Ηλιακή Φυσική
Μάθημα 1: Ηλιακό στέμμα

Προτεινόμενη βιβλιογραφία

Solar Astrophysics P. V. Foukal, Wiley-VCH, 2004, ISBN 3-527-40374-4

The Solar Corona Leon Golub and Jay M. Pasachoff, Cambridge Univ. Press, 1997, ISBN 0 521 48535 5

The Sun: an Introduction M. Stix, Astronomy & Astrophysics Libr., Springer, 2004, ISBN 3 540 20741 4

Physics of the Solar Corona: An Introduction **Markus Aschwanden, Springer Praxis, 2005. ISBN 3 540 22321 5**

The Sun: some basics

Mass	1 $M_\odot$ = 1.989 × 10^{30} kg
Radius (photosphere)	1 $R_\odot$ = 696,000 km
Mean density	1,410 kg m^{-3} (Earth: 5,510 kg m^{-3})
Irradiance (at Earth)	1.368 kW m^{-2}
Luminosity	3.85 × 10^{23} kW
Effective temperature	5778 K
Mean distance from Earth	1 AU = 149,600,000 km = 1/206265 parsec
Rotation period	~25 days (equator), ~35 days (poles)
Rotation speed (equator)	2 km s^{-1}
Magnetic field strength (typical values)	General solar ~ 10^{-4} T Sunspot ~ 0.4 T Chromospheric plage ~ 0.02 T Prominence ~ 0.001-0.01 T
Solar wind velocity	300 -700 km s^{-1}
Solar wind mass loss	5 × 10^{16} kg/year = 2.5 × 10^{-14} $M_\odot$/year

Μπορούμε να δούμε το στέμμα;

