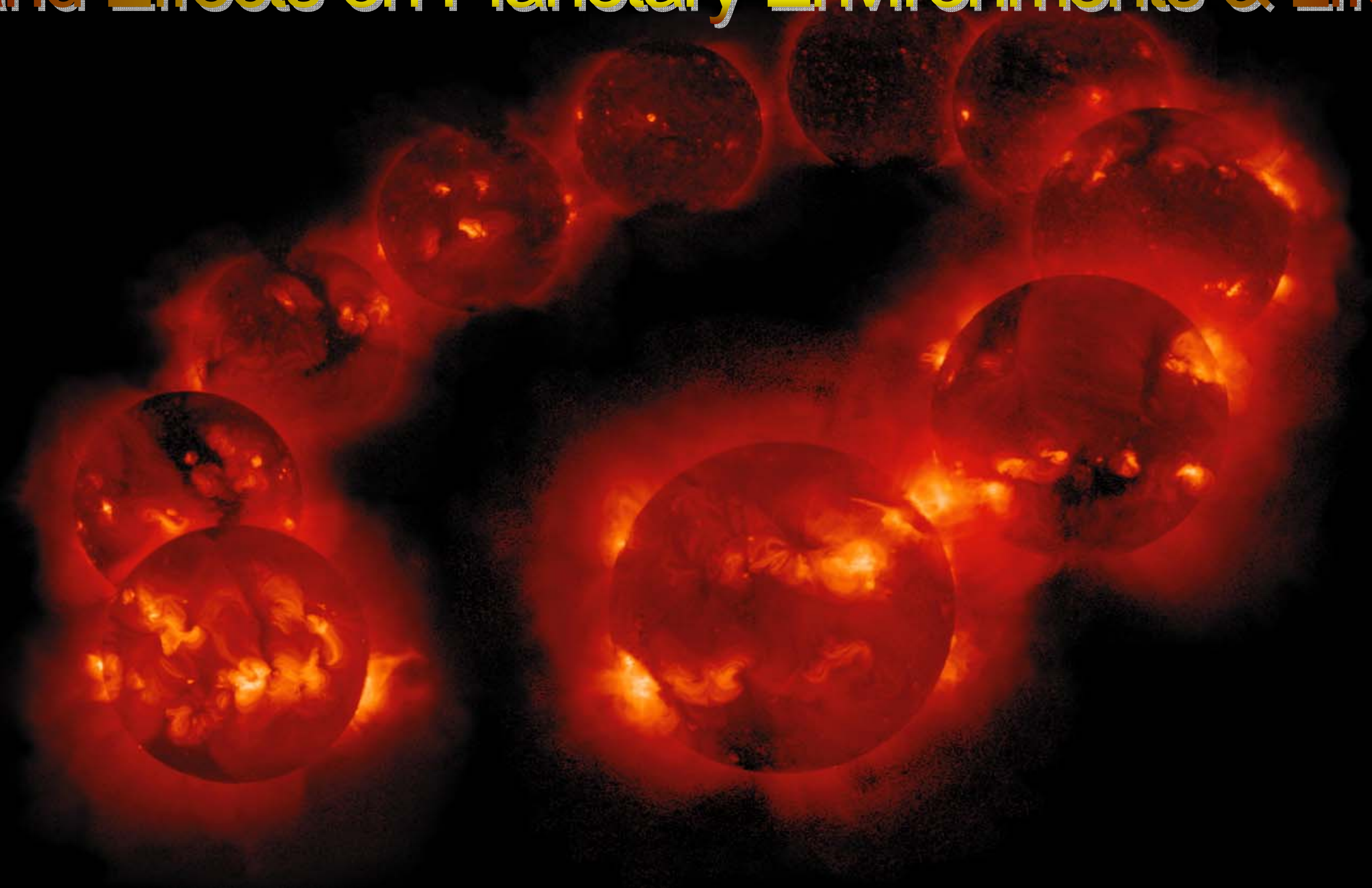
High Energy XUV Emission of the Paleo-Sun and Effects on Planetary Environments & Life



Edward Guinan
Villanova University

Outline

I. Introduction to the The Magnetic Sun
II. The Sun in Time Program: Background & Science Rational
III. Rotation-Age-Activity Relations and Irradiances for Solar-like Stars
IV. Effects of the Young Sun’s High XUV Emissions and Wind Fluxes on Paleo-Planetary Environments
V. Future Plans

Collaborators

“Sun in Time” Program

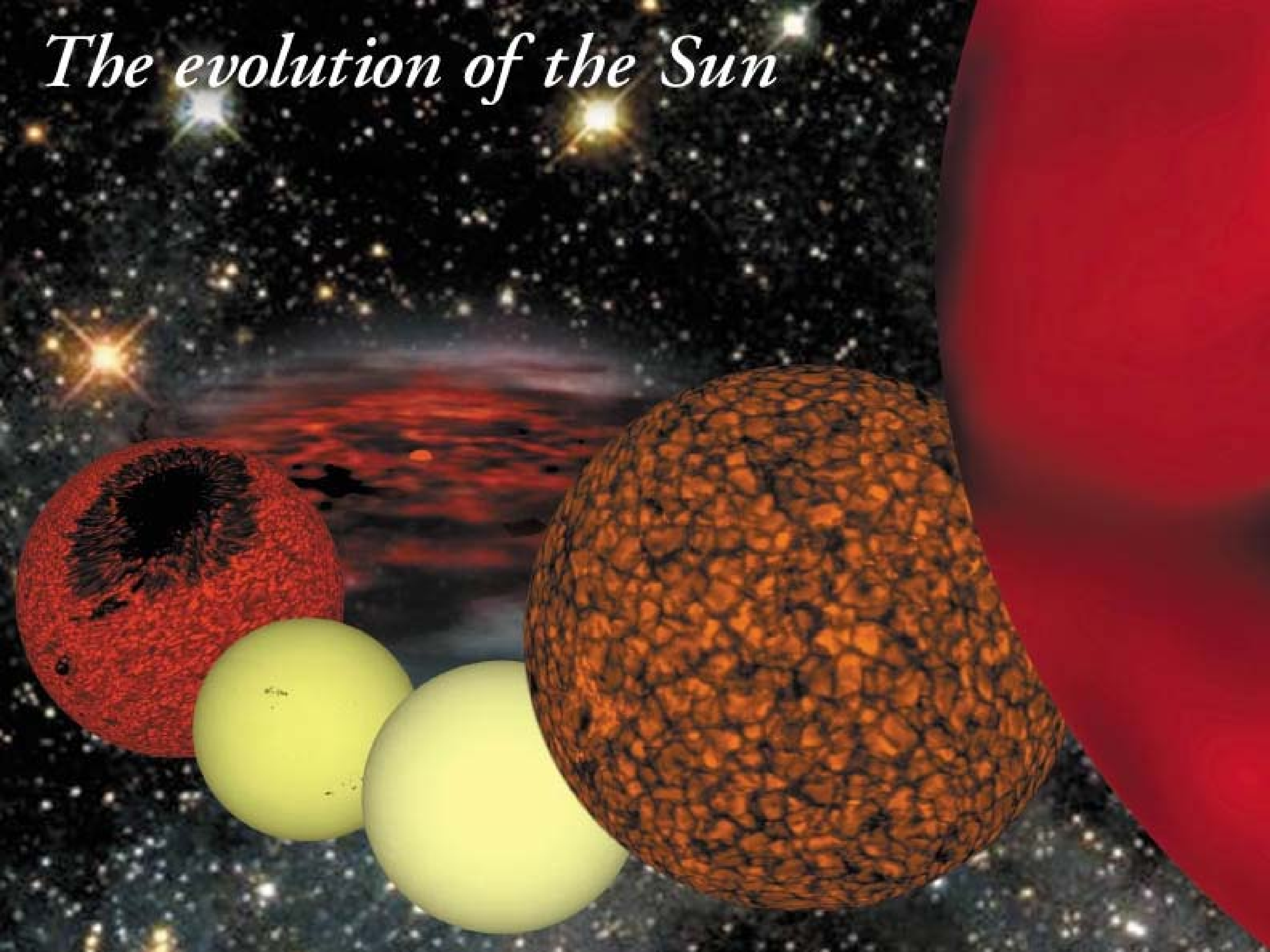
Solar/Stellar Magnetic Activity and Dynamics

Ignasi Ribas	University of Barcelona
Laurence DeWarf	Villanova University
Scott Engle	Villanova University
Manuel Güdel	PSI, CH
Marc Audard	ETHZ, CH
Graham Harper	Univ. of Colorado, CASA
Brian Wood	Univ. of Colorado, CASA

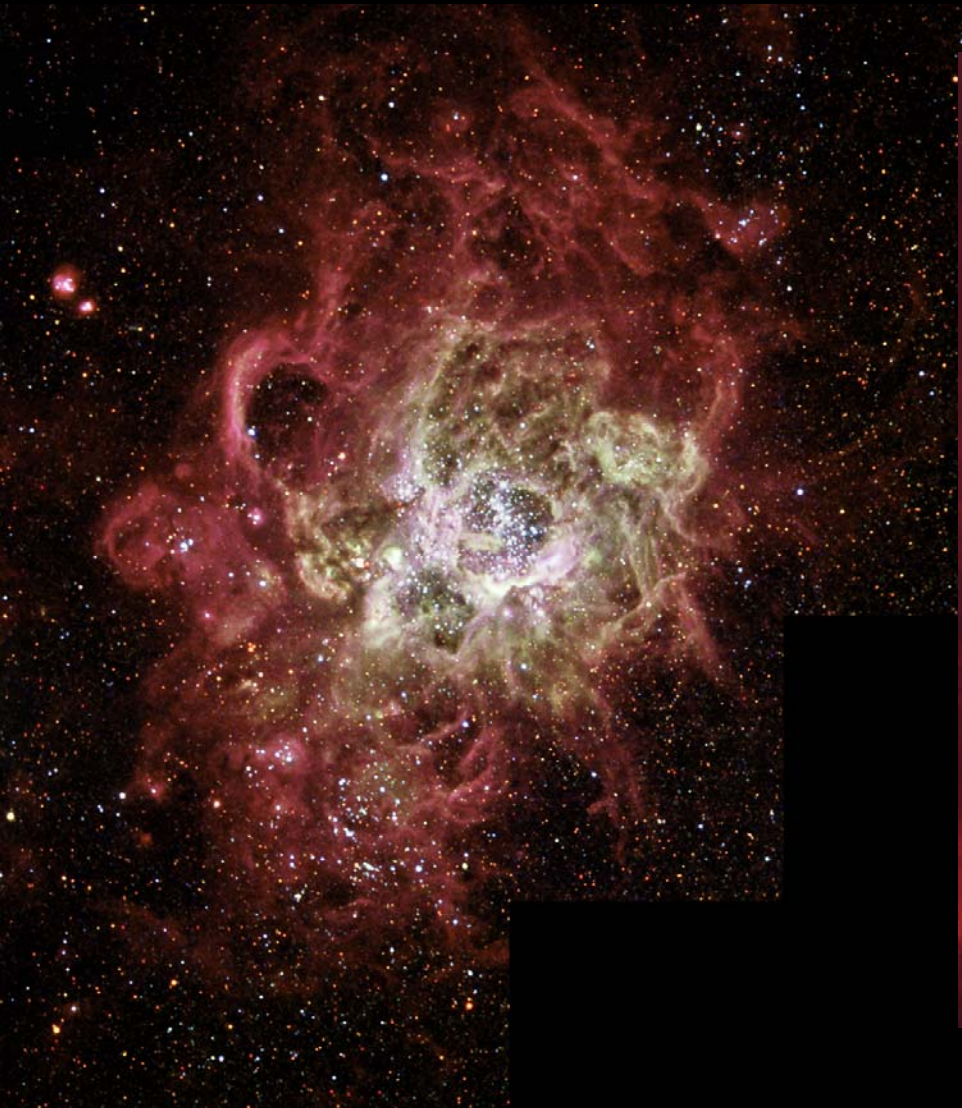
Planets, Paleoplanets, and Exoplanets

Helmut Lammer	Graz, Austria
Franc Selsus	CAB, Spain
Jim Kasting	Penn. State University
Craig Wheeler	University of Texas, Austin
John Scalo	University of Texas, Austin
Dirk Schulze-Makuch	Washington State University

The evolution of the Sun



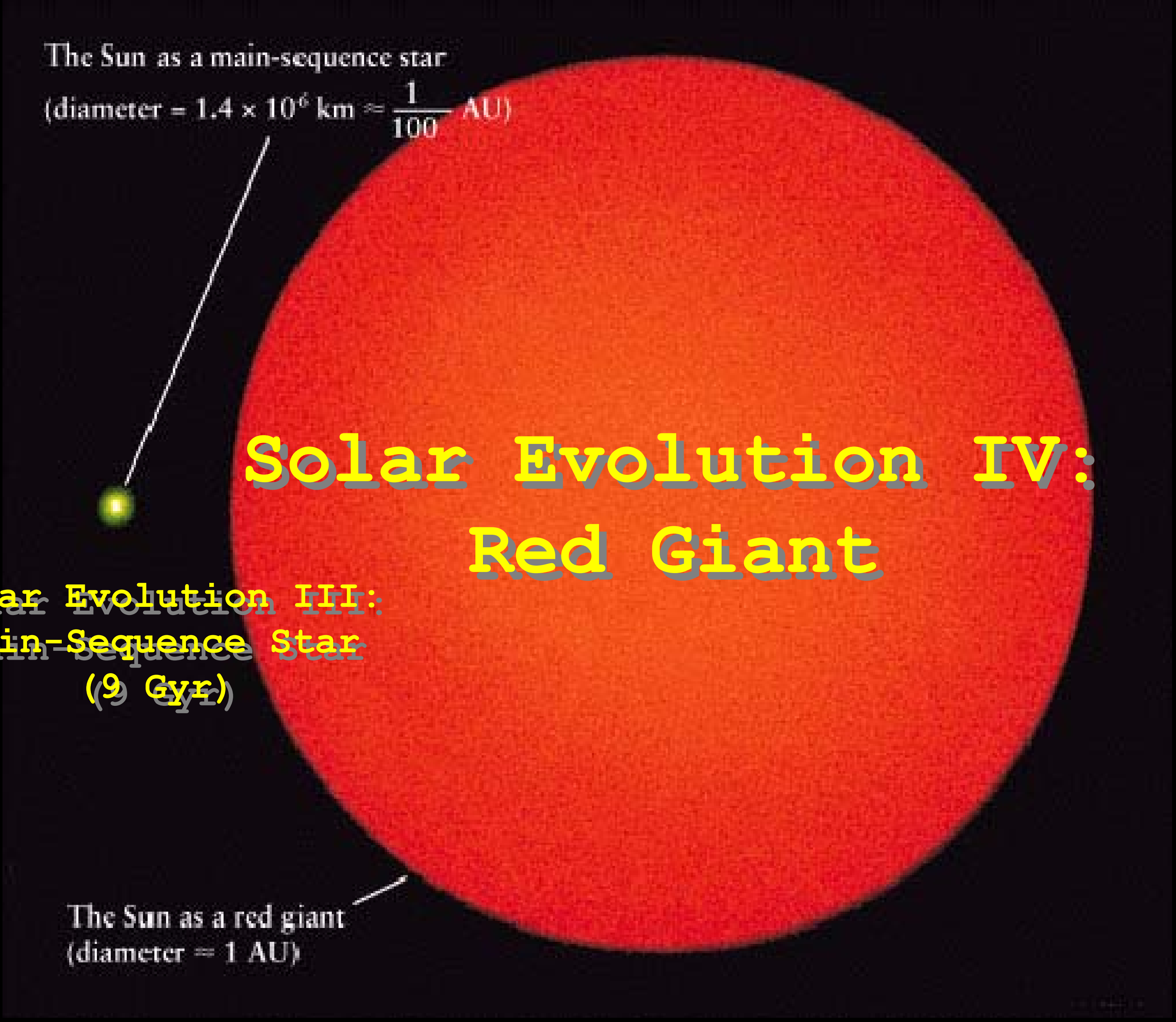
Solar Evolution I: Star-Forming Regions



Solar Evolution II: T-Tauri Star

Solar Evolution IV: Red Giant

Solar Evolution III: Main-Sequence Star (9 Gyr)

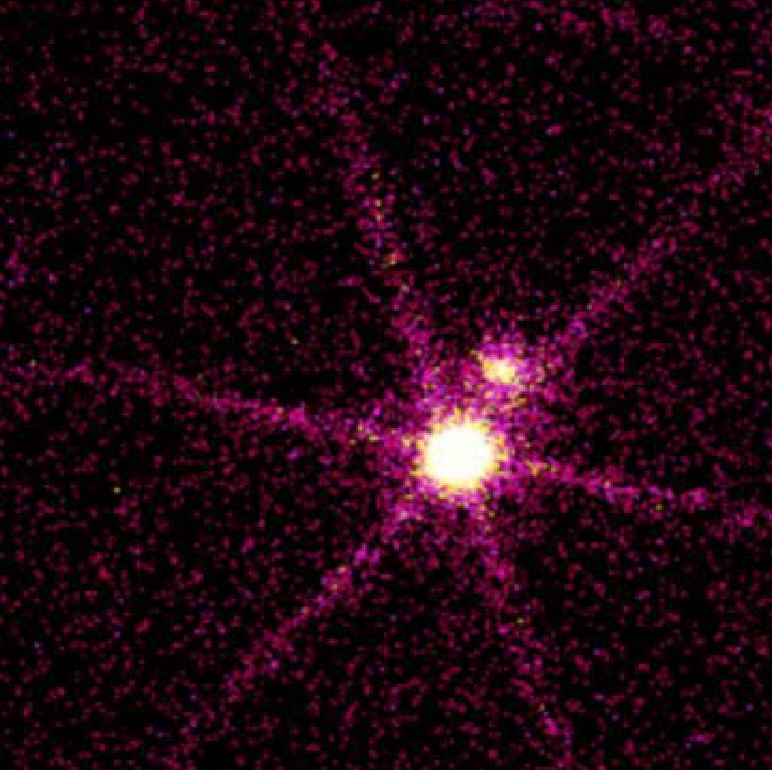


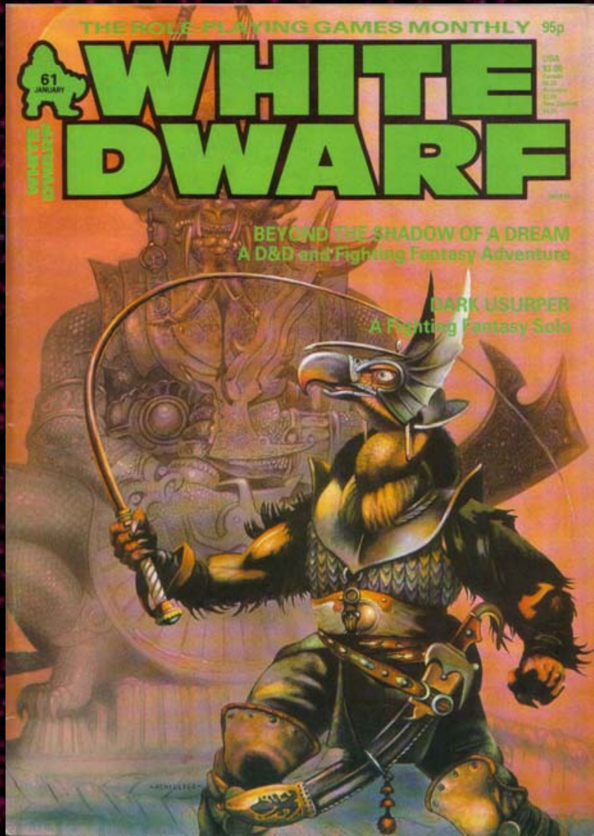
Planetary Nebula NGC 6543: The "Cat's Eye Nebula"

Solar Evolution V: Planetary Nebula

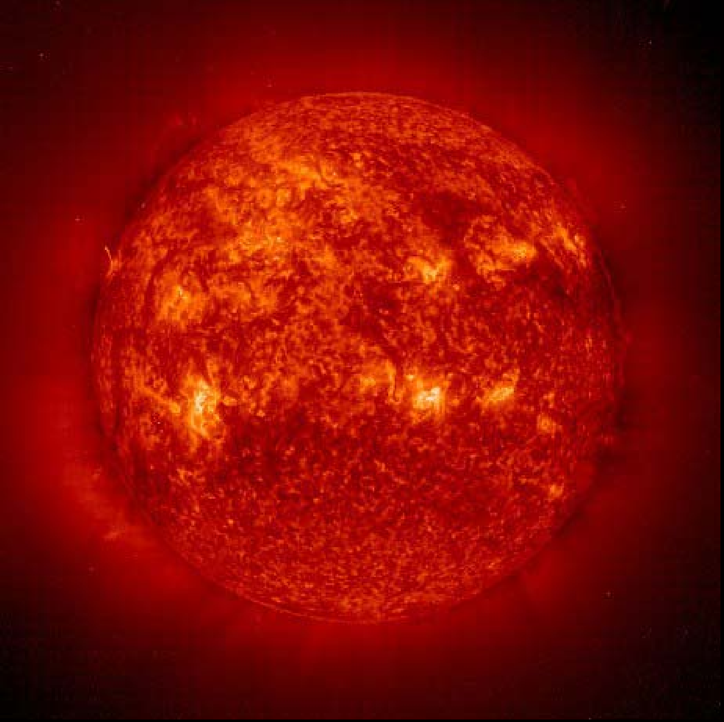
Planetary Nebula NGC 2440

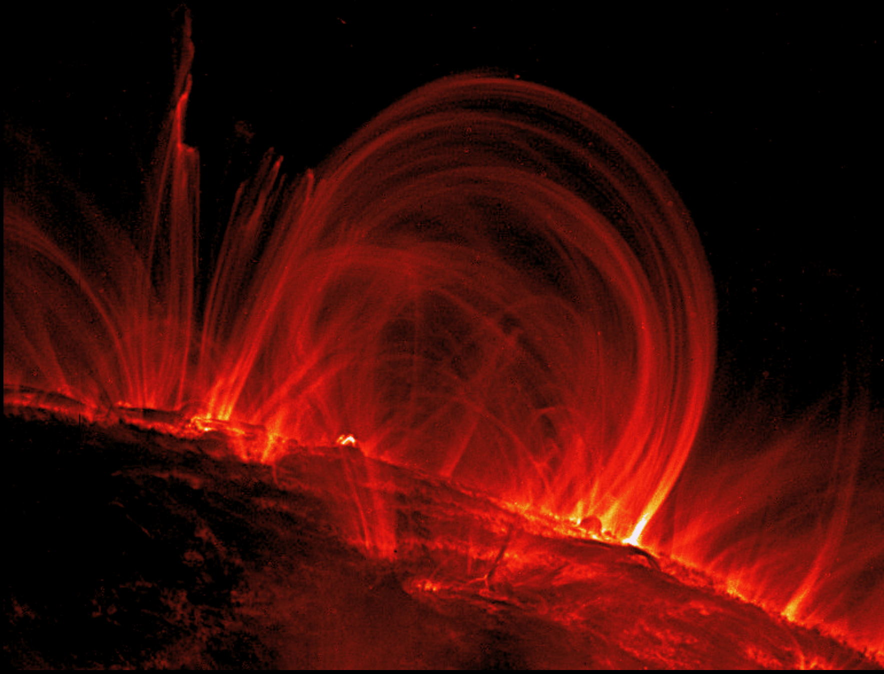
Sirius A/B: Chandra Image



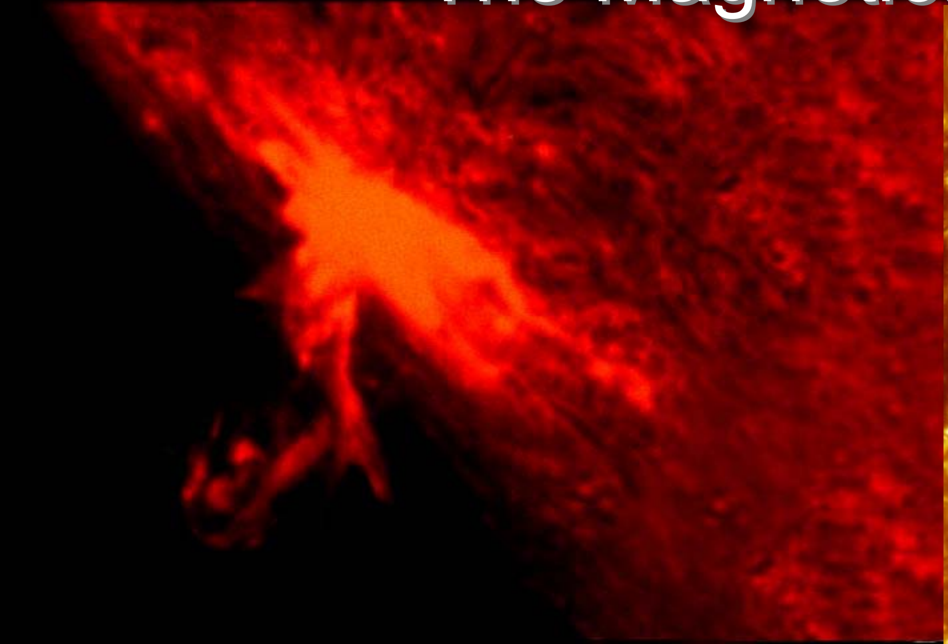


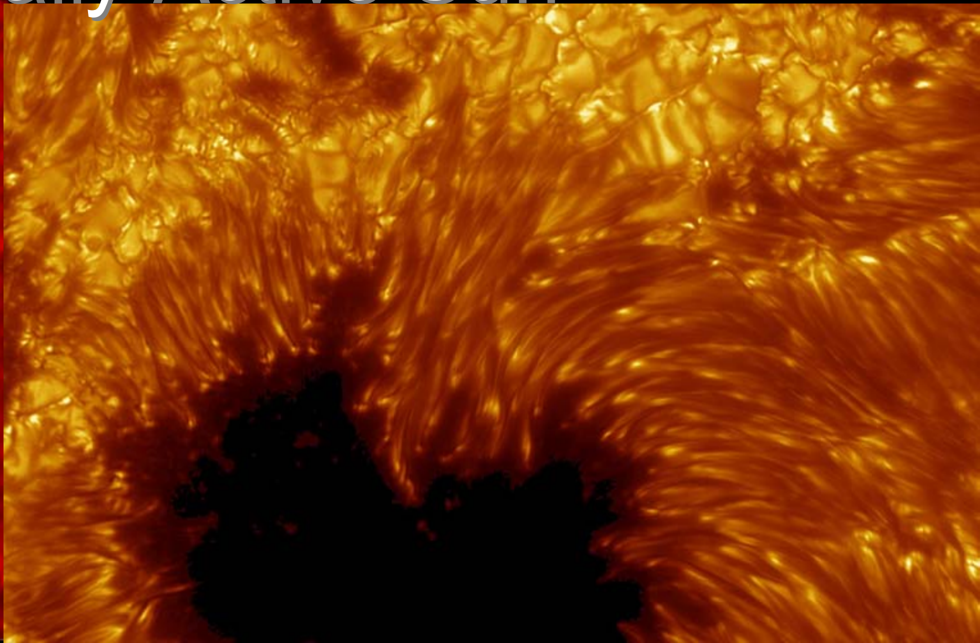
The final stage of our Sun's evolution is a white dwarf.



