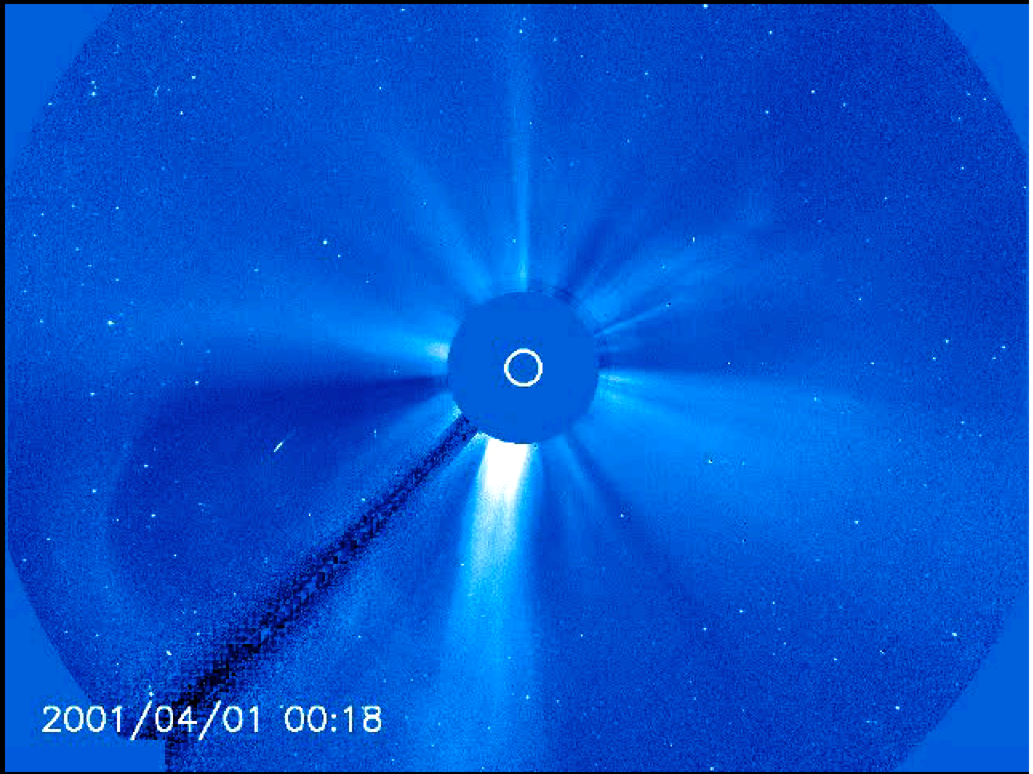
# FUSE Observations of Young to Old dG, dK & dM Stars: Critical Tests of Dynamos, X-FUV irradiances and Impacts on Planetary Environments and the Development of Life





<u>Collaborators</u>

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| | |
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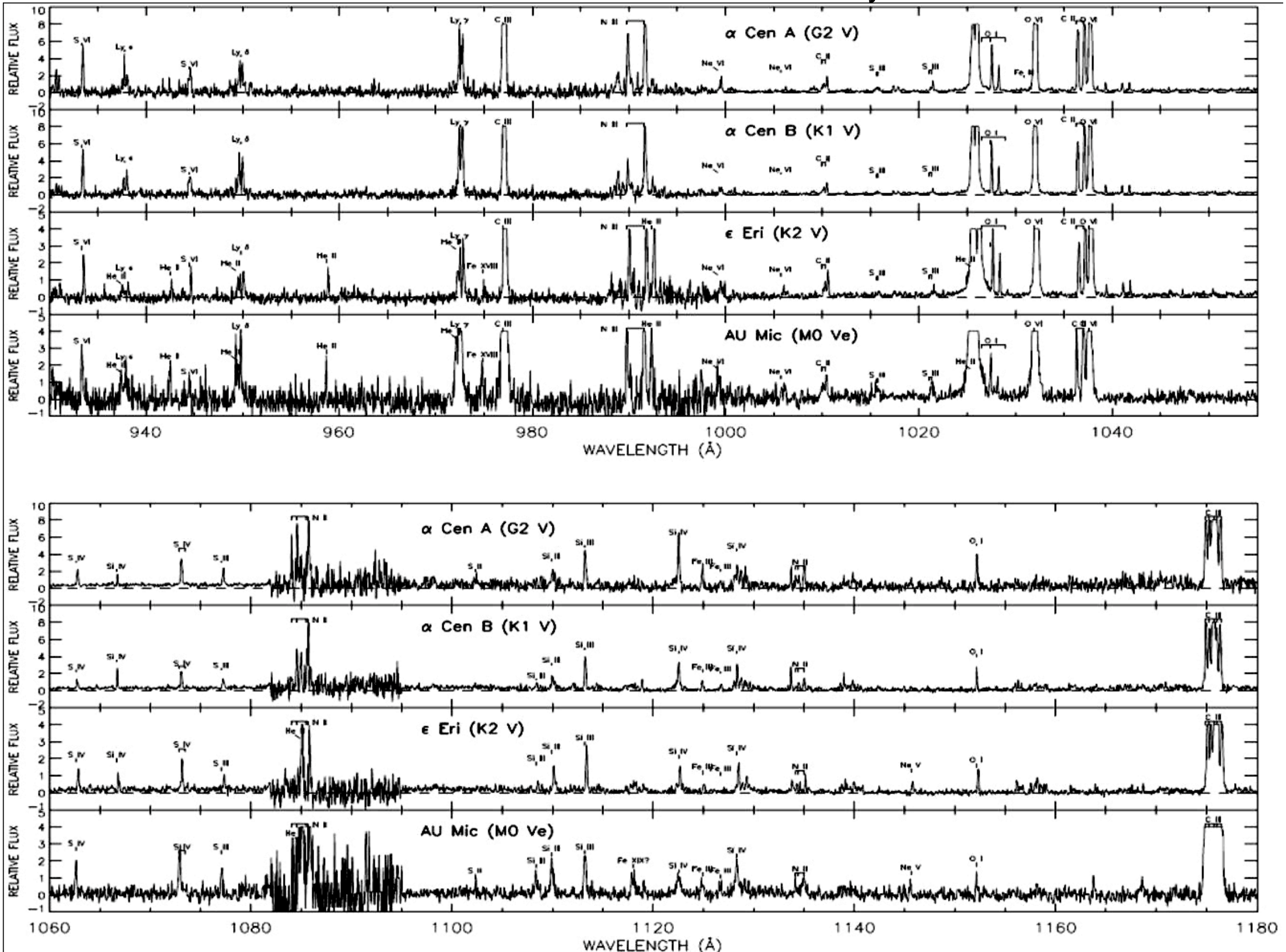
# FUSE FUV Spectral Interval (910-1185 A)

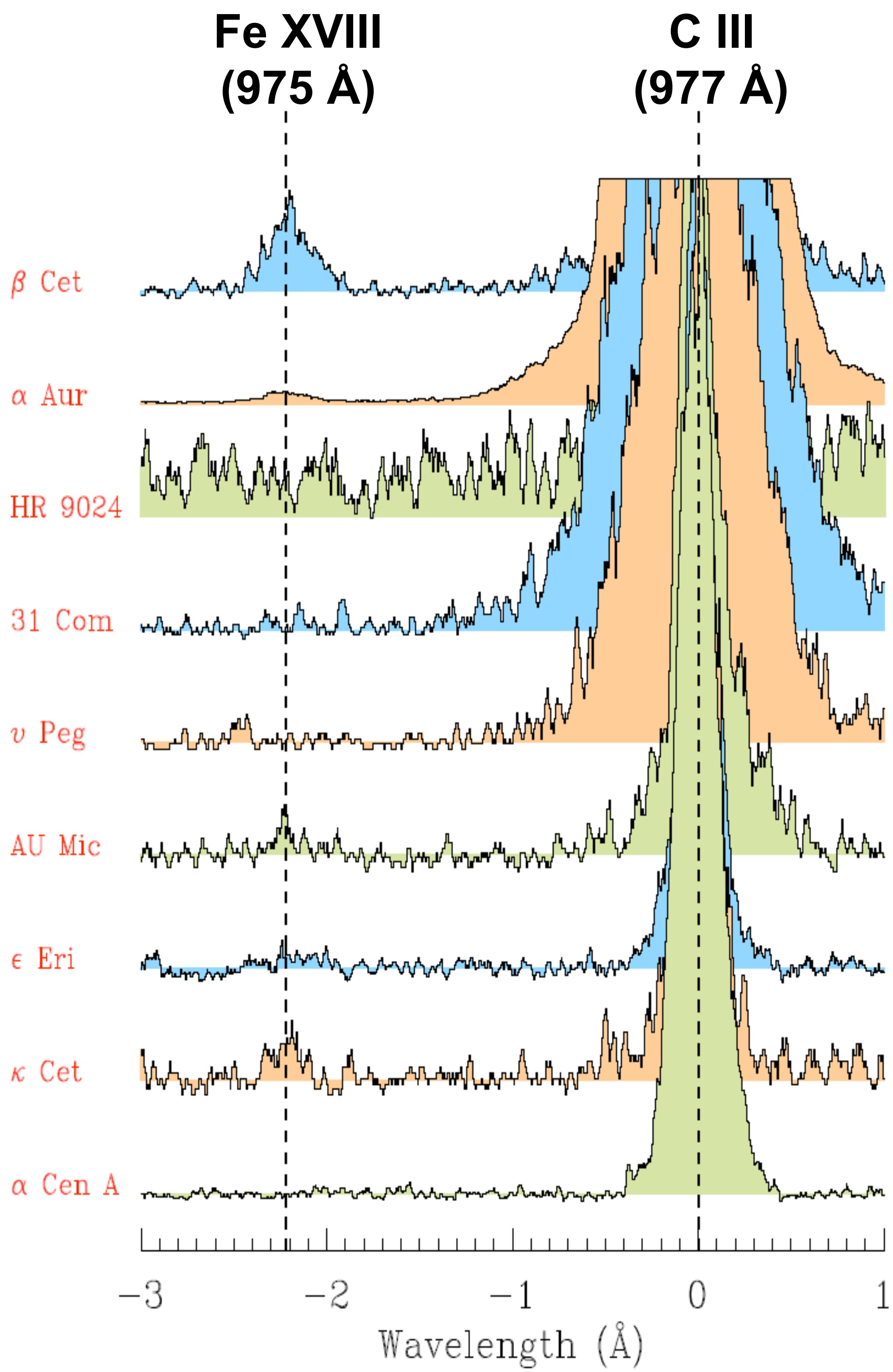
- **This small (275 Å) wavelength interval amazingly contains many crucial diagnostic emission lines for the study of activity in cool stars**
- **The FUSE FUV region is sensitive to plasma temperatures of ~10,000 K – 6 MK (over three decades of temperature!)**
- **Allows for simultaneous observations of emission lines originating from the chromosphere through the transition region and corona of magnetically active stars.**

| | |
|---|---|
| Chromosphere<br>(8000 – 20,000 K) | Lyman series:<br>Ly-β, Ly-_, etc. (very strong)<br>C II, Si II, Fe II (weak) |
| Chromosphere / Coronal Transition Region<br>(20,000 – 300,000 K) | C III - 977 / 1075 Å (very strong)<br>Si IV + S VI (weak) |
| Transition Region - Low Corona<br>(300,000 – 500,000 K) | O VI – 1032 / 1038 Å (very strong)<br>He II (moderate – weak) |
| Corona<br>(0.5 – 6 MK) | Fe XVIII – 975 Å<br>Fe XIX – 1118 Å (weak/blended) |
| | |
| Diagnostic of $N_e$, $P_e$ | ♦ $F_{C\,III}$ (${}^{975}/_{1075}$) |