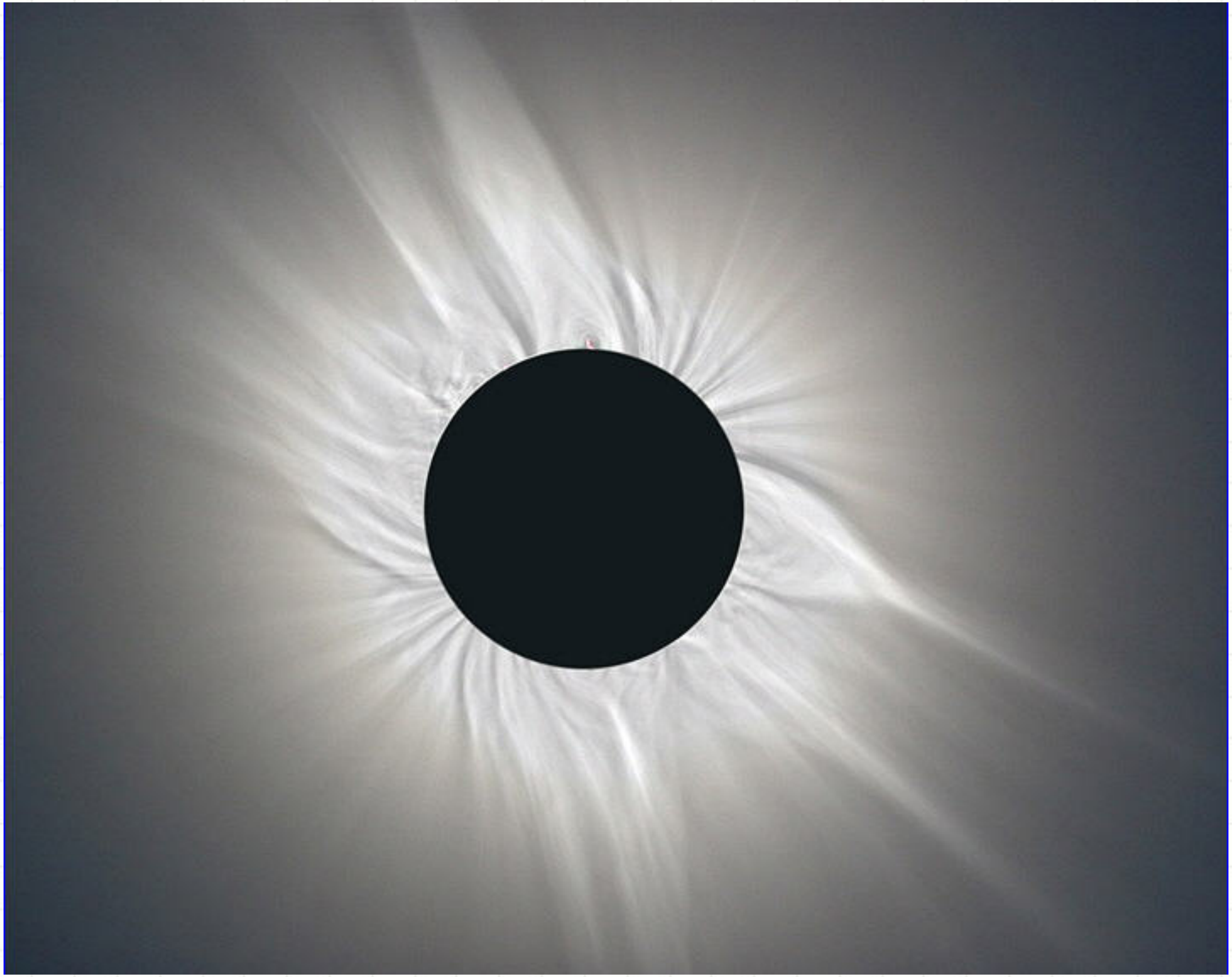

Total Eclipse
Klaus Nomi

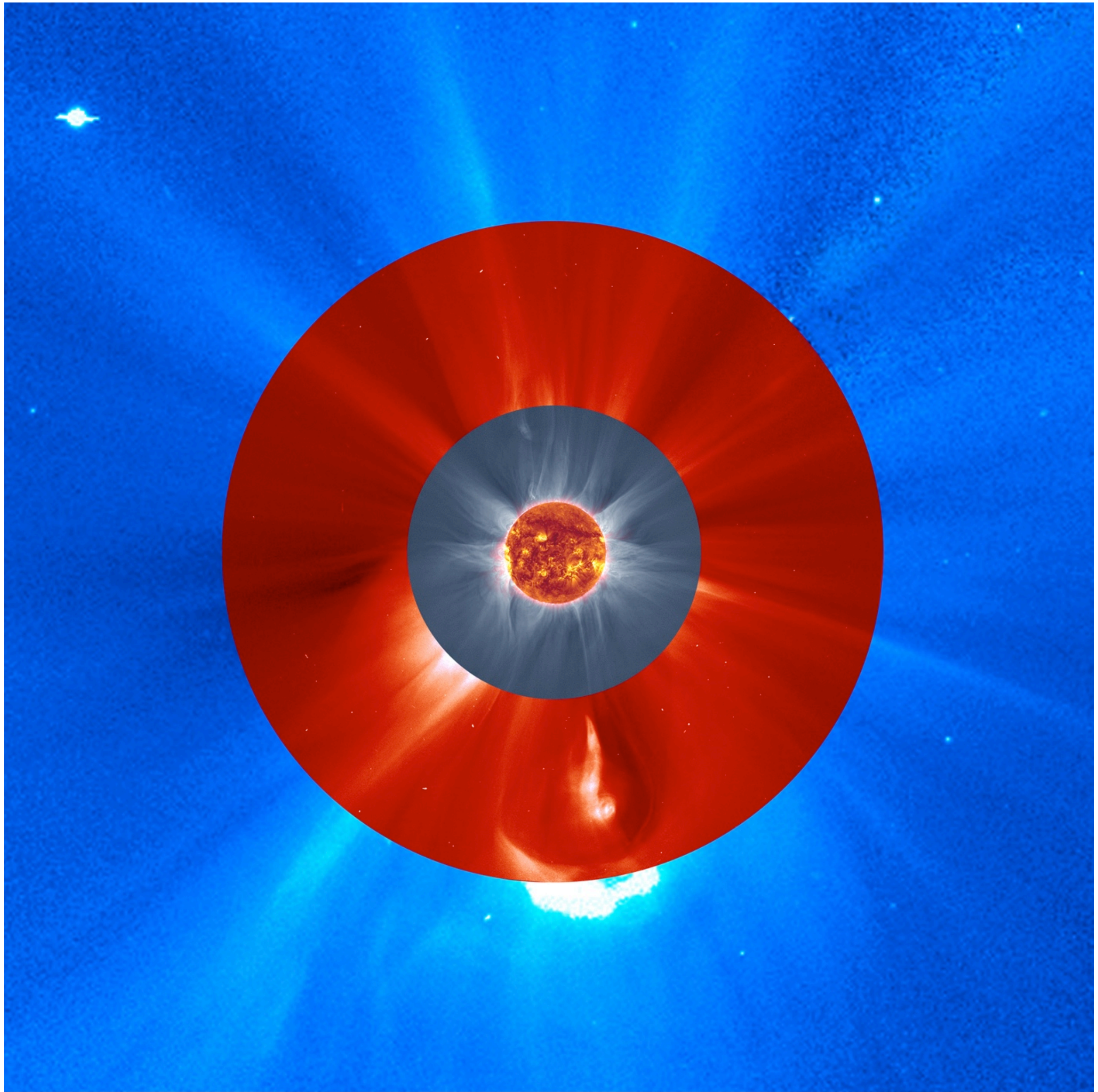
Diamonds and Rust

Tuesday, August 22, 2017

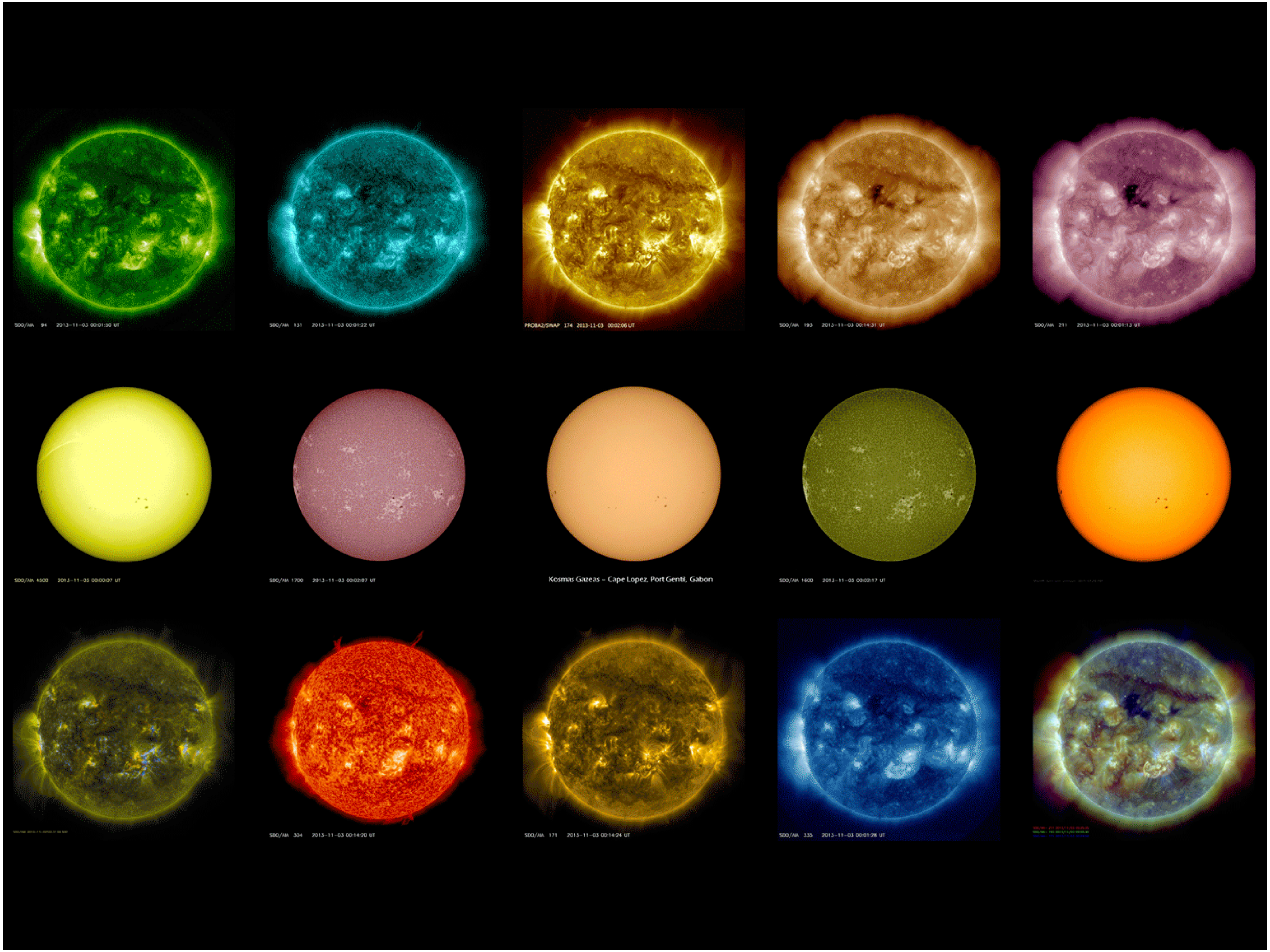
Έκλειψη

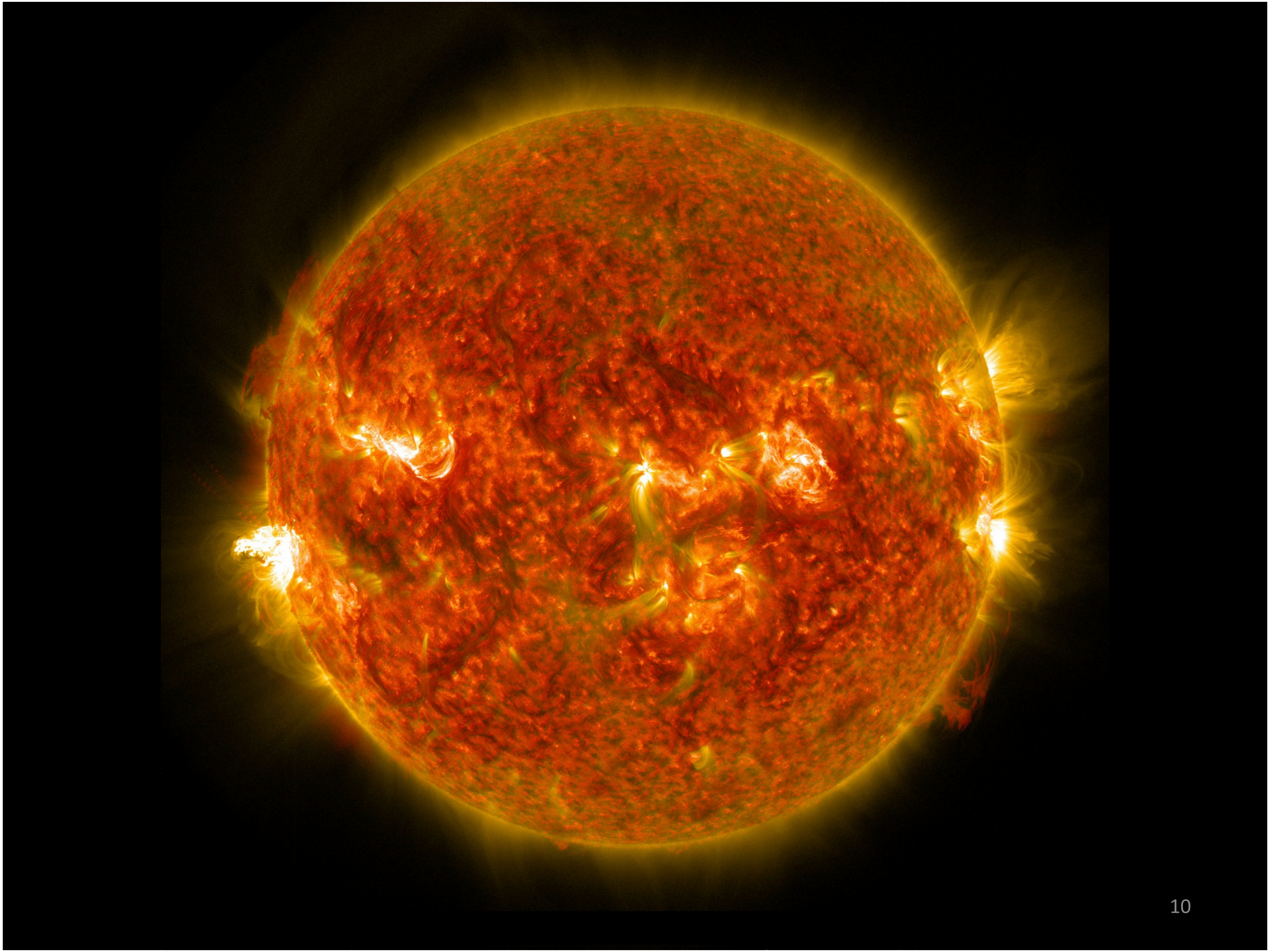
Παρά την πολυετή ερευνητική και διδακτική μου εμπειρία σε θέματα ηλιακής και διαστημικής φυσικής, παρά τις αμέτρητες φωτογραφίες και τα αμέτρητα βίντεο που είχα δει, θαυμάσει,



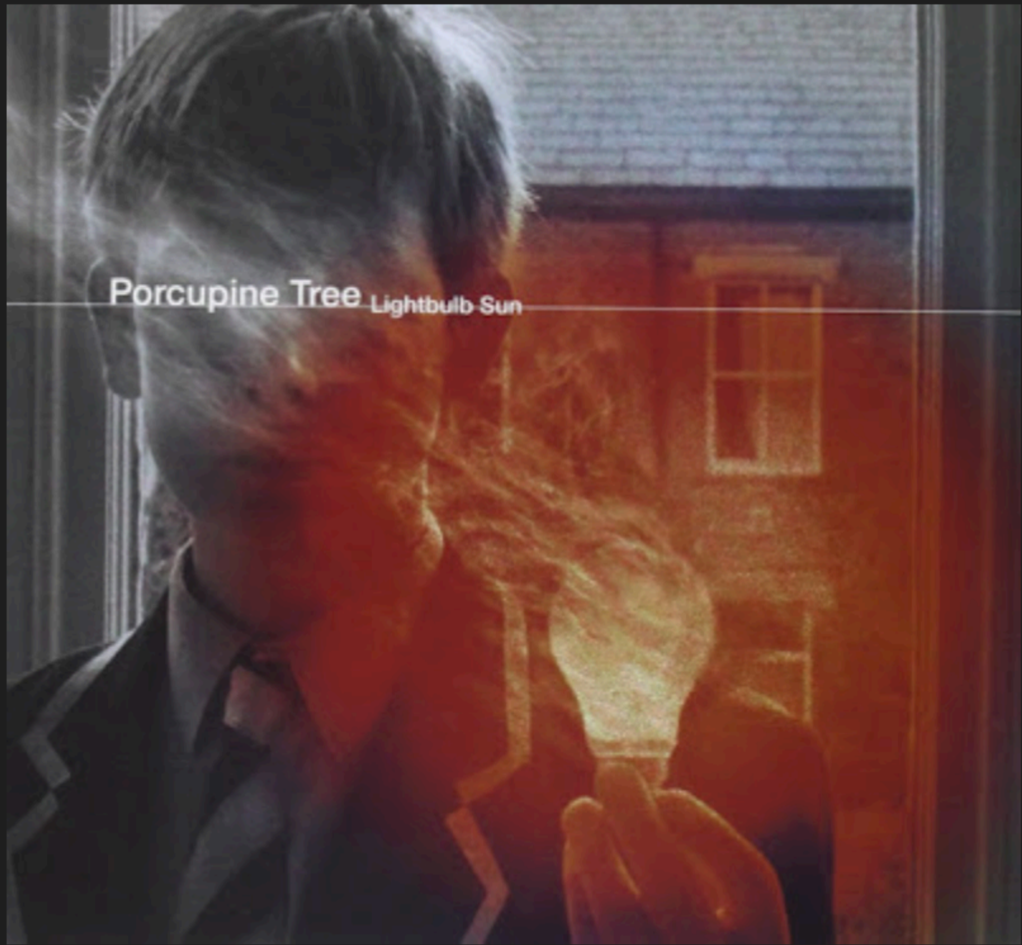


4-33 solar radii with LASCO-C3 instrument in white light, SOHO, ESA/NASA
2-6 solar radii with LASCO-C2 instrument in white light, SOHO, ESA/NASA
1-3 solar radii with ground-based images from: Cape Lopez, Port Gentil, Gabon (K. Gazeas)
Pokwero, Uganda (P. Horálek, J. Sládeček, M. Druckmüller)
Solar disk in extreme ultraviolet light (30.4 nm), SDO/AIA, NASA
Solar disk in extreme ultraviolet light (17.4 nm), PROBA2/SWAP, ESA/ROB


SDO/AIA 94 2013-11-03 00:01:50 UT
SDO/AIA 131 2013-11-03 00:01:22 UT
PROBA2/SWAP 174 2013-11-03 00:02:06 UT
SDO/AIA 193 2013-11-03 00:14:31 UT
SDO/AIA 211 2013-11-03 00:01:13 UT
SDO/AIA 4500 2013-11-03 00:00:07 UT
SDO/AIA 1700 2013-11-03 00:02:07 UT
Kosmas Gazeas – Cape Lopez, Port Gentil, Gabon
SDO/AIA 1600 2013-11-03 00:02:17 UT
SDO/AIA 304 2013-11-03 00:14:20 UT
SDO/AIA 171 2013-11-03 00:14:24 UT
SDO/AIA 335 2013-11-03 00:01:28 UT



Lightbulb Sun



The solar radiation energy absorbed in some form by the Earth's atmosphere, oceans, continents and living organisms in or on them has an average value of **250 watts per square meter**. 250 watts correspond to the power of four humble standard lightbulbs.

Despite its rather modest magnitude this energy, combined with the equally modest greenhouse effect of the terrestrial atmosphere, keeps the average temperature of our planet at 15 degrees centigrade, making life - as we know it - possible on Earth.

The Sun is a lightbulb

Είναι λοιπόν αλήθεια ότι η ισχύς της ηλιακής ακτινοβολίας που φτάνει στην επιφάνεια της Γης έχει μάλλον ταπεινό μέγεθος.

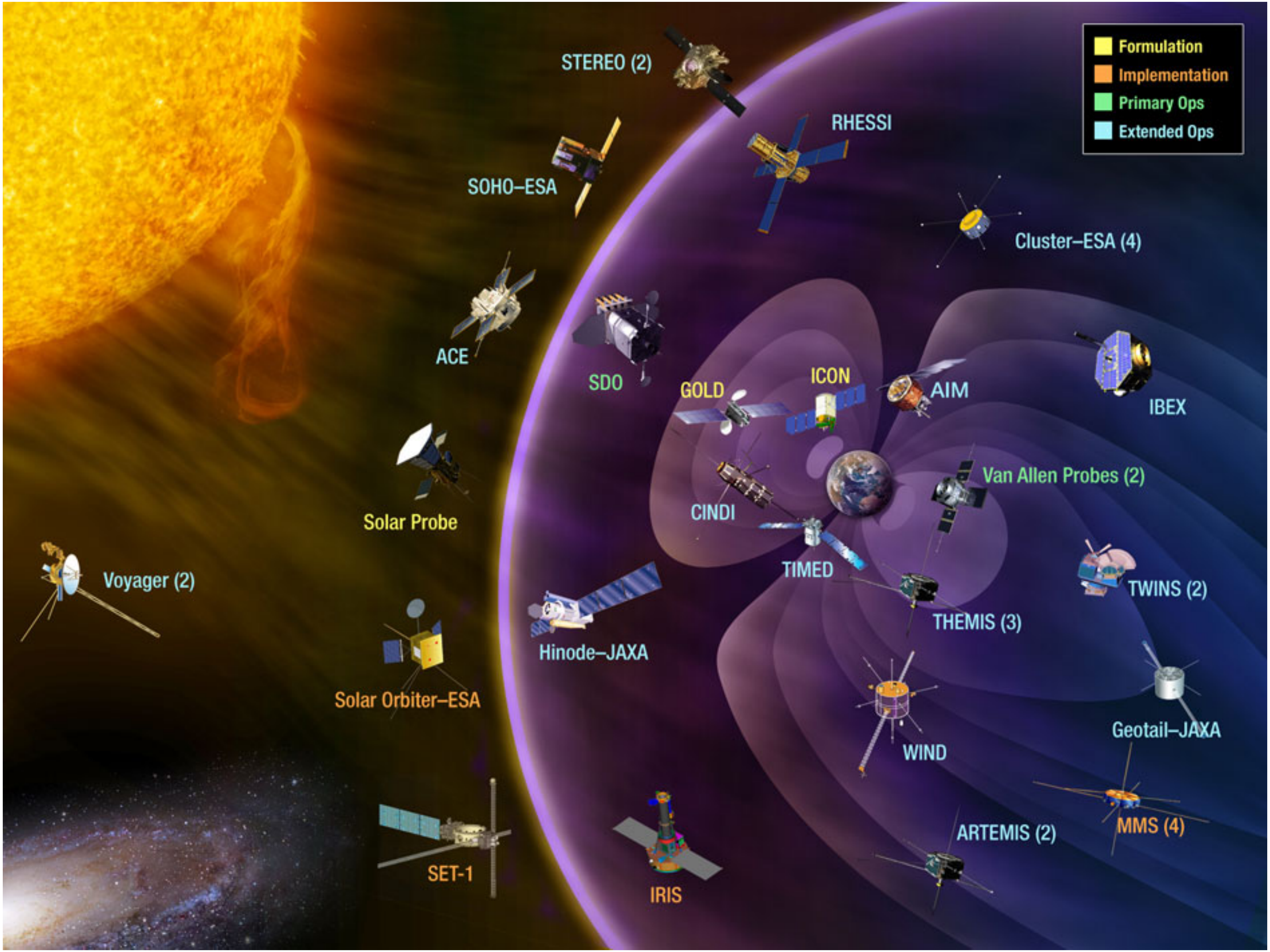
Αλλά είναι επίσης αλήθεια ότι χωρίς αυτήν δεν θα υπήρχε ίχνος ζωής.