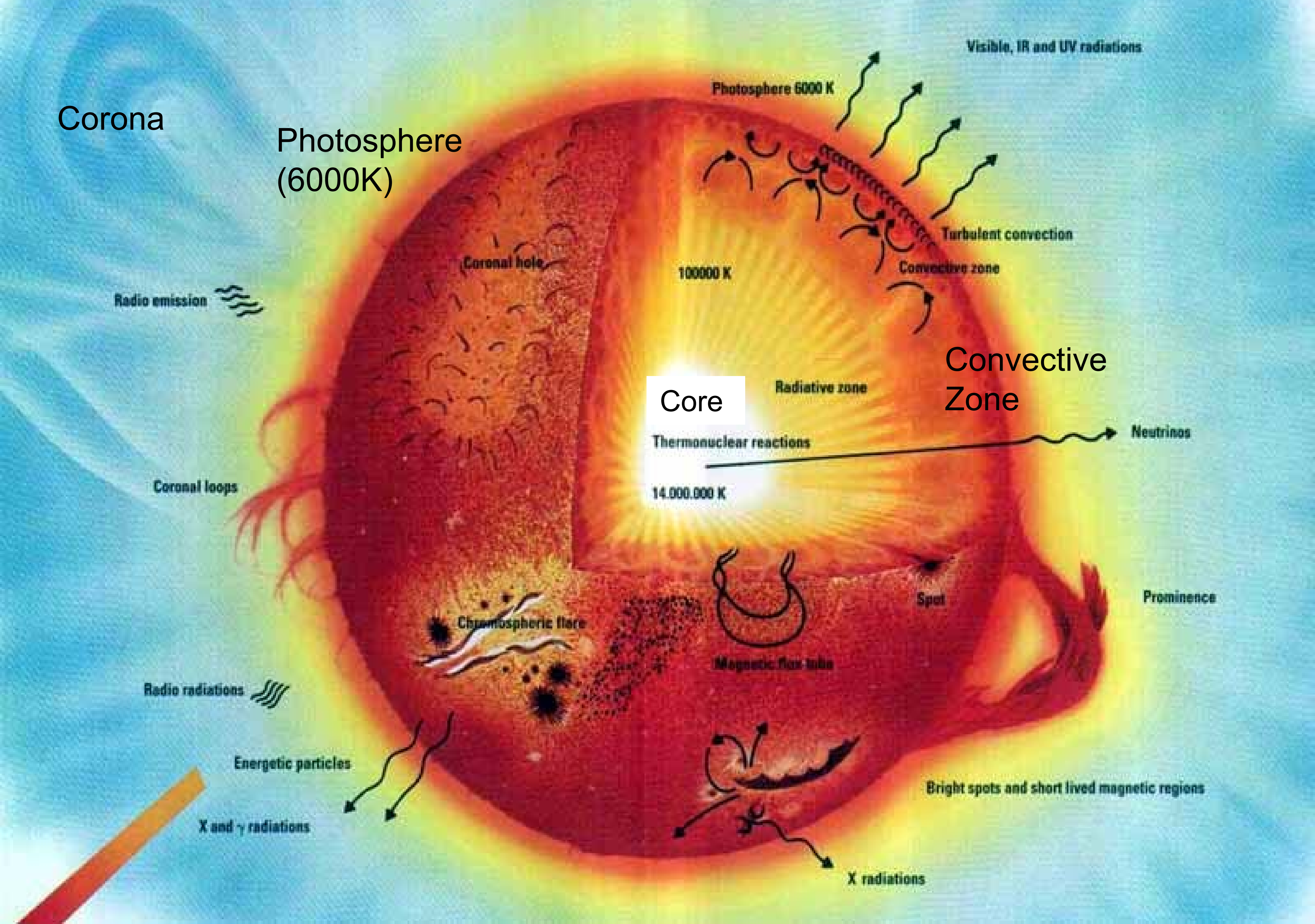


The Magnetically Active Sun

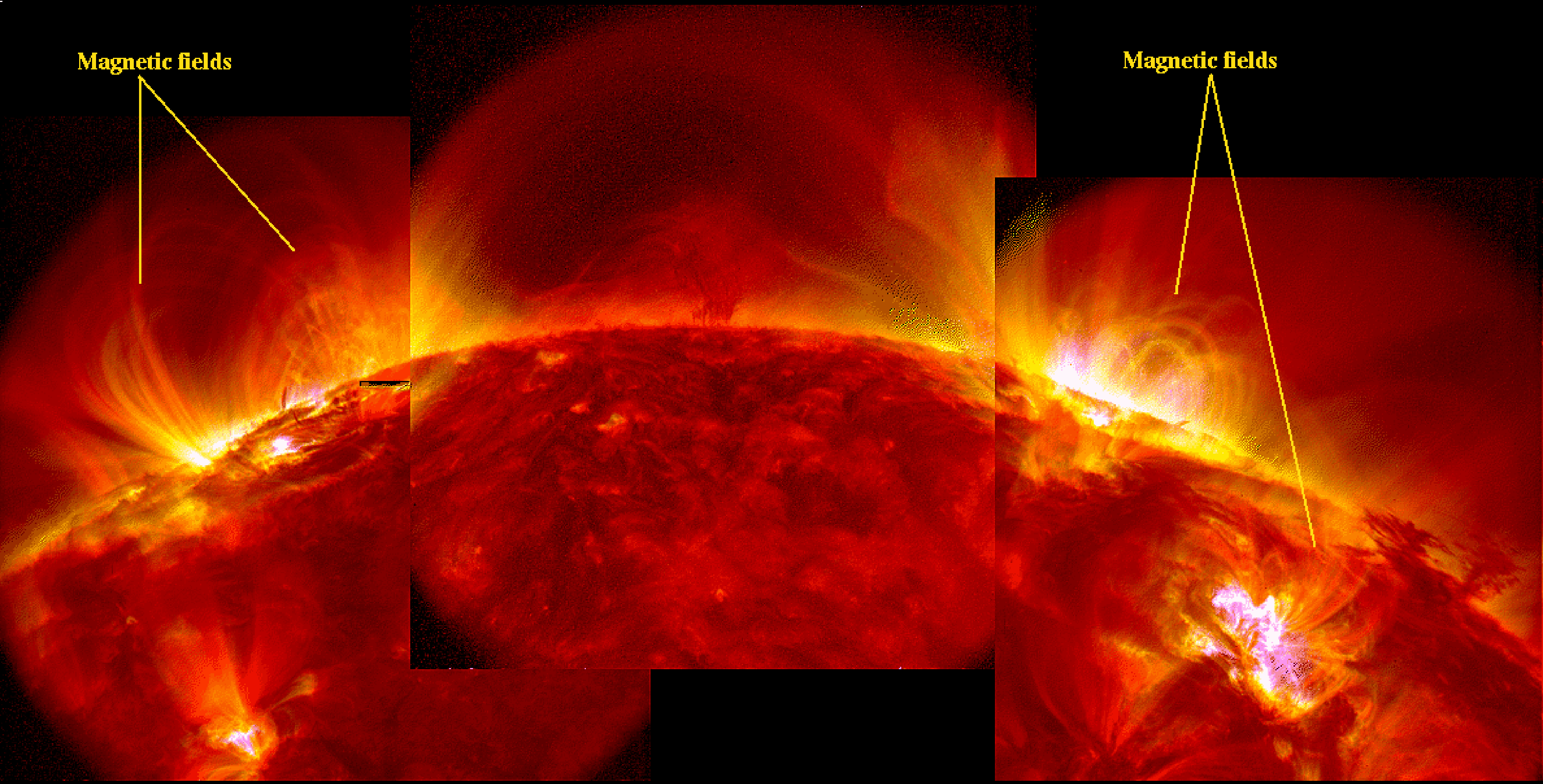




Cross-Section of the Sun: from Interior to Corona

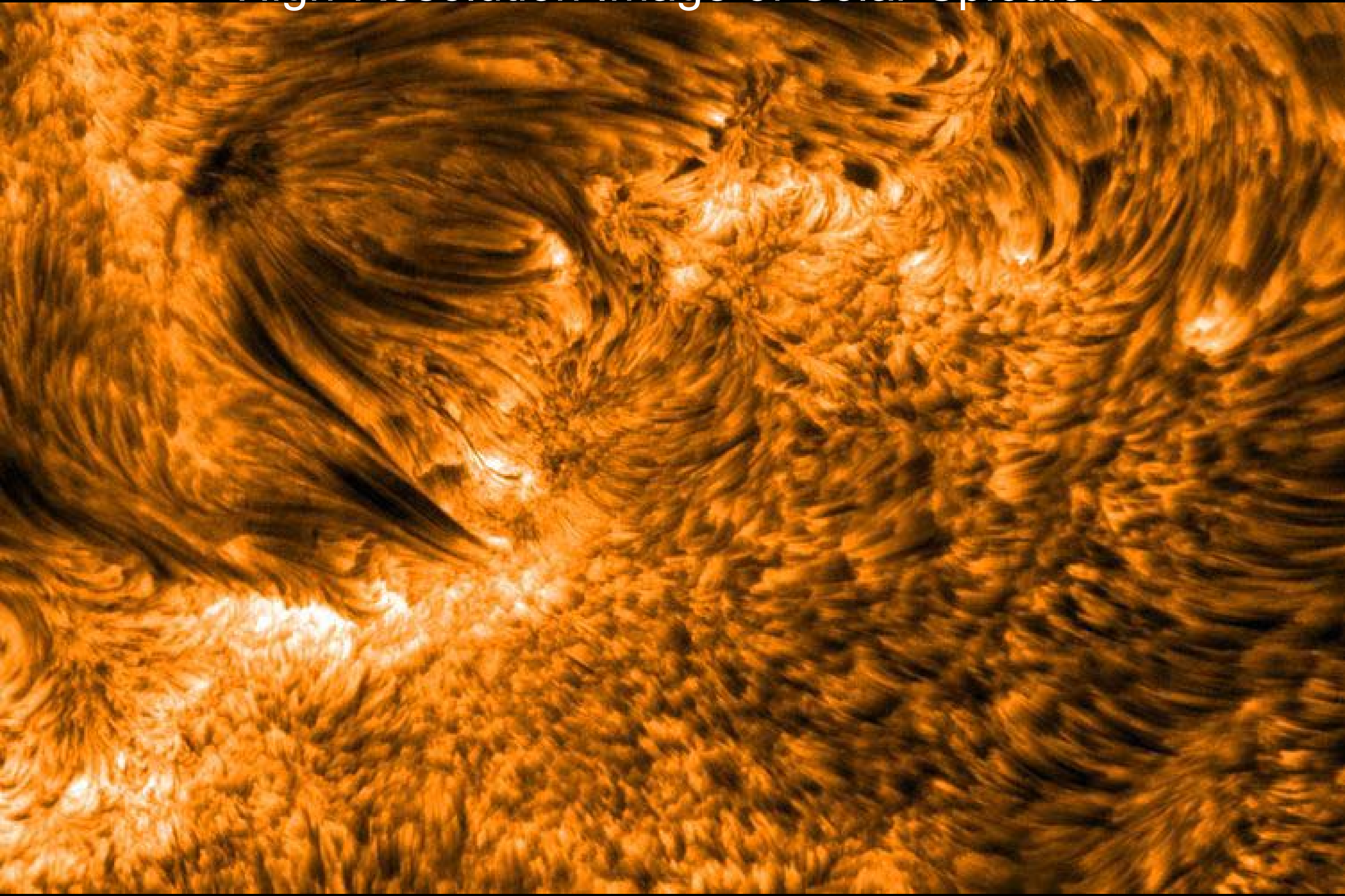


Transition Region of the Sun

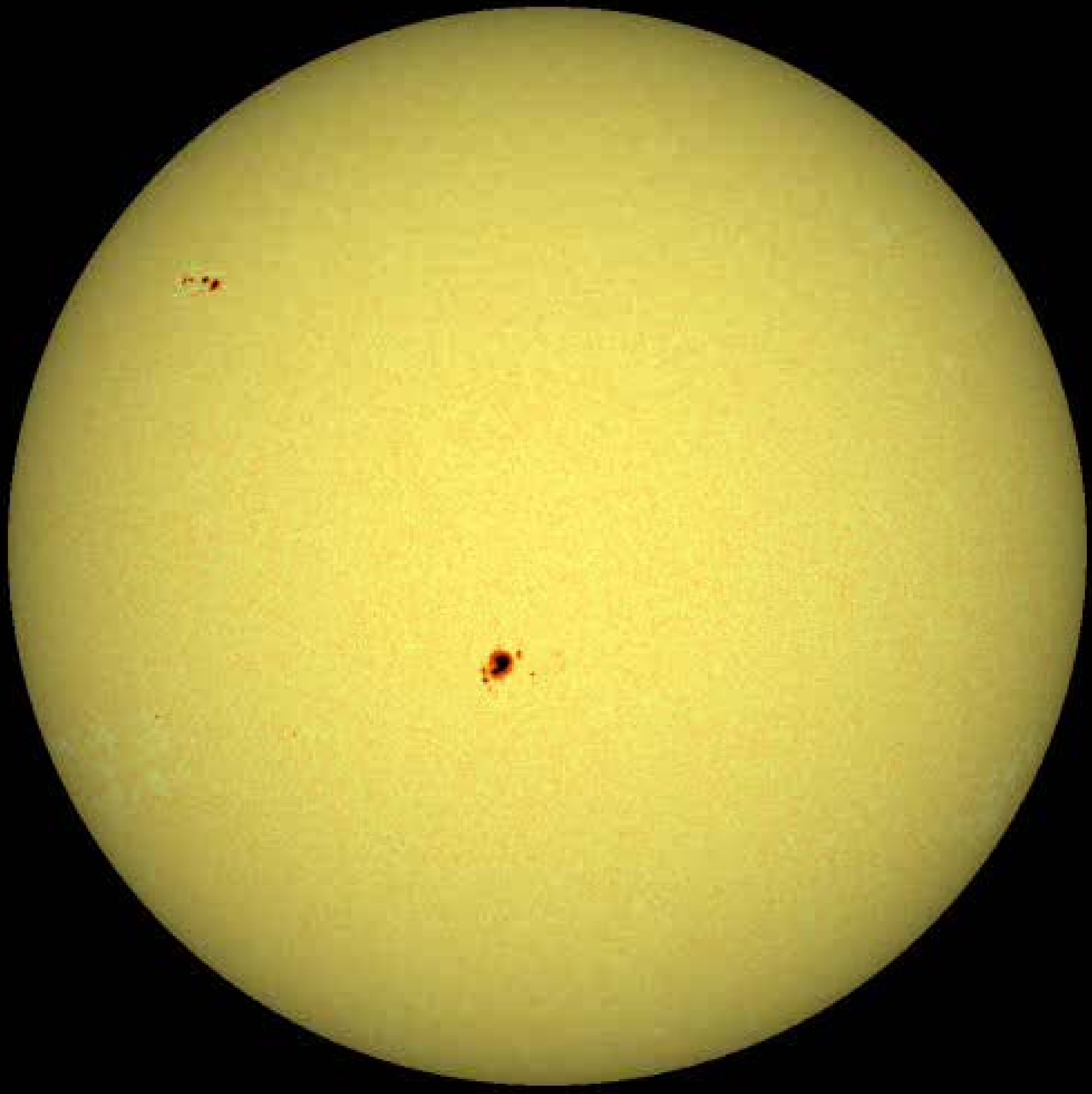


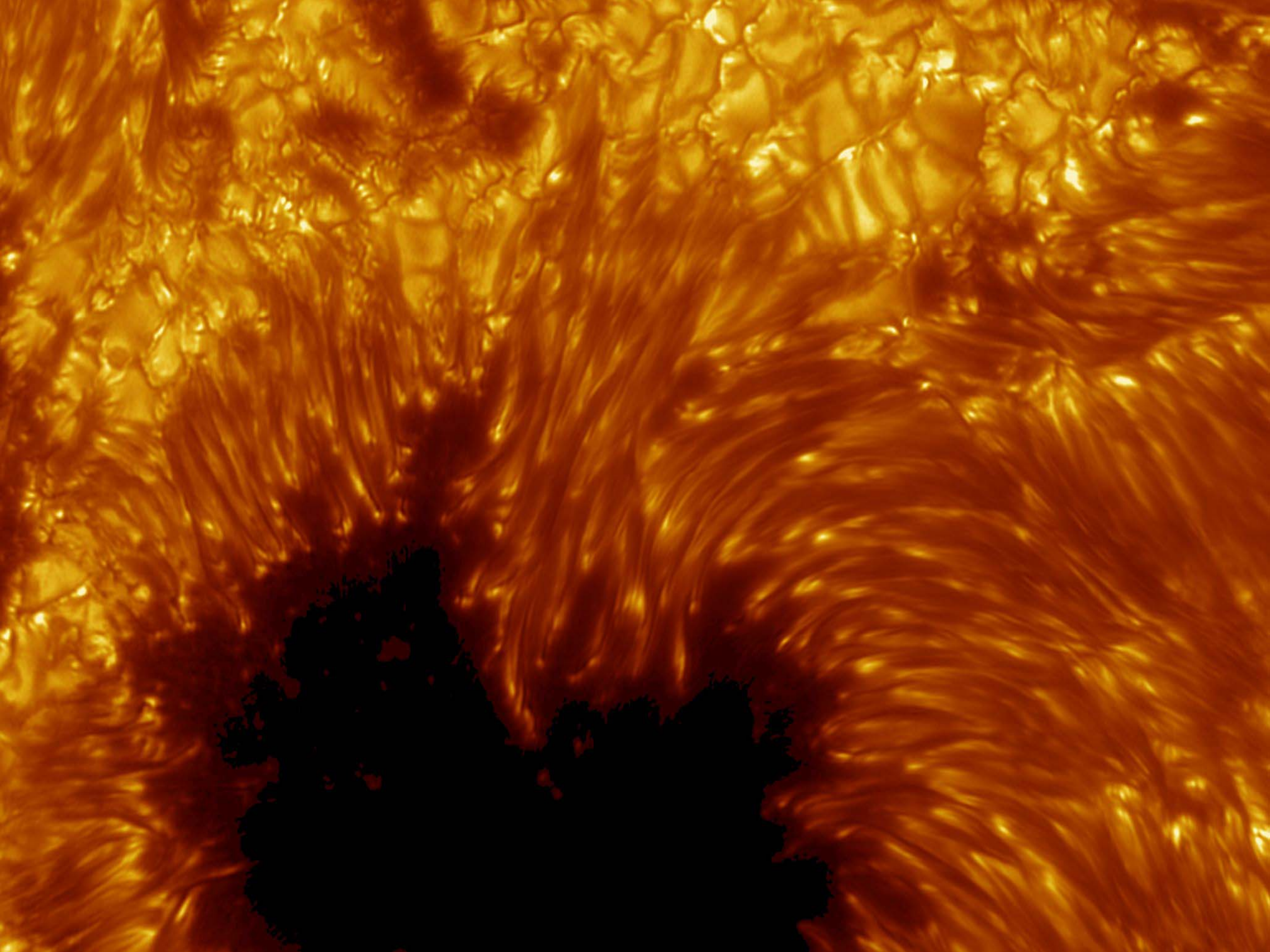
In the Far-Ultraviolet, Showing Magnetic Structures
(taken with TRACE)