## dG-dM Stars from the FUSE Cool Star Survey

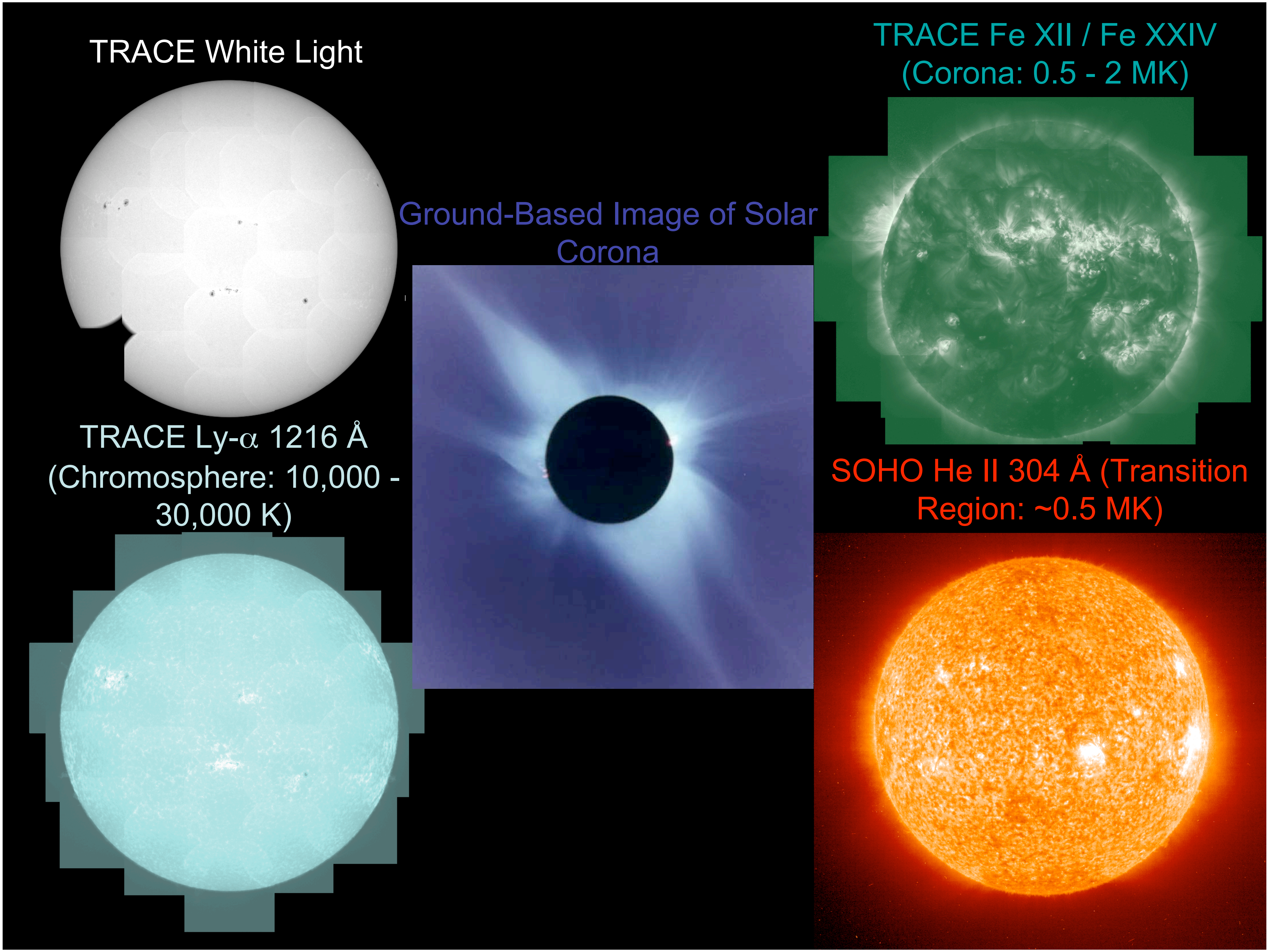



Taken from Ake, Dupree, Linsky & the FUSE Cool Star Team (2003)