Το θεμέλιο της ζωής στη Γη

1. Φως
2. Φωτοσύνθεση
3. Διοξείδιο του άνθρακα
4. Όλα τα ανωτέρω

Photosynthesis
is the foundation of life on Earth
providing
the food, oxygen and energy
that sustains the biosphere and
human civilisation


National Aeronautics and Space Administration



Formulation
Implementation
Primary Ops
Extended Ops
STEREO (2)
RHESSI
SOHO–ESA
Cluster–ESA (4)
ACE
SDO
GOLD
ICON
AIM
IBEX
Solar Probe
CINDI
Van Allen Probes (2)
TIMED
Voyager (2)
TWINS (2)
THEMIS (3)
Hinode–JAXA
Solar Orbiter–ESA
WIND
Geotail–JAXA
ARTEMIS (2)
MMS (4)
SET-1
IRIS

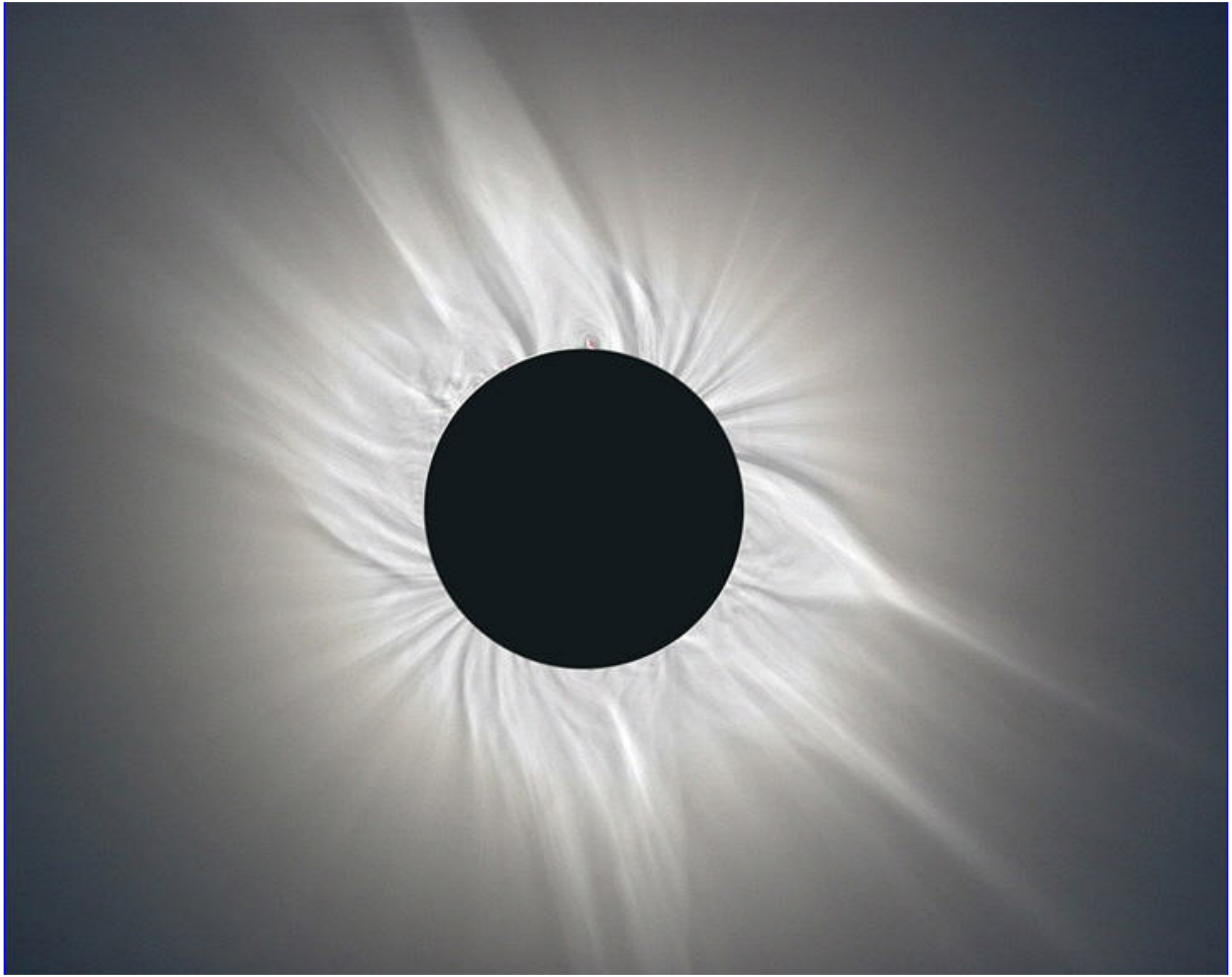
Το ηλιακό στέμμα

Corona


Corona Extra
LA CERVEZA MAS FINA
IMPORTED BEER FROM MEXICO
Corona Extra
LA CERVEZA MAS FINA
MEXICO, D.F.

Το ηλιακό στέμμα
ή
Η ηλιακή <u>κορώνη</u>
(Solar Corona)

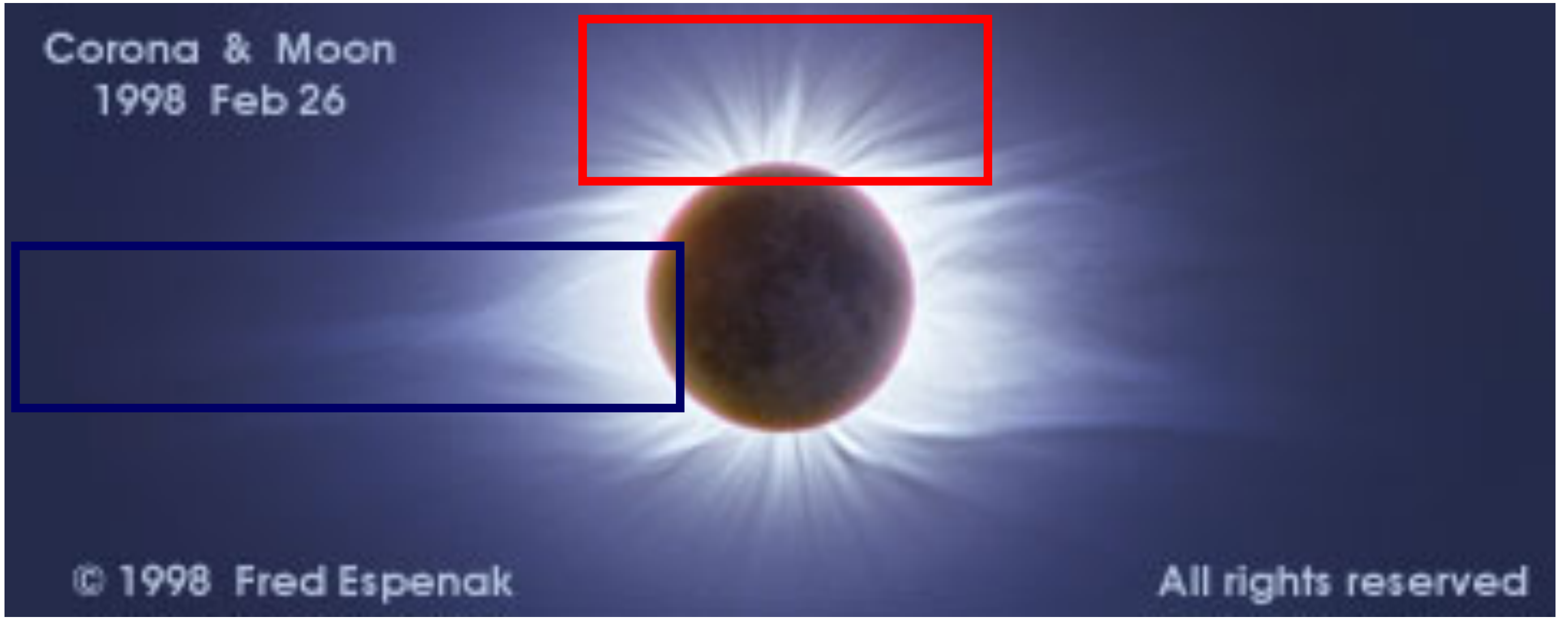
Στο ορατό μέρος του φάσματος



White-light corona during total solar eclipse, 2006 March 29

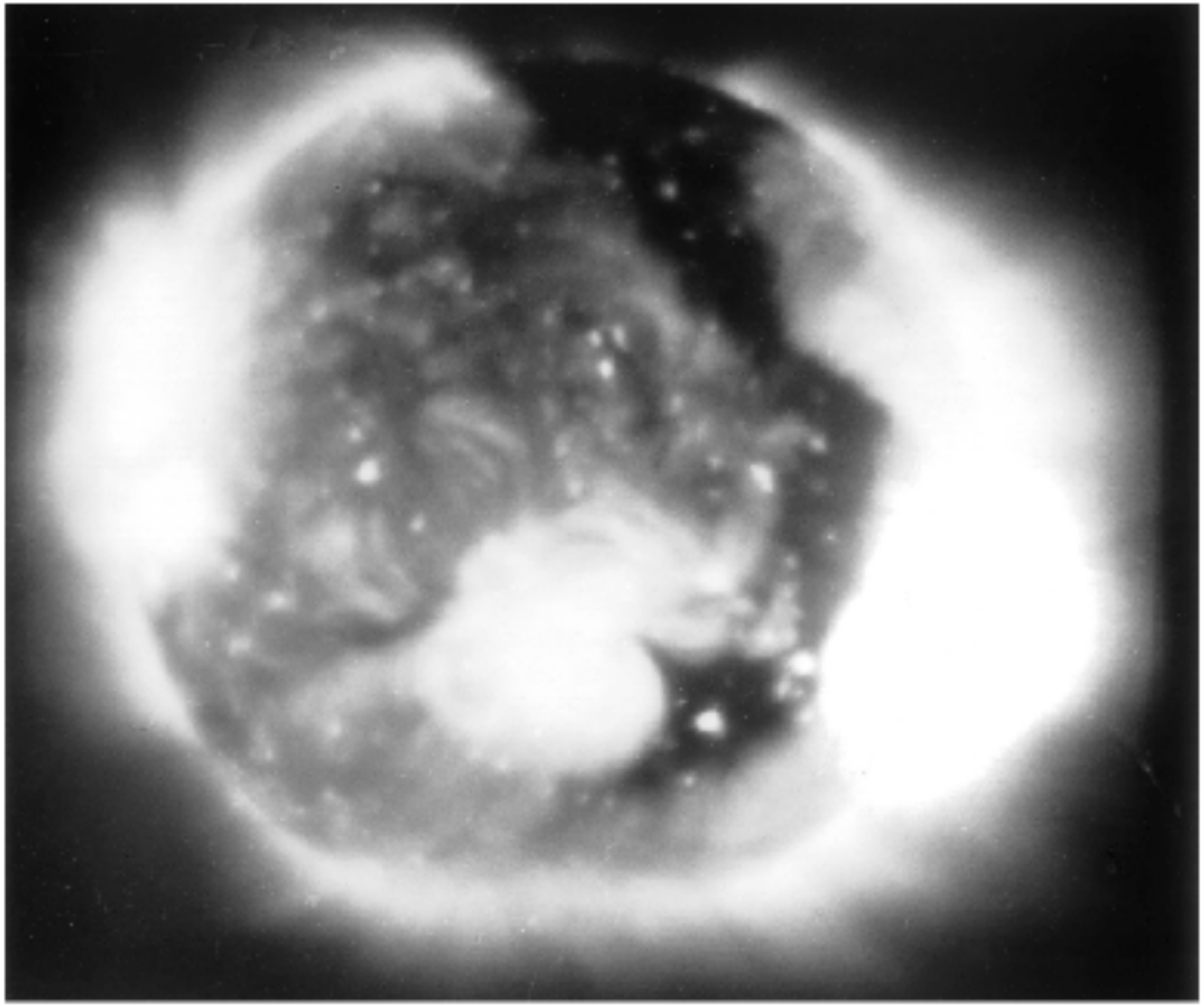
Large-scale structures

- Two types of structures:
  - Thin plumes near the poles
  - Long streamers near the equator



How persistent is this structuring?

Skylab X-ray telescope
1973-1979

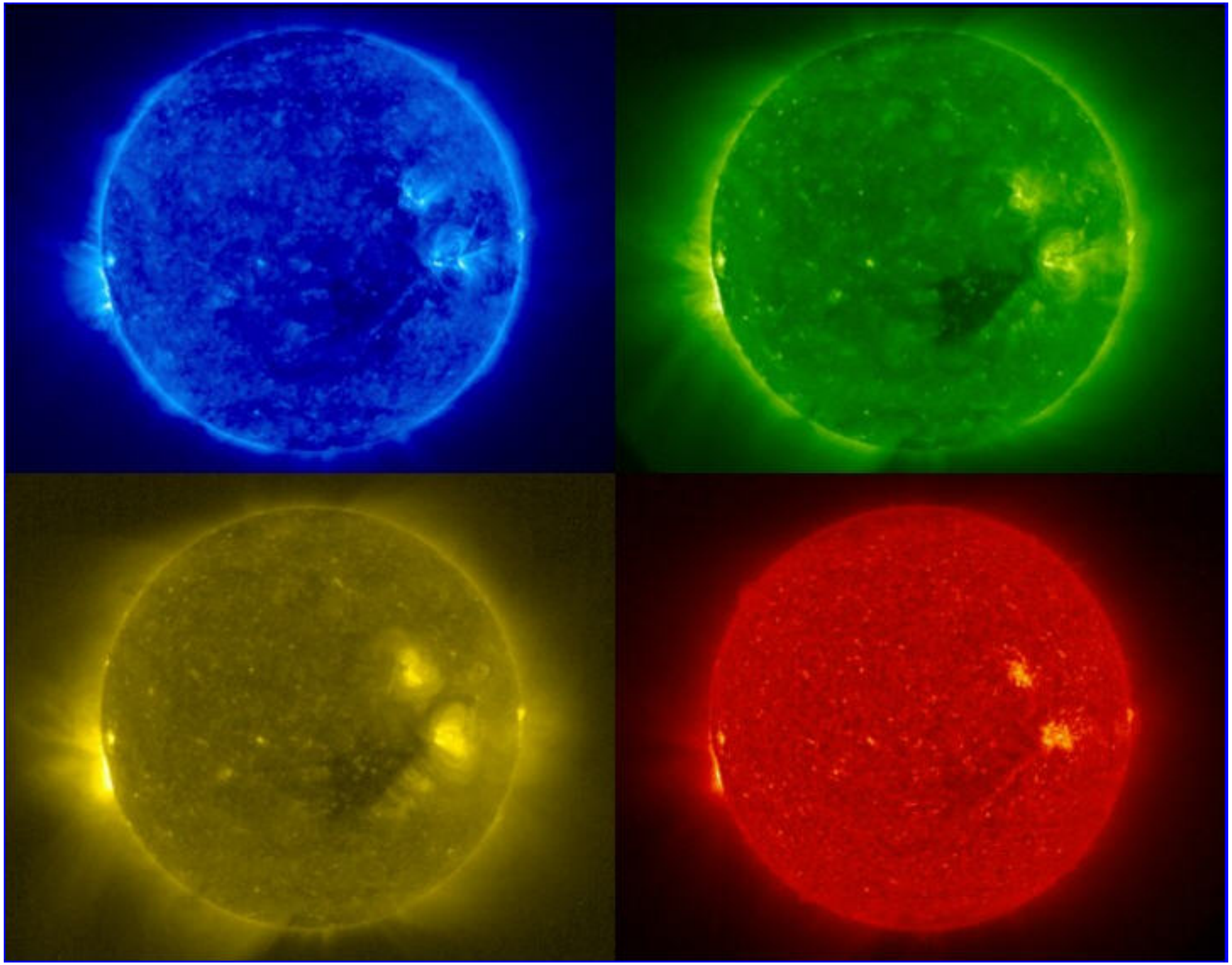


Σε άλλα μήκη κύματος (STEREO, Δεκέμβριος 2006)