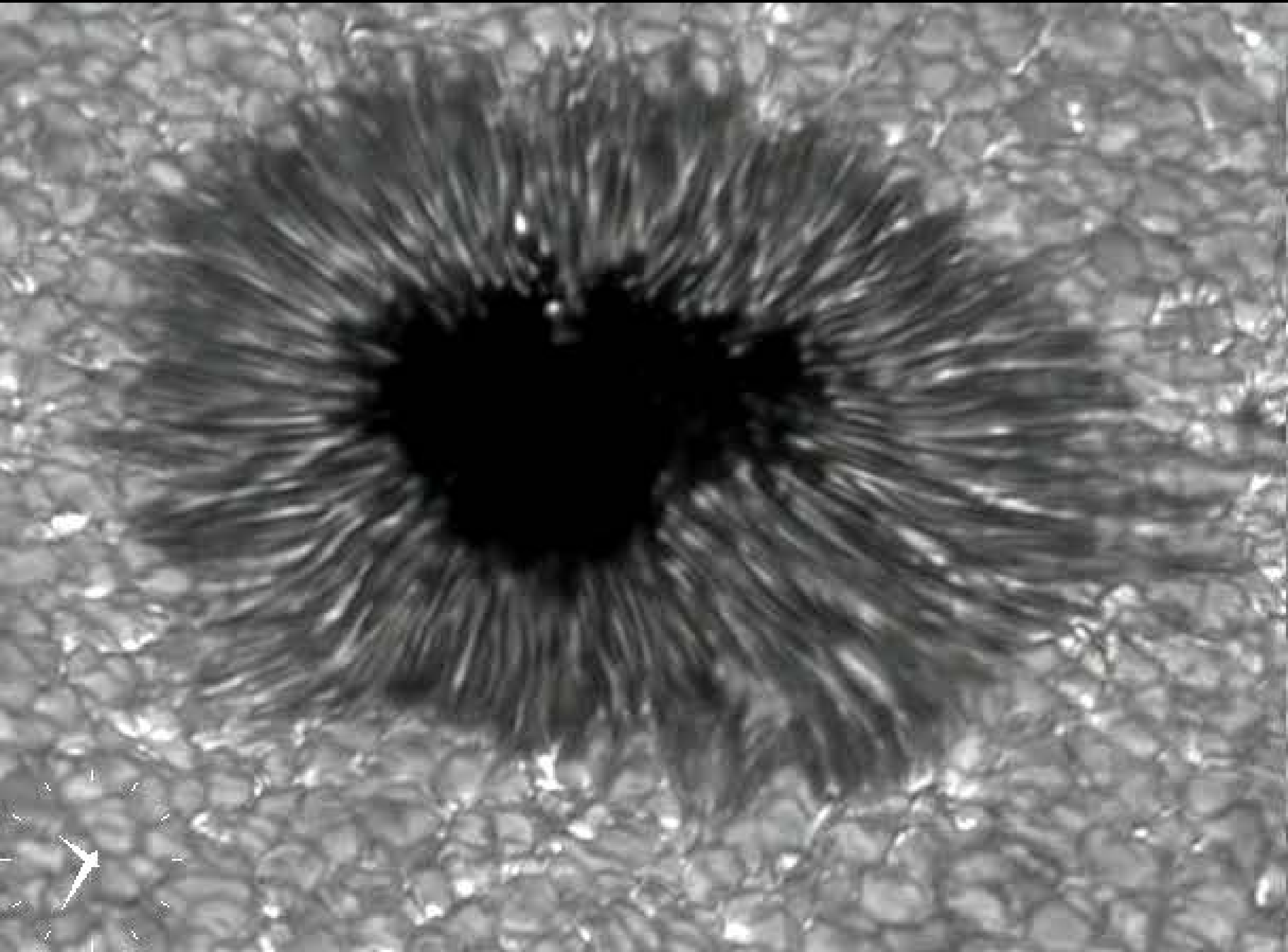
High-Resolution Image of Solar Spicules

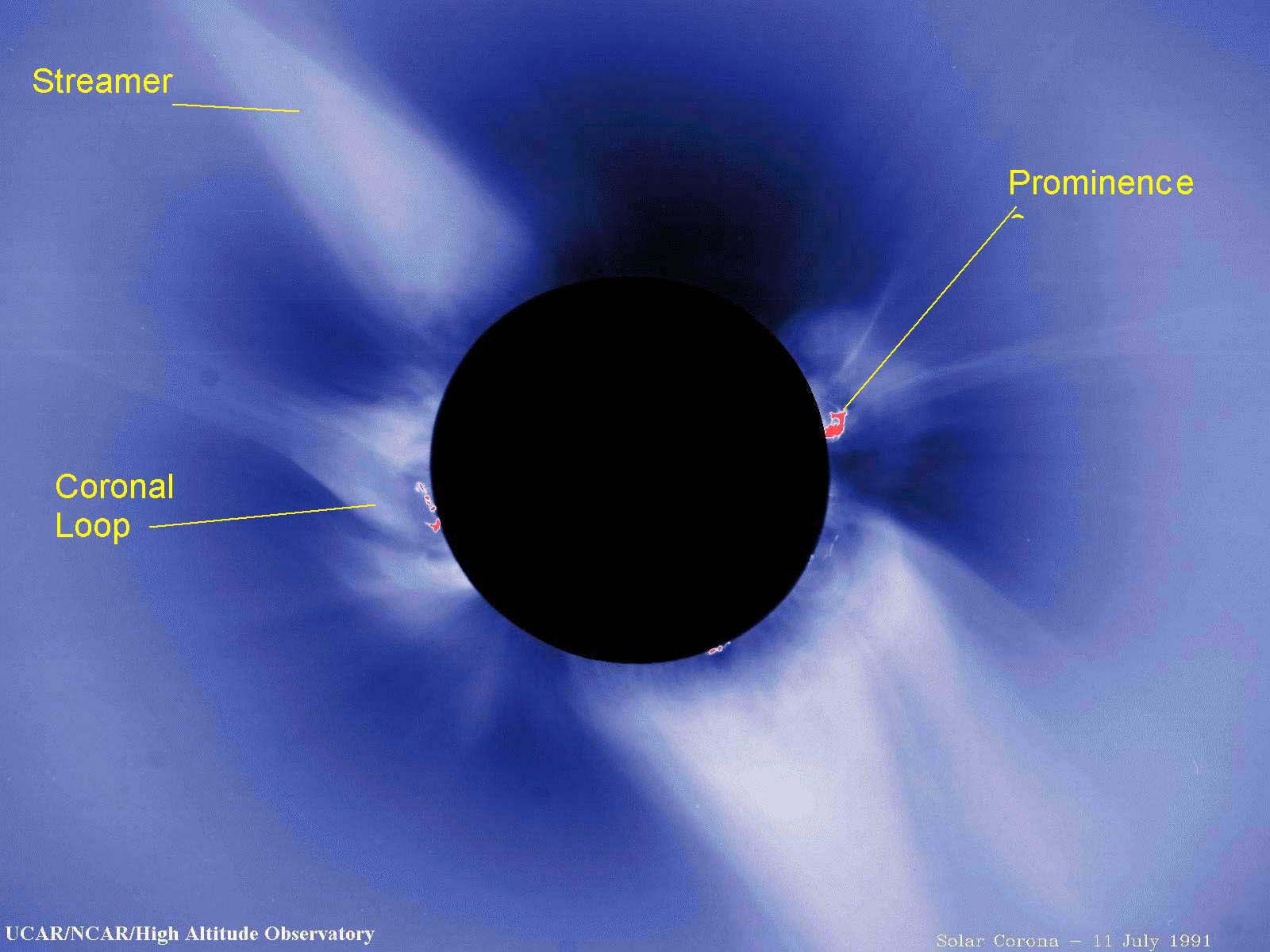


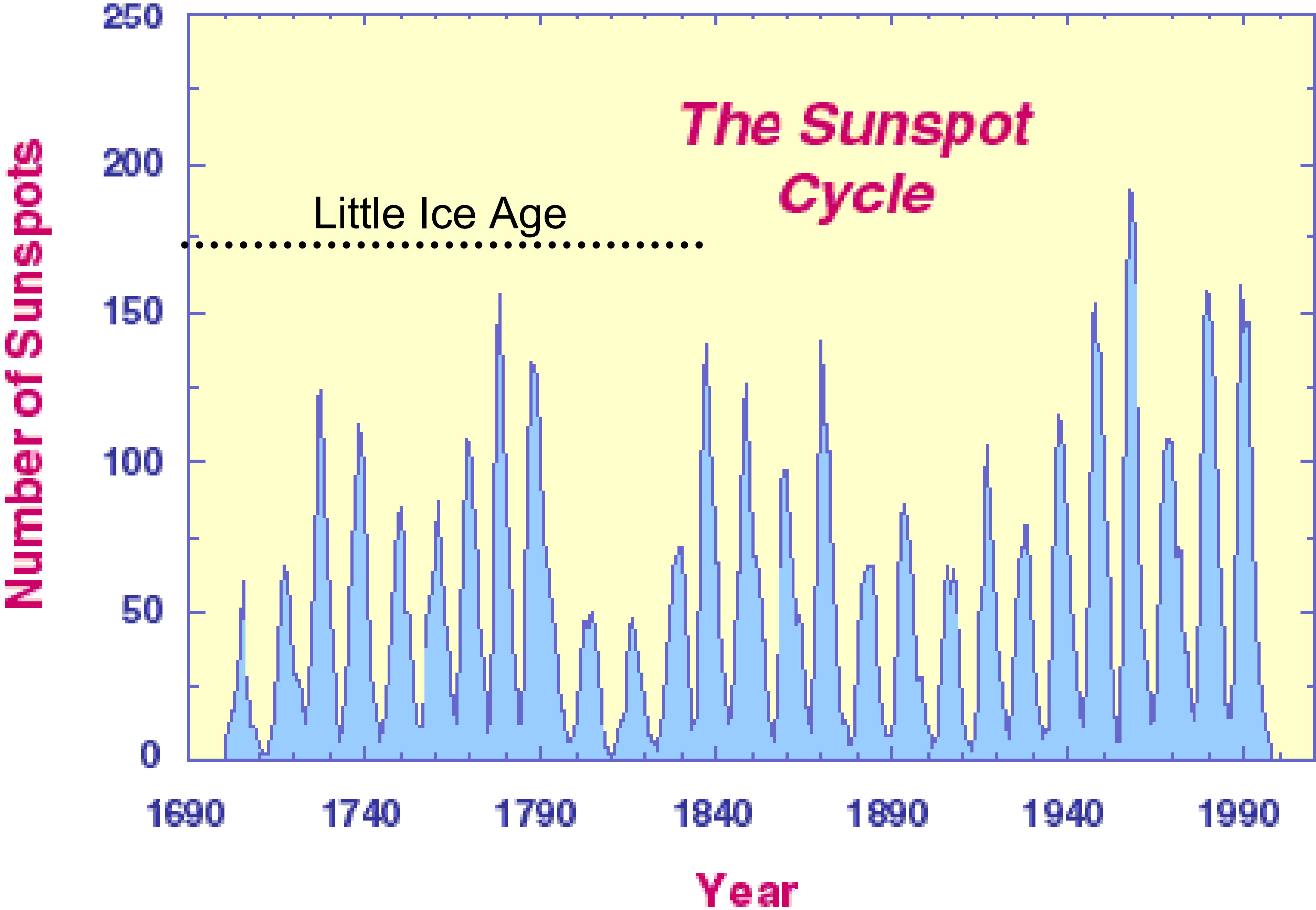
Found in the Transition Region between the Chromosphere & Corona (credit: Swedish Solar Telescope)





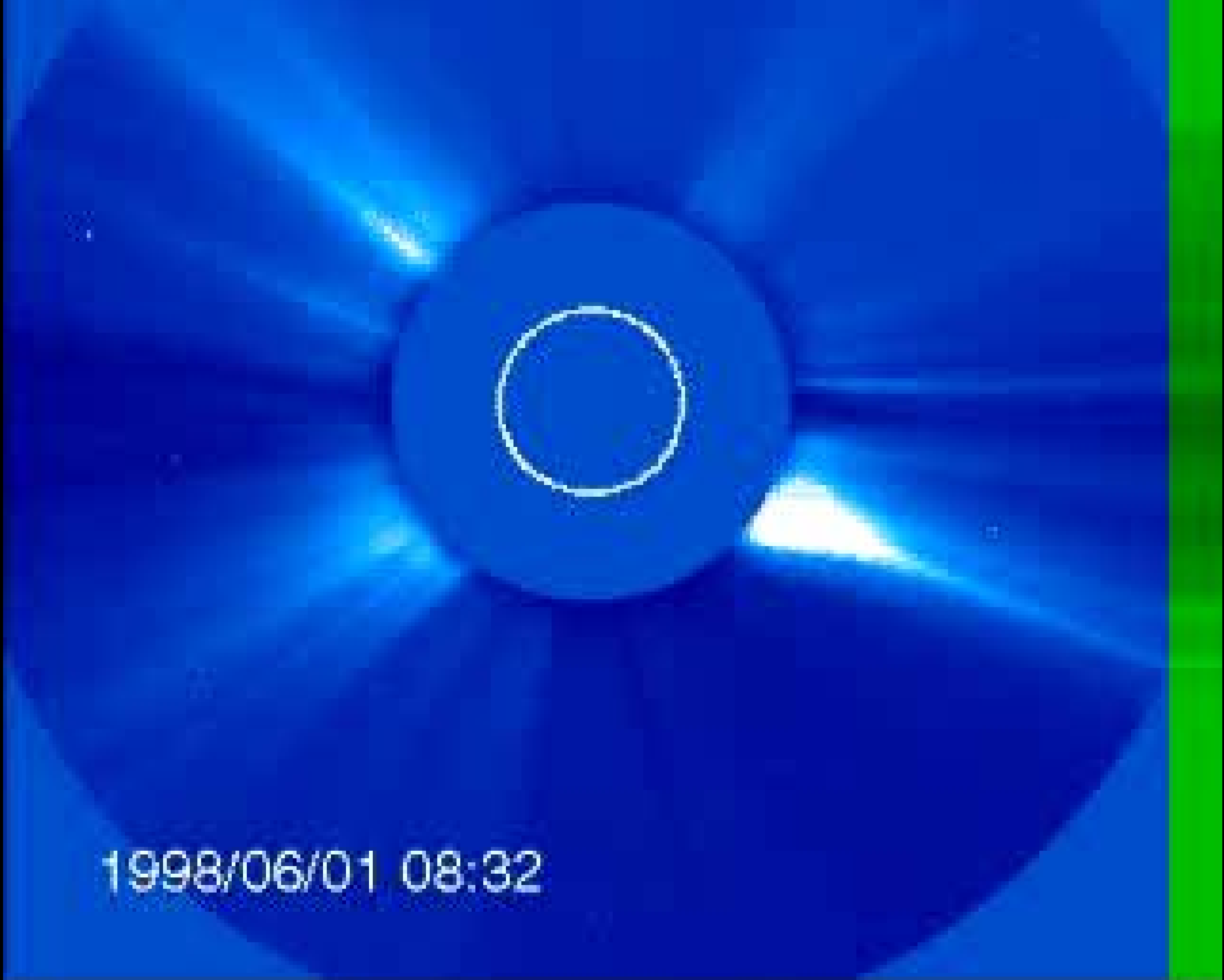



Streamer
Prominence
Coronal
Loop
UCAR/NCAR/High Altitude Observatory
Solar Corona – 11 July 1991



The Sunspot Cycle
Little Ice Age
Number of Sunspots
Year
250
200
150
100
50
0
1690
1740
1790
1840
1890
1940
1990


SOHO
(C) Daryl Pederson
Steele Hill/NASA


1998/06/01 08:32

The “Sun in Time” is a comprehensive multi-frequency program to study the magnetic evolution of the Sun through stellar proxies.

The main features of the stellar sample are:

- Single nearby G0-5 stars
- Known rotation periods
- Well-determined temperatures, luminosities and metallicities
- Age estimates through membership in moving groups, period-rotation relationships or evolutionary model fits

→ We use these stars as laboratories to study the solar dynamo by varying only one parameter: rotation.

Observational Data

Multi-frequency program with observations in the X-ray, EUV, FUV, NUV, optical, IR and radio domains.

We will focus here on the high-energy irradiance study (X-ray and UV). Most of the observations have been acquired from space satellites to overcome atmospheric absorption.

Why high energy?

Several studies (Canuto et al. 1982, 1983; Luhmann & Bauer 1992; Ayres 1997) suggest that the strong X-ray and UV radiations of the young Sun could have had a major influence on the developing paleoatmospheres of the planets photoionization and photochemical reactions

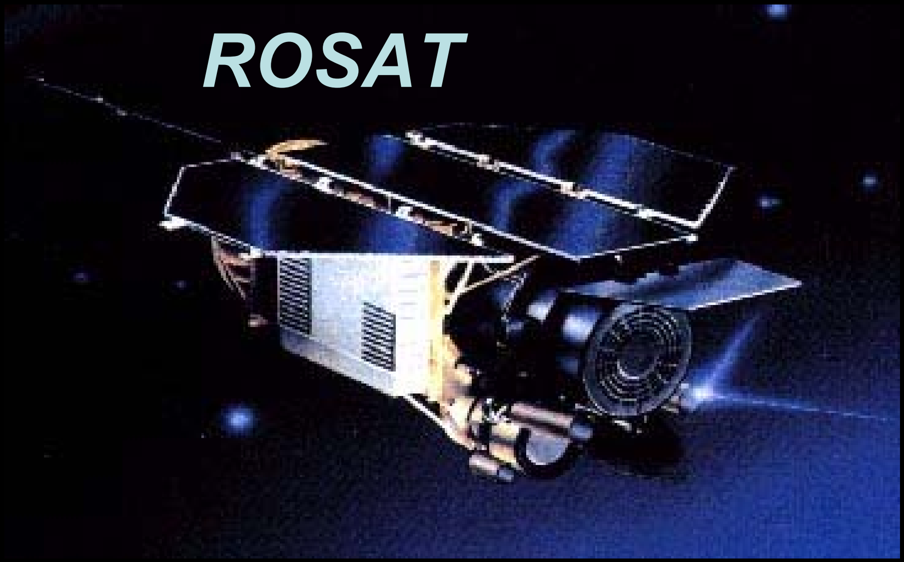
(O_2, O_3, CO_2, H_2O)

Partial List of Sun in Time Program Stars

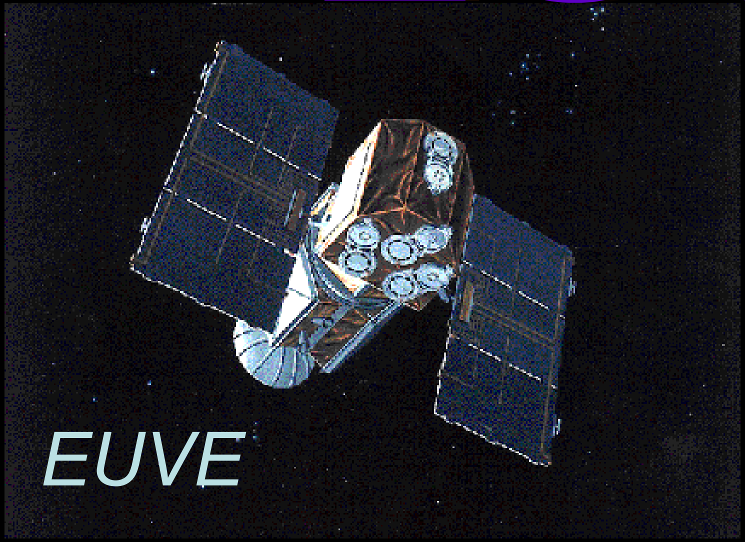
Table 1. Program stars; proposed target is in **boldface** (underlined: targets accepted previously)

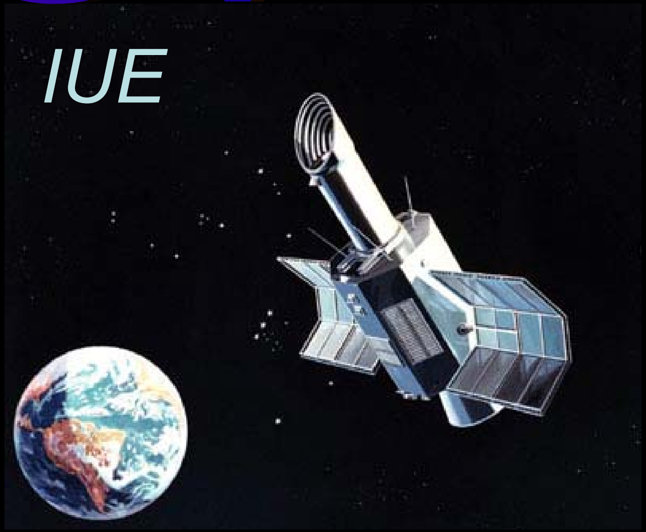
Star	Spect Type	ROSAT PSPC (cts/s)	ASCA SIS0 (cts/s)	Dist. (pc)	$P_{\rm rot}$ (d)	$\log L_X$ (erg/s)	Age (Gyr)	Age indicator, Membership
47 Cas B	G0-2 V	2.2	0.59	33.54	~1.0	30.31	0.07	Pleiades Moving Group
EK Dra	G0 V	0.9	0.20	33.94	2.75	29.93	0.07	Pleiades Moving Group
π^1 UMa	G1 V	0.88	···	14.27	4.68	29.10	0.3	Ursa Major Stream
HN Peg	G0 V	···	0.078	18.39	4.86	29.12	0.3	Rotation-Age Relationship
χ^1 Ori	G1 V	0.41	···	8.66	5.08	28.99	0.3	Ursa Major Stream
BE Cet	G2 V	0.40	···	20.4	7.65	29.13	0.6	Hyades Moving Group
κ^1 Cet	G5 V	1.08	0.11	9.16	9.2	28.79	0.75	Rotation-Age Relation
β Com	G0 V	0.36	···	9.15	12.4	28.21	1.6	Rotation-Age Relationship
15 Sge	G5 V	0.065	···	17.7	13.5	28.06	1.9	Rotation-Age Relationship
18 Sco	**G2 V**	···	···	**14.03**	**23±3**	**<28.0**	**~4.4**	**Isochrones**
Sun	G2 V	···	···	1 AU	25.4	27.3	4.6	Isotopic Dating on Earth
α Cen A	G2 V	1.64	0.113	1.35	~24	27.12	5-6	Isochrones, Rotation
β Hyi	G2 IV	0.11	···	7.47	~28	27.18	6.7	Isochrones

X-ray



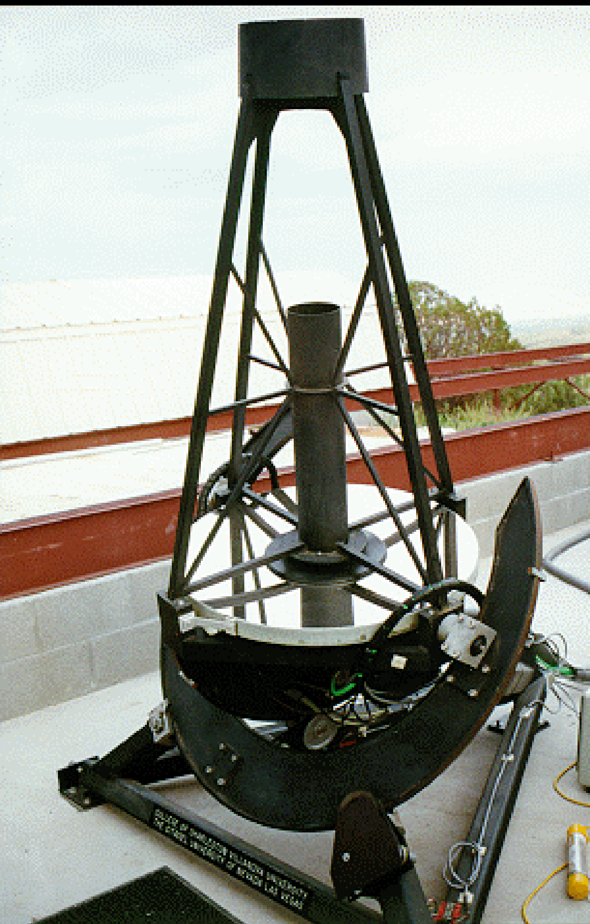
EUV/UV



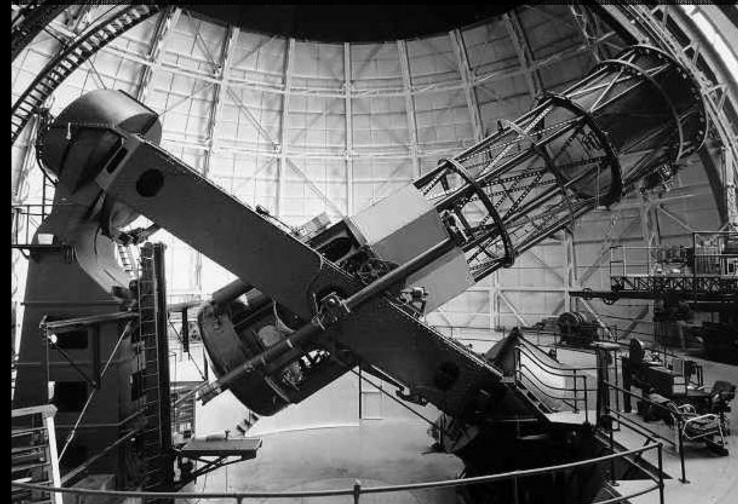


Optical

FCAPT

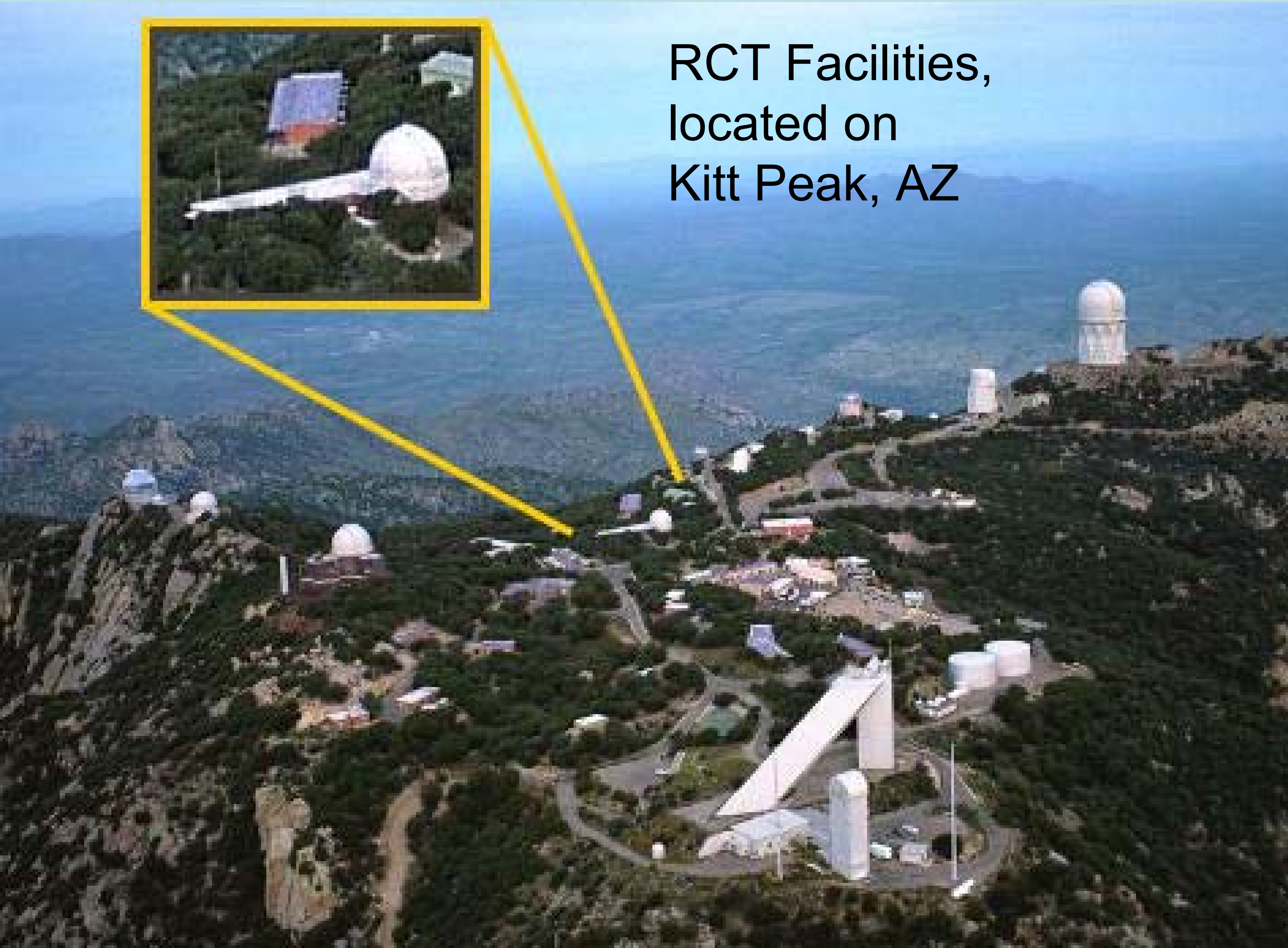


Mt. Wilson 100”

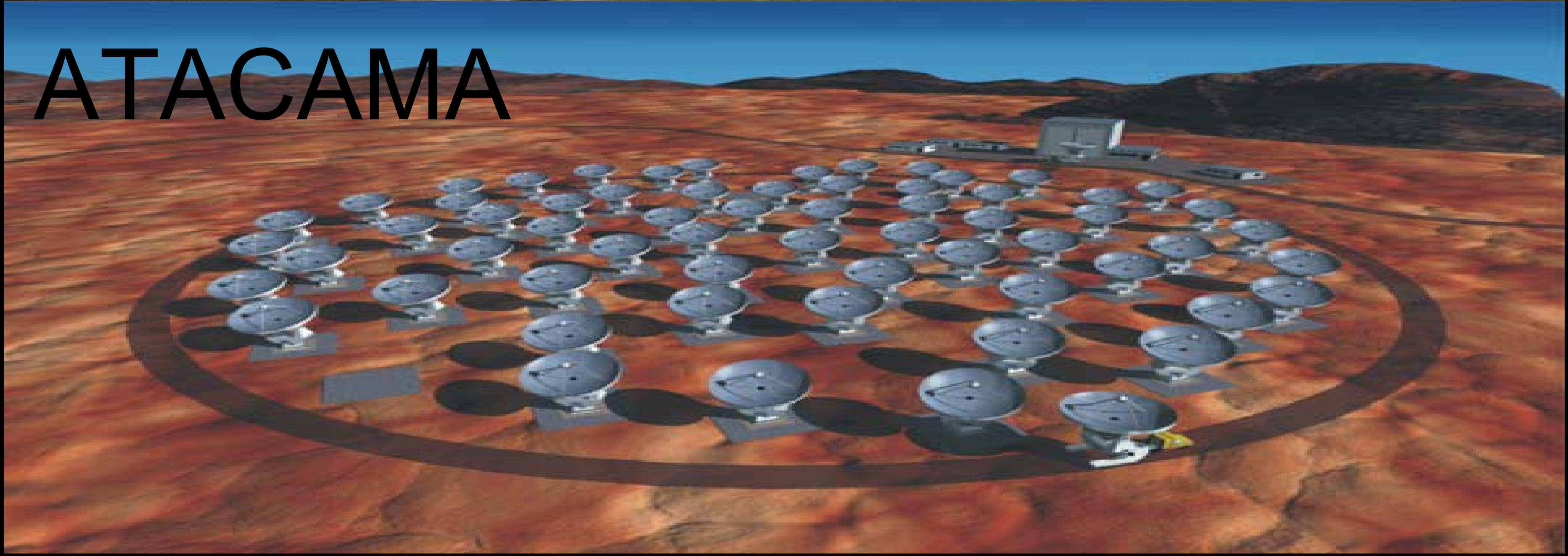


VU 15”