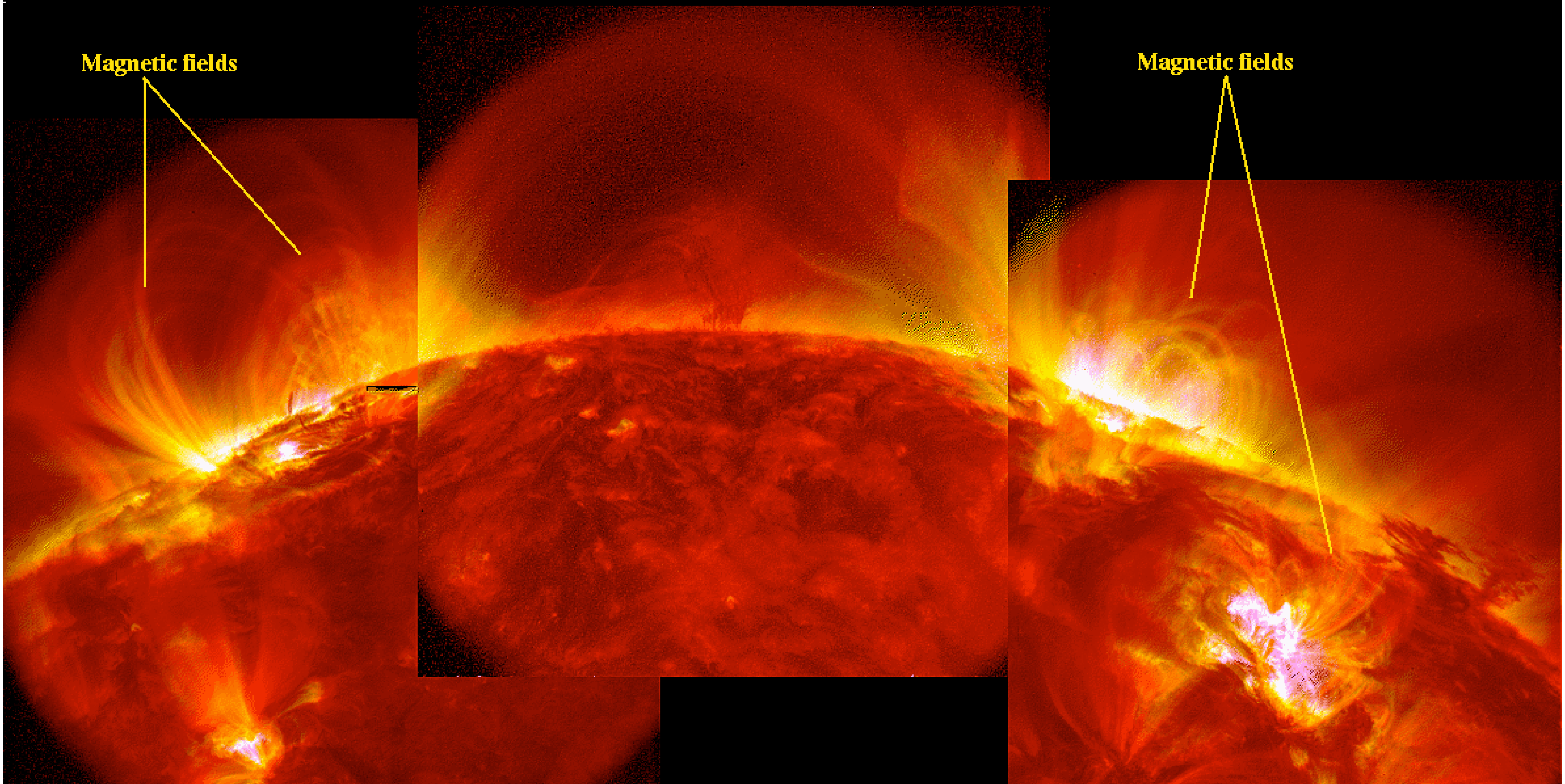



# FUSE Coronal Line (Fe XVIII) Study of Solar Proxies


Redfield, Ayres, Linsky & Guinan

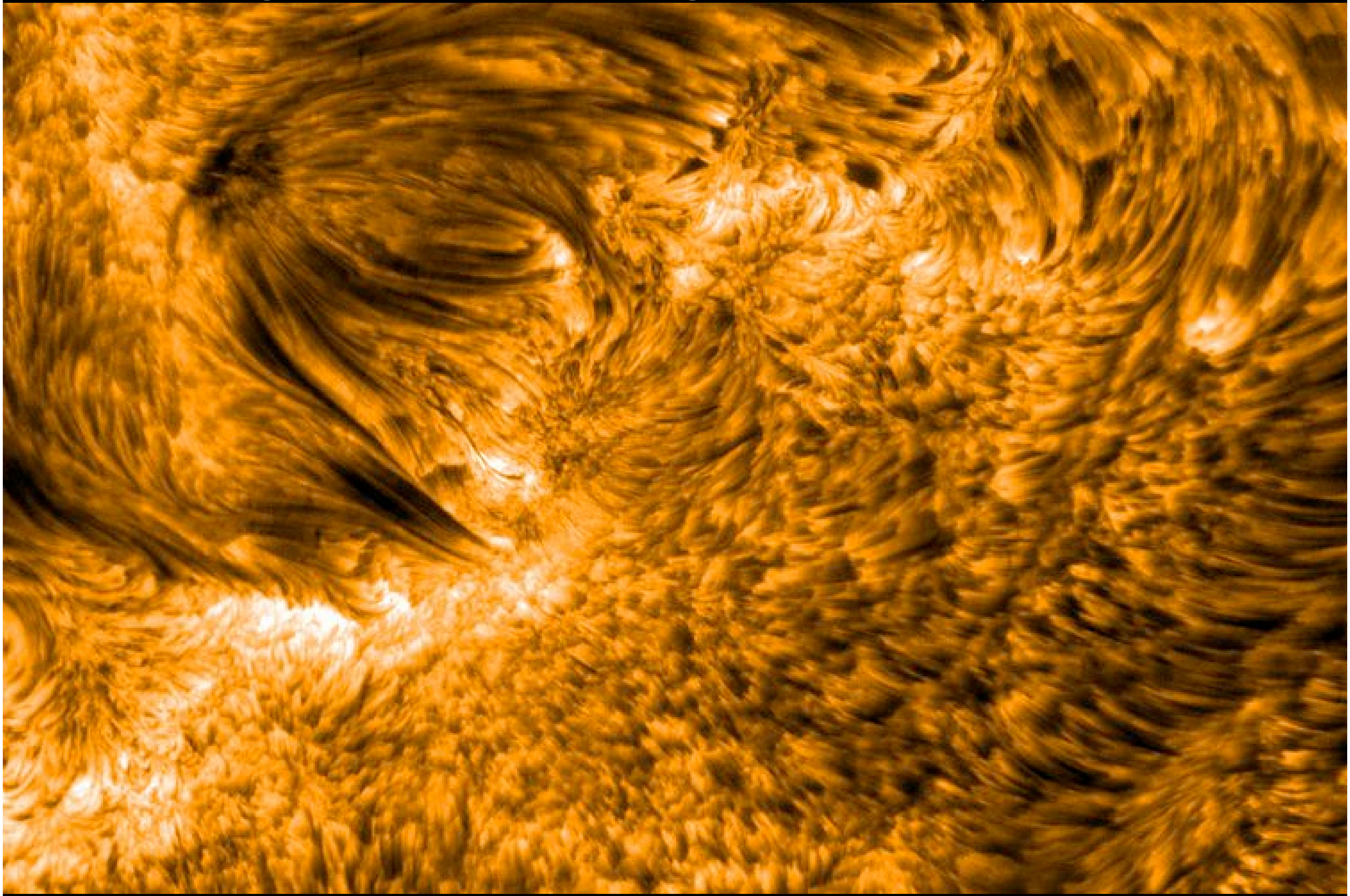

TRACE White Light
TRACE Fe XII / Fe XXIV
(Corona: 0.5 - 2 MK)
Ground-Based Image of Solar Corona
TRACE Ly-α 1216 Å
(Chromosphere: 10,000 - 30,000 K)
SOHO He II 304 Å (Transition Region: ~0.5 MK)

# Transition Region of Sun



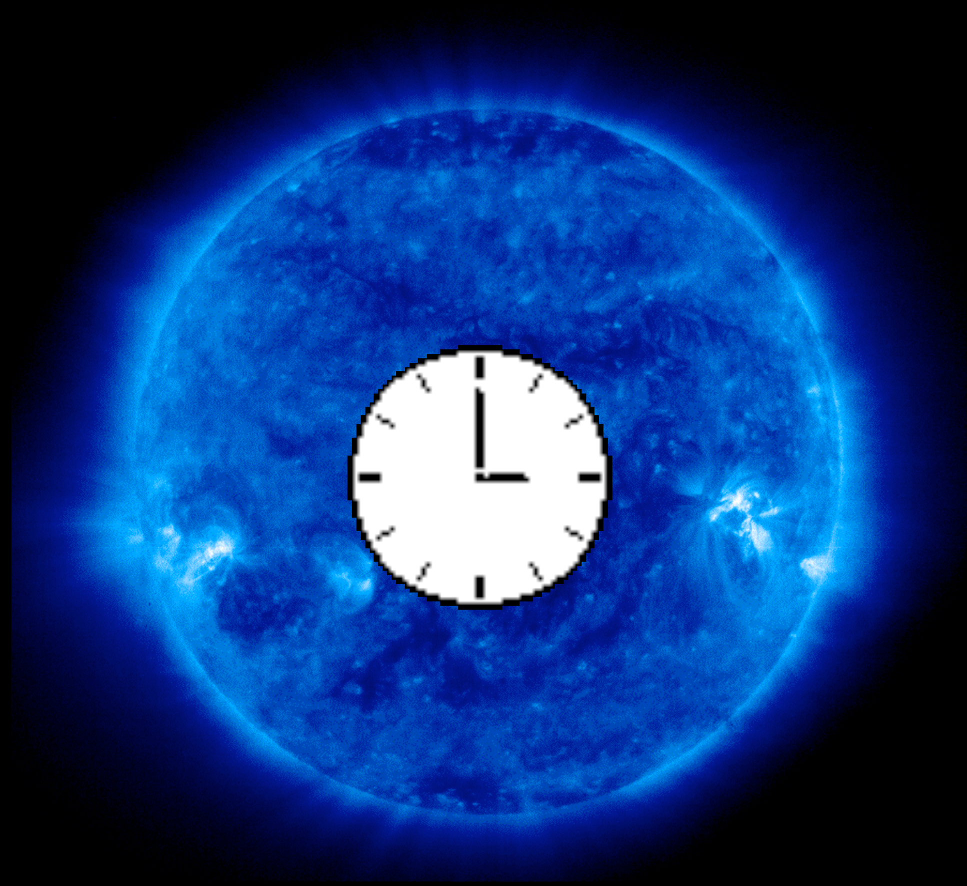

In the Far-Ultraviolet, Showing Magnetic Structures
(taken with TRACE)

# High-Resolution Image of Solar Spicules



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

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

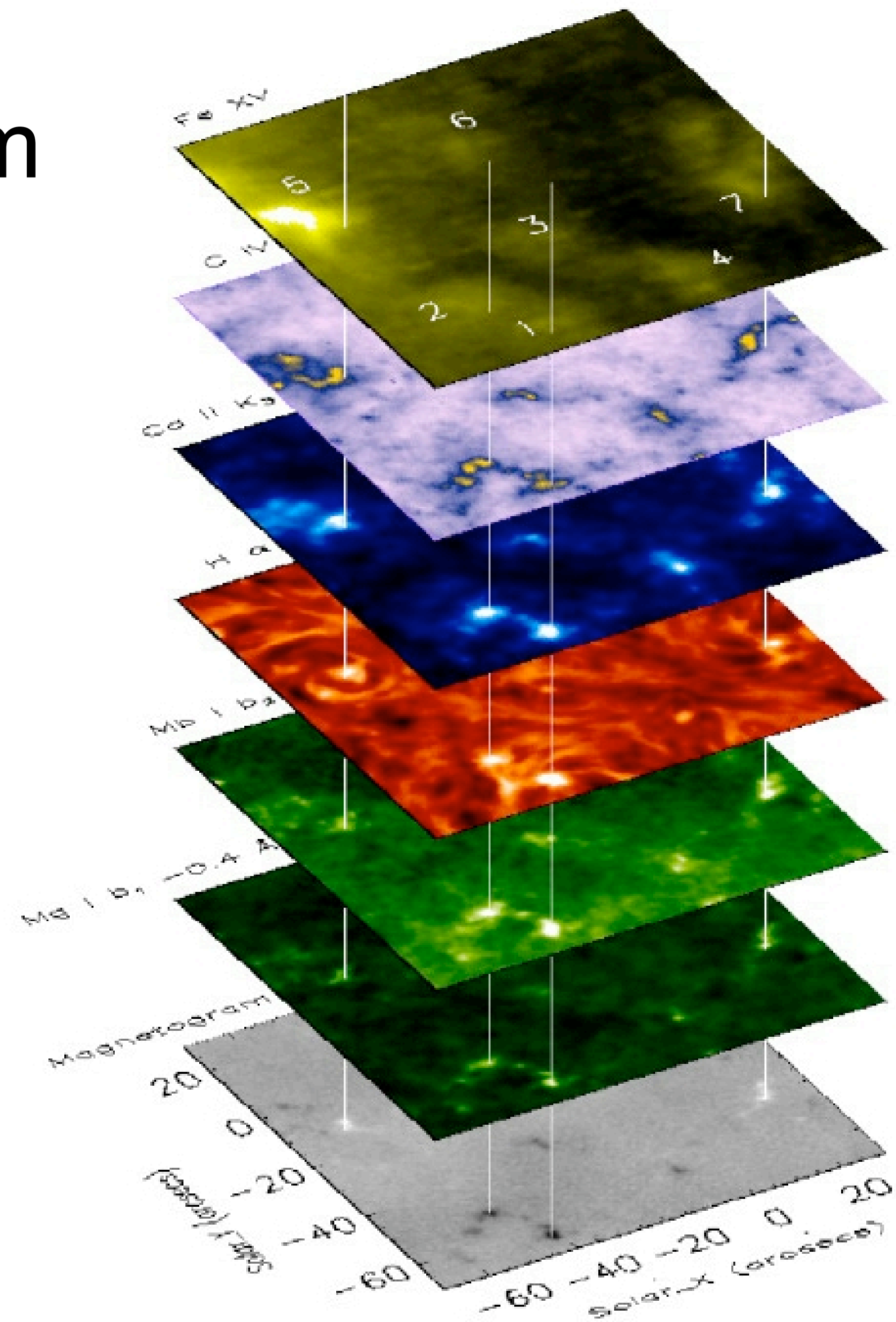


# The main features of the stellar sample are:

- 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
- Recently, this program has been extended to include dK & dM stars of different ages
- 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 FUV). Most of the observations have been acquired from space satellites to overcome atmospheric absorption.