17.1nm

(Fe X/Fe XI)

1 MK



19.5nm

(Fe XII)

1.5 MK

28.4nm

(Fe XV)

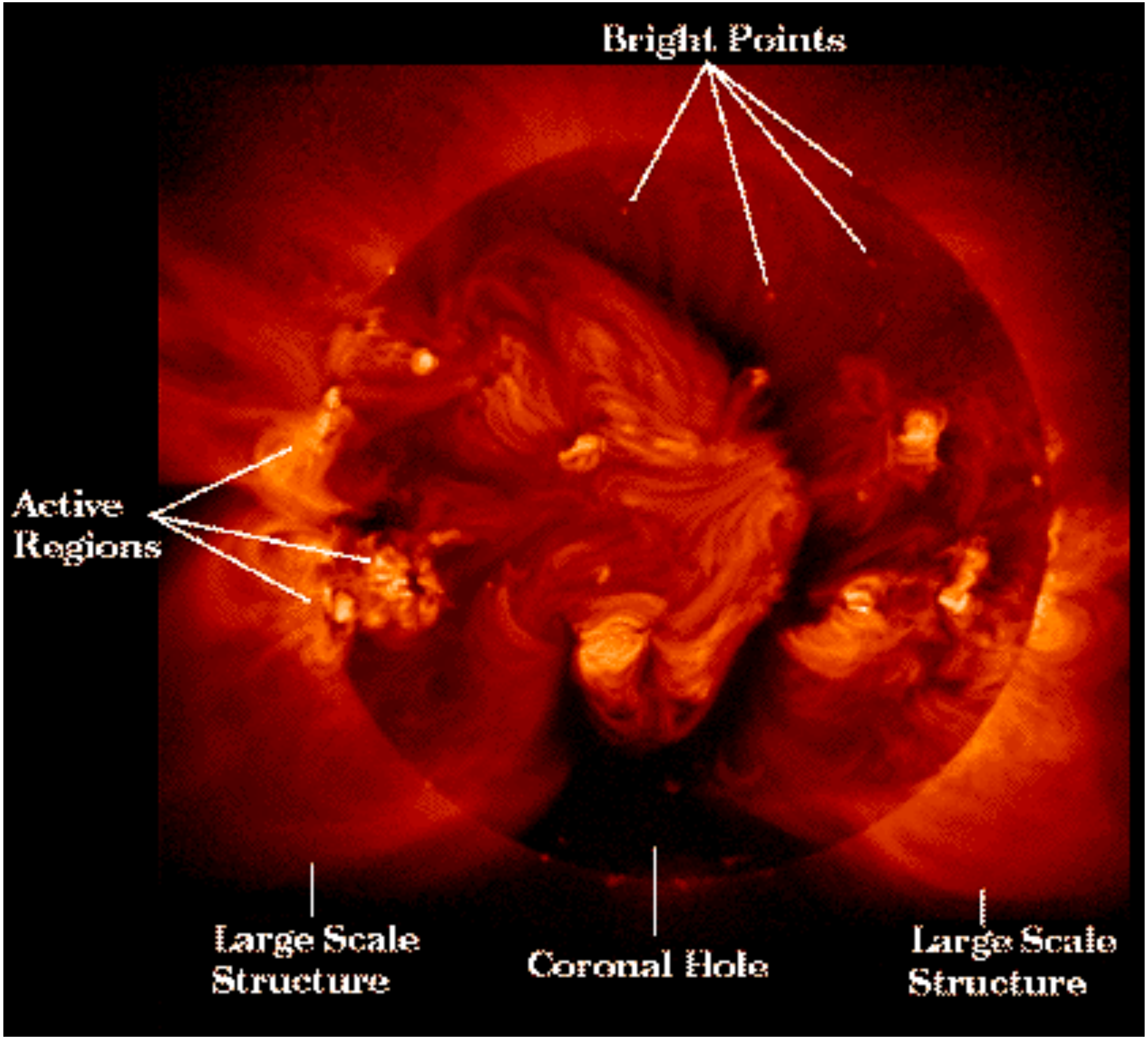
2.5 MK

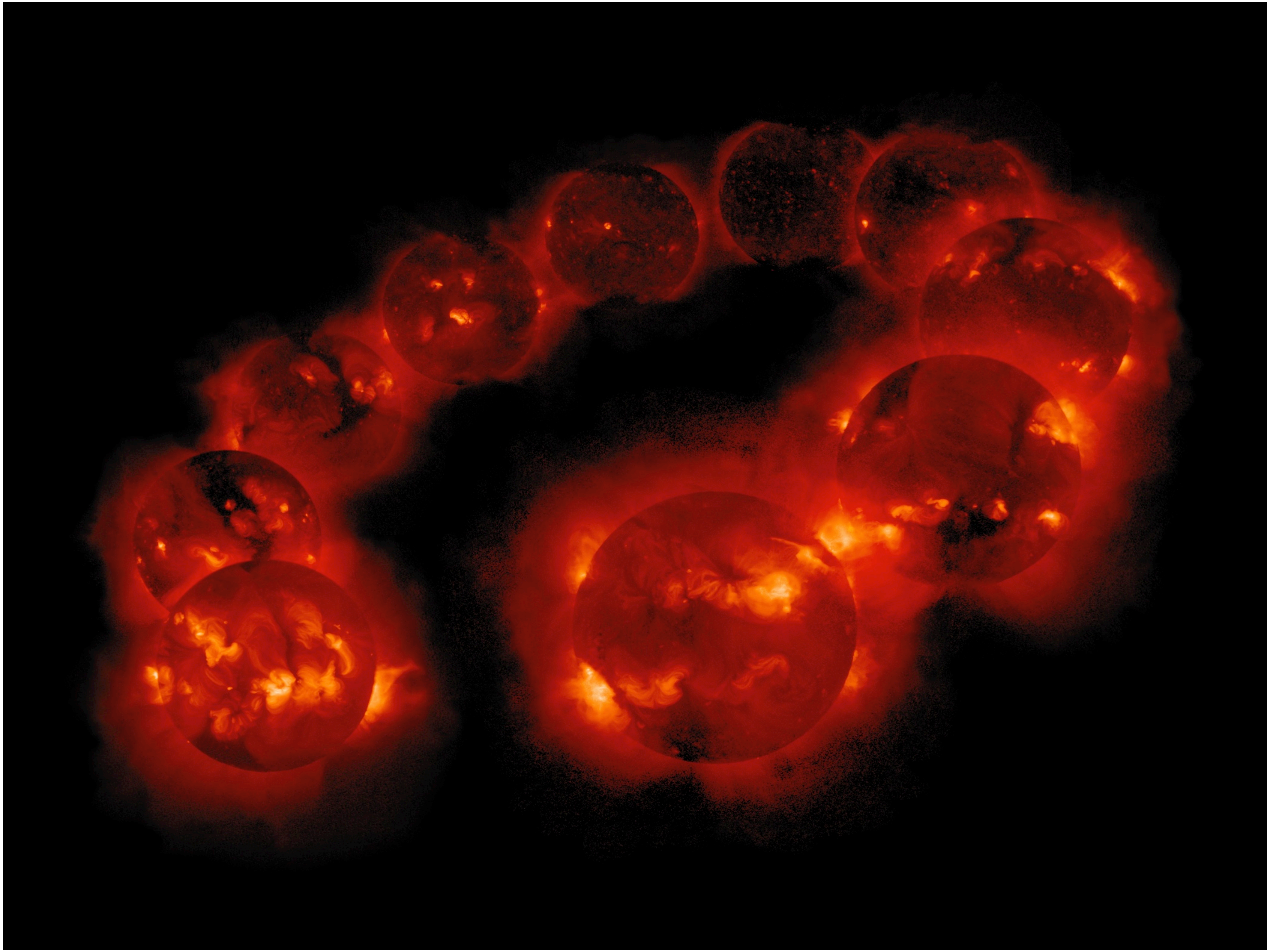
30.4nm
(He II:
chrom.)

80 kK

Solar-A Yohkoh 1991-2005(5 arcsec)