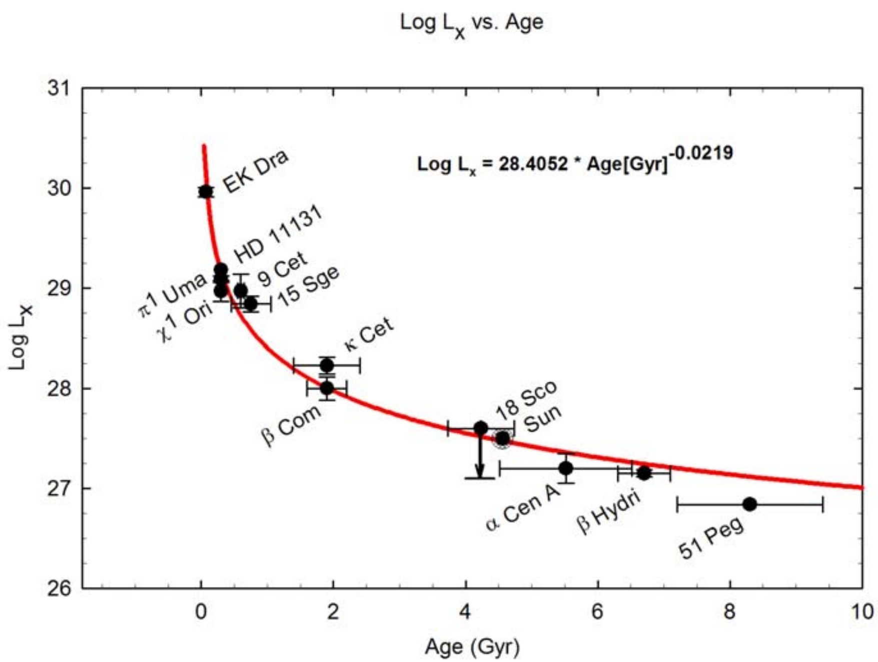
RCT

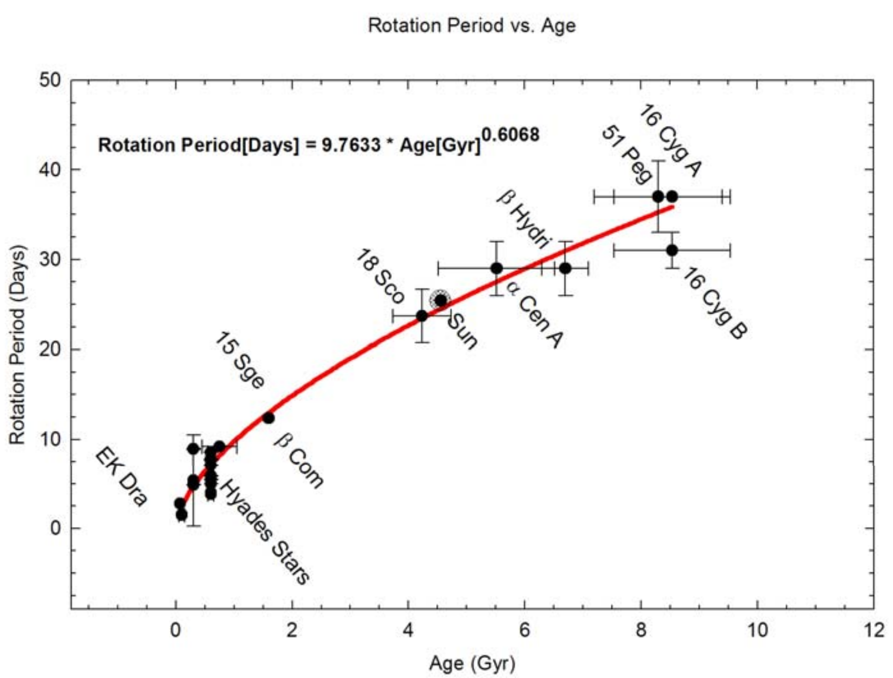

RCT Facilities,
located on
Kitt Peak, AZ

Radio



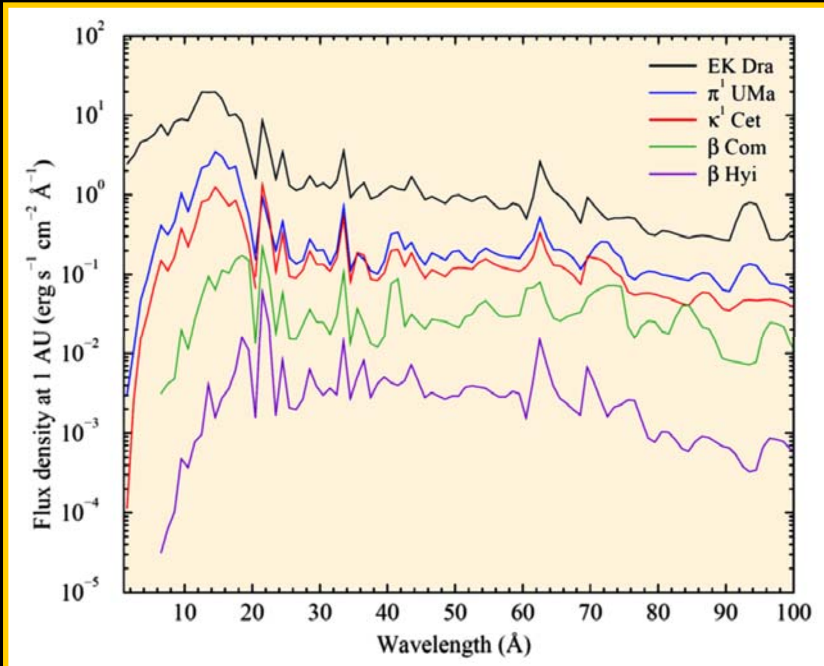
Spin-Down of Sun and Decrease in Activity with Age as Observed from Solar Analogues



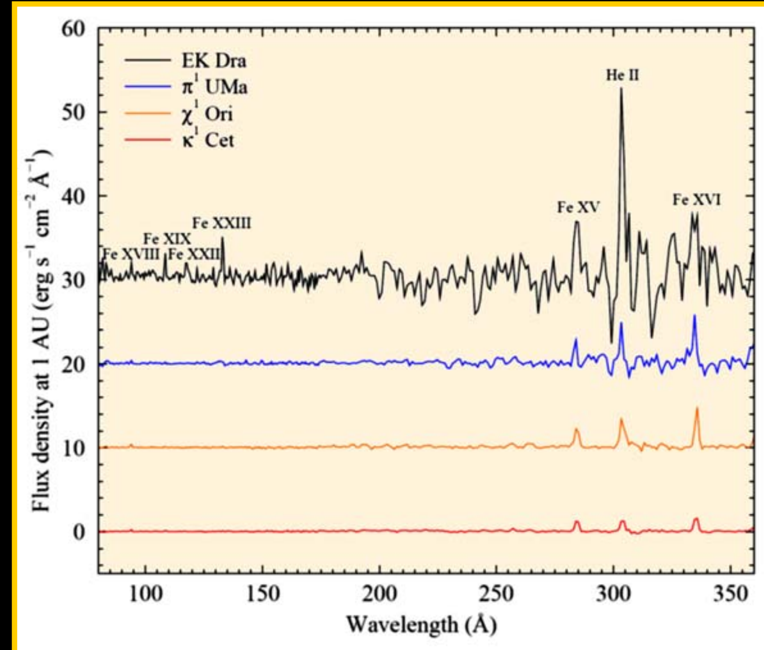


Age vs. X-ray Luminosity (log L_X)

Age vs. Rotational Period

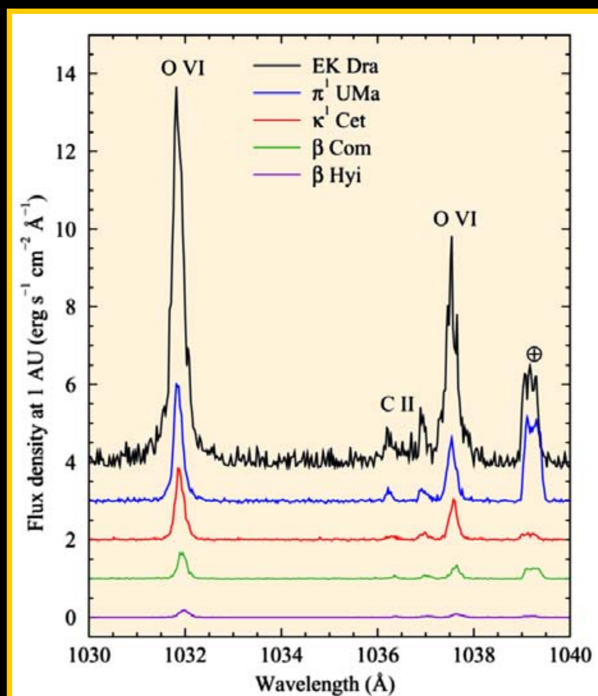


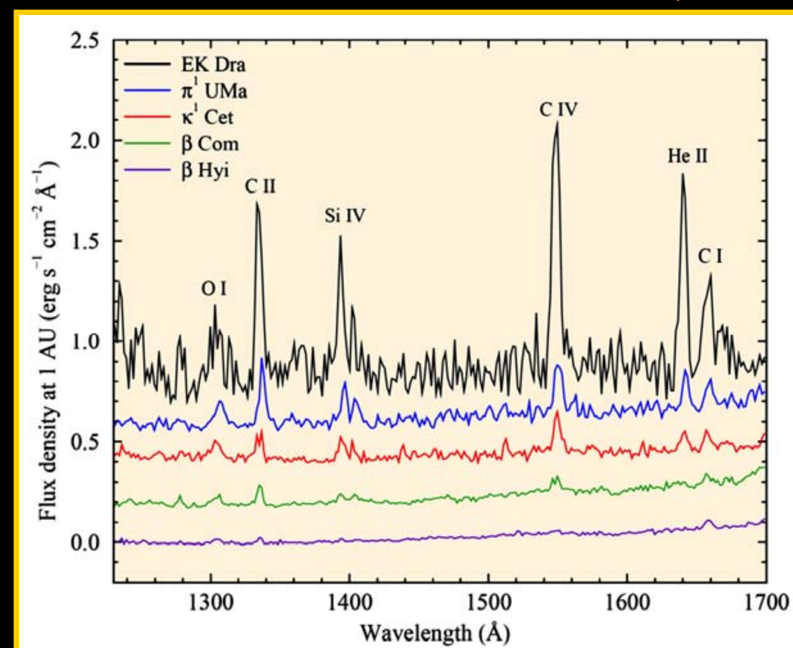
X-rays



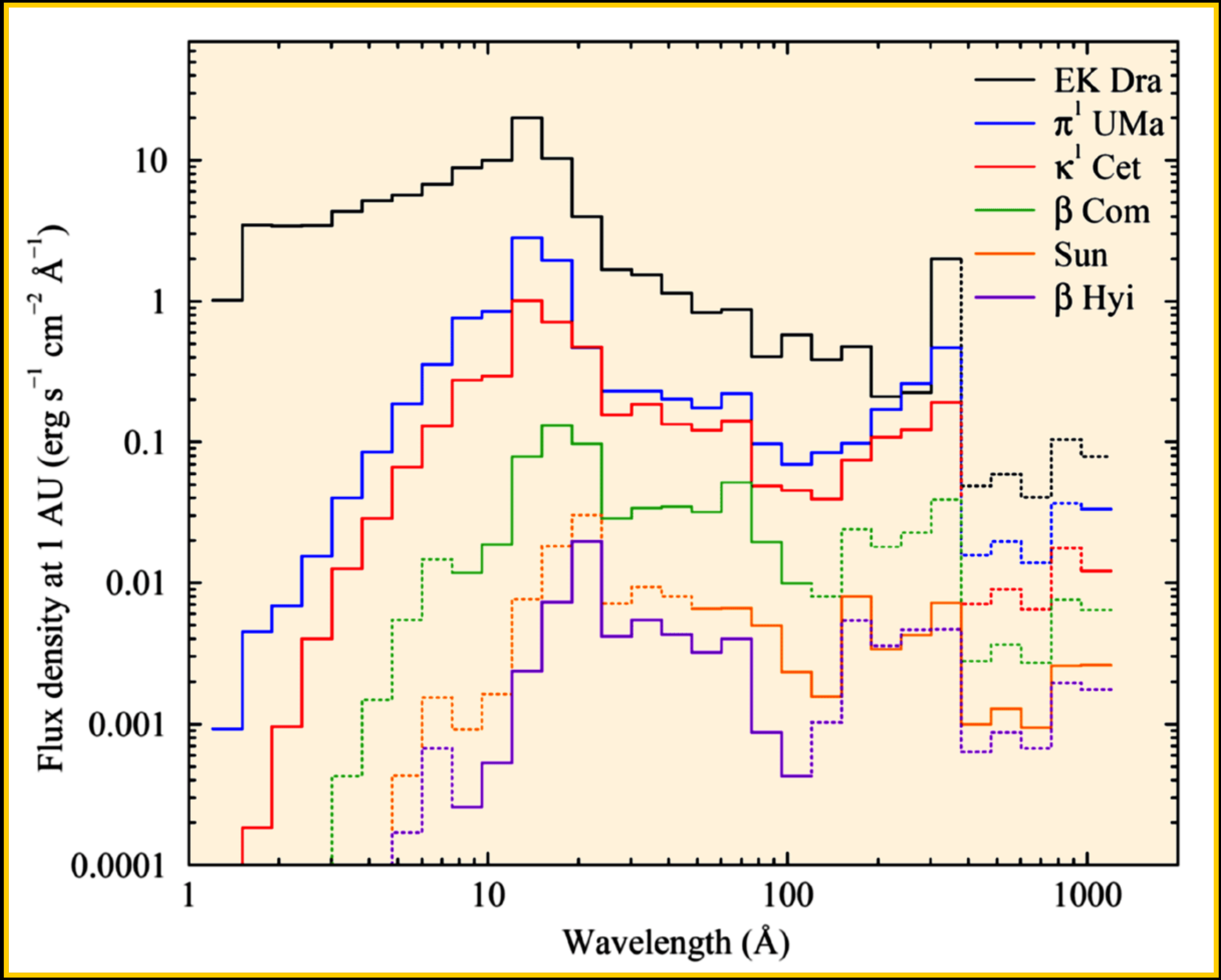
EUV

UV





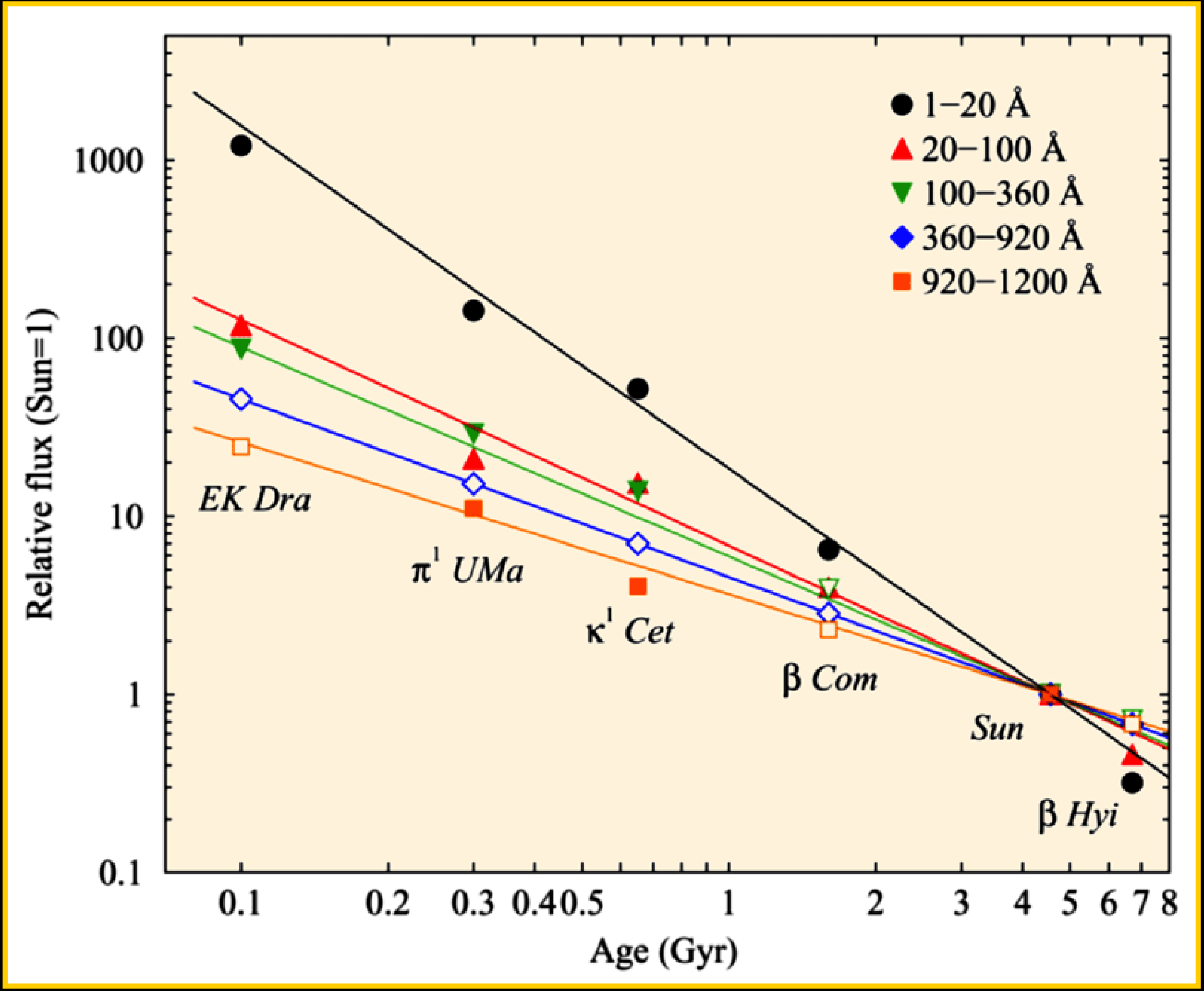
FUV



The young post-ZAMS Sun had stronger emissions:

- ↘ **100-1000x in X-rays**
- ↘ **10-100x in the EUV-FUV**
- ↘ **5-10x in the UV**

Ribas et al. (2004, in press)

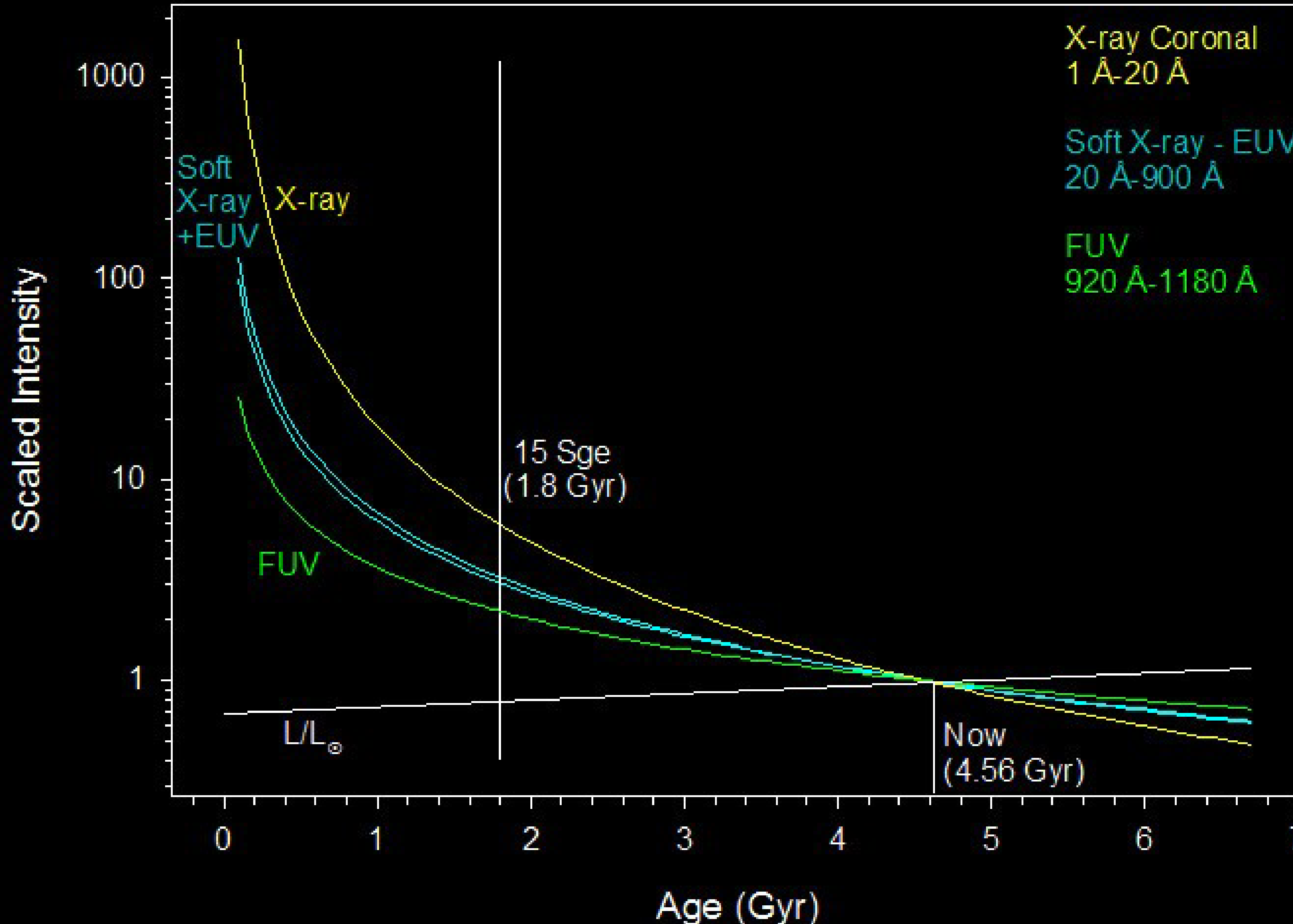


- The flux density evolution scales well with power-law relationships of different slopes

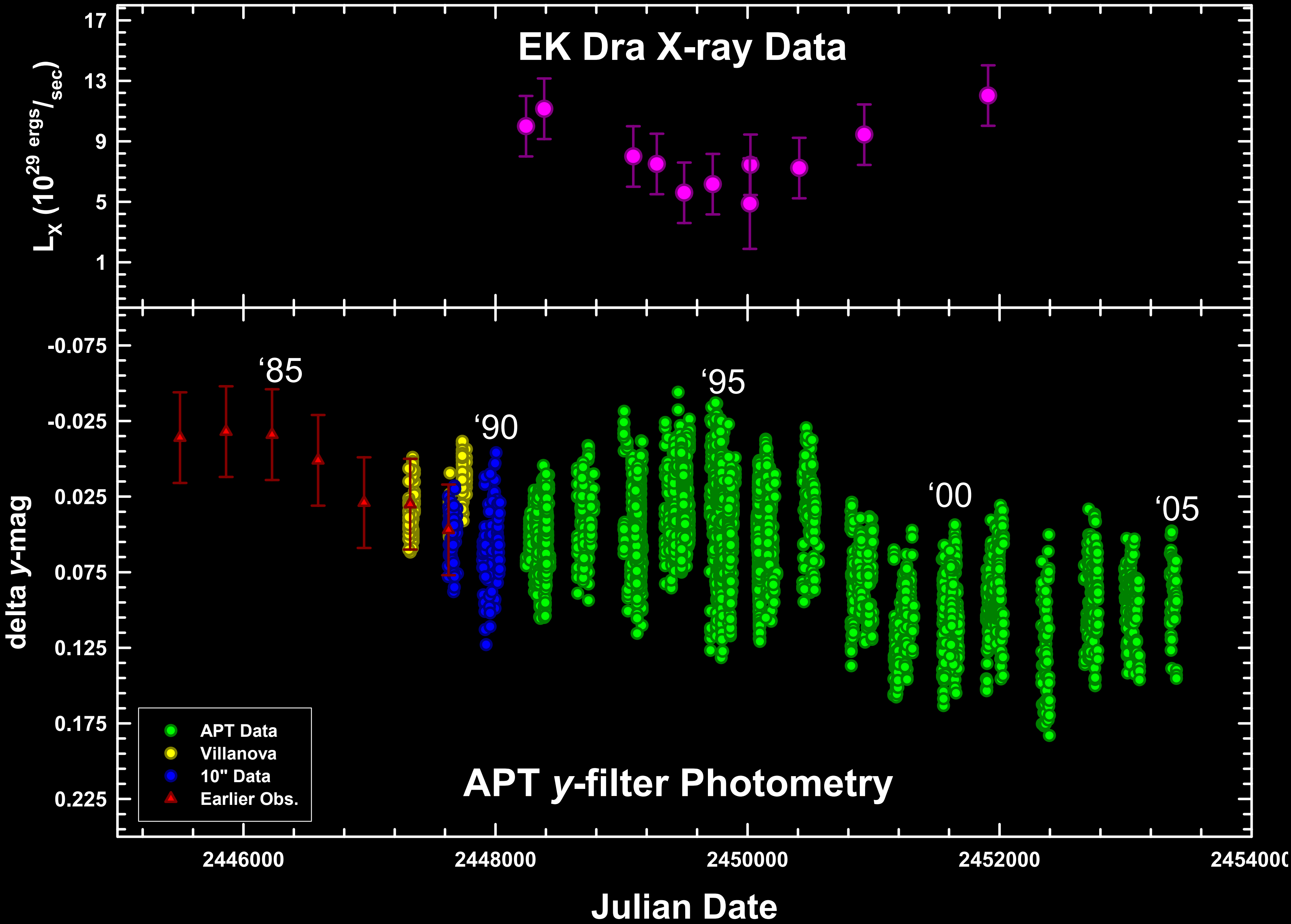
- The overall XUV flux (1-1200 Å) decrease has a slope of −1.2 □ 3x higher than today 2.5 Gyr ago, 6x 3.5 Gyr ago, 100x ZAMS!