# Major Goals of the Sun-in-Time Program

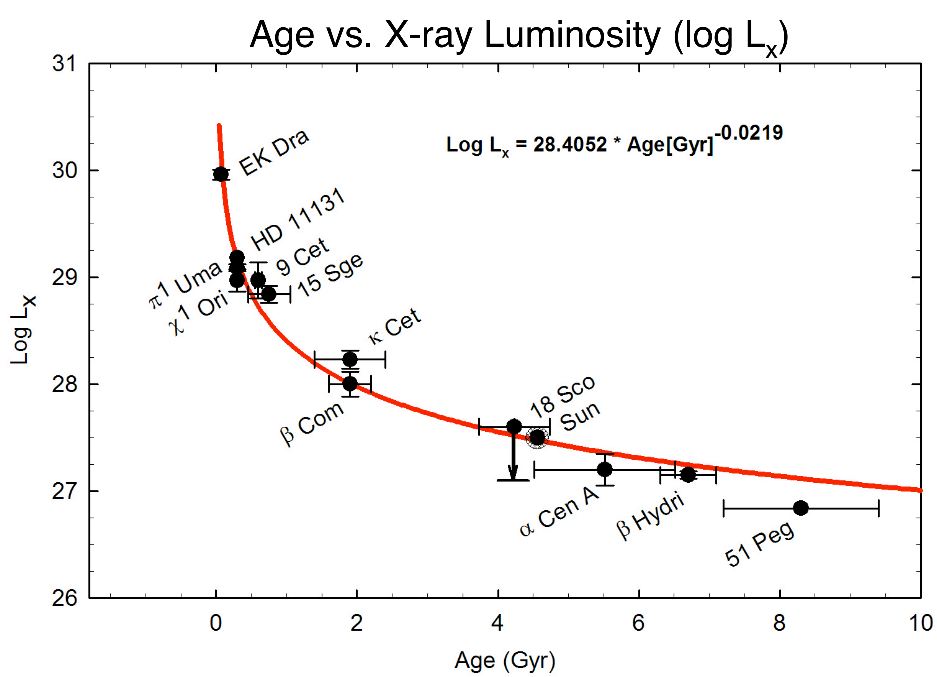
1. Study Solar/Stellar Dynamos, Magnetic heating / energy transfer from chromosphere, transition region (TR) & corona. Solar analogs (G0-5 V) selected are similar (Mass, Radius, Depth of Convective Envelope). Differ only in one important parameter – **ROTATION**. Fortunately, FUSE contains a number of important emission features arising from all atmospheric levels.

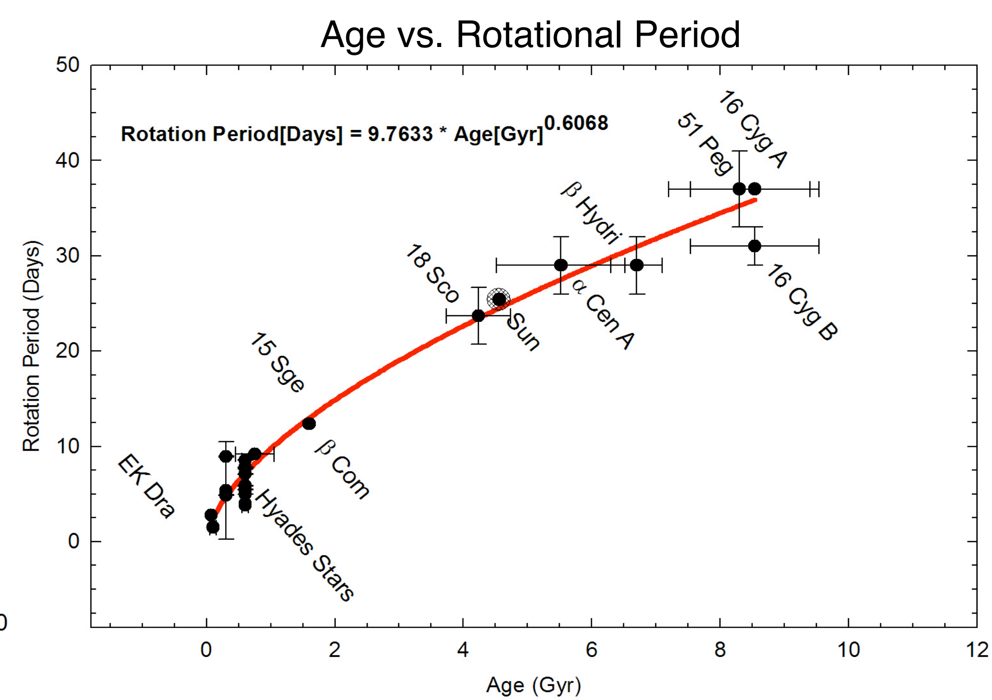


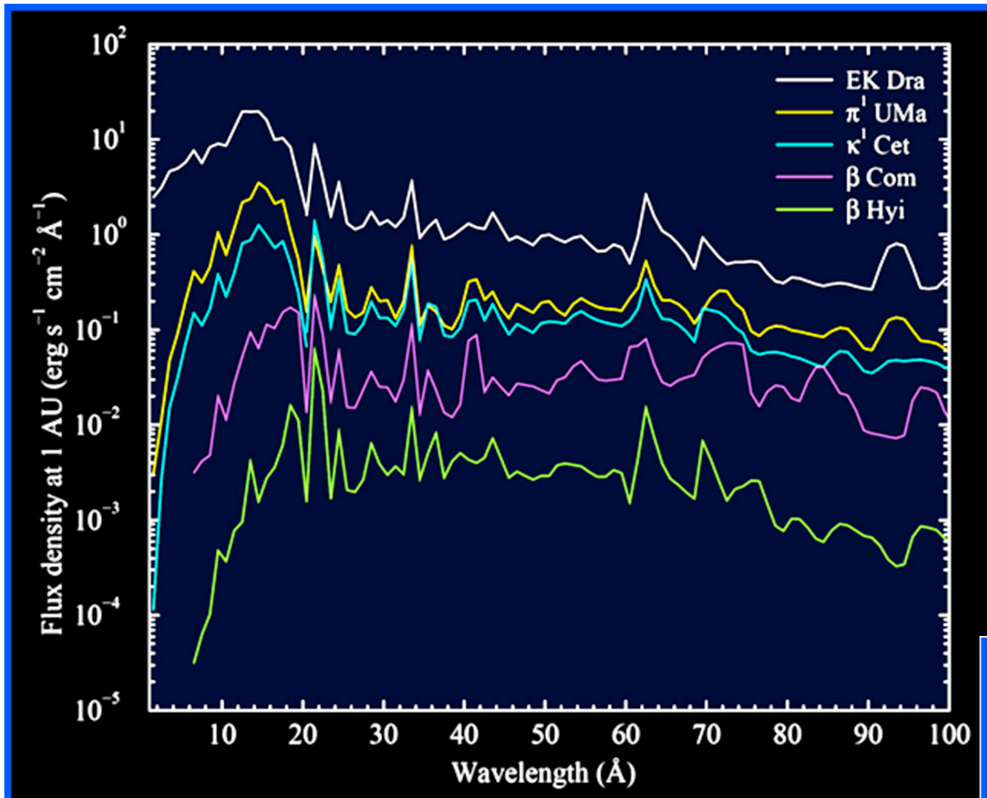
## 2. X-ray/FUV Irradiance (1-1500 Å) for solar proxies with

- different ages (~100 Myr – 8.5 Gyr)
- different rotation periods ($P_{rot}$ ~ 1 – 40d)
- vastly different levels of dynamo related chromospheric, TR & coronal emissions.