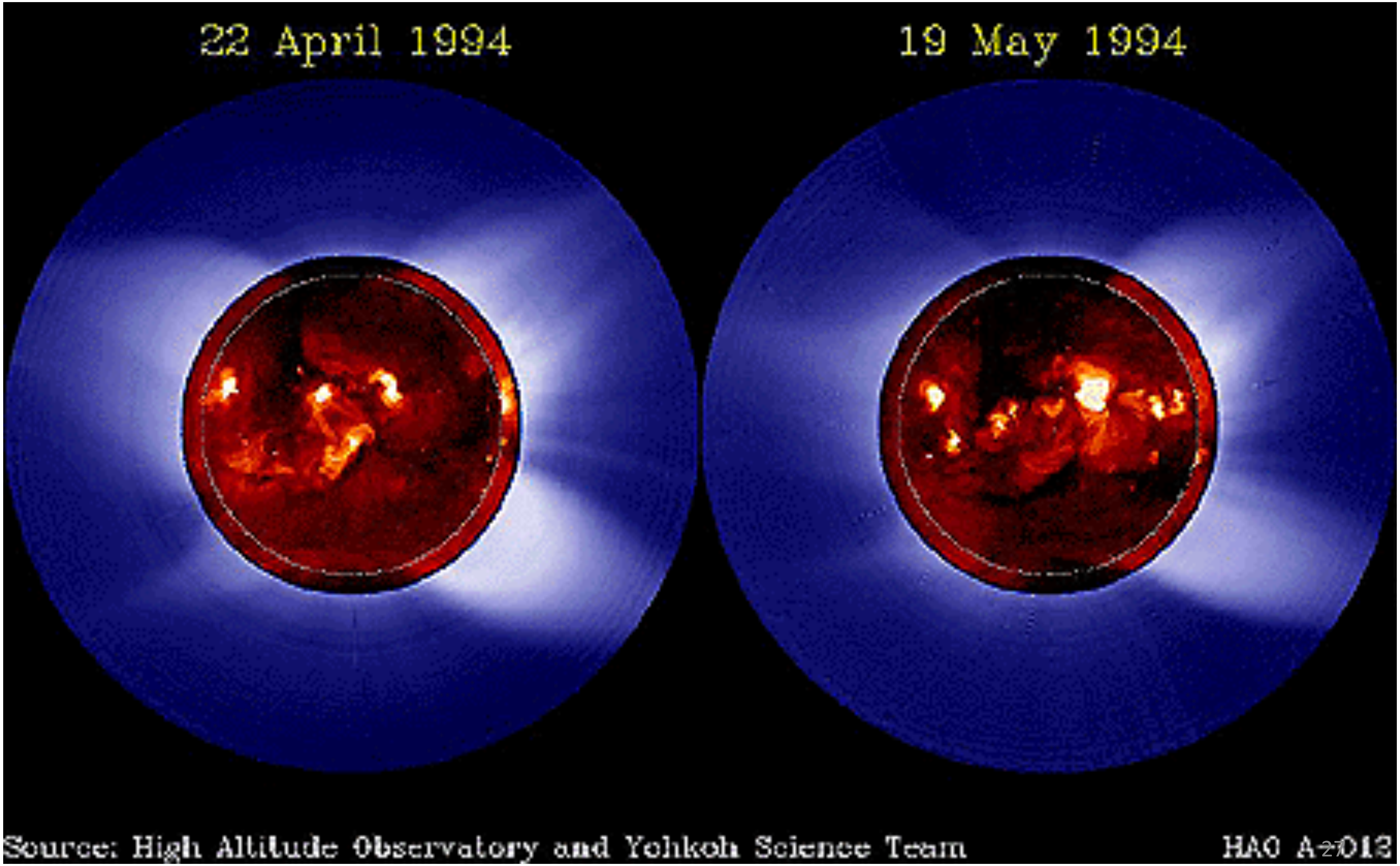
A dynamic magnetic world

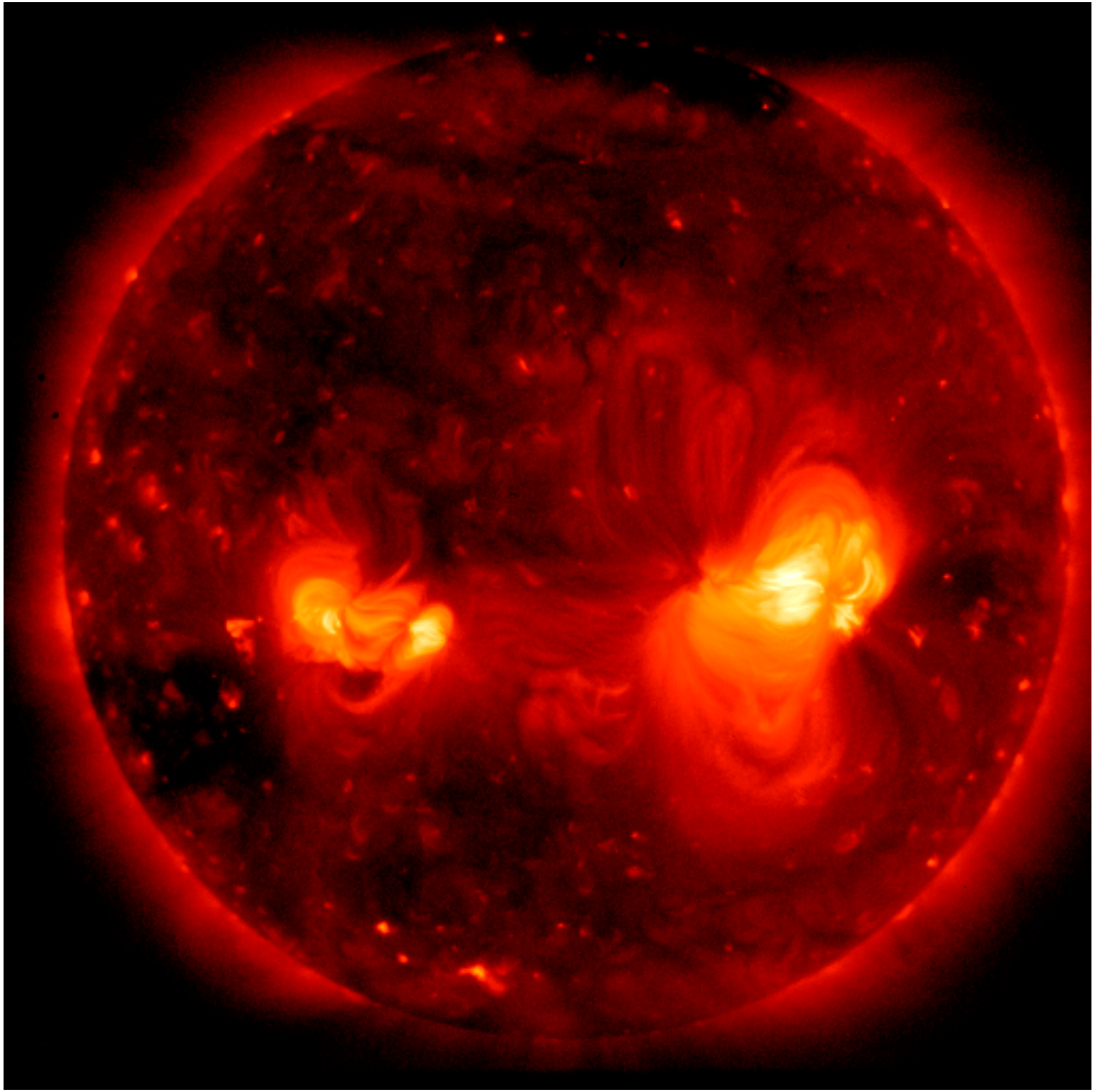




White-light and X-ray corona images superimposed:

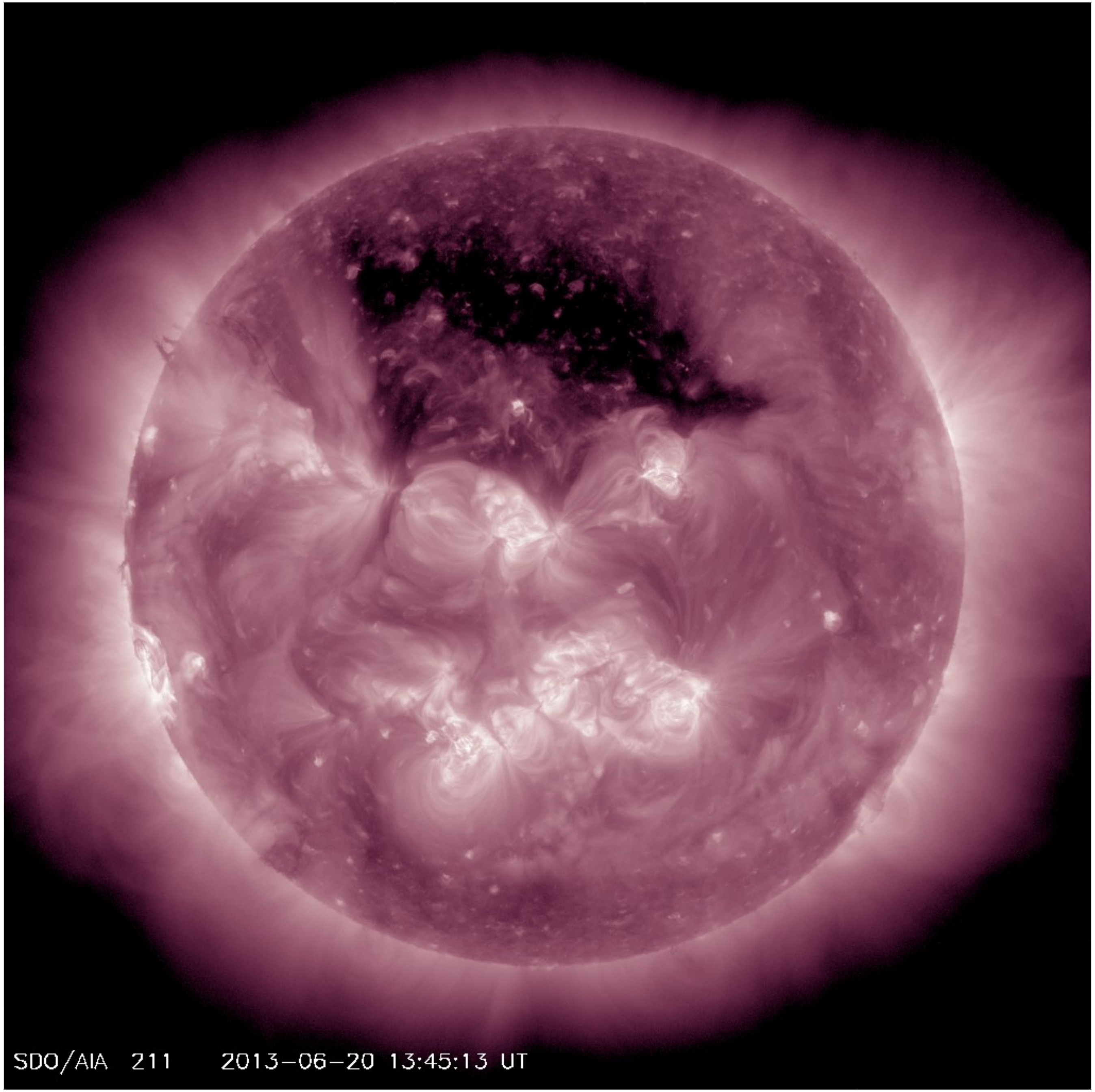
High Altitude Observatory (WL) and Yohkoh (X-rays)





Solar-B Hinode 2006-... (1 arcsec)

Stunning detail on structure & dynamics



SDO
2010-…
(0.6 arcsec)

Corona: Physical Properties

Corona has much **higher temperature** than chromosphere or photosphere: **10^6 K – 2 × 10^6 K**

Densities are **lower** than those of chromosphere or photosphere: $n = 10^{13} - 3 \times 10^{14}$ m^{-3}, out to 2 solar radii from Sun's centre.

Pervaded by a magnetic field, strength ~1mT, mostly in form of loop structures.

SDO Highlights

Coronal Rain

https://www.youtube.com/watch?v=HFT7ATLQQx8

I've seen things …

https://diamantia-kai-skouria.blogspot.com/2009/05/artwork-john-berkey-ive-seen-things-you.html

Corona: Physical Properties

Temperature, density, and magnetic field strength **much enhanced over sunspot regions** (“active regions”)

Reduced density and temperature and open magnetic fields at poles, particularly at solar minimum: **coronal holes**.

Undergoes an **11-year activity cycle** like photosphere and chromosphere: brighter and more irregular at solar maximum.

Corona is a fully ionized gas (plasma)

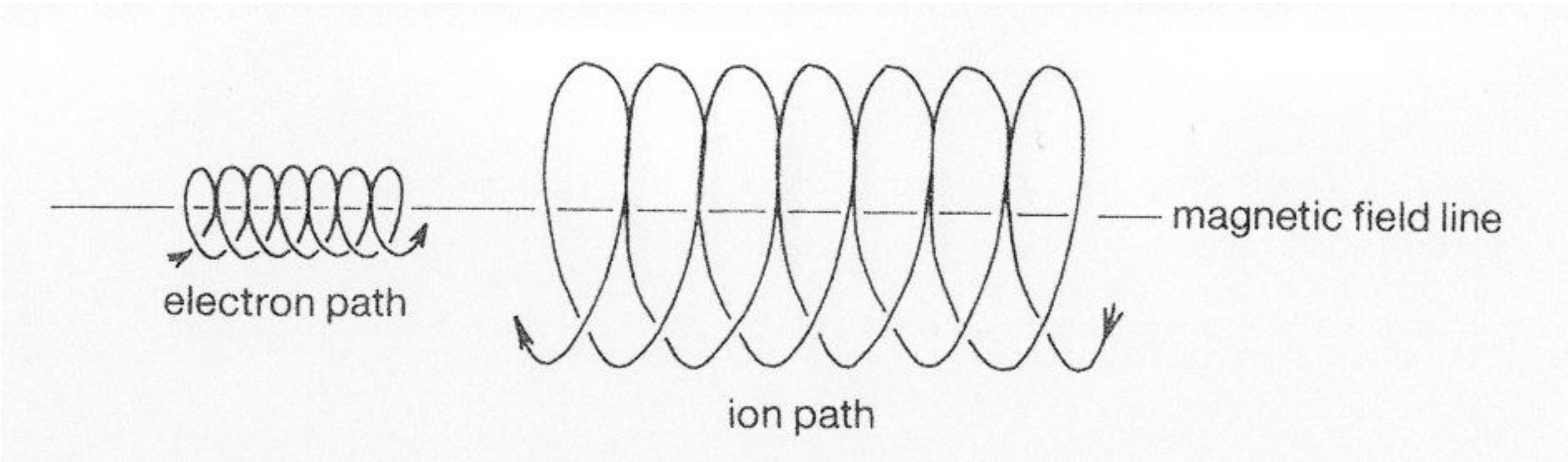
Because of the high temperature, corona is practically a **fully ionized gas** (**plasma**).

Nearly all H and He atoms are **fully stripped**.

So particles are almost entirely **protons, α particles (He nuclei), and free electrons**.

They perform **helices** along magnetic field lines, radii of gyration depending on particle speed, charge, and mass, and on B-field strength.

Paths of charged particles in magnetized plasma



Radius of gyration = $m\ v\ /\ (q\ B)$

where m = particle mass,

v = component. of velocity perpendicular to the magnetic field B,

q = particle charge = Ze (e = 1.6 x 10^{-19} Coulomb)

Corona: Physical Properties

Densities are **lower** than those of chromosphere or photosphere:

$n = 10^{13} - 10^{15}\ \mathrm{m}^{-3}$,

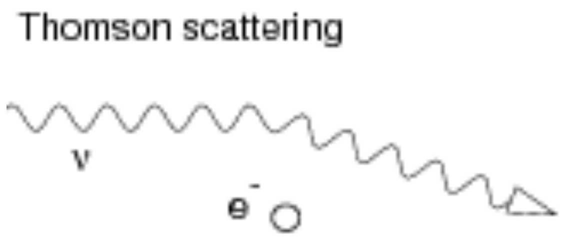
out to 2 solar radii from Sun's centre.

White-light emission from corona

White-light emission is photospheric radiation scattered by free electrons **(Thomson scattering)**

The white light corona (K-corona)

- Coronal emission consists of photospheric radiation scattered off coronal electrons



A photon is deflected by an electron
A few photons are deflected ~ 90°

- This process is equivalent to that responsible for the halo around a street lamp in the fog

Πυκνότητα πλάσματος στο στέμμα

Electron Cross section

$$6.65 \times 10^{-29}\ m^2$$

N free electrons

$$N \times 6.65 \times 10^{-29} = 10^{-6}$$

$$N = 1.5 \times 10^{22}$$

100.000 km = 10^8 m

$$n = 10^{14}\ m^{-3}$$

White-light emission from corona

White-light emission is photospheric radiation scattered by free electrons – **Thomson scattering**.

Electron cross section for Thomson scattering is **6.65×10^{-29} m^2**: If there are ***N* free electrons along a line of sight**, the coronal surface brightness in terms of the photospheric brightness is $N \times 6.65 \times 10^{-29}$.