XUV Irradiances and Luminosity Changes Over Time For the Sun from Solar Proxies

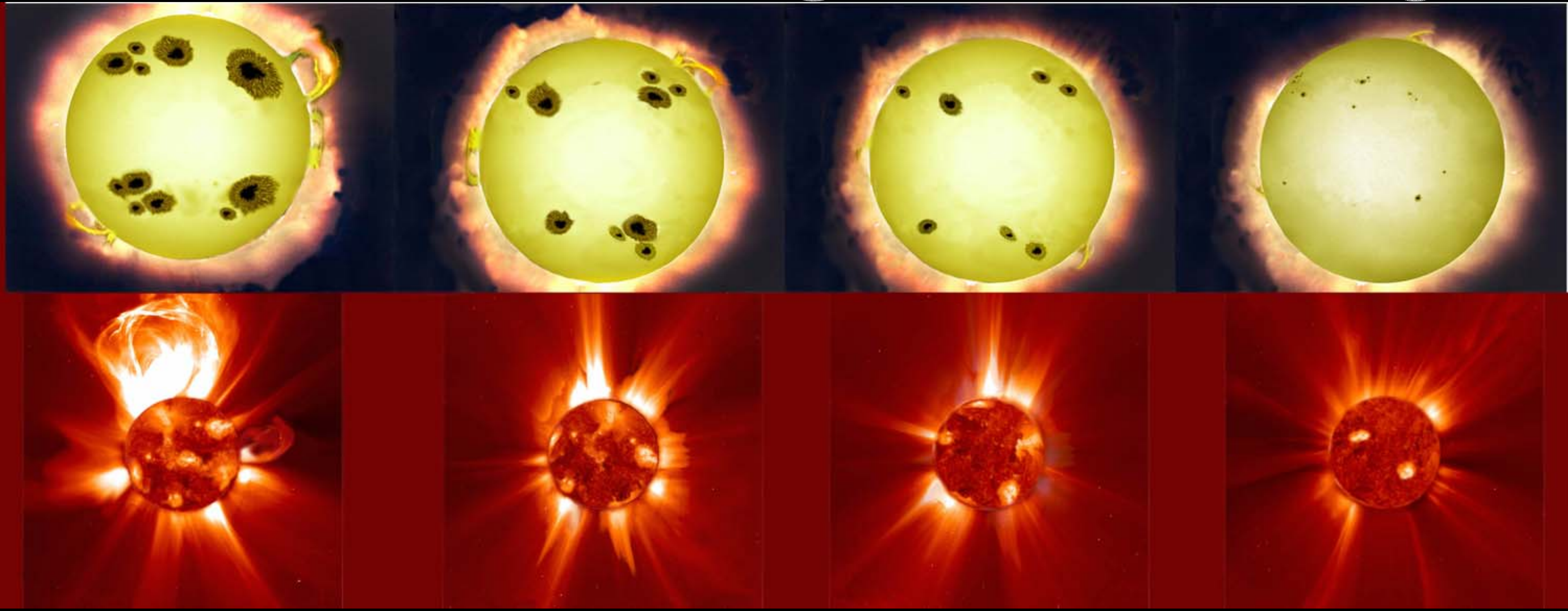
Note: ZAMS Sun has luminosity 70% that of present Sun



Long-Term X-ray / Coronal & Optical Variations of the young "*Sun in Time*" star EK Dra (~100 Myr) displaying ~10 year cycle

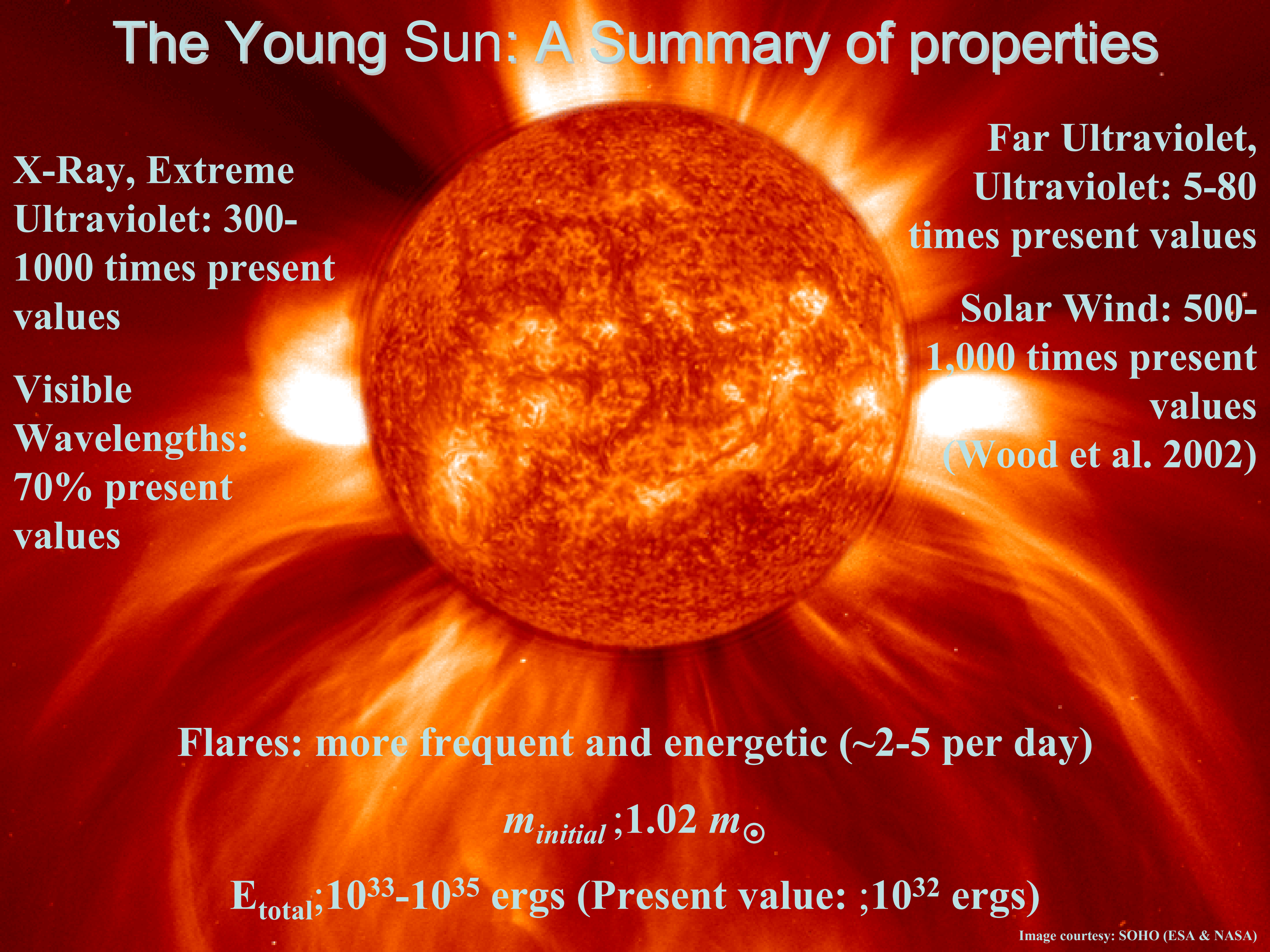


Our Sun Throughout the Ages



Artwork Designed by: Joseph DePasquale

The Young Sun: A Summary of properties



X-Ray, Extreme Ultraviolet: 300-1000 times present values

Visible Wavelengths: 70% present values

Far Ultraviolet, Ultraviolet: 5-80 times present values

Solar Wind: 500-1,000 times present values (Wood et al. 2002)

Flares: more frequent and energetic (~2-5 per day)

$m_{initial}$;1.02 $m_{\odot}$

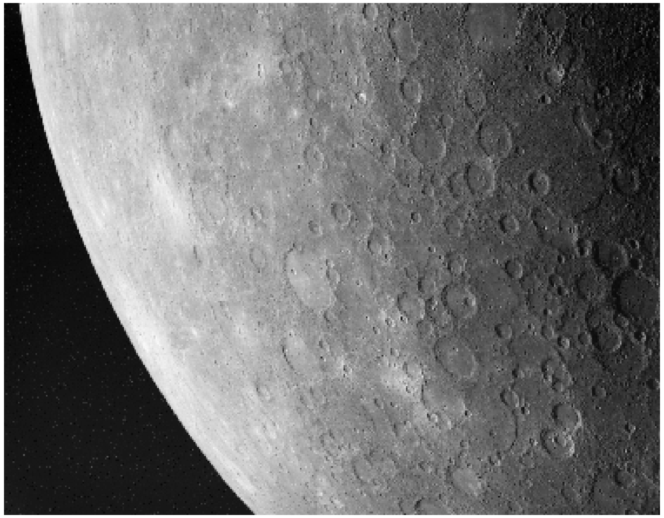
E_{total};10^{33}-10^{35} ergs (Present value: ;10^{32} ergs)

Image courtesy: SOHO (ESA & NASA)

Some Consequences of the Young Sun's Enhanced Activity and XUV Flares I: Mercury

Mercury

- Extremely large iron core



- Possible Erosion of outer surface by strong XUV Radiation and winds of the young sun

- Mercury is the nearest planet to the Sun
(*d* = 0.39 AU) and receives the highest levels of solar radiation and wind

The Erosion and Sublimation Effects of the Young Active Sun on Mercury’s Surface

Lammer, H., Tehrany, M.G., Hanslameier, A. & Kolb, C.

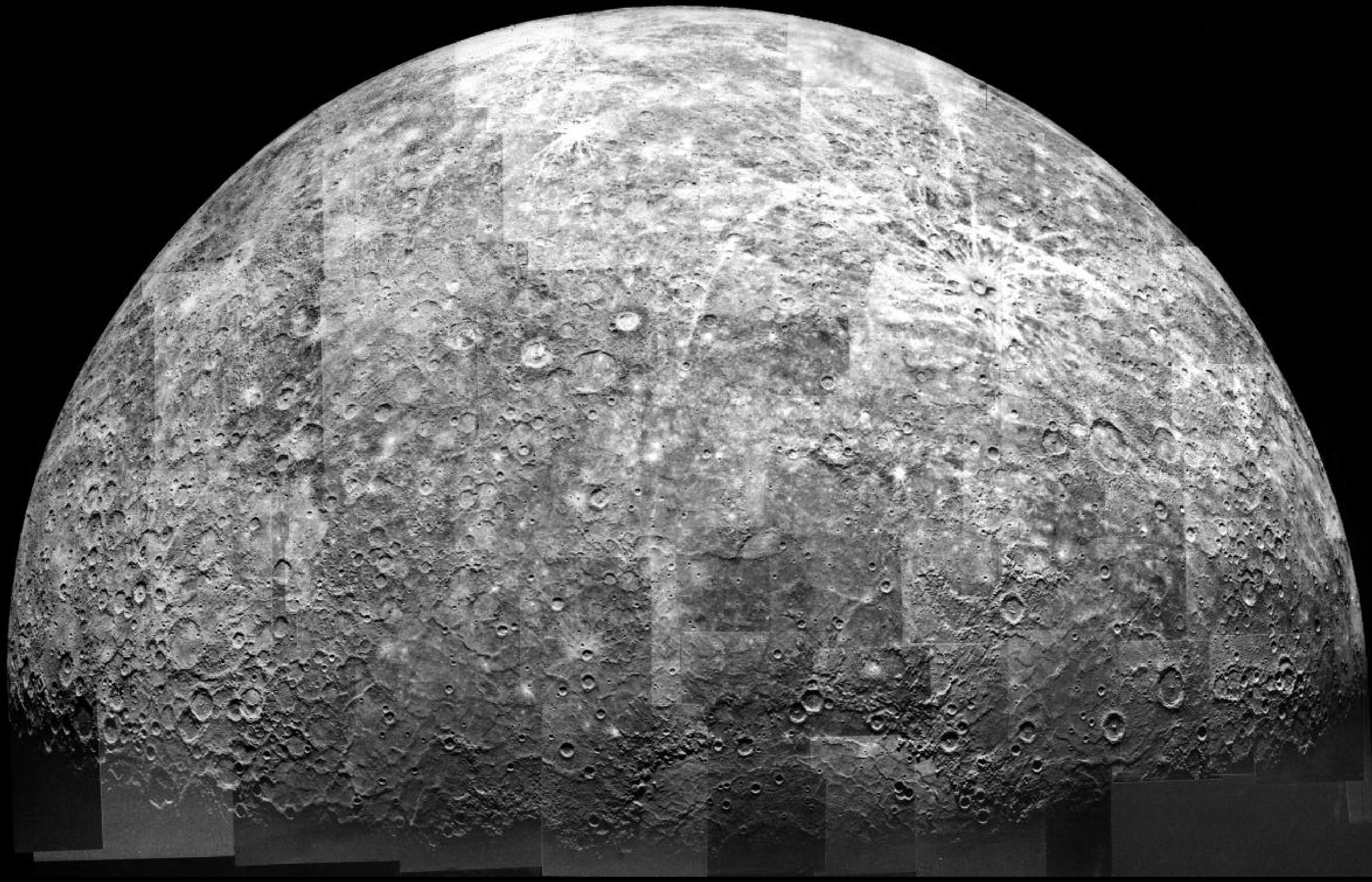
Astrobiology Institute

Graz, Austria

E.F. Guinan & I. Ribas

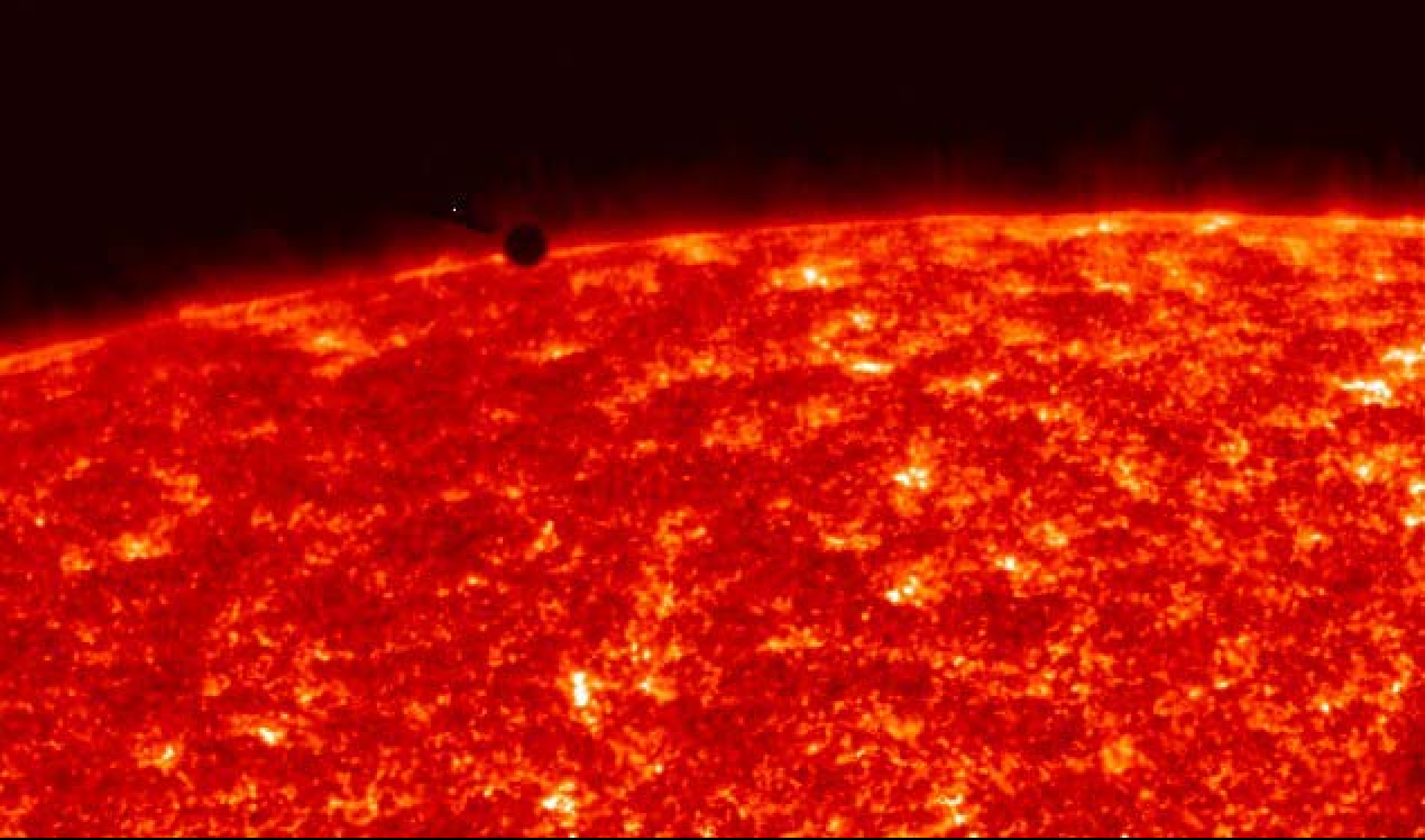
Villanova University

U. de Barcelona



Mariner 10 Photomosaic of Mercury

Image Credit: Mariner 10, NASA

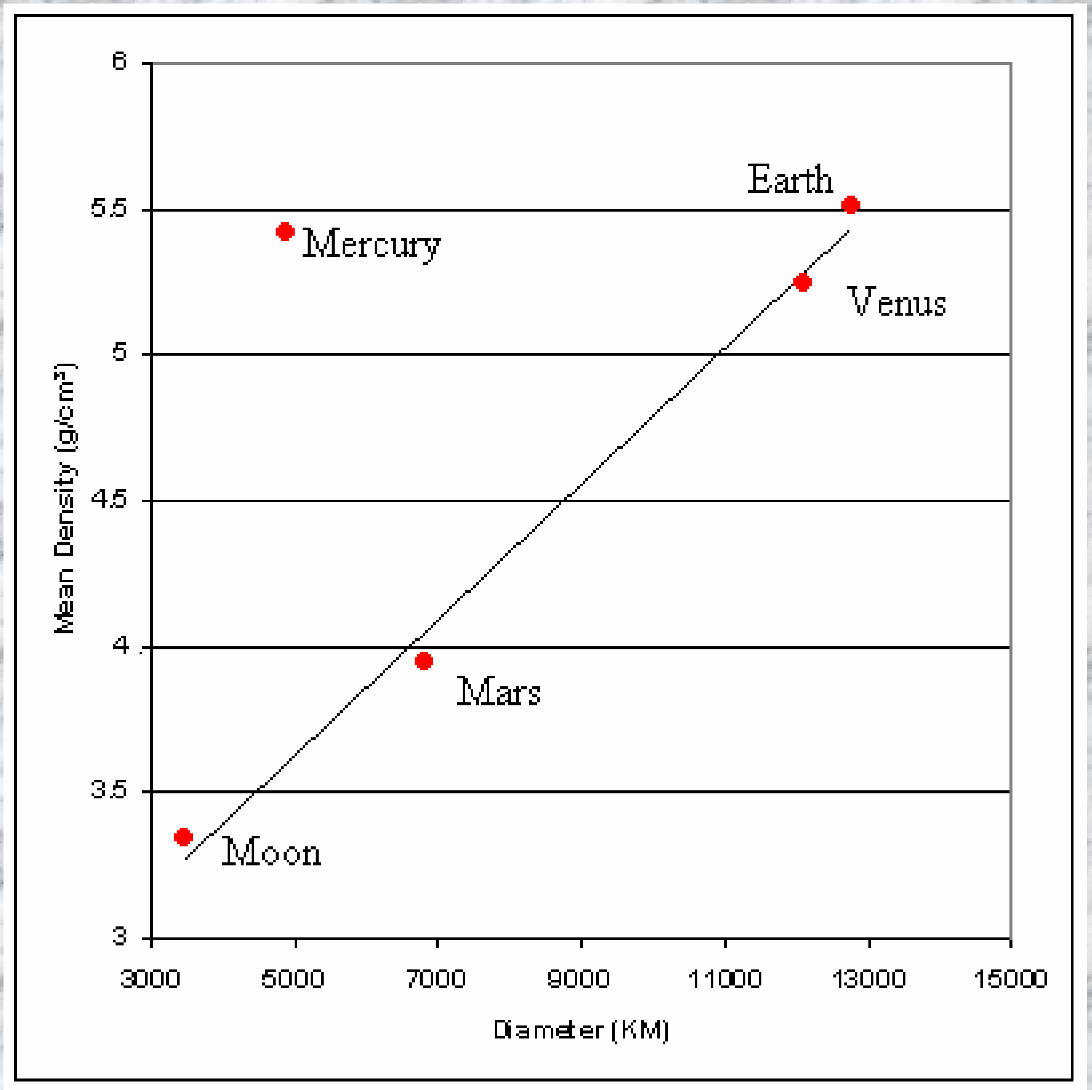


Mercury transiting the sun, as seen by the TRACE satellite on November 15, 1999.

Image Credit: The Trace Project

There's Something About Mercury

- Variation of mean density with diameter of the terrestrial planets (as well as the Moon). Note that Mercury has a much higher mean density than expected given its size.



Earth and Mercury drawn to actual scale- Illustrating the difference in size

Earth and Mercury drawn to the same scale-Illustrating the relatively large core of Mercury

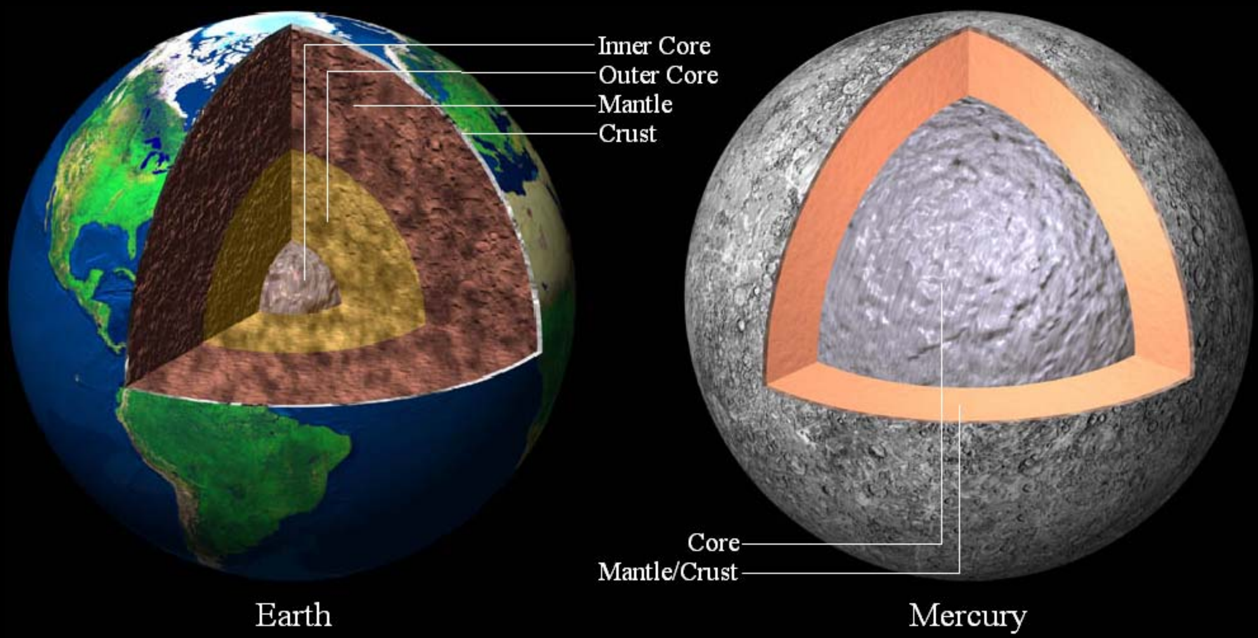


Image credits: Walter Myers (top); Calvin J. Hamilton (bottom)

Erosion and Sublimation Effects on Mercury's Surface: Past and Present

- Ground based observations of heavy constituents like Na^+, K^+, and O^+ in Mercury's present exosphere implicate a strong exosphere-surface interaction related to the particle and radiation environment of the nearby Sun.
- Recent studies on isotope anomalies in planetary atmospheres and meteorites indicate that our early Sun underwent a highly active phase after its origin, including continuous flare events where that particles and radiation environment was several hundred times higher than it is today.
- Because Mercury is the closet planet of the Sun, its surface is exposed more than all other solar system bodies by such an enhanced solar wind and particle flux.

Erosion and Sublimation Effects on Mercury's Surface: Past and Present

- To estimate how such effects may have effected Mercury's surface, we investigate its surface erosion and sublimation during the planets history by using solar analogue G-type stars.
  - The astrophysical parameters of these Sun-like stars were studied inside the *Sun in Time* program.

One possible explanation is that Mercury's lighter mantle/crust was eroded away by the strong (<1,000 times present values) winds and the early Sun's higher extreme ultraviolet fluxes

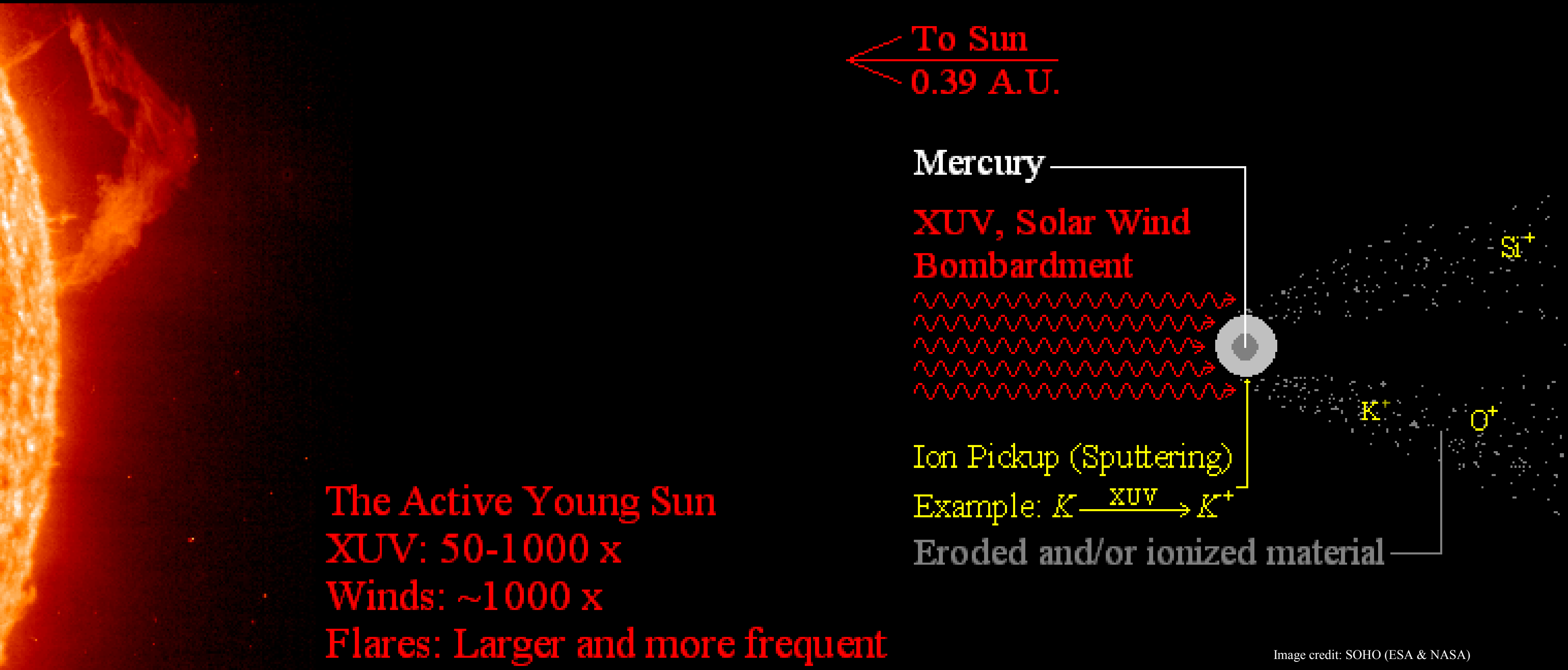


Image credit: SOHO (ESA & NASA)

Some Consequences of the Young Sun's Enhanced Activity and XUV Flares II: Venus

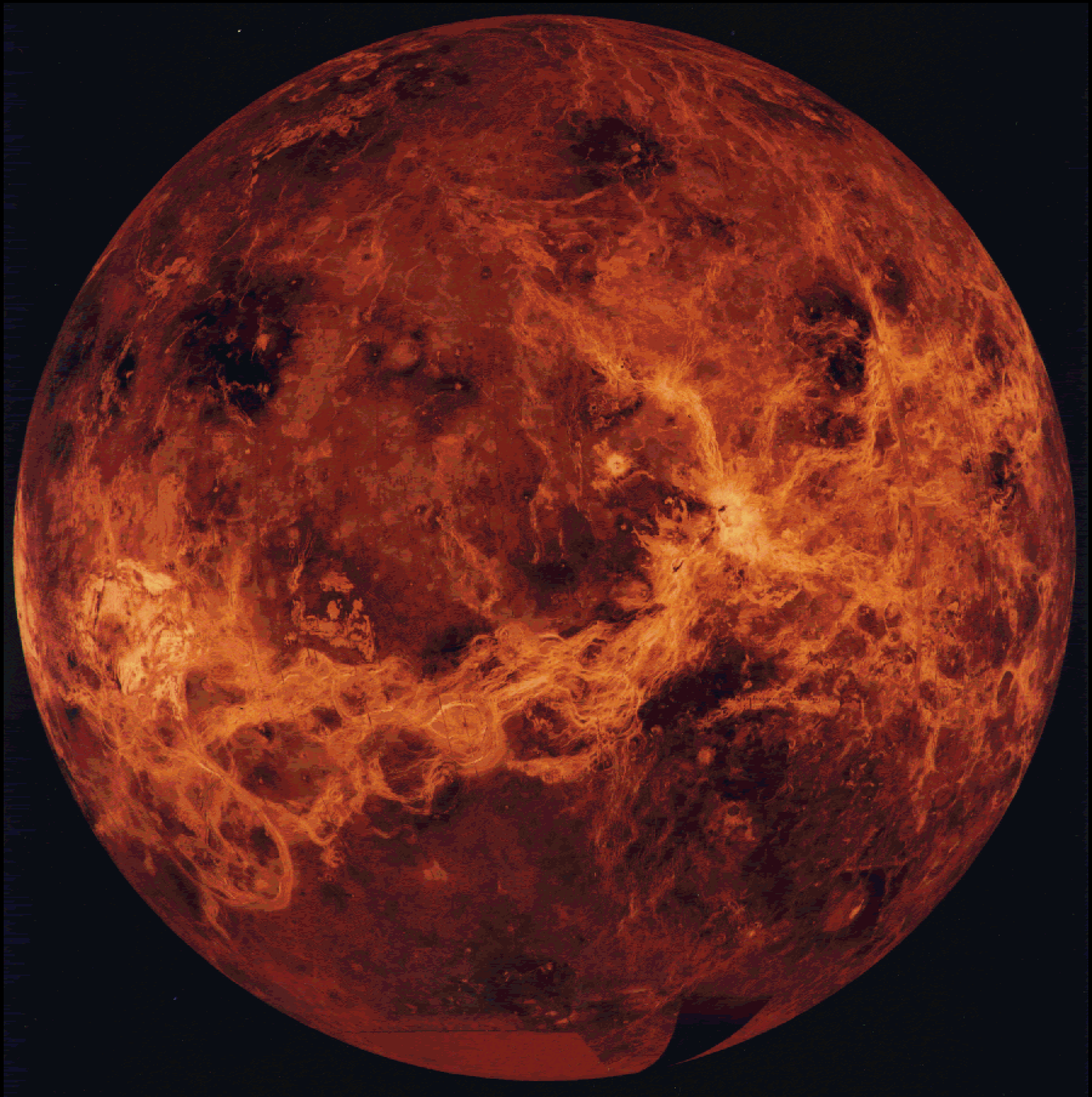
Venus

- No water or oxygen
- Thick 100 bar atmosphere of mostly (97%) CO_2
- *d*= 0.71 AU

- Photochemistry/photoionization Effects
  - Venus has a slow rotation period (P_{rot} = 243 days) and a very weak magnetic dynamo.
  - Venus is thus not protected from the Sun's plasma by planetary magnetic field.