## 3. Spin-Down of the Sun _ Decrease in Magnetic Activity



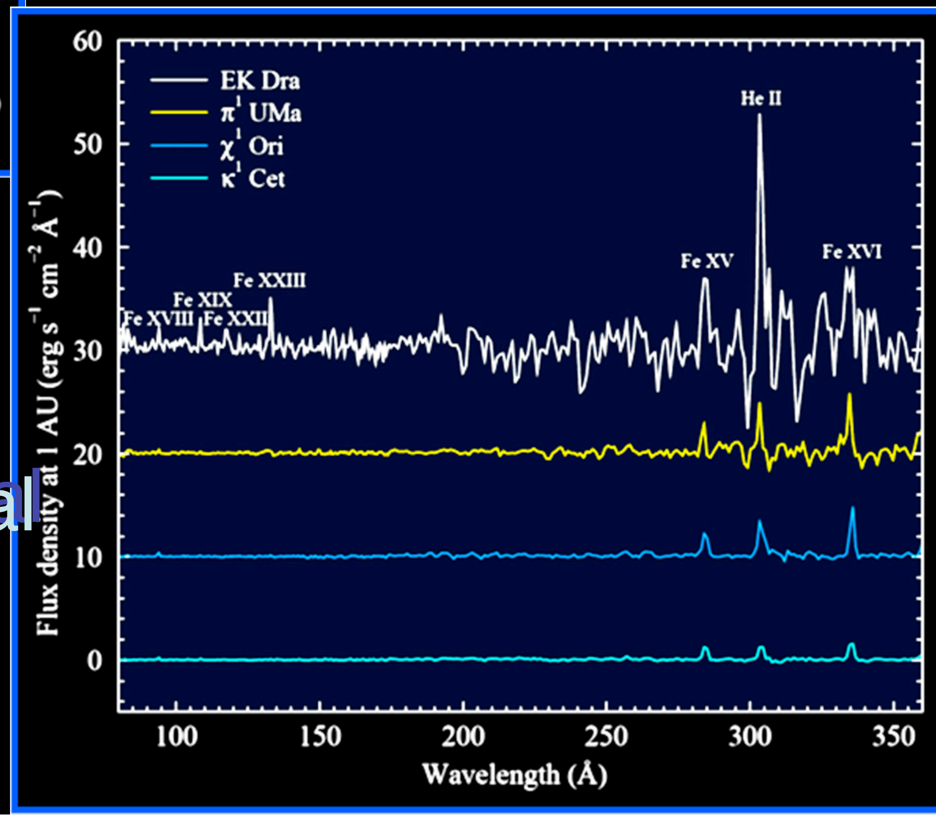






# Coronal X-ray (ROSAT)

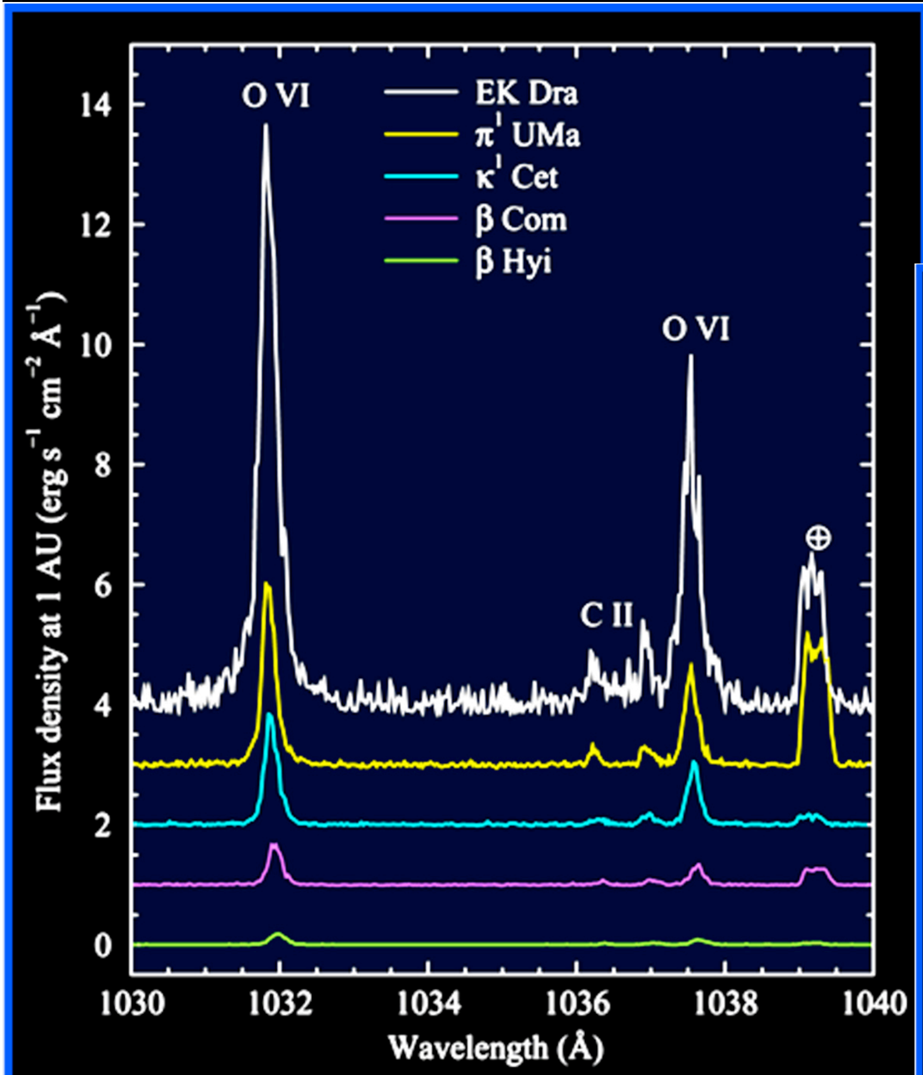
# EUV (EUVE)