White-light emission from corona

In fact, **coronal surface brightness is**

$\sim 10^{-6} \times$ photospheric brightness

(about the brightness of the full Moon)

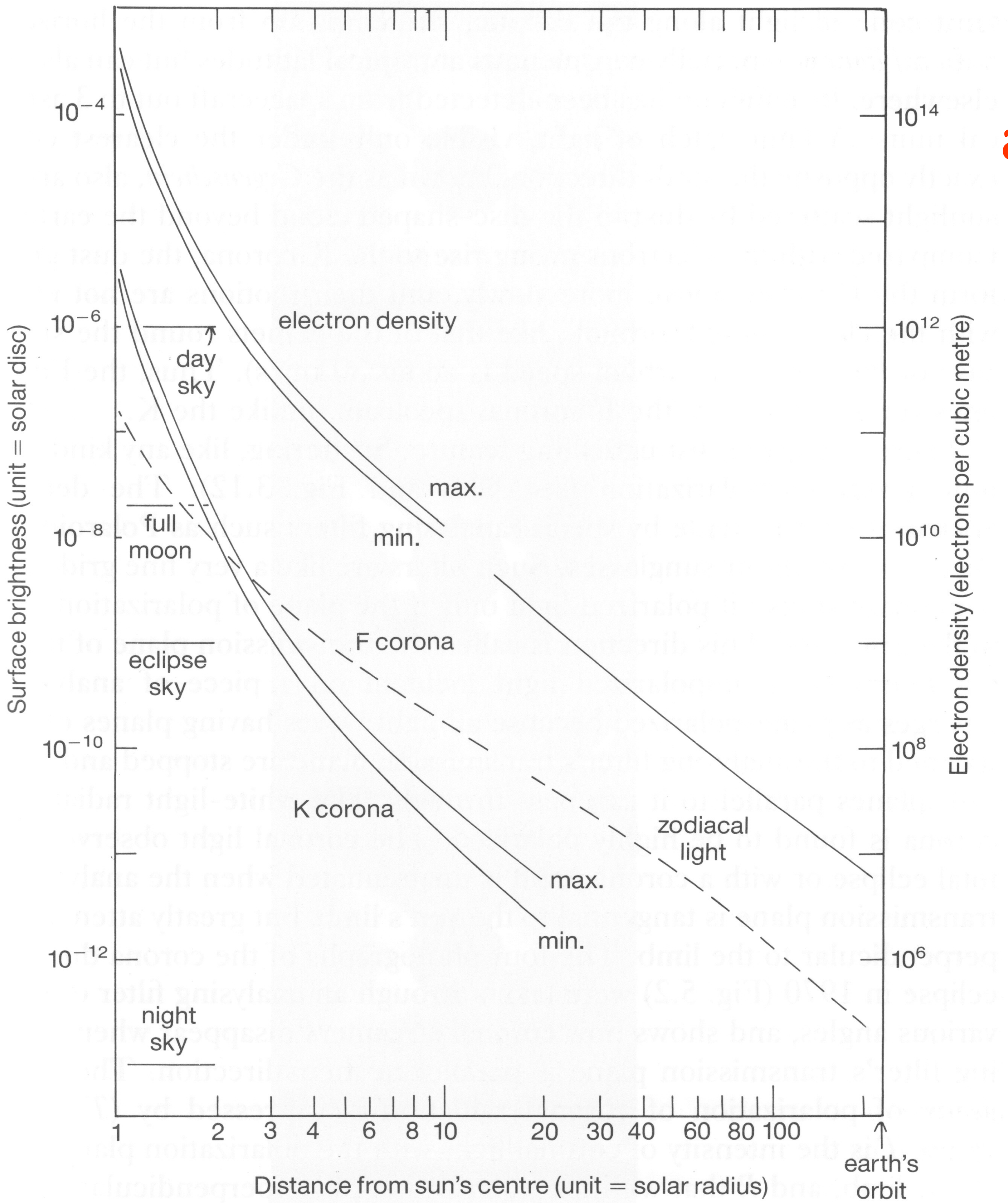
So $N \times 6.65 \times 10^{-29} = 10^{-6}$, or

$\boldsymbol{N = 1.5 \times 10^{22}}$ **electrons**.

Coronal streamer extent ~100,000 km = $\boldsymbol{10^8}$ **m.**

So very roughly the density of electrons is $\boldsymbol{\sim 10^{14}\ m^{-3}}$.

Density (particles/m³) and surface brightness of the solar corona



Electron density near Sun is ~10^{14} m^{-3}.

Figure shows the surface brightness of K (electron) and F (dust) corona separately.

The K (electron) corona

K corona is the **electron-scattered** component: ***Kontinuerlich***.

It dominates out to 2 $R_\odot$ (measuring from Sun centre).

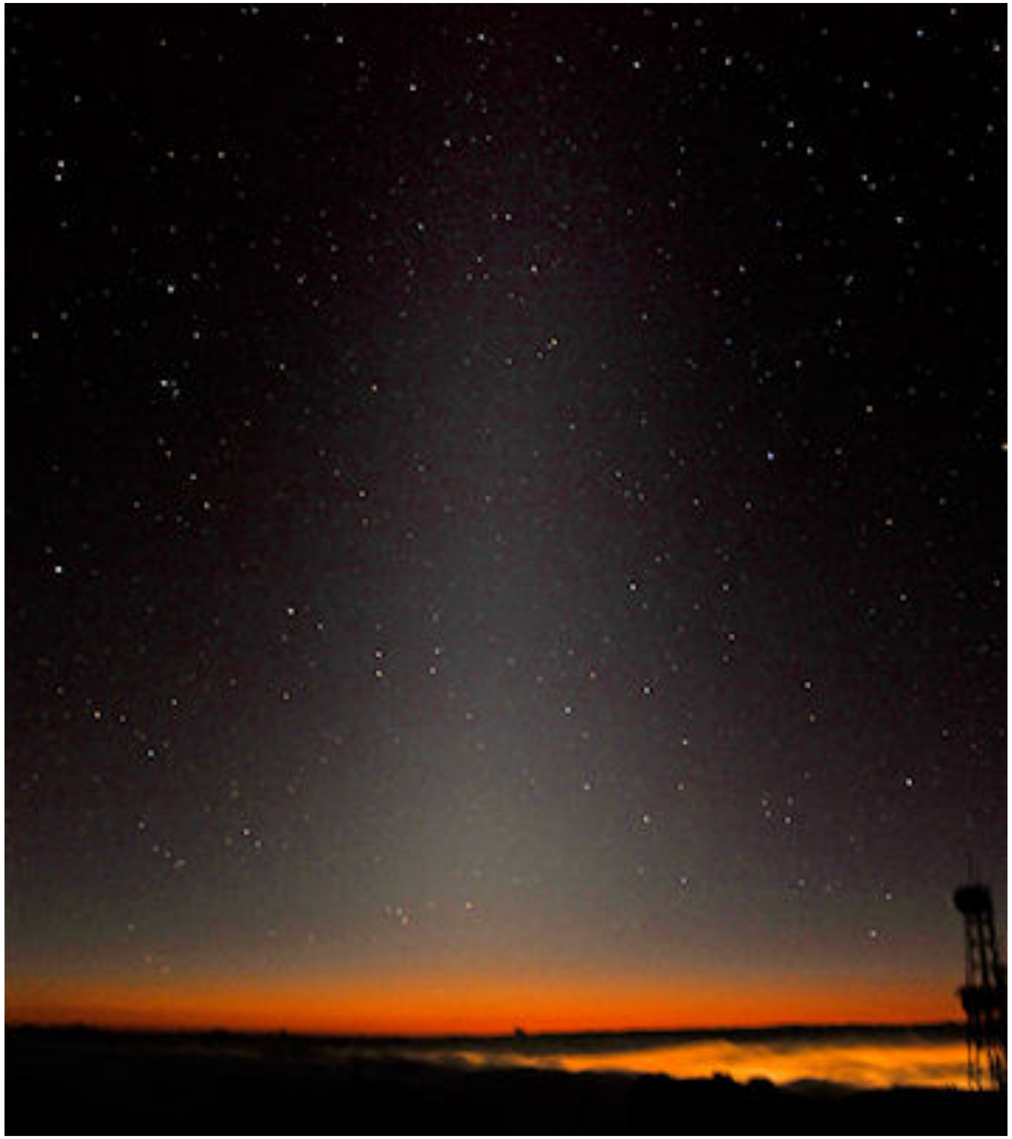
It has a **white-light** spectrum consisting of a **featureless continuum** – no Fraunhofer lines.

The F (dust) corona

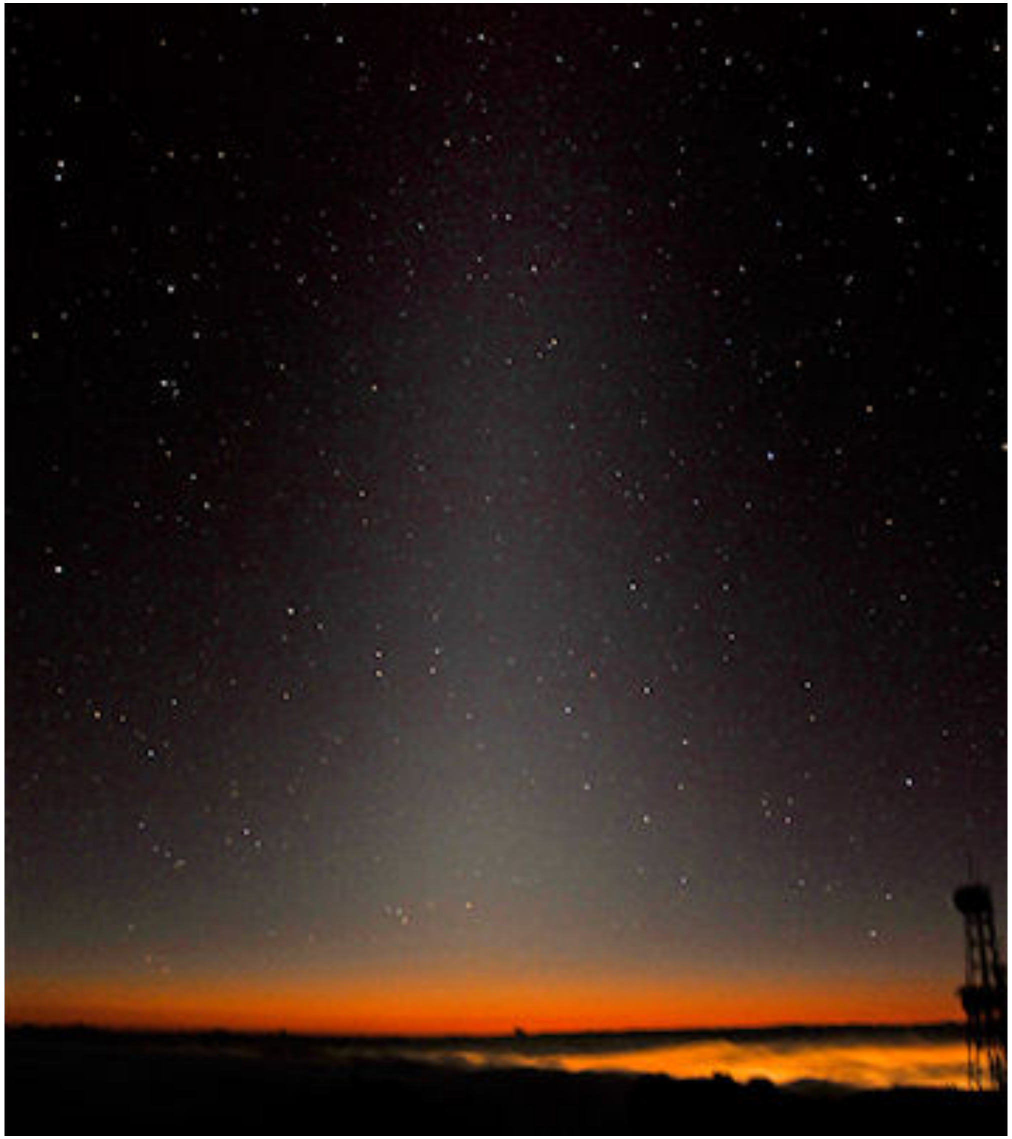
F corona is the **dust-scattered** component: ***Fraunhofer*** corona.

It dominates beyond 2.5 $R_{\odot}$, becoming the **zodiacal light** at large distances.