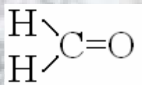
- Investigate evolution of the Venus' atmosphere
  - Maybe the young Sun's enhanced activity played a major role? (e.g. $H_2O \xrightarrow[FUV]{} OH + H$)

Magellan synthetic aperture radar mosaic of Venus



Earth

Some Consequences of the Young Sun's Enhanced Activity and XUV Flares III: Earth

- A Young active Sun may have played a major role in the evolution of the Earth's atmosphere and possibly the origin and evolution of life.
- Problems under Study:
  - Destruction of methane (CH_4) by the early Sun's strong FUV radiation
  - Formation of ozone (O_3)
  - Photochemical reactions leading to the formation of organic molecules →
  - H_2CO (formaldehyde) → 
    - Element/building block of Ribose, a key ingredient of life
  - Many other problems

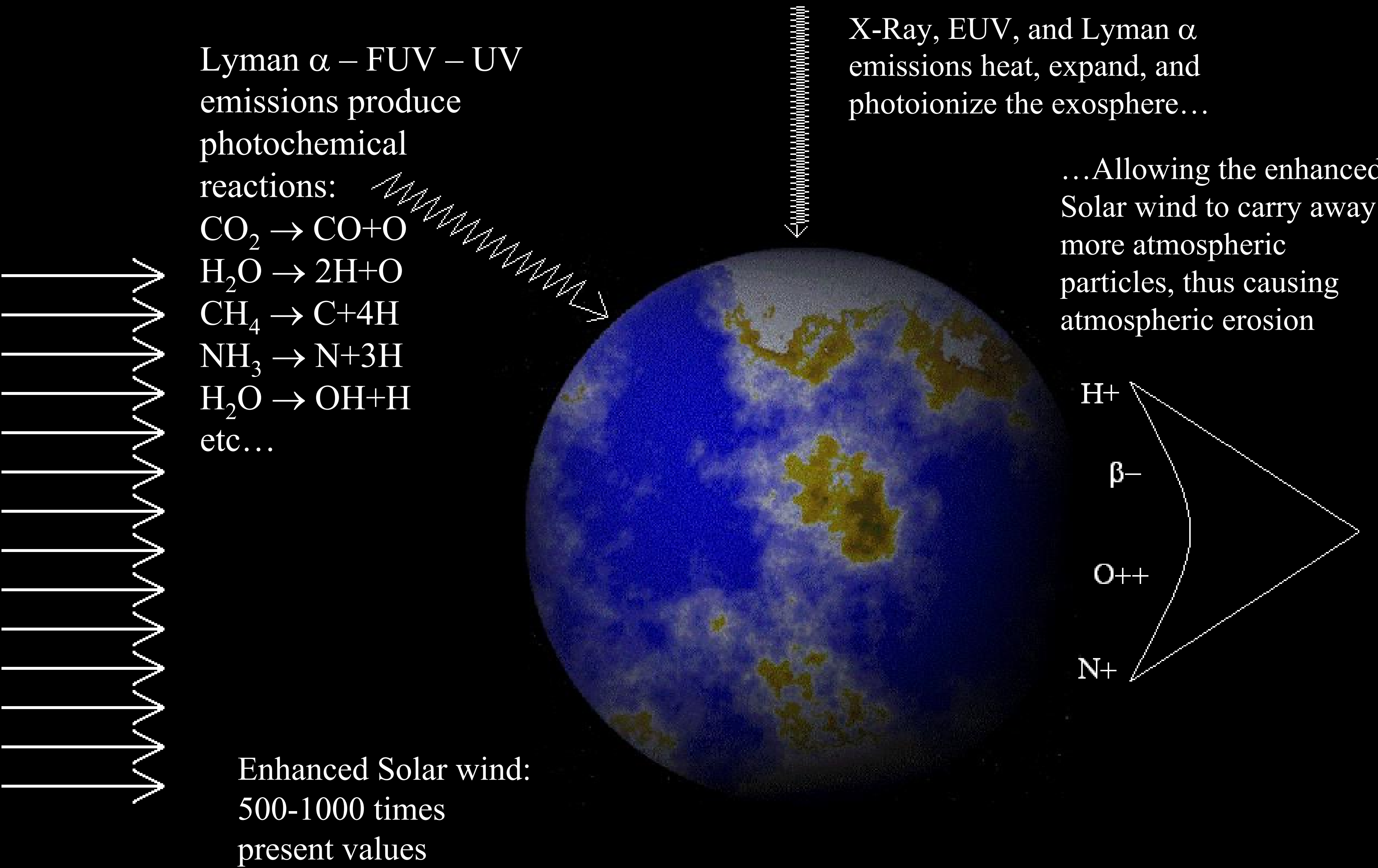
$$CO_2 \underset{}{\overset{FUV}{\rightleftarrows}} CO+O$$

$$H_2O \rightleftarrows OH+H$$

$$CO+H \rightarrow HCO$$

$$HCO+HCO \rightarrow H_2CO+CO$$

It's ALIVE!



Effects of the young Sun on the Earth

Some Consequences of the Young Sun's Enhanced Activity and XUV Flares IV: Mars and Beyond

Mars

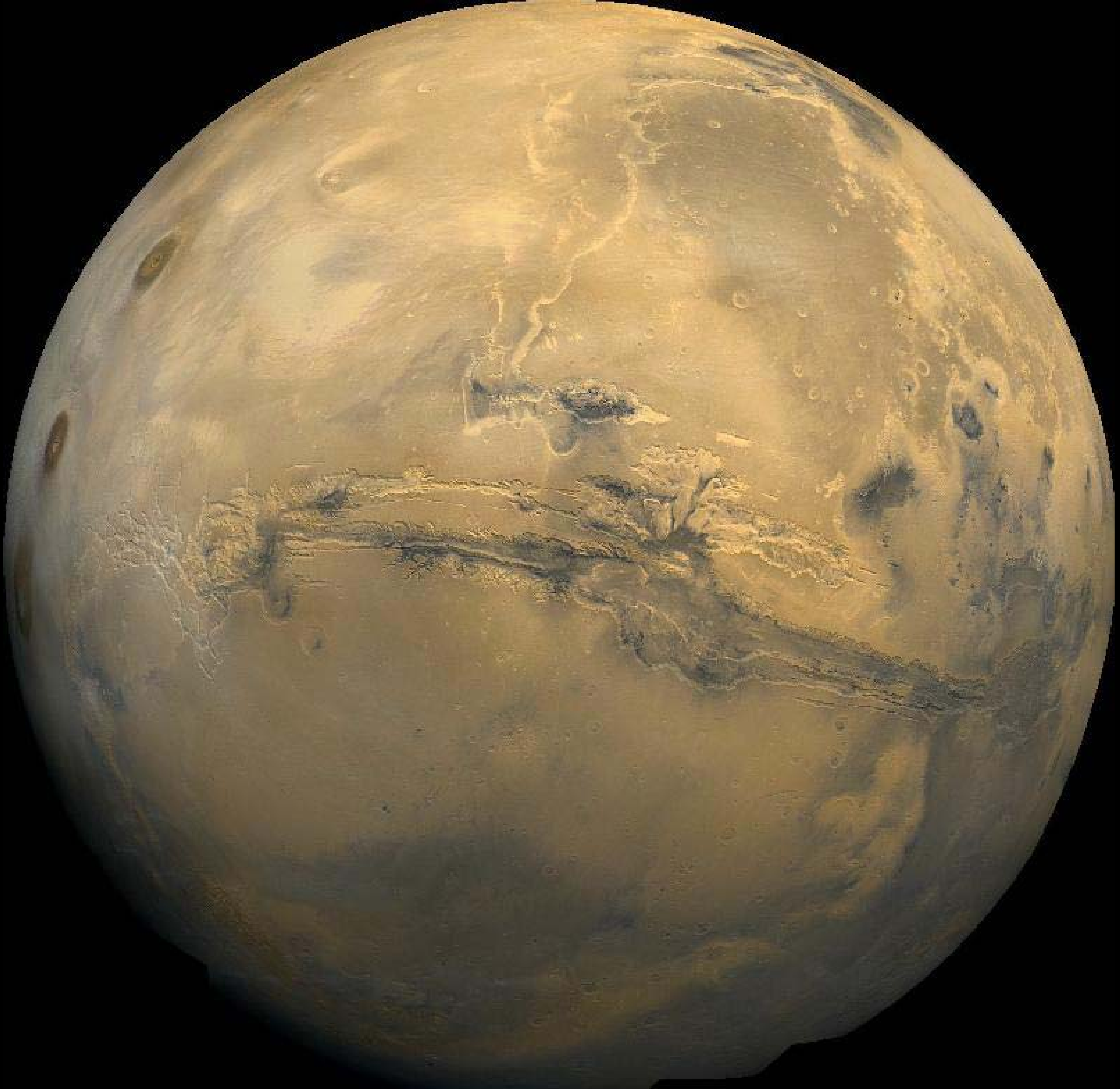
- *d*=1.52 AU

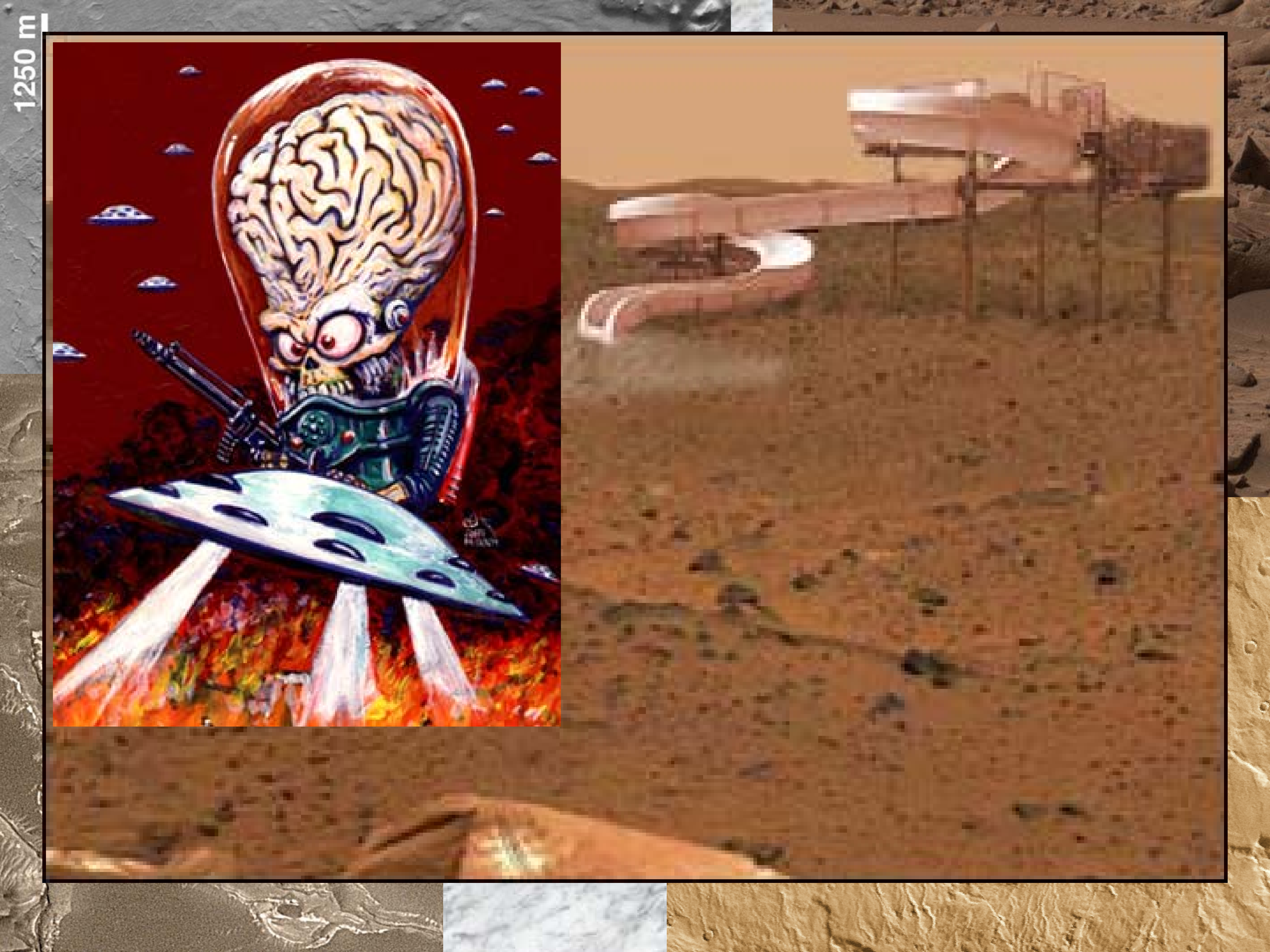
- Today, Mars is a cold dry planet with a thin (7 mb at the surface) atmosphere rich in CO_2
- Mars also possesses a very weak magnetic field
- There is also geological evidence of running water and possibly a permanent layer of permafrost
- It is important to study the effects of the active young Sun on Mars
    - Loss of water and atmosphere
    - Soil oxidation
    - Possible early life

Extrasolar Planets

- (150+)

- Determination of the XUV fluxes and winds of the host stars to extrasolar planets is critical

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Loss of water from Mars: Implications for the oxidation of the soil

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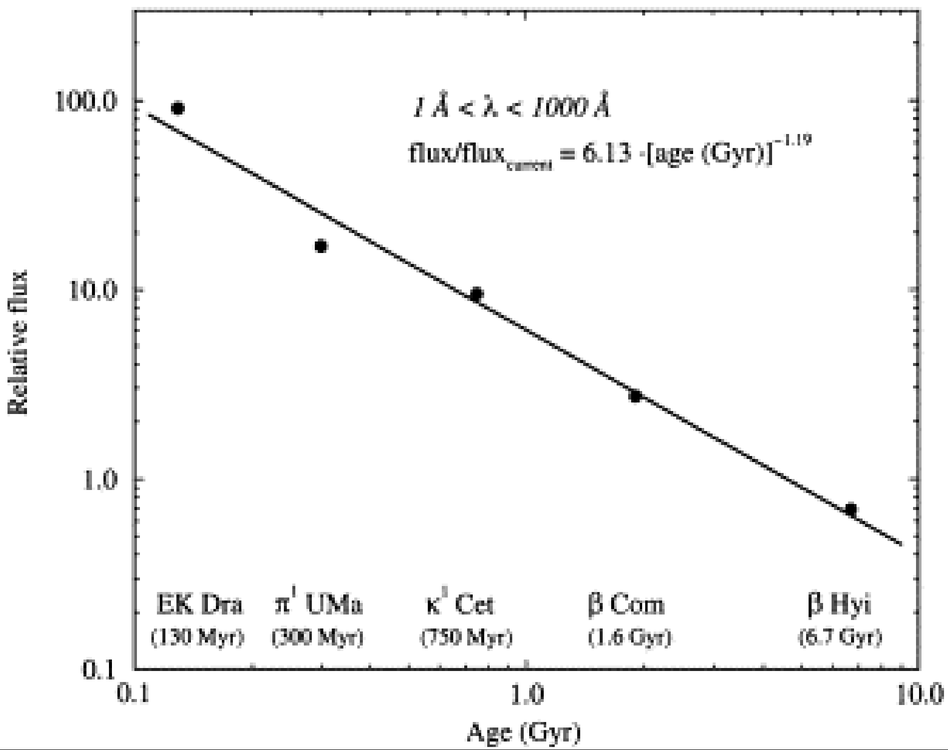
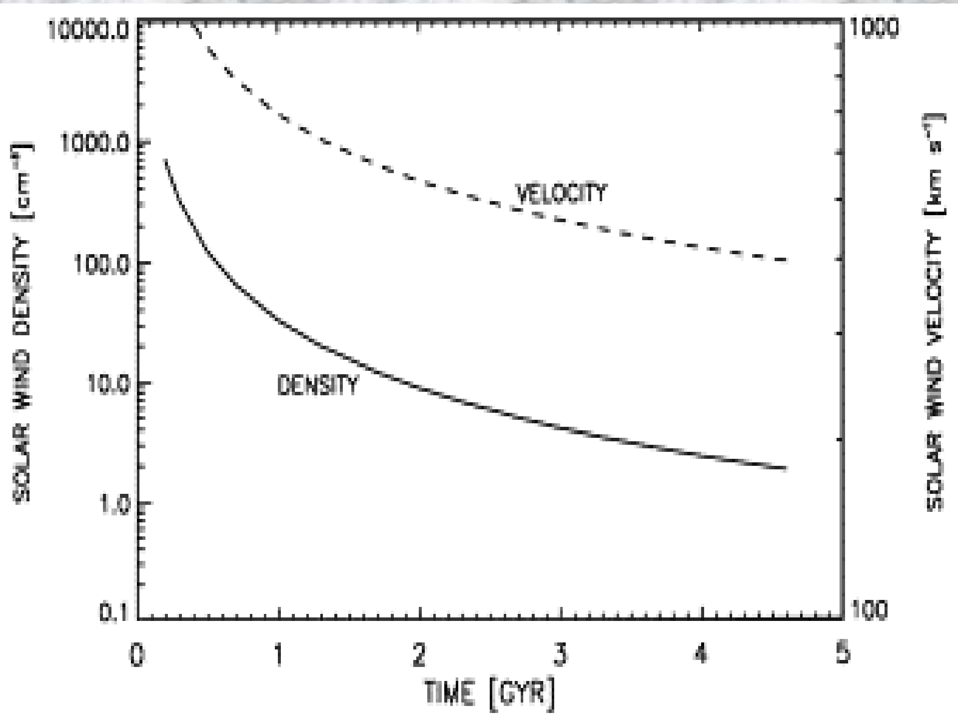




Relative solar XUV flux as function of solar age calculated by using data for 5 solar proxies in the *Sun in Time* program.

The solid line shows the average solar wind density at 1.5 AU over the Martian history, based on our power law relationship derived from estimates of stellar winds of solar-like stars [Selsis et al., 2002b]. The dashed curve shows the evolution of the solar wind velocity based on a model of [Newkirk, 1980].

The Effects of the Young Active Sun on the Evolution of Mars' Atmosphere

Early Sun: Strong XUV Irradiances
~50-1000x present
Winds > 500x present
Strong, frequent flares

Mars in the Past

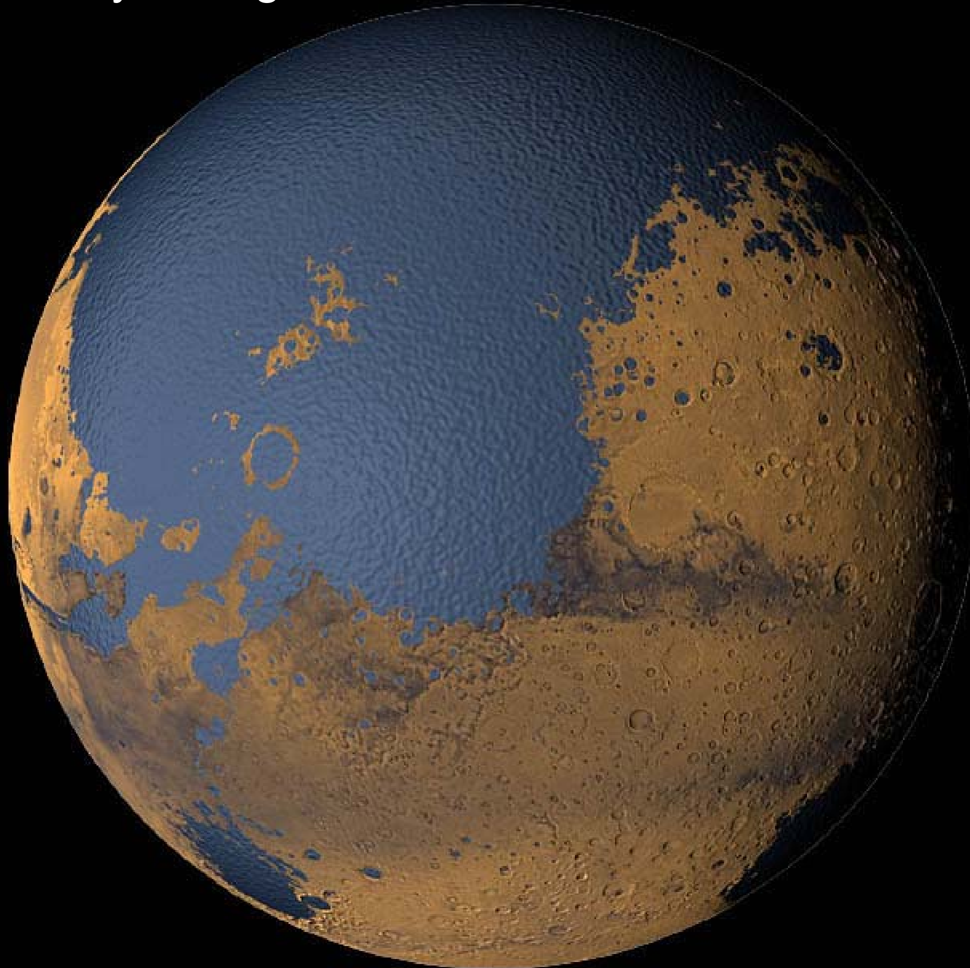
- >3.0 Gyr ago
- ~1 Bar Atmosphere
- Warm, moist atmosphere
- Liquid water oceans
- CO_2, N_2, O_2, H_2O
- (hot) liquid Fe-Ni Core & rapid rotation
- Implied strong magnetic field
- Magnetosphere

Mars in the Present

- ~$^{1}/_{90}$ Bar Atmosphere
- Cold, dry, frozen CO_2 polar caps
- 95% CO_2 , N_2, A Iron oxide soil
- Tectonically dead solid Fe core
- No significant magnetic field

Modeling the Early Environment of Mars

Young Sun rotating ~5-10x faster, producing a strong magnetic dynamo and resulting very strong XUV irradiation, winds & flares



Early Mars probably had a warm, wet atmosphere with a strong Greenhouse Effect. Also, for <1.5 Gyr after formation, Mars had strong magnetic fields and a magnetosphere that protected its XUV irradiated outer atmosphere from erosion (ion pickup reactions) by the Sun's strong, massive winds.

- But about 3.0-3.5 Gyrs ago Mars lost its magnetic field as its molten core cooled & solidified.
- After that time, Mars's atmosphere is exposed to the Sun's strong winds & XUV radiation and loses most of its atmosphere.
- But not all of the H_2O is lost, loss of greenhouse gases causes Mars to rapidly cool, and some frozen water is left behind (permafrost?).