Coronal Emission



# FUV (FUSE)

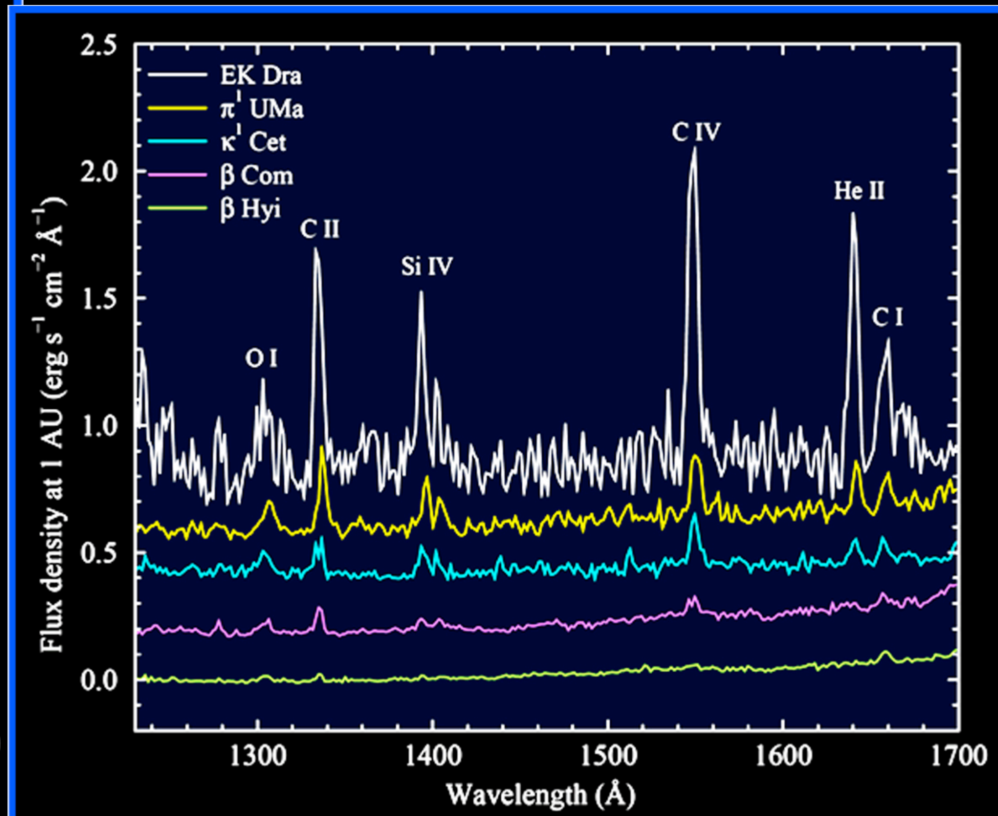
Transition Region
Chromospheric Coronal

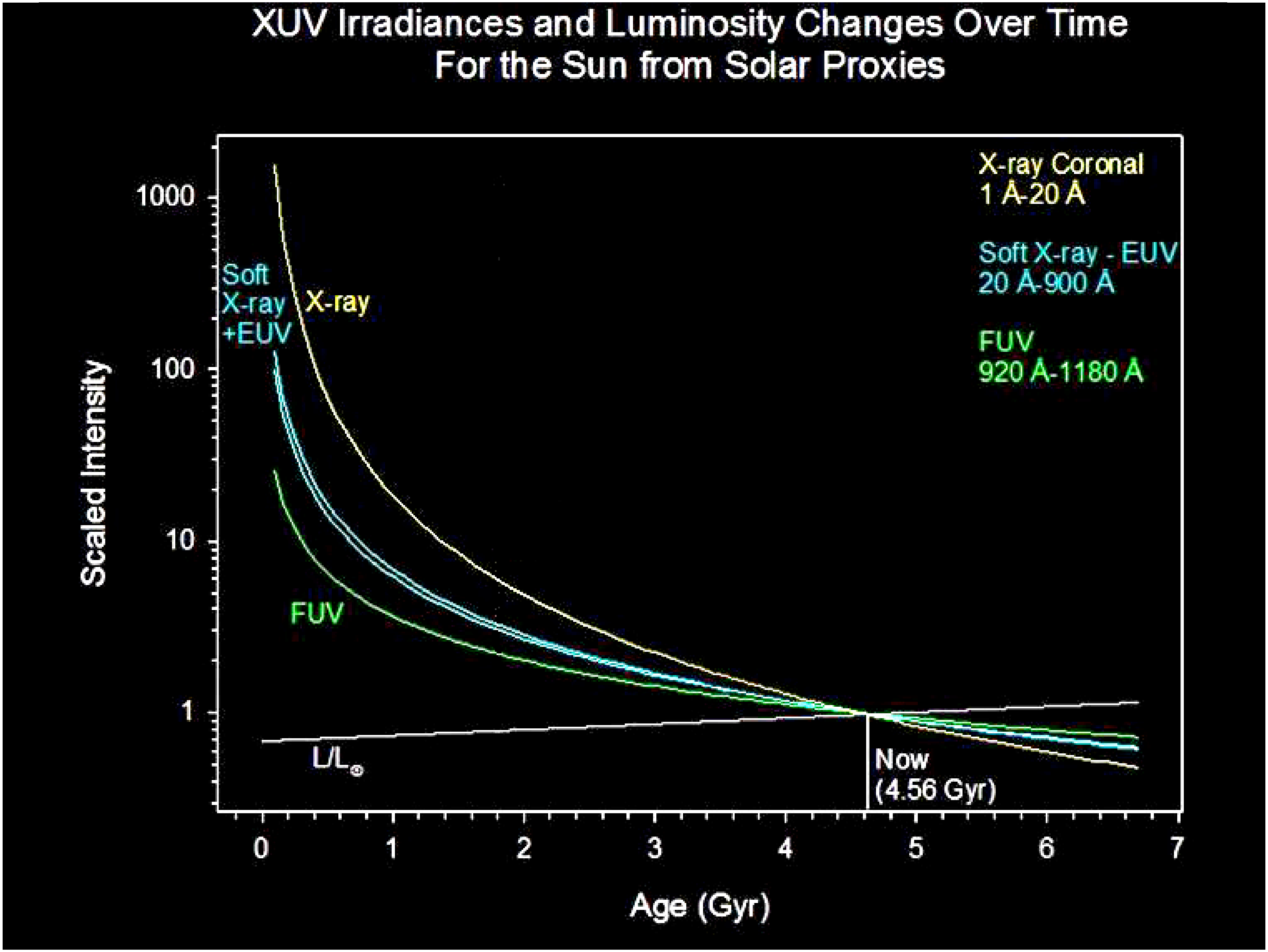



# FUV / UV

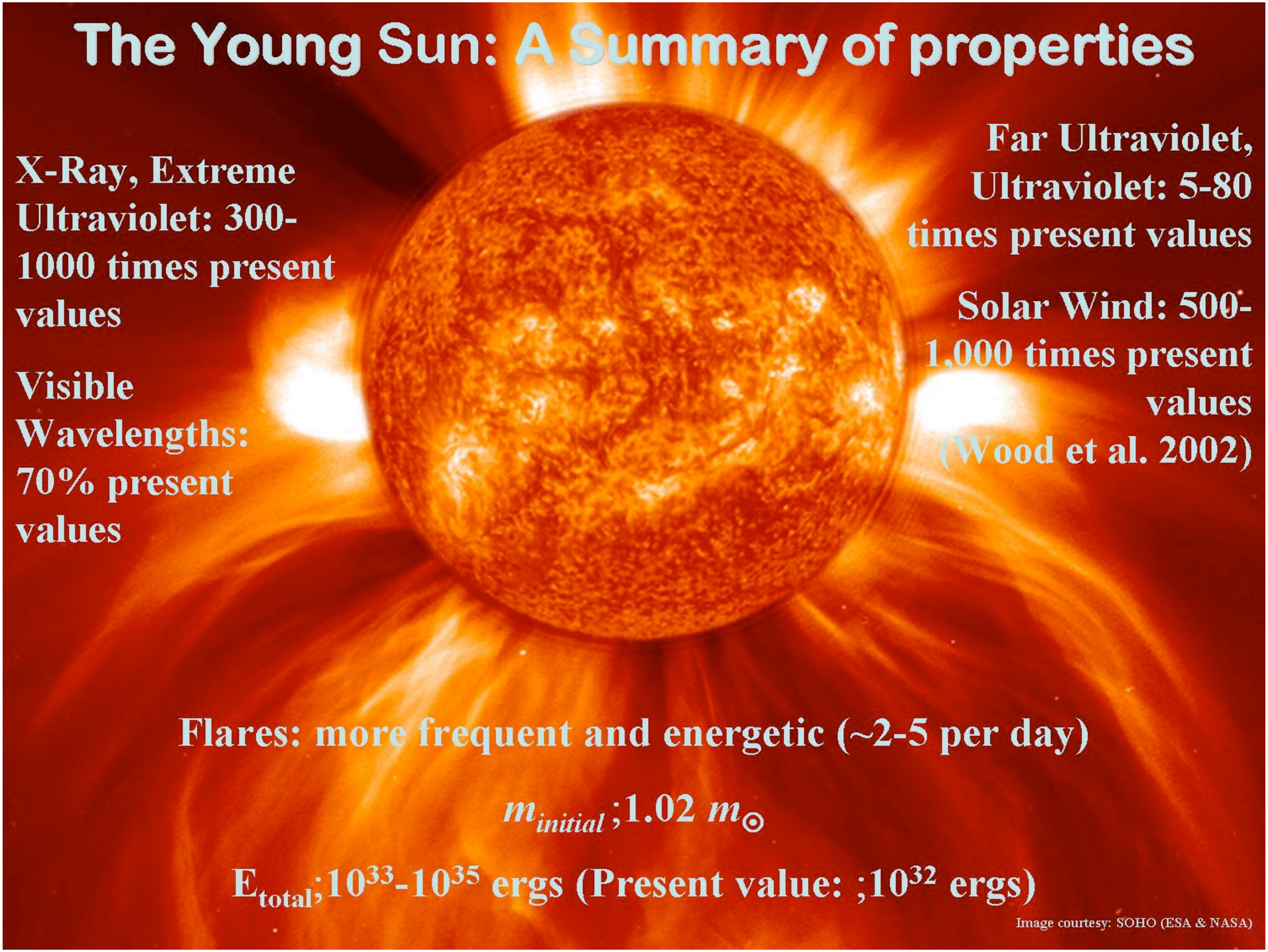
# (From IUE) TR /

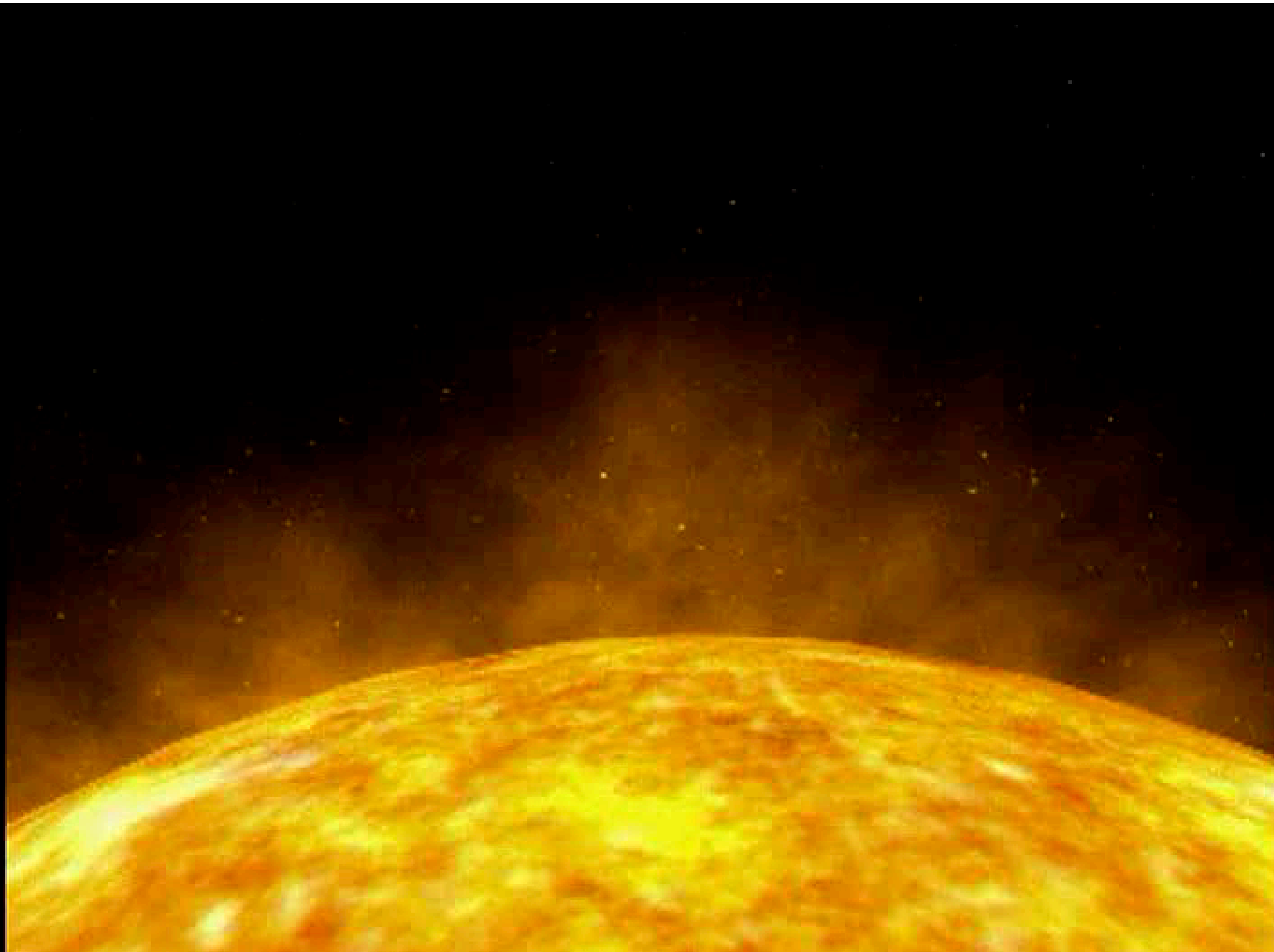
Chromospheric Emissions



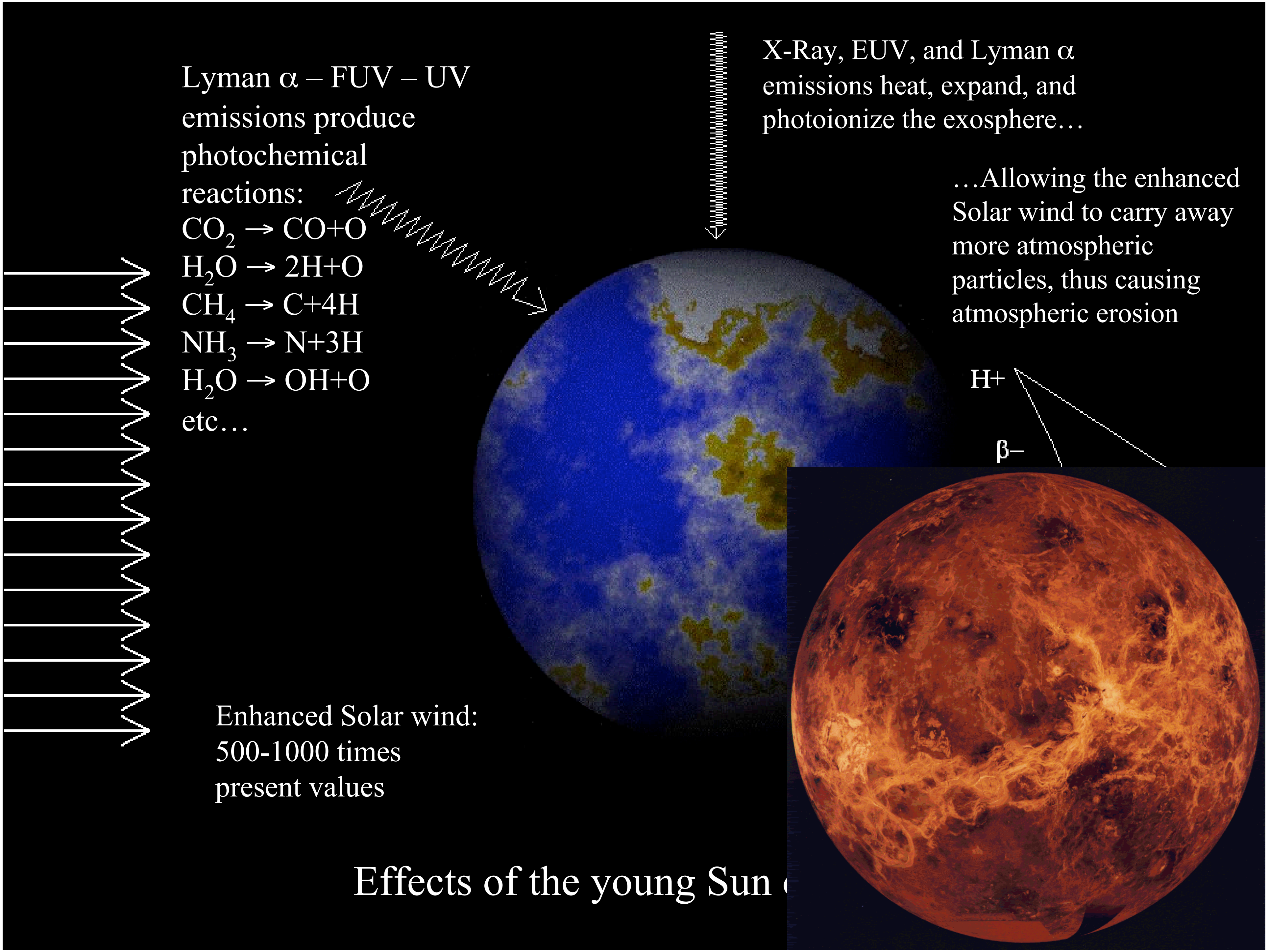


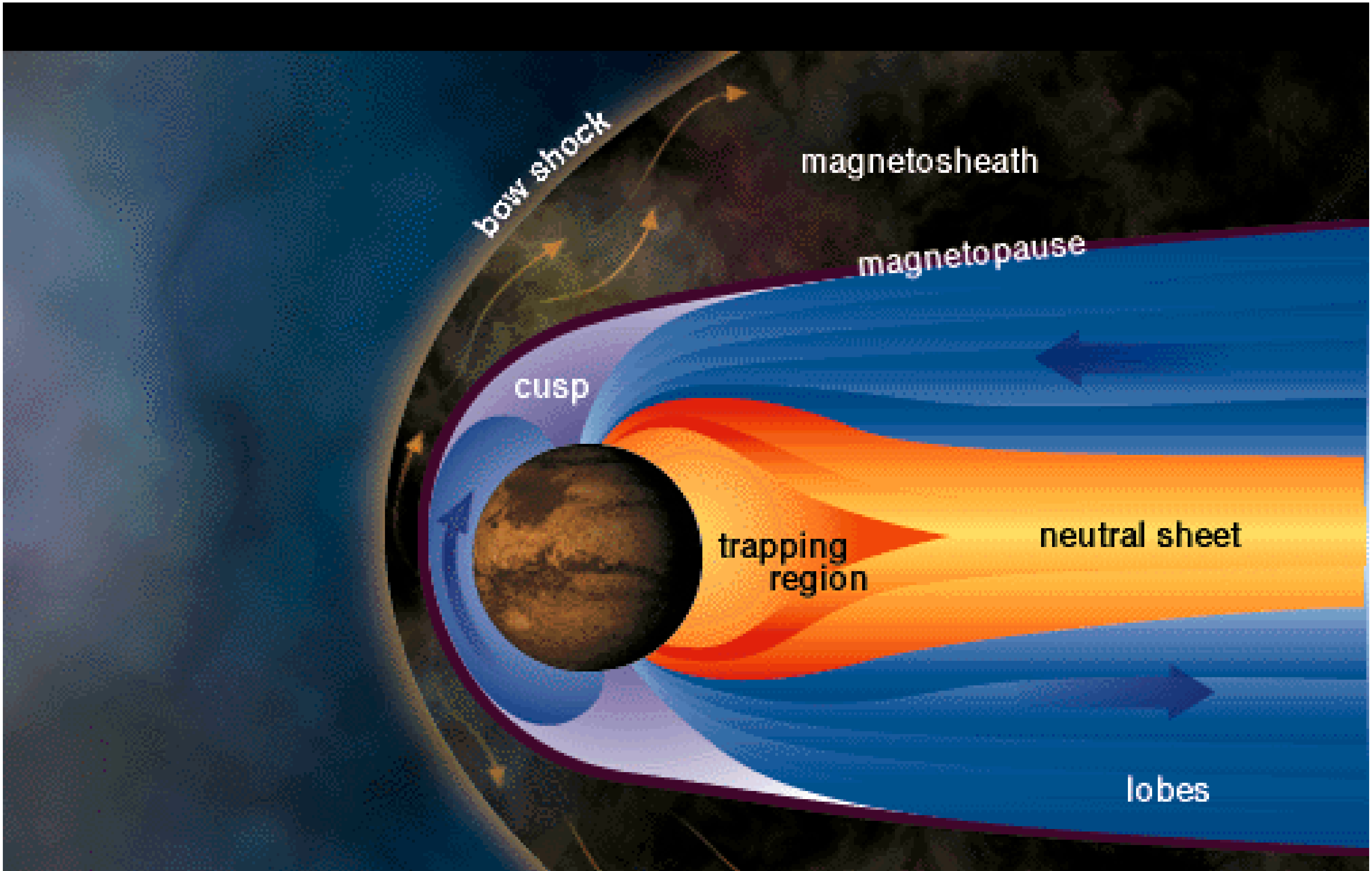
XUV Irradiances and Luminosity Changes Over Time
For the Sun from Solar Proxies
X-ray Coronal
1 Å-20 Å
Soft X-ray - EUV
20 Å-900 Å
FUV
920 Å-1180 Å
Soft
X-ray
+EUV
X-ray
FUV
L/L⊙
Now
(4.56 Gyr)
1000
100
10
1
0
1
2
3
4
5
6
7
Scaled Intensity
Age (Gyr)


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)