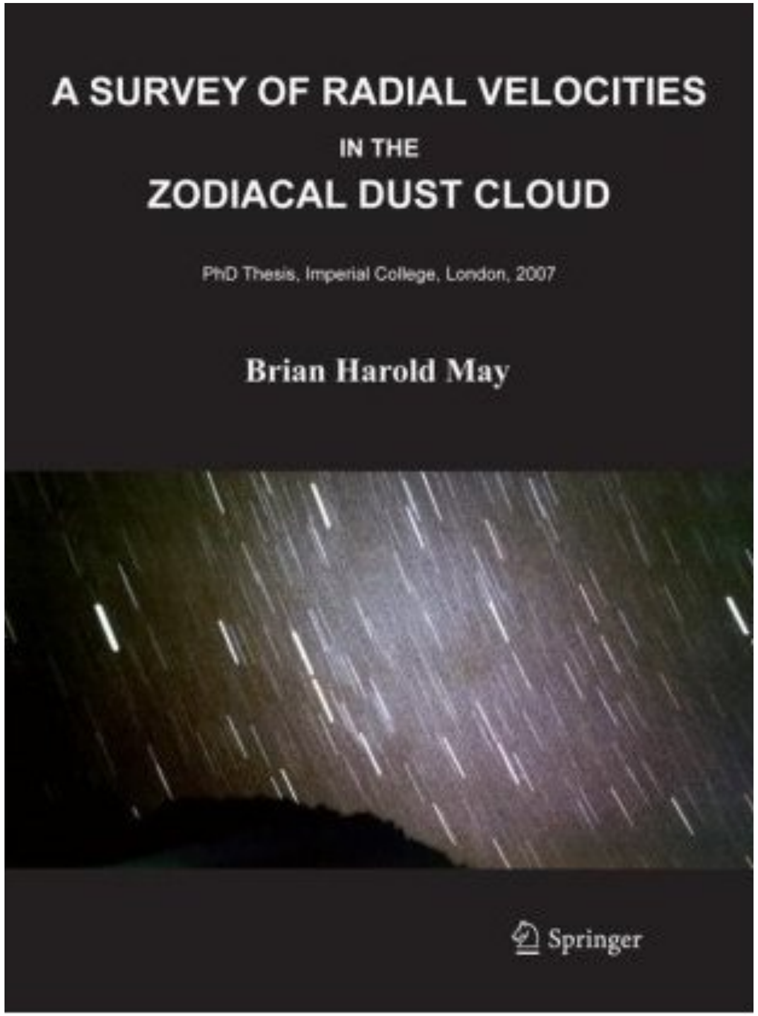
Zodiacal Light



Zodiacal Light and rock music?



Brian May's contribution to coronal physics



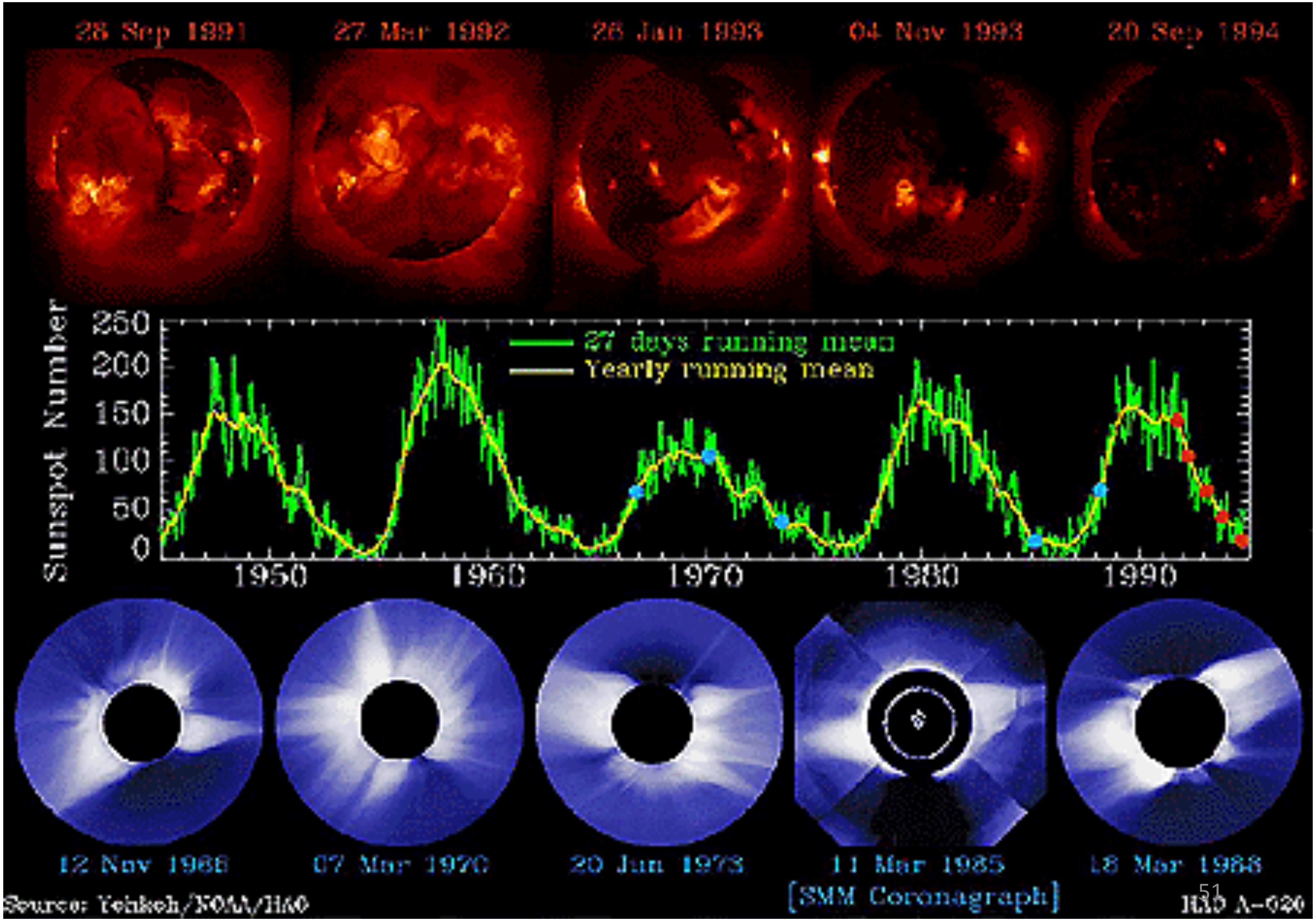
https://www.youtube.com/watch?v=81t8mi5i0X0&list=PLBnJv6rImVe9XXPLwK2CvysVd_CnrYB8I

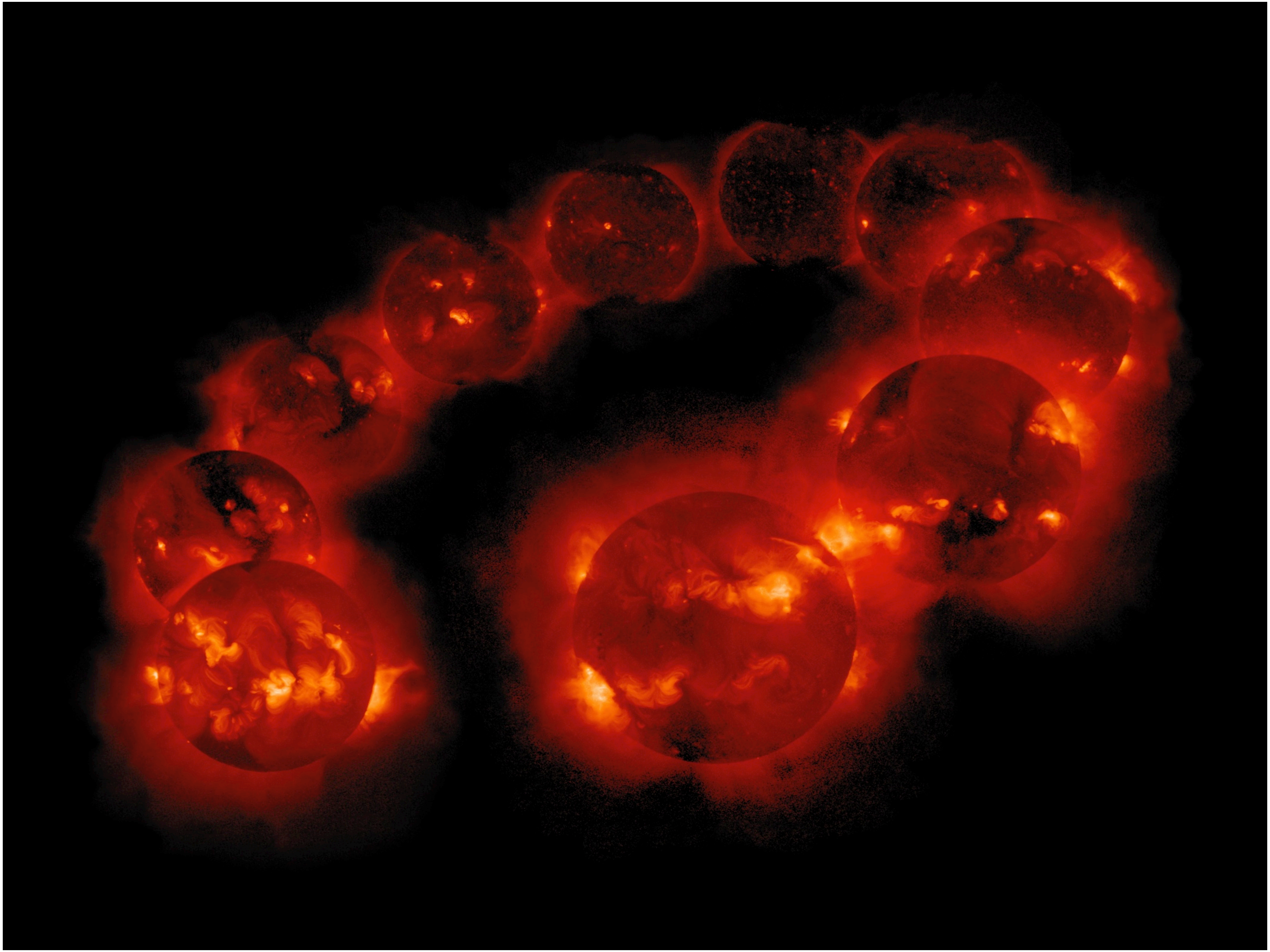
Solar corona 11-year cycle

Yohkoh X-rays

Sunspot number

Spacecraft white-light corona

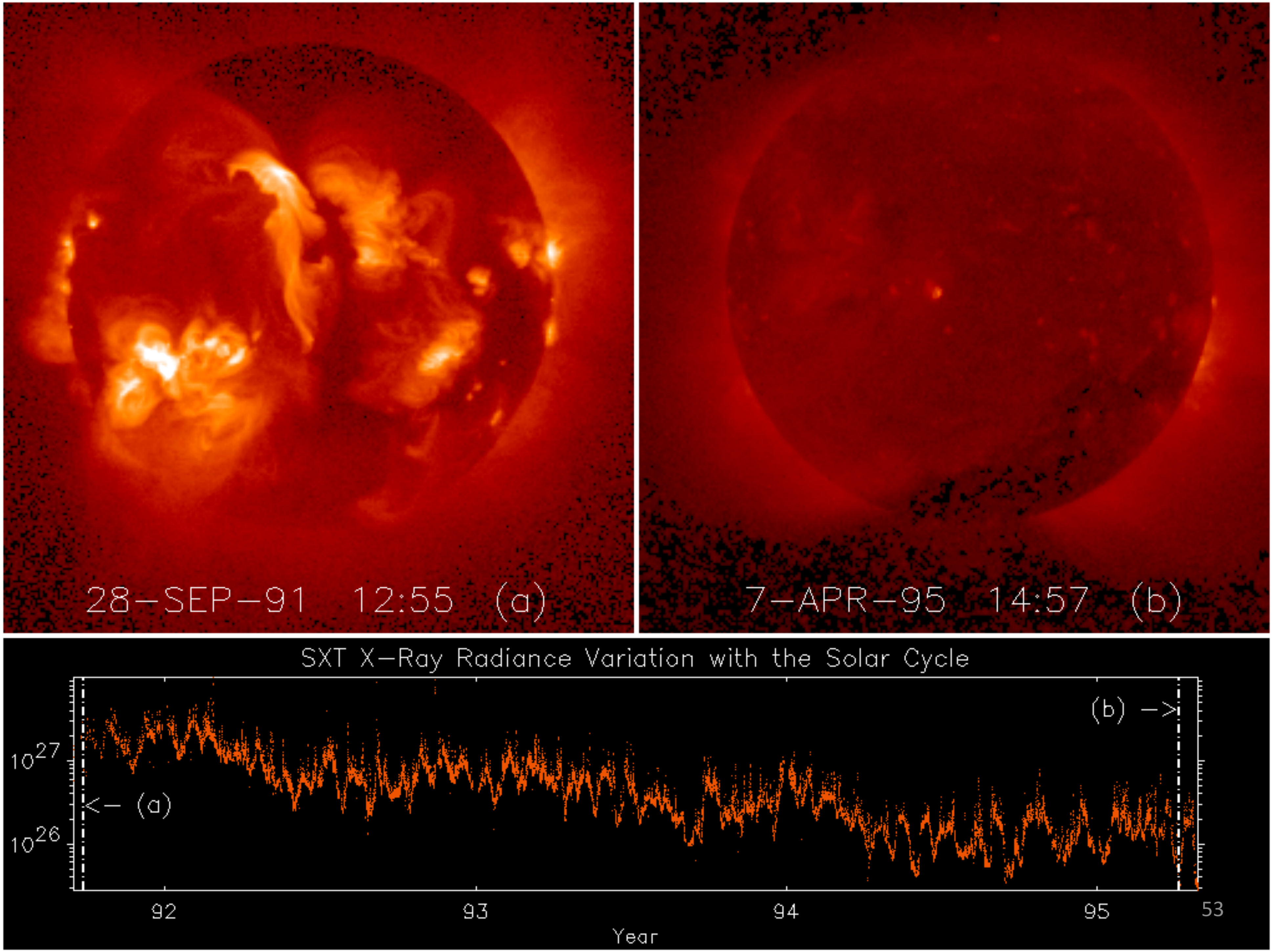




Solar maximum

Yohkoh SXT data

Solar minimum



Appearance of the Solar Corona

White-light corona has **loops** (closed structures) and **streamers** (open structures), changing with the solar cycle.

Streamers are mostly concentrated around the solar equator at sunspot minimum. Loop-like structures dominate at sunspot maximum, occurring over all latitudes during maximum.

X-ray coronal structures related to white-light structures – practically identical at low altitudes above photosphere.