* see Icarus, Volume 165, Issue 1, p. 9-25

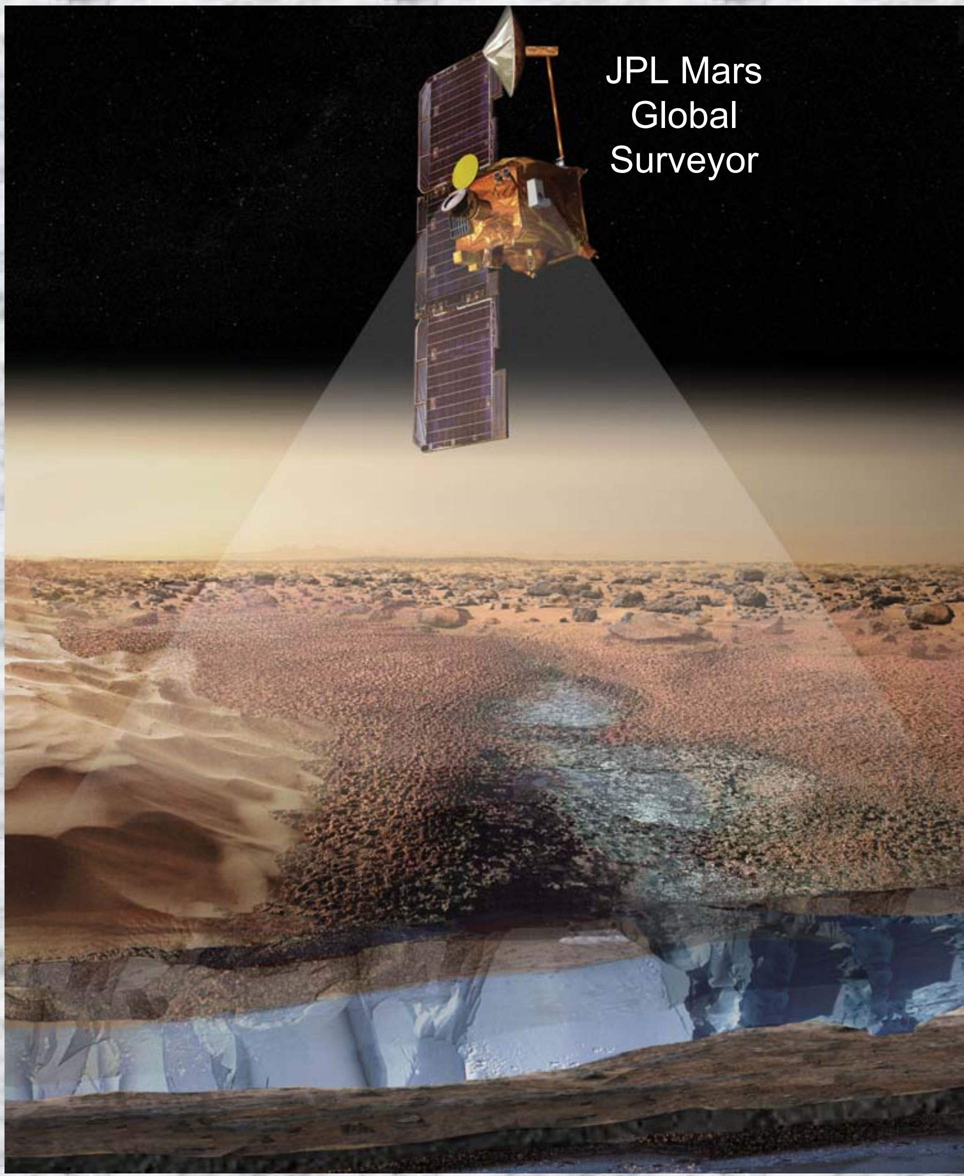
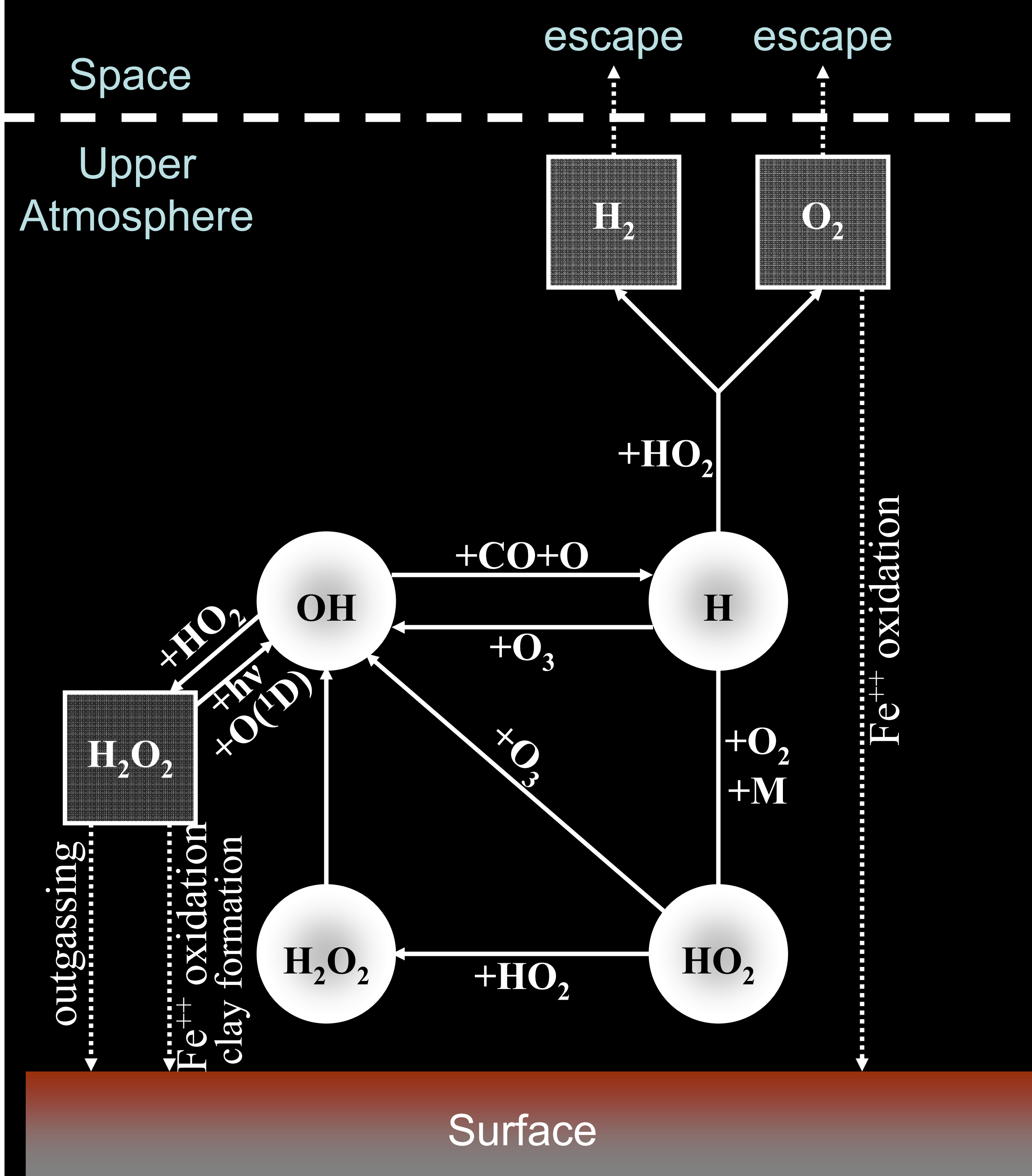
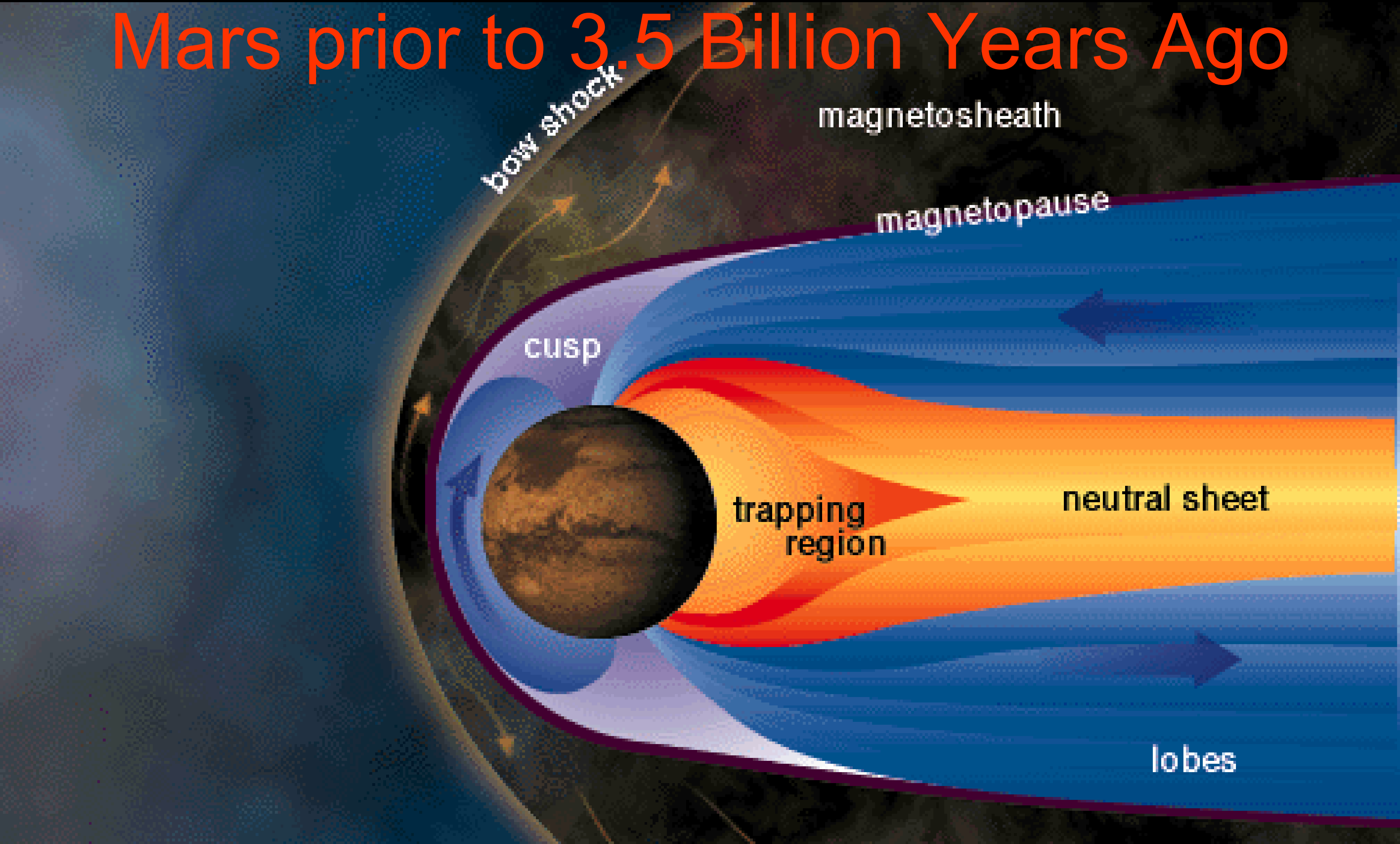


Illustration of the cycles and loss mechanisms for H_2O on Mars. Loss to space, surface oxidation via atmosphere-surface interaction processes, and hydration reactions are important.



Mars prior to 3.5 Billion Years Ago



- A liquid iron core produced a magnetic field strong enough to protect the young Martian atmosphere and surface water from the punishing effects of the young Sun’s intense solar wind

Mars after 3.5 Billion Years Ago

- Roughly 3.5 Billion years ago, Mars' core solidified, shutting down the Martian magnetic dynamo.
- Without a magnetic field, the outer Martian atmosphere was subjected to the ionizing effects and strong winds of the sun, and began to erode.
- At this time, water disassociates into 2H+O, where the lighter Hydrogen is lost to the space while the heavier Oxygen combines with iron on its surface

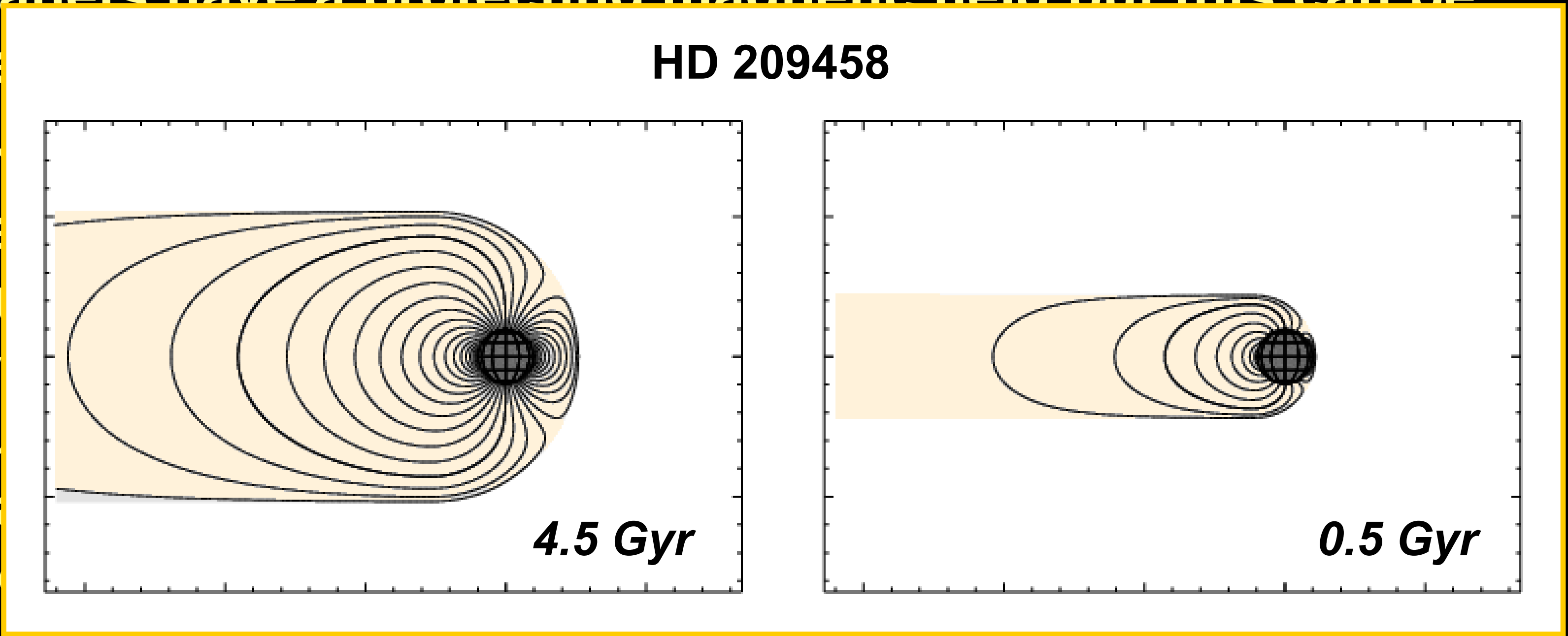
Some Further Investigations & Future Plans

- HST/STIS (now ACS) Spectroscopy of Ly-α for more program stars. (Ly-α emission is the strongest contributor to the FUV irradiance.)
- Direct measures of mass loss (winds) of solar program stars.
  - Ly-α – Astrospheres: B. Wood
  - Radio (mm/cm) Observations - $F_V \leftrightarrow v^{2/3}$: VLA/IRAM/100m. Greenbank; Future → ALMA
- Determinations of flare characteristics for program stars between 30Myr – 1Gyr using FUSE/EUVE archival data
- Study of Microbial Survival Rates in UV Radiative Environments (Dr. Schulze-Makuch)
- Calculation of hydrodynamic mass-loss on Uranus/Jupiter-sized planets within 1AU of host star. (Lammer, H. et al. 2003ApJ...598L.121L & Griessmeier et al. 2004A&A...425..753 "The effect of tidal locking on the magnetospheric and atmospheric evolution of ``Hot Jupiters")
- Expanding sample to dK & dM stars to study Activity-P_{rot}-Age Relations/XUV Spectral Irradiances/Winds(?) in support of upcoming exosolar planet missions such as COROT, Kepler, SIM & TPF-Darwin

Evaporation of planetary atmospheres

- **Most straightforward application to pure-H atmospheres ⇨ Hot Jupiters**
- **XUV radiation deposits its energy in the exosphere, which heats up and expands**
- **The exosphere temperature (and not T_{eff}) drives the evaporation**
- **Well-known formalism in most cases (Jeans escape): particles with velocity above escape are lost to space**
- **When escape rates are very high, Jeans escape is not applicable and hydrodynamic treatment must be used**
- **This mass loss from Hot Jupiters has been measured in HD 209458 to be $>10^{10}$ g s^{-1}(Vidal-Madjar et al. 2003, 2004) !**

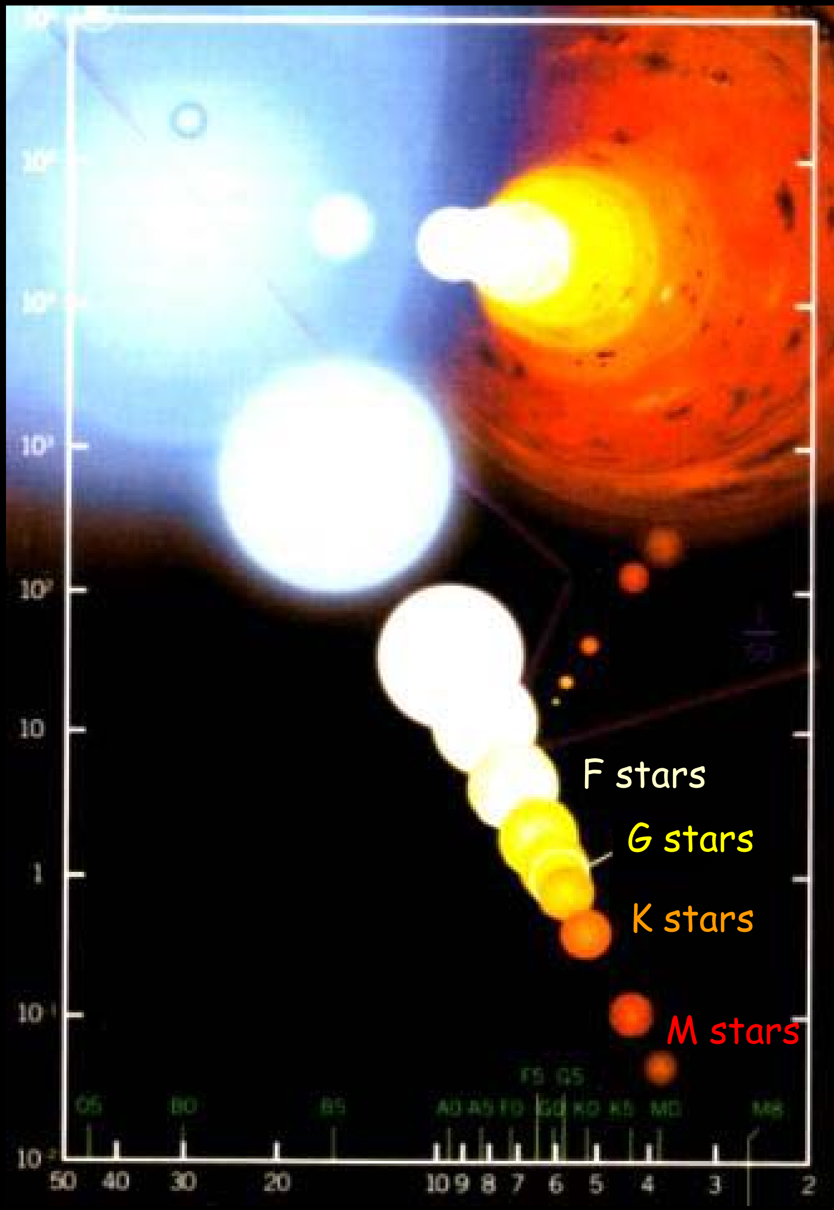
- In addition, non-thermal loss processes also play a role
- These are driven by the stellar particle flux (wind), which causes erosion by sputtering and ion pickup
- Planets have a protecting magnetic field but this can be we
- Th wa pa pr pu ma th



- In those conditions the non-thermal loss process may be greatly enhanced (>10^{10} g s^{-1})
- **All these calculations could explain the cutoff at 0.03-0.05 AU!**

Grieβmeier et al. (2004)

Other stellar types...

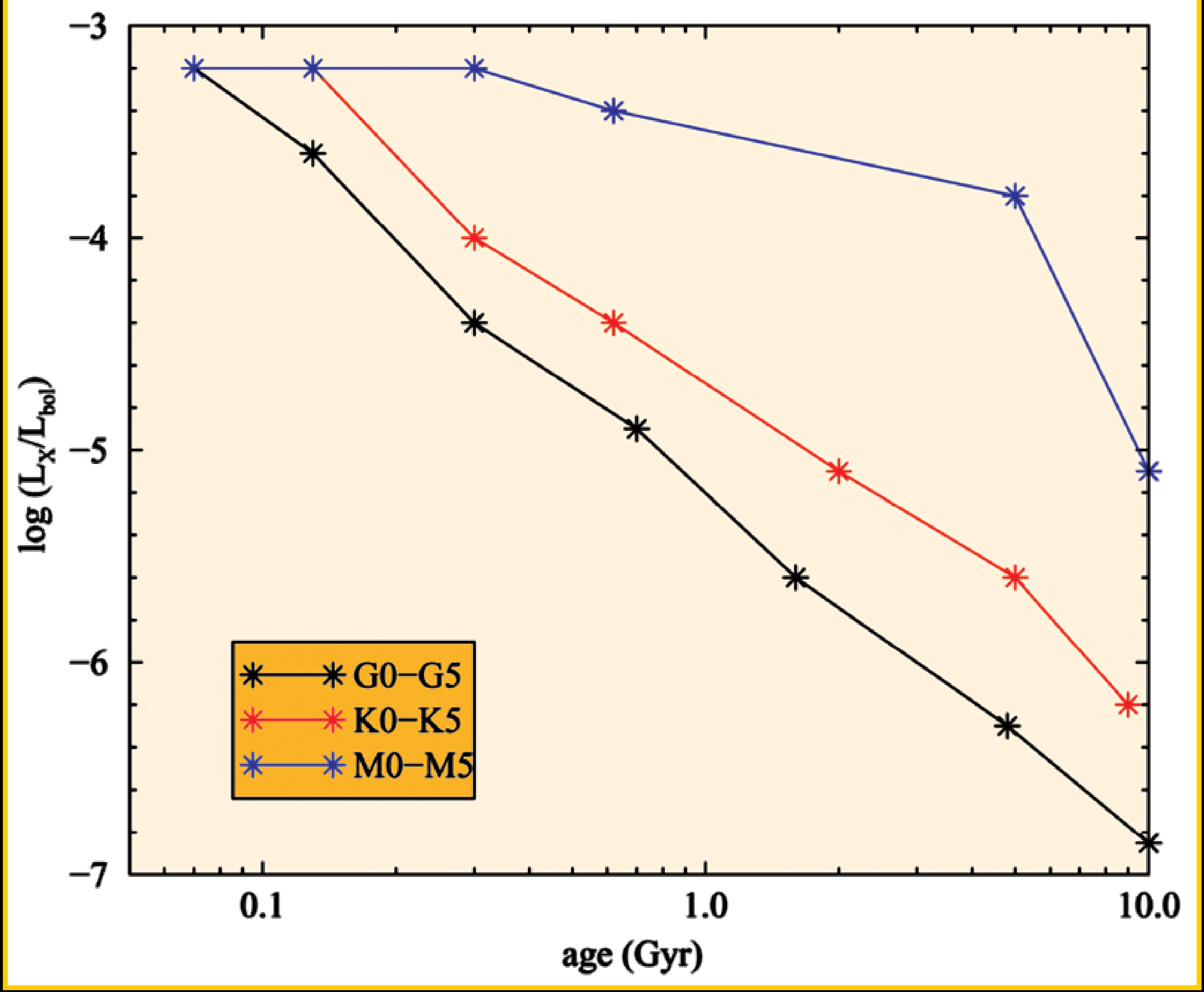


In principle low-mass stars are prime candidates for searches of planets in the HZ:

- ✓ Long lived (>10Gyr)
- ✓ Very abundant in the solar neighborhood
- ✓ Better contrast star/planet

However, solar-type stars are active when young, but lower mass stars stay active for longer periods of time!!