# The Effects of the Active Young Sun on Planets


Lyman α – FUV – UV emissions produce photochemical reactions:
$CO_2 \rightarrow CO+O$
$H_2O \rightarrow 2H+O$
$CH_4 \rightarrow C+4H$
$NH_3 \rightarrow N+3H$
$H_2O \rightarrow OH+O$
etc…
X-Ray, EUV, and Lyman α emissions heat, expand, and photoionize the exosphere…
…Allowing the enhanced Solar wind to carry away more atmospheric particles, thus causing atmospheric erosion
H+
β–
Enhanced Solar wind: 500-1000 times present values
Effects of the young Sun



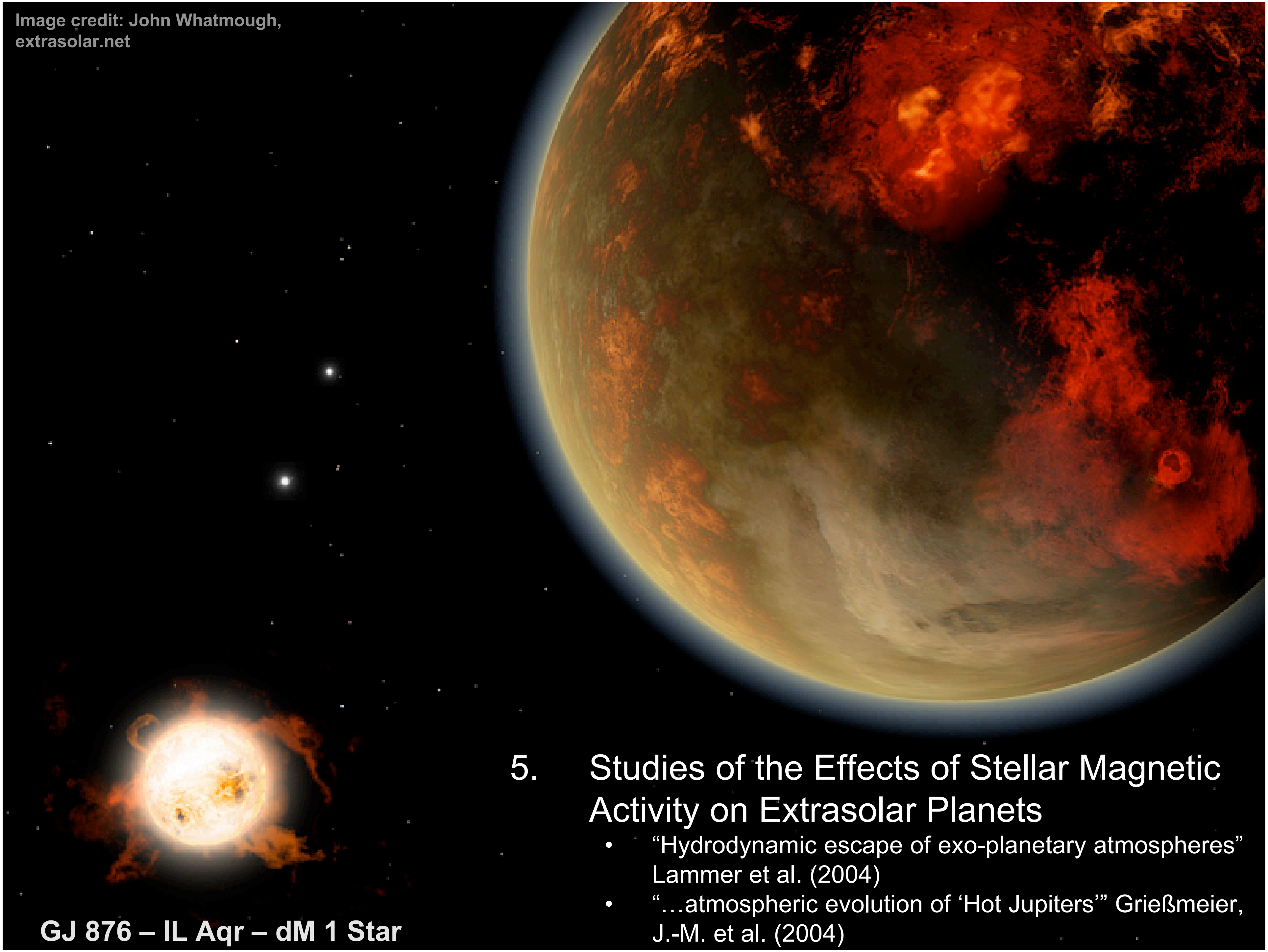

⊙ A liquid iron core produced a magnetic field strong enough to protect the young Martian atmosphere and surface water from the punishing effects of the young Sun's intense solar wind

