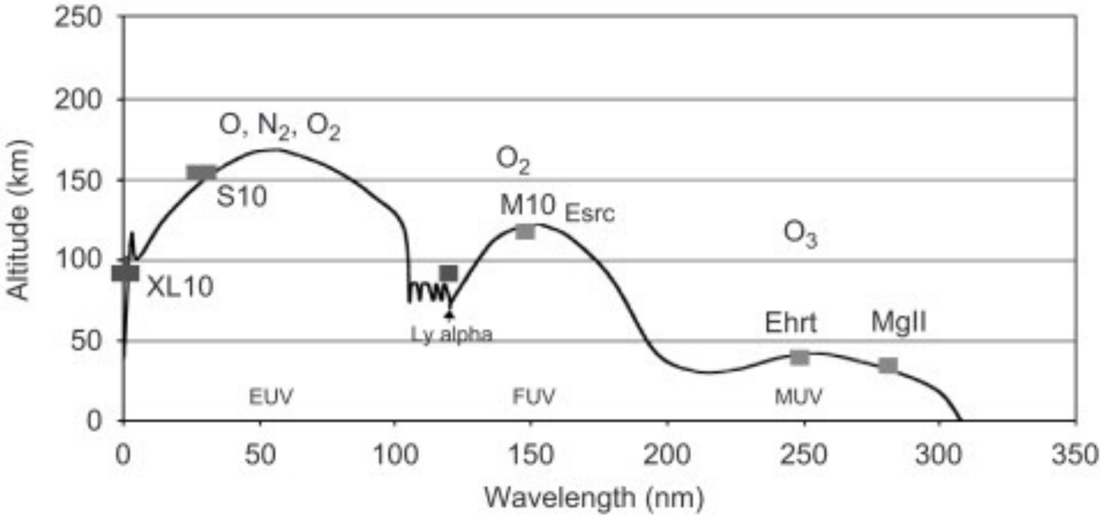
The spectrally integrated solar emission between **26–34 nm** offers the best overall performance in the density reconstruction (*T. Dudok de Wit and S. Bruinsma*, 2011)

Solar Irridiance: proxies

- The F10.7 (10.7 cm) is a daily index derived from solar radio measurements taken at 2800 MHz – used as a proxy for solar EUV (measurement since 1947)
- Inadequacy
  - the generation mechanisms for 10.7 cm microwave emission and those for EUV are quite different. They represent two different parts of the electromagnetic emissions from the sun. Details of their differences can be found in White [1999]. F10.7 is a type of radio emission produced by Bremsstrahlung and gyro-resonance in the domain of classical physics while EUV/X-ray is produced by line emissions involving atomic physics
- Improvement:
  - Adding contributions from other wavelengths;
  - Correction of F10.7 to make it more accurate proxy for solar EUV (eliminating the gyroresonance contribution, optical depth effects on the radio limb. *Schonfeld et al.*, 2015)

Solar Irridiance: additional indices used in models

- Including other wavelength contributions (Tobiska et al., 2008)
  - S10.7* (26-34 nm)
  - M10.7* (280 nm), the MgII index (the core-to-wing ratio of the Mg II K-line at 280 nm).
  - XL10.7 (0.1-8nm, 121nm) E_SRC (145-165 nm, FUV), E_HRT (245-254nm, MUV)



Indices: Have to have observing facility/instruments

Solar indices for atmospheric heating, spectral category, subcategory, wavelength range (nm), solar source temperature region, solar source feature, altitude region of terrestrial atmosphere absorption (km), and terrestrial atmosphere thermal region