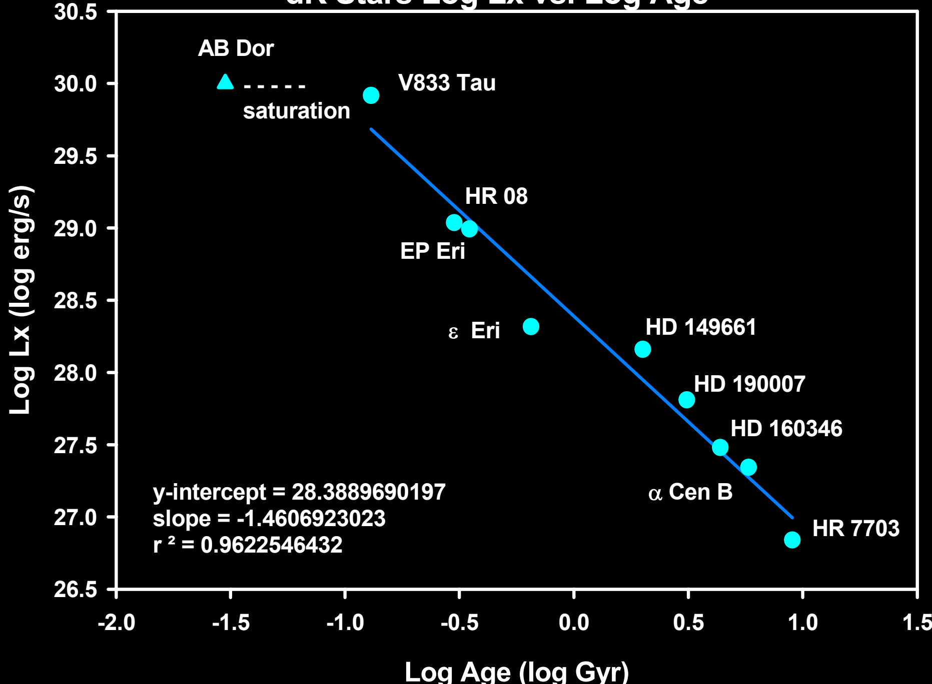
⇨ Potential for very severe erosion of atmospheres



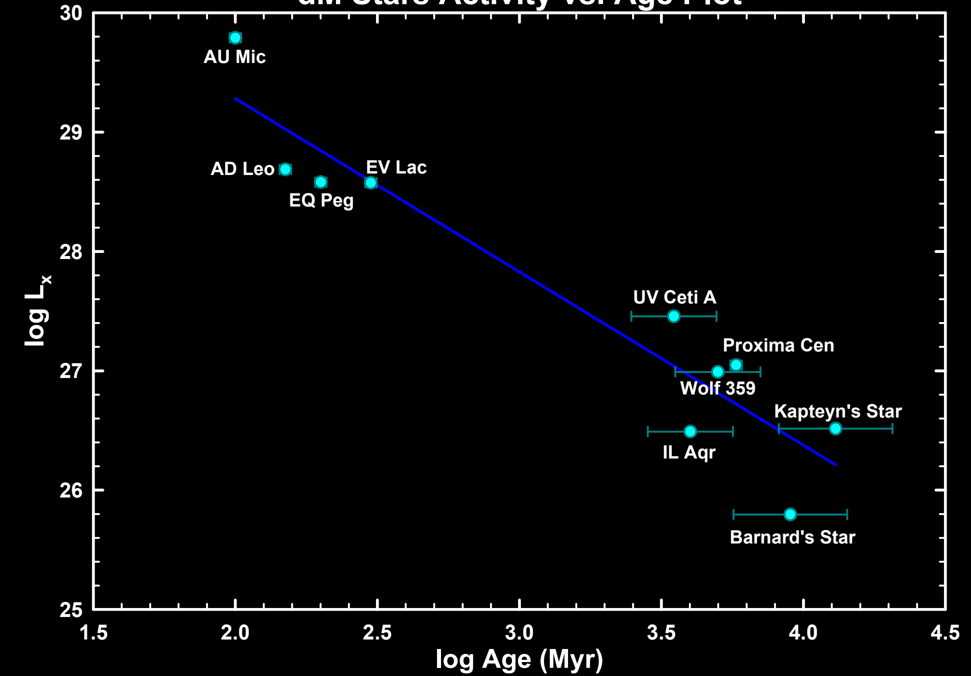
- The irradiances stay at saturated levels ($L_X/L_{bol} > 10^{-3}$) for longer (up to 1 Gyr in the case of M stars!)
- If the emissions scale similarly to G stars:
  - K stars XUV > 3-4 x XUV of G stars at same age
  - M stars XUV > 10-100 x XUV of G stars at same age

Initial Results From Our Investigation of dK & dM Stars

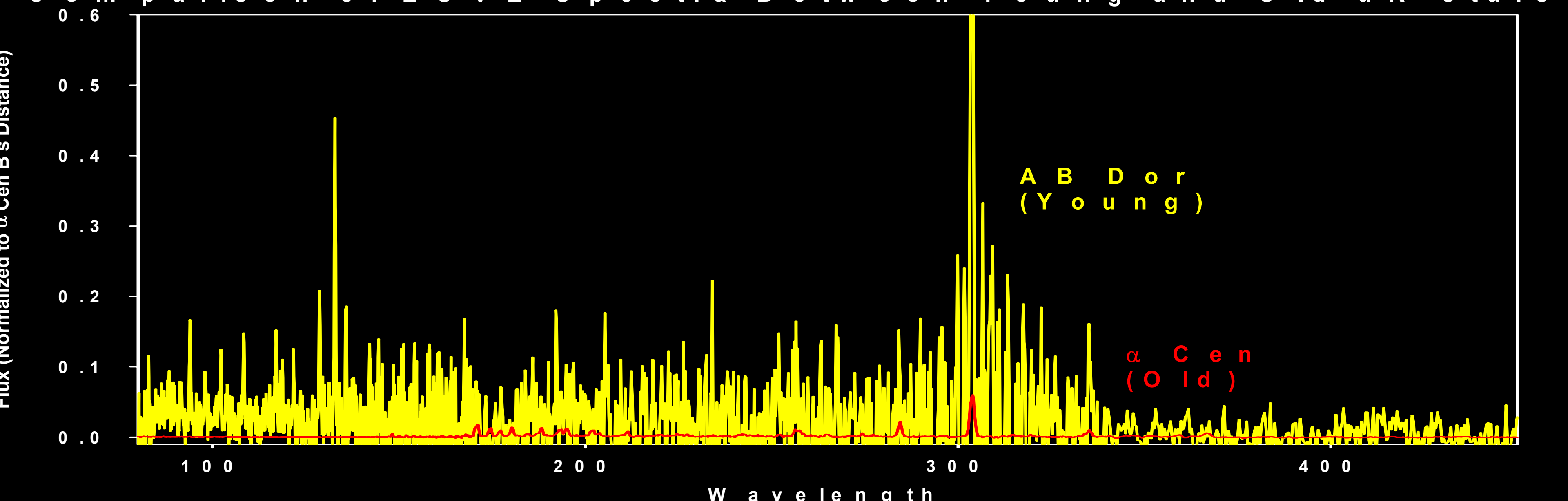
dK Stars Log Lx vs. Log Age



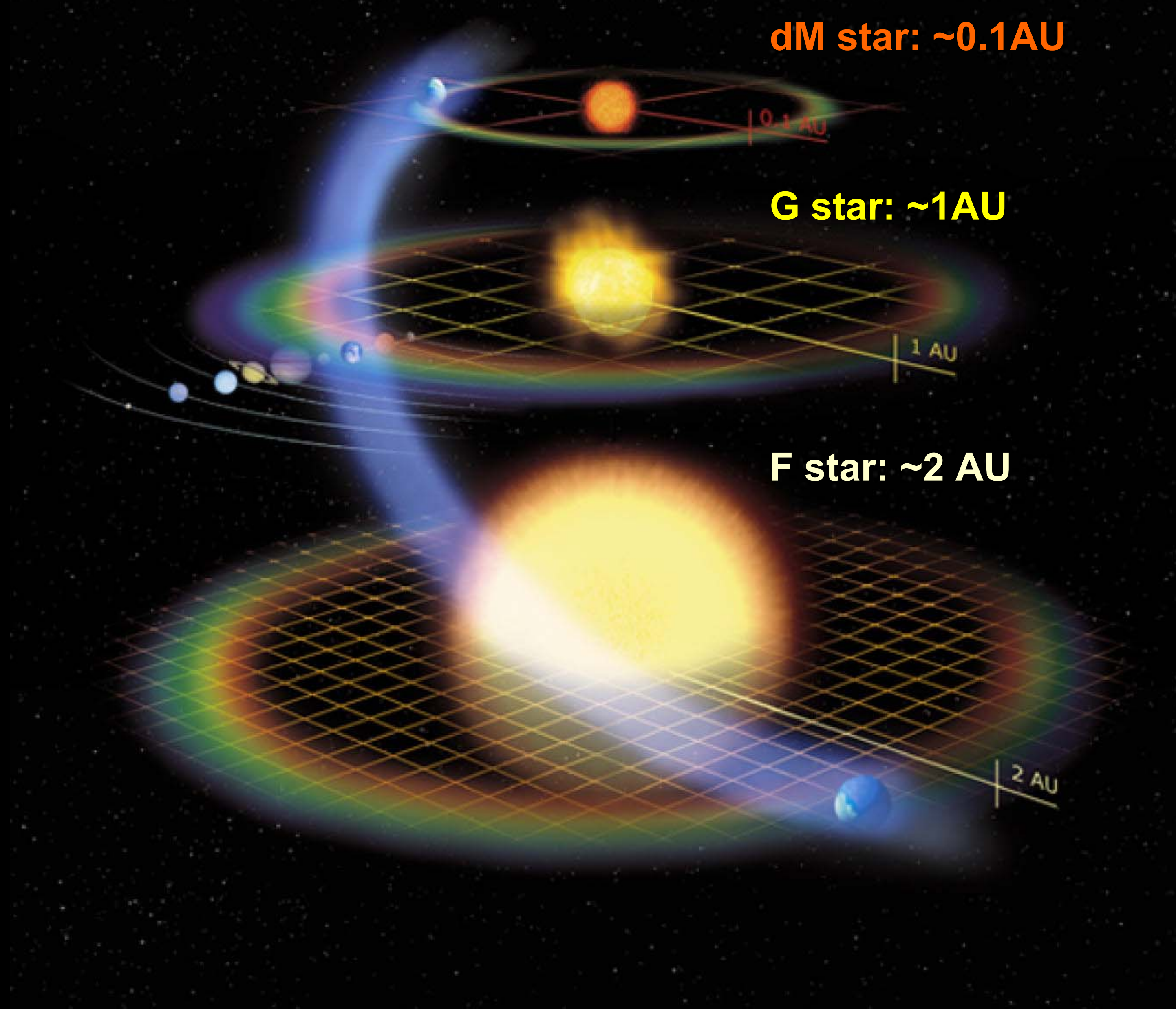
dM Stars Activity vs. Age Plot

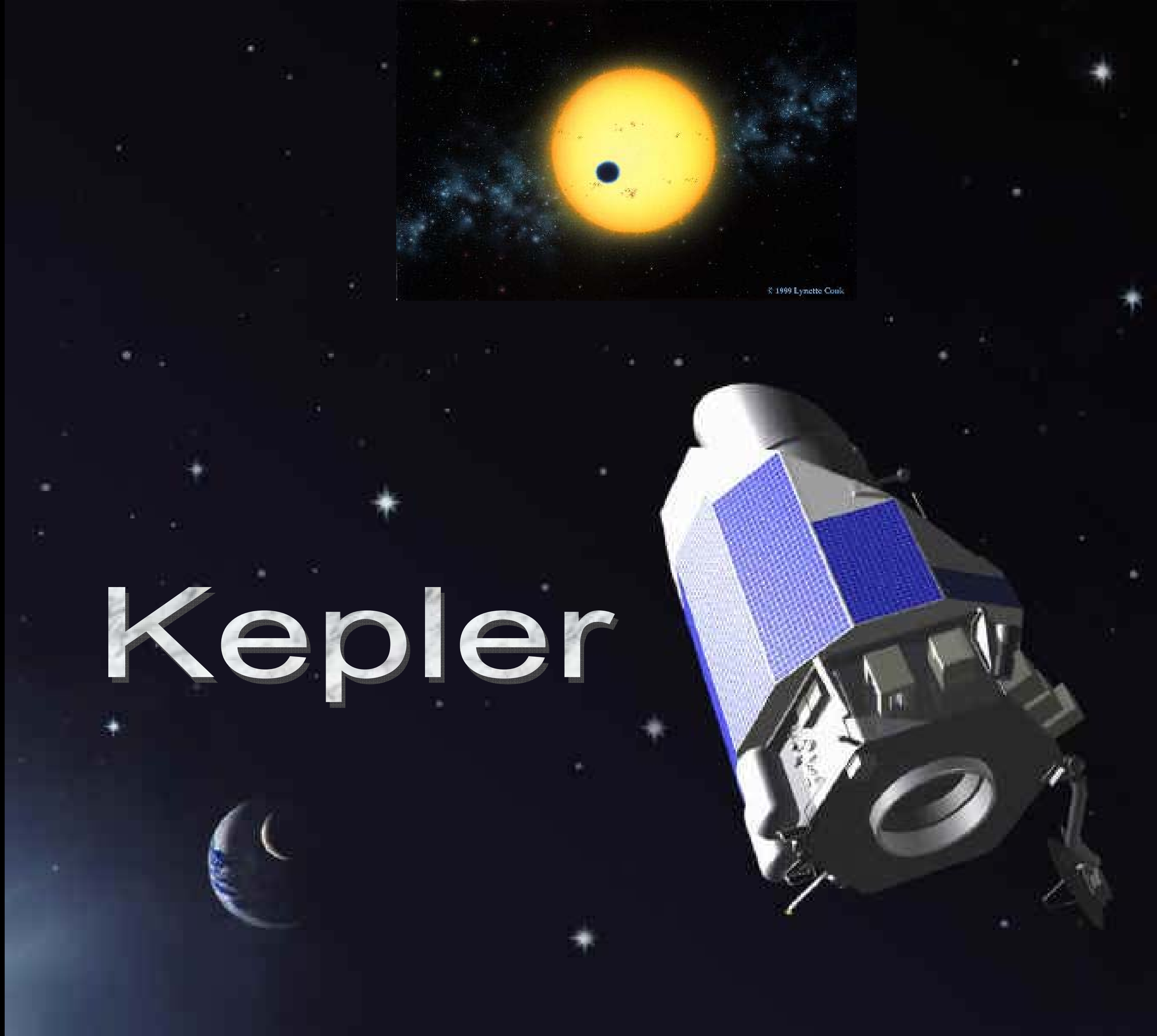


Comparison of EUVE Spectra Between Young and Old dK-stars



Liquid Water Habitable Zones around...

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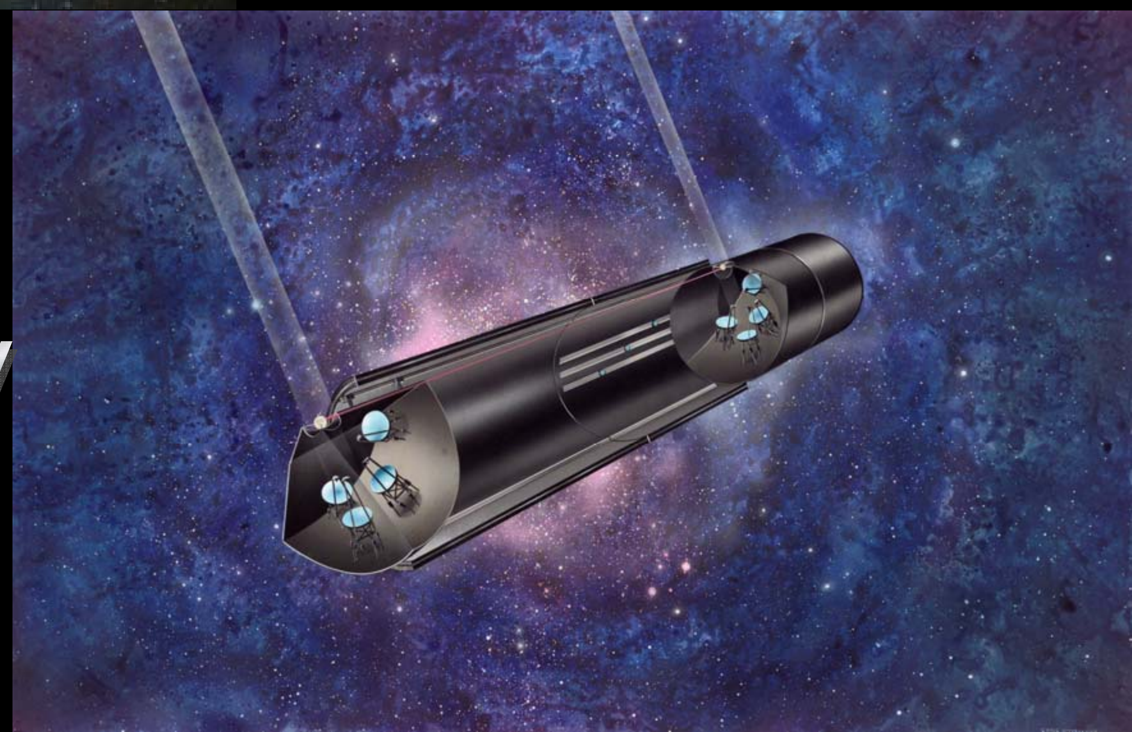
Kepler

Interferometric Space-based Missions

SIM

Space Interferometry Mission

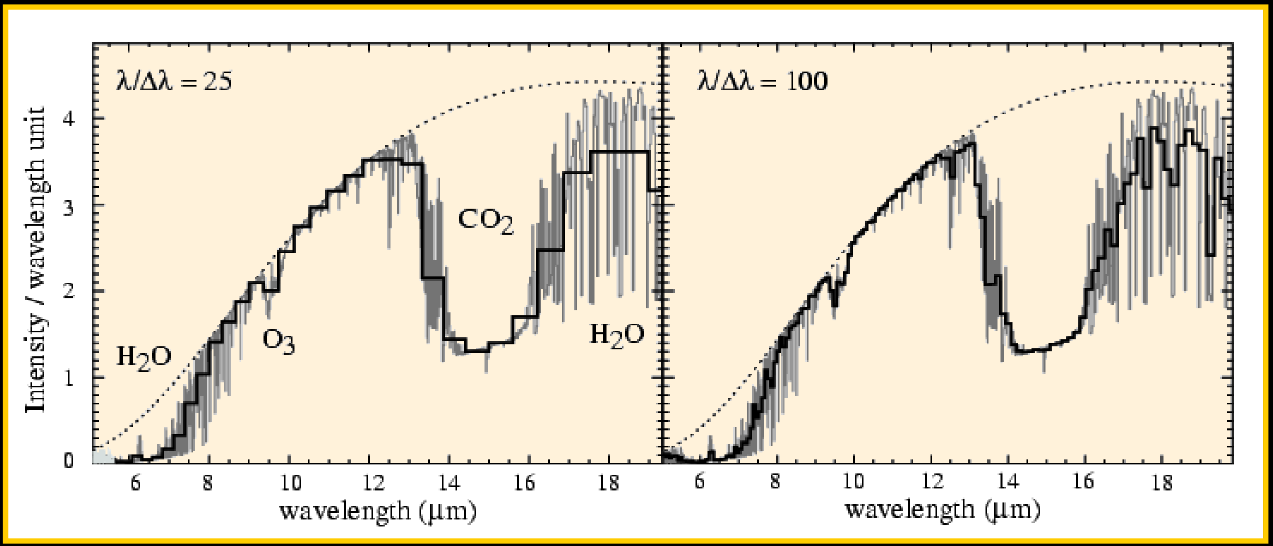


TPF

Terrestrial Planet Finder

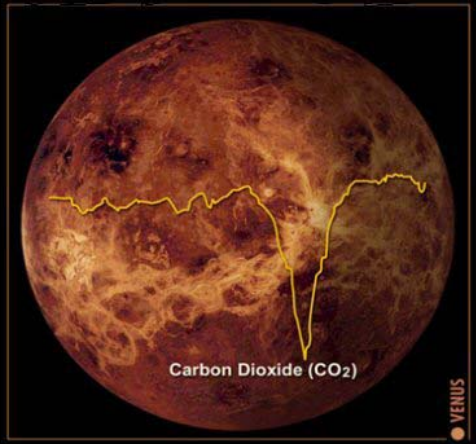
It will even be possible to obtain low-resolution spectroscopy of the planets

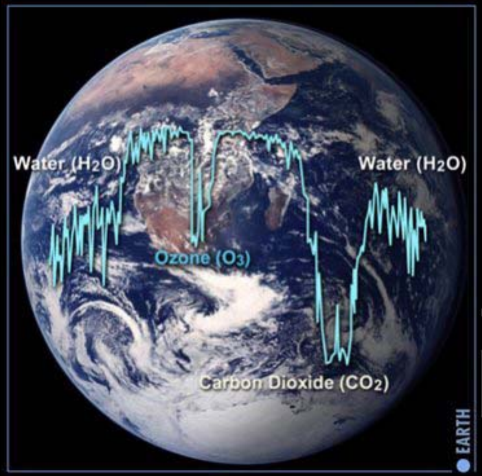
⇨ Characterization of their atmospheres and detect presence of life through O_3!

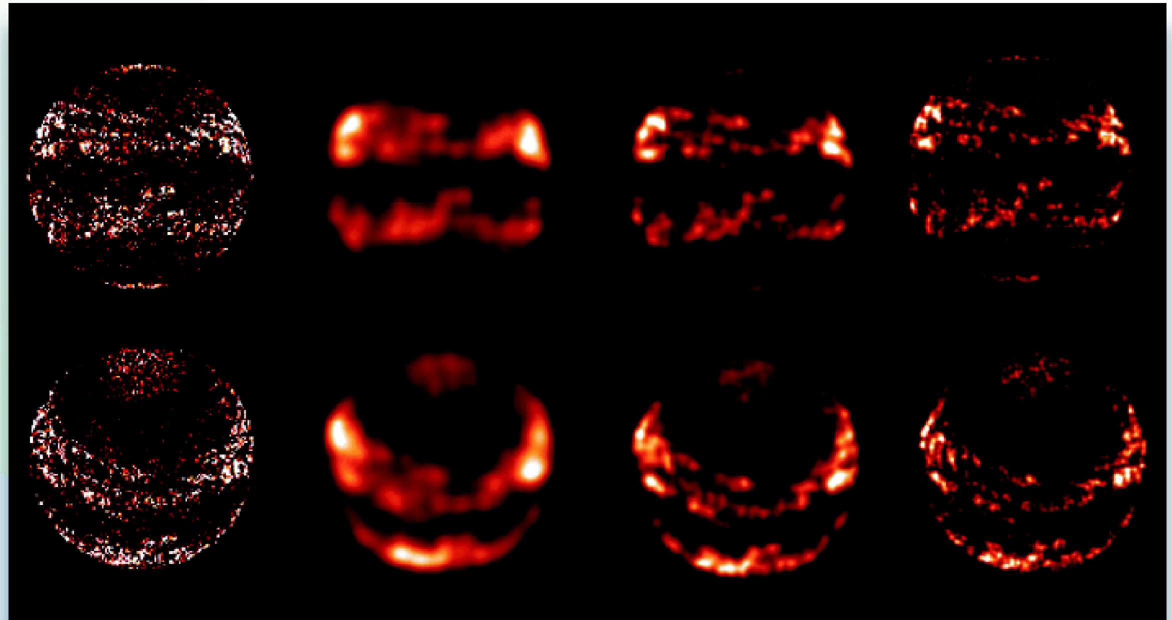


But some studies (Selsis et al. 2002) caution that purely abiotic processes can also produce O_3

More sophisticated biomarkers need to be devised



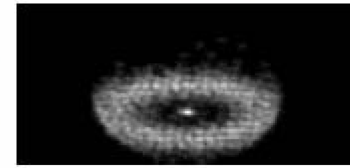




The potential of the Stellar Imager: Model CIV 1550 Å images of a star like the Sun (left) and simulated interferometric images for maximum baselines of 125 m, 250 m, and 500 m (2nd-4th columns). The top and bottom rows show views of a Sun-like star with a rotation axis in the plane of the sky and with that axis tilted by 40°, respectively. The simulated reconstructions assume observations of a star at 4 pc with 870 baseline pairs, e.g., 2 configurations of a 30-element array or 20 configurations of a 10-element array, with 800 CLEAN iterations. (Simulations computed with SISIM, written by R. Allen and J. Rajagopal/STScI.)

SI imaging of planet forming environments: magnetosphere-disk interaction region

0.1 mas



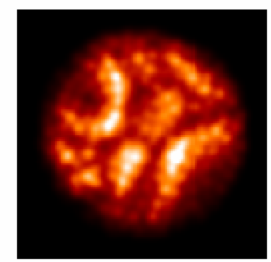
SI simulation in Ly α–fluoresced H2 lines

Baseline: 500 m

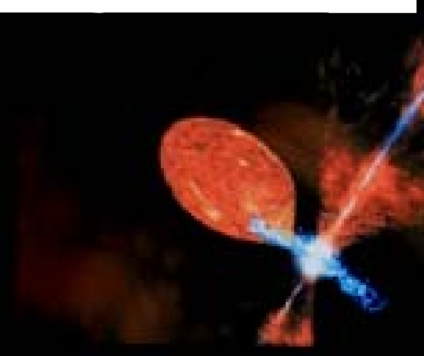
Evolved giant star at *2 Kpc* in *Mg H&K line*

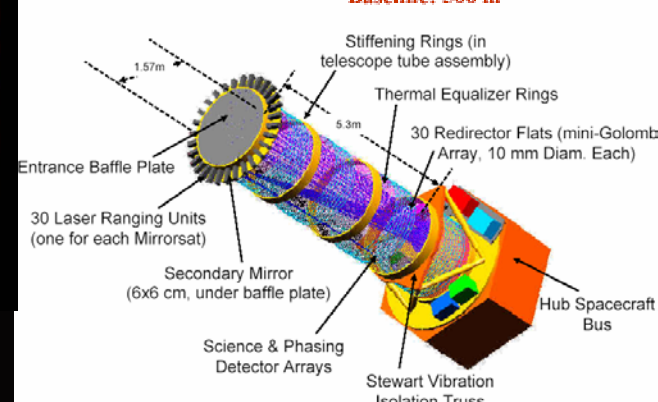
Model

SIsim image (2mas dia)



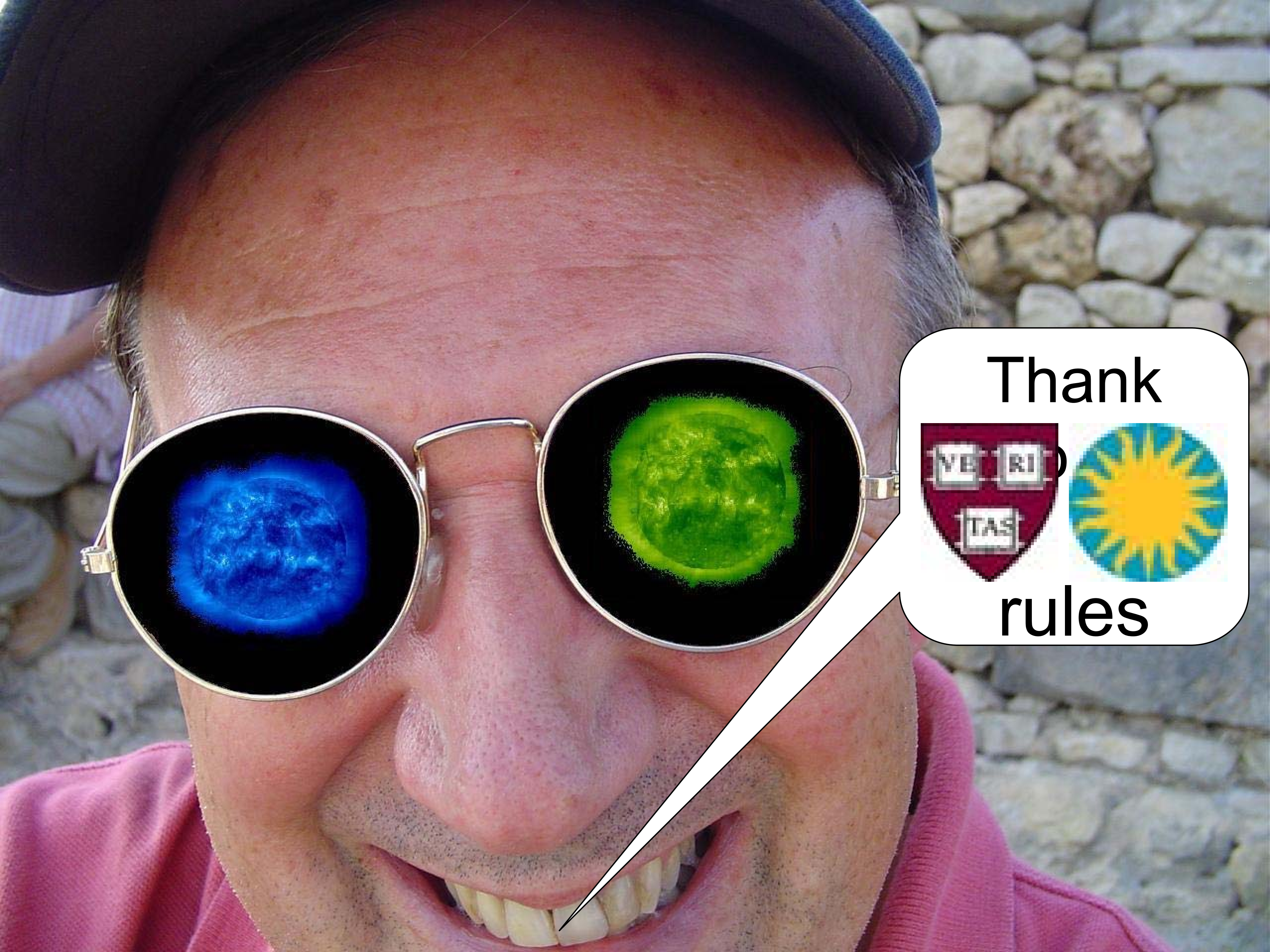
Baseline: 500 m





http://hires.gsfc.nasa.gov/~si

The End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