# 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.

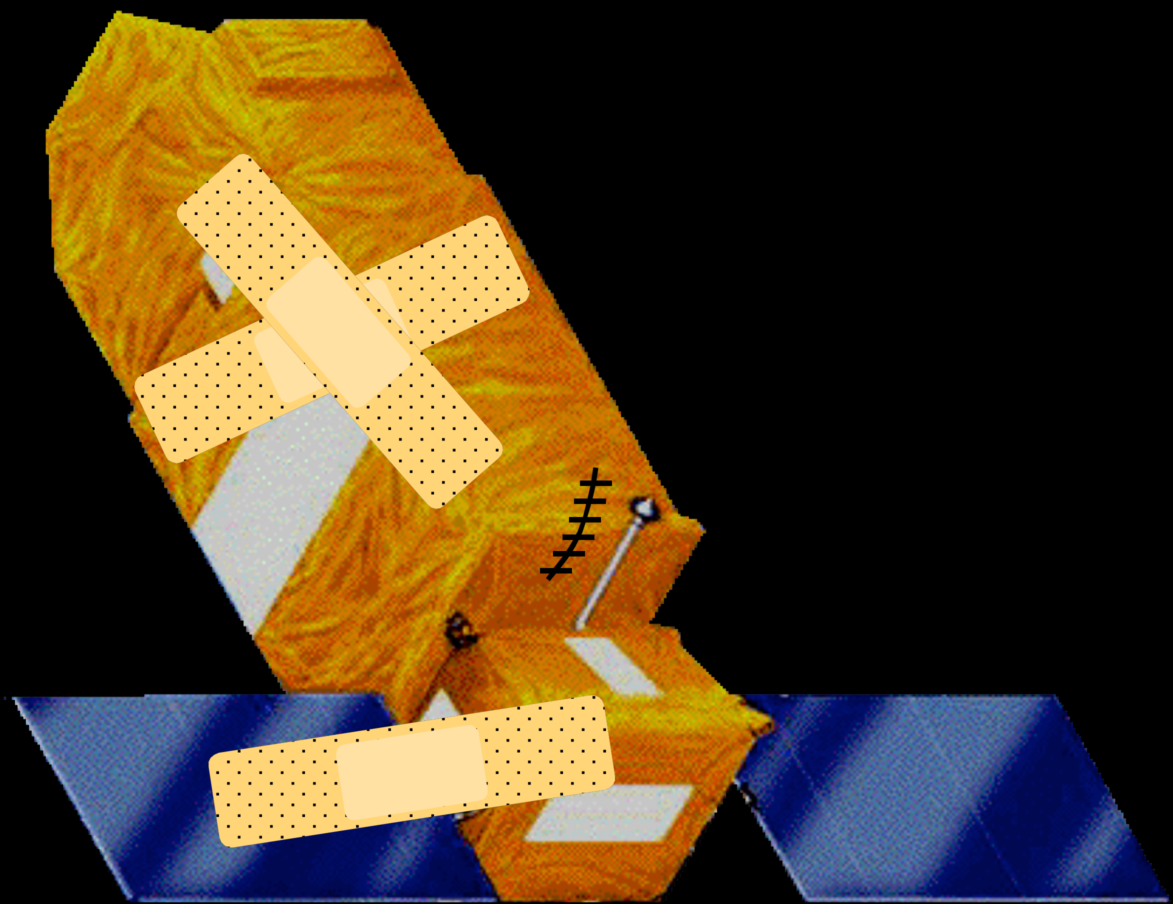
€ At this time, water disassociates into 2H+O, where the lighter Hydrogen is lost to the space while the heavier Oxygen combines with iron on its surface




# 5. Studies of the Effects of Stellar Magnetic Activity on Extrasolar Planets

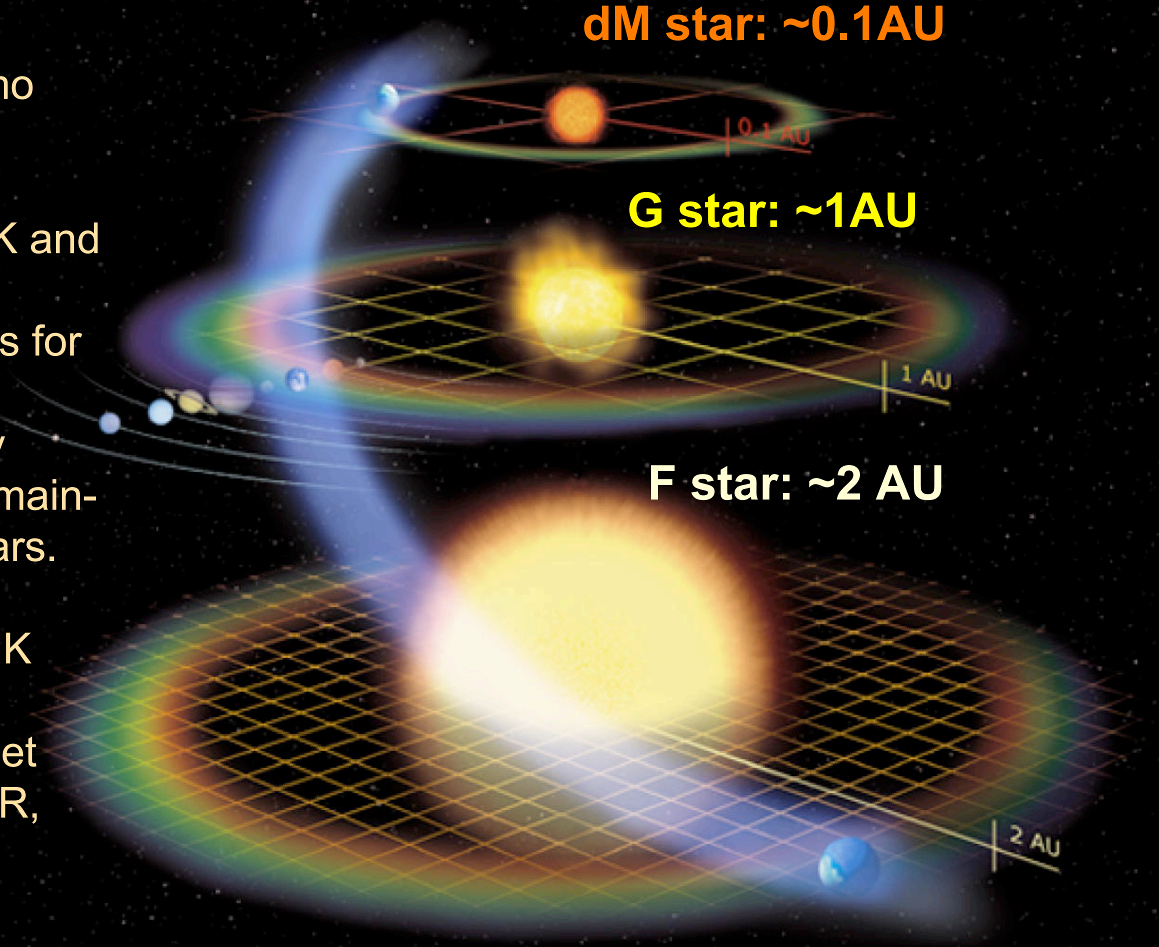
- "Hydrodynamic escape of exo-planetary atmospheres" Lammer et al. (2004)
- "…atmospheric evolution of 'Hot Jupiters'" Grießmeier, J.-M. et al. (2004)

# Examples of Additional Work to be Done with FUSE



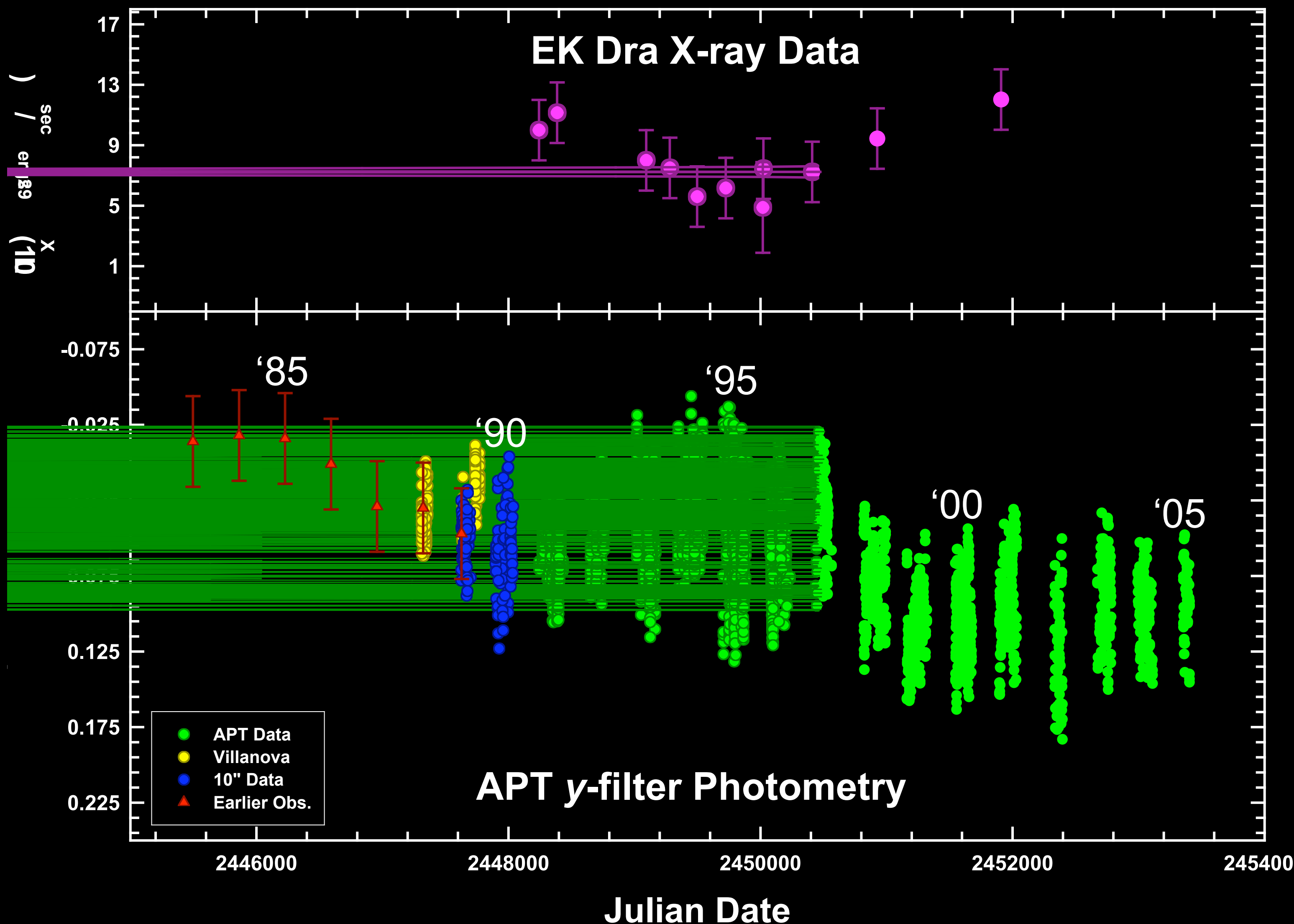
# Liquid Water Habitable Zones around...

1. Observations of additional dK and dM stars to fill in and expand the rotation-age-activity parameter space:
   - Input for stellar magnetic dynamo studies of stars with different Convective Zone Depths
   - Accurate FUV Irradiances for dK and dM stars of different ages and combine with X-ray observations for calculating effects of X-FUV irradiances of planets hosted by these stars. Note that >80% of main-sequence stars are dK & dM stars. Need these data to understand evolution of planets hosted by dK and dM stars. Also important for upcoming exoplanet missions such COROT, KEPLER, SIM, and TPF.



## 2. Observations of Activity Cycles of dG, dK,& dM Type Stars:

- Combine new FUSE observations of selected active stars with existing earlier FUSE observations to study magnetic activity cycles.