Solar indices studied for atmospheric heating

Index	IS 21348 spectral category	IS 21348 spectral sub-category	Wavelength range (nm)	Solar source temperature region[a]	Solar source feature[a]	Atmosphere absorption (unit optical depth, km)[b]	Terrestrial atmosphere absorption (thermal region)[b]
X_{hf}	X-rays	X-rays	0.1–0.8	Hot corona	Flare	70–90	Mesosphere
X_{b10}	X-rays	X-rays	0.1–0.8	Corona	Active region background	70–90	Mesosphere
$XE_{10.7}$	X-rays and UV	XUV + EUV	1–40	Chromosphere, corona	Active region, plage	90–200	Lower, mid thermosphere
$E_{10.7}$	X-rays and UV	XUV + EUV	1–105	Chromosphere, corona	Active region, plage, network	90–500	Thermosphere
*$F_{10.7}$	Radio	Radio	10.7E7	Transition region, cool corona	Active region	90–500	Thermosphere
*$S_{10.7}$	UV	EUV	26–34	Chromosphere, corona	Active region, plage, network	200–300	Thermosphere
$XL_{10.7}$	X-rays and UV	X-rays + H Lyman-α	0.1–0.8, 121	Chromosphere, transition region, corona	Active region, plage, network	70–90	Mesosphere
H Lyα	UV	H Lyman-α	121	Transition region, chromosphere	Active region, plage, network	70–90	Mesosphere
E_{SRC0}	UV	FUV	125–175	Photosphere, chromosphere	Plage and network	90–125	Mesosphere, lower thermosphere
E_{SRC1}	UV	FUV	151–152	Chromosphere	Plage and network	125	Lower thermosphere
E_{SRC2}	UV	FUV	144–145	Chromosphere	Plage and network	125	Lower thermosphere
E_{SRC3} (E_{SRC})	UV	FUV	145–165	Photosphere, chromosphere	Plage and network	125	Lower thermosphere
*$M_{10.7}$	UV	MUV	280	Chromosphere	Active region	20	Stratosphere
E_{SRB}	UV	FUV + MUV	175–205	Photosphere	Plage and network	50–70	Mesosphere
E_{HRT}	UV	MUV	245–254	Photosphere	Network, background	25	Stratosphere

Forecasting Solar Irradiance/Indices

- Since F10.7 and solar EUV originate from the sun, a long lead-term forecasting of them requires a good understanding of the dynamic evolution of solar atmosphere/dynamo. Henney et al. [2012] and [2015] adopt such an approach in forecasting F10.7 radio flux and solar EUV intensity by utilizing predictions of the global solar magnetic field. The synopsis is that significant correlation is found between the solar EUV and FUV bands and the weaker magnetic fields associated with plage regions during nonflaring periods. Similarly, the observed F10.7 signal is found to correlate well with strong magnetic field (i.e. sunspot) regions. Air Force Data Assimilative Photospheric Flux Transport (ADAPT) model is used to estimate Earth side solar magnetic field distribution, which is used to forecast irradiance.
- Solar photospheric magnetic field is used to create a multicomponent proxy for solar activity (Warren et al., 2021)
- Flares times: more complex variations of solar EUV spectral intensity and F10.7 flux. Forecasting of them becomes even more challenging.
- FISM1, FISM2 (Chamberlin et al, 2007, 2008, 2020): An empirical model of the solar ultraviolet irradiance created to fill spectral and temporal gaps in the satellite observations. FISM1/2 estimates solar ultraviolet irradiance variations due to the solar cycle, solar rotations, and solar flares.
    - FISM-M FISM for Mars

I-T models implementation/treatment of solar irradiance

- CTIPe (Coupled Thermosphere Ionosphere Plasmasphere Electrodynamics Model): F10.7
- USU-GAIM (Utah State Univ. Global Assimilation of Ionospheric Measurements): F10.7
- WACCM-X (Whole Atmosphere Community Climate Model with thermosphere and ionosphere extension): F10.7
- SAMI3 ((uses EUVAC - a solar EUV flux model: with 37 wavelength bins)
- JB2006/2008 (F10.7, S10.7, M10.7 – uses more indices, broader wavelength coverage)
  - Empirical thermospheric density model – basis of the HASDM (High Accuracy Satellite Drag Model) used in United States Space Force (USSF)'s operation for collision avoidance. NASA Earth Science Mission Operations also relies on it.
- DTM 2013 (Bruinsma, 2015): uses F30 (30 cm radio flux, measured in Japan since 1957) performs better than DTM2009 that uses F10.7
  - The Drag Temperature Model (DTM) is a semi-empirical model describing the temperature, density, and composition of the Earth's thermosphere

Summary

- Need continuous measurement of SSI covering a broad-spectrum range
- Modification of the ionosphere-thermosphere models to take improved/different solar irradiance

extras