Appearance of the Solar Corona

Streamers are mostly concentrated around the solar equator at sunspot minimum.

Solar corona during the recent deep solar minimum: 2009 solar eclipse

M. Druckmuller, Brno Observatory, Czech Rep. 2009 July 22

Appearance of the Solar Corona

Smaller but brighter loops associated with sunspots: **active regions** are seen in extreme ultraviolet and X-ray emission.

Numerous **X-ray bright points** – actually very small loops – occur over all phases of sunspot cycle and at all latitudes.

Coronal holes – reduced X-ray emission with well-defined boundaries – occur at sunspot minimum at the **N and S poles**. **Lower-latitude holes also occur** during the declining phase of the cycle, and may grow and coalesce with polar holes of the same polarity.

Gas and magnetic pressures

Coronal structures are loops and streamers, closely following magnetic field.

This must mean that the **plasma (ionized gas) pressure $N\,k_B\,T$ << magnetic pressure $B^2/2\mu_0$** ($\mu_0 = 1.26 \times 10^{-6}$ H m^{-1}).

For an active region, $T \sim 4$ MK, $N \sim 10^{17}$ m^{-3}, so plasma pressure is $10^{17} \times 1.38 . 10^{-23} \times 4 . 10^{6}$ = **5.5 Pa.**

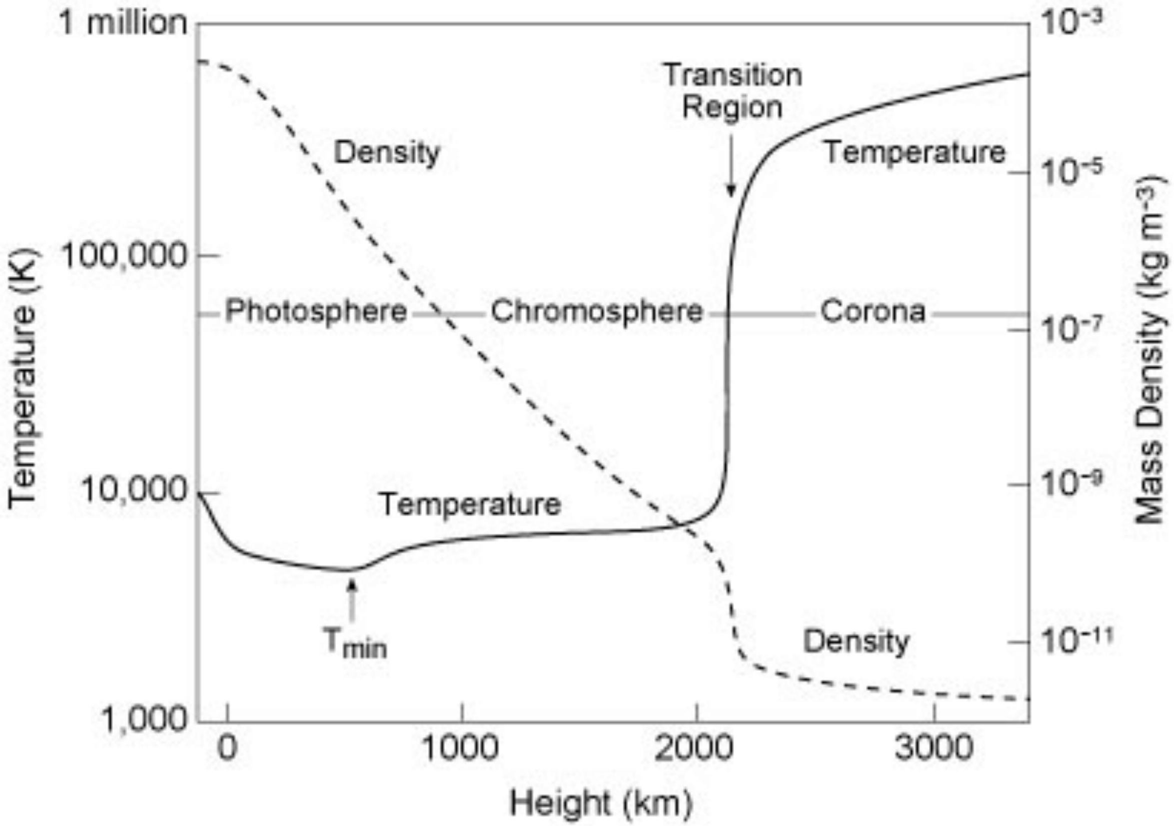
B cannot (easily) be directly measured in the corona but can be inferred from models: above an active region, B~0.01 T. Magnetic pressure is about **40 Pa**.

CORONAL HEATING

Coronal Heating

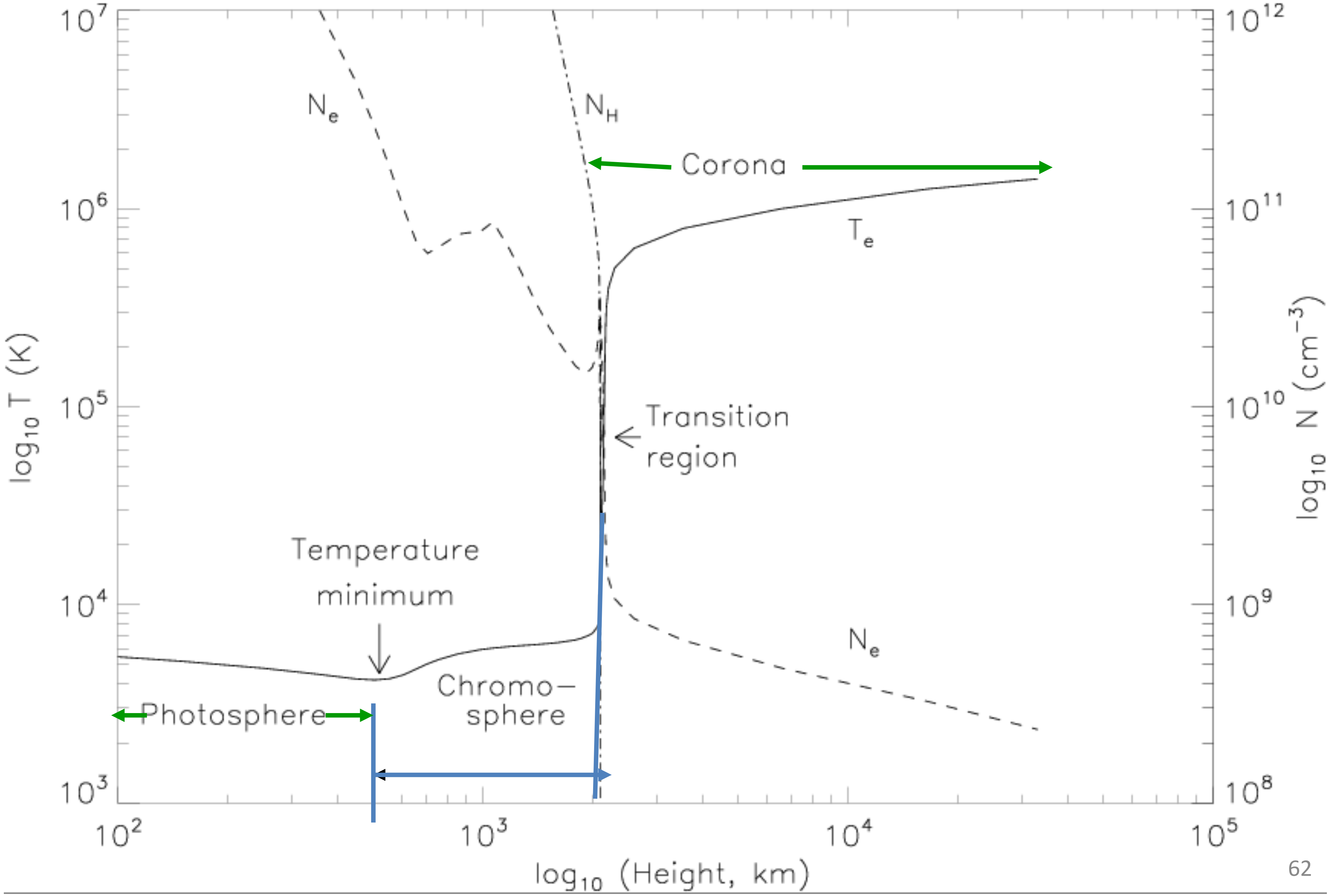
The solar corona has a temperature of 1—2 MK
- in active regions up to 2—5 MK!

The temperature of the photosphere is only 6400 K.

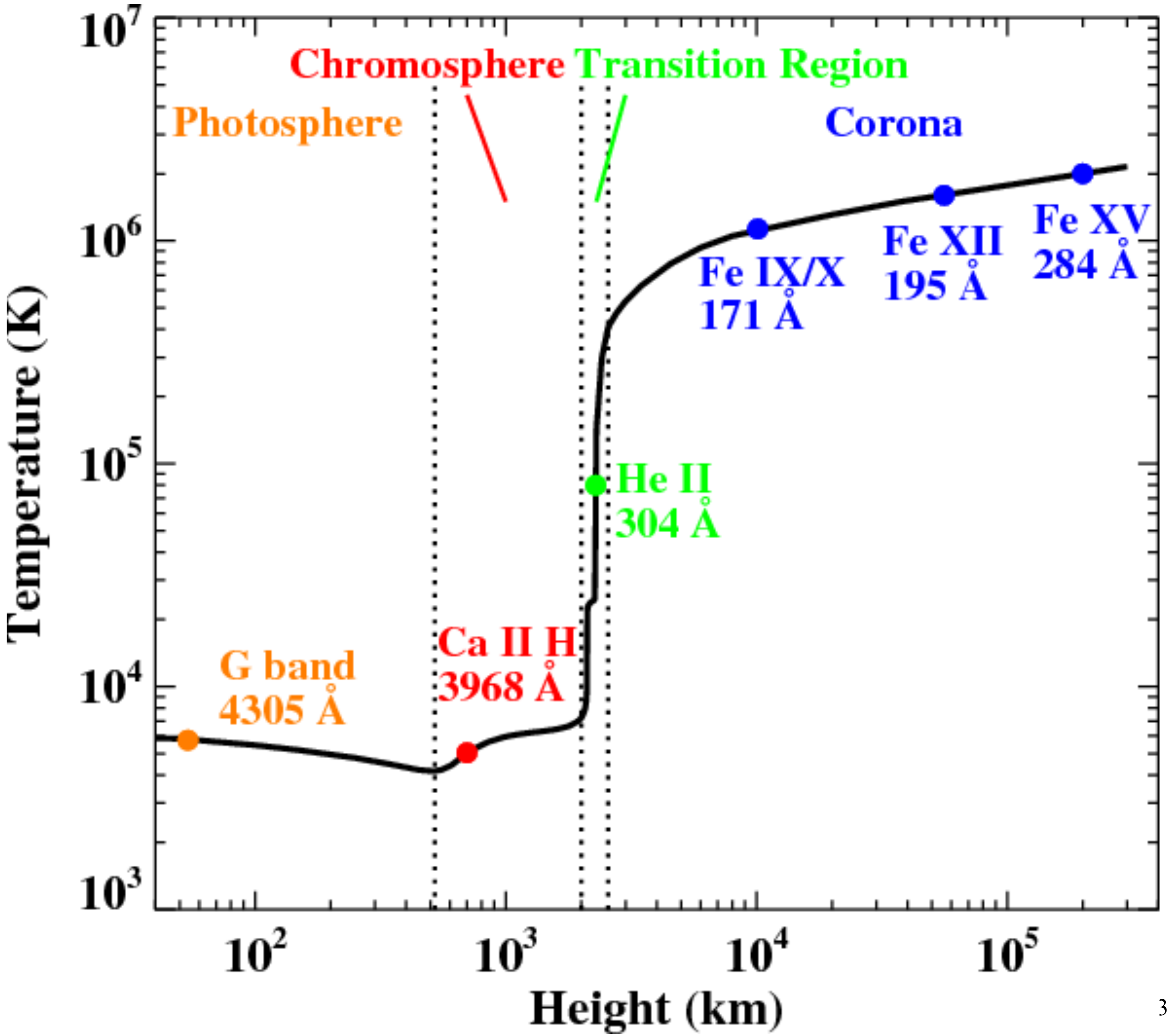


1 million
100,000
10,000
1,000
Temperature (K)
10^{-3}
10^{-5}
10^{-7}
10^{-9}
10^{-11}
Mass Density (kg m^{-3})
0
1000
2000
3000
Height (km)
Density
Transition Region
Temperature
Photosphere
Chromosphere
Corona
Temperature
T_{min}
Density

C-to-C Temperature Profile



Coronal Heating



Coronal Heating

There must therefore be a heating mechanism that raises the coronal temperature to these high values.

Radiative transfer of energy (as in the solar interior) **does not play a role** – photospheric radiation passes straight through the corona without being absorbed.

There is a **correlation of temperature with magnetic complexity** – complex active regions are hotter than “quiet” coronal regions where the field is relatively simple. So the **heating**

Two main possibilities for the magnetic heating of the corona

Either the corona is heated by the dissipation of waves – magnetohydrodynamic (**MHD**) waves – that are associated with the magnetic field **B**;

Or the corona is heated by **lots of tiny flares** that are beyond the limits of observation: flares are sudden releases of energy due to the conversion of magnetic energy ($B^2/2\mu$) to heat energy and the acceleration of particles. A large flare releases ~10^{25} J, so many **"nanoflares"** (energy/nanoflare ~10^{16} J or less) might heat the corona (first proposed by E. N. Parker in 1988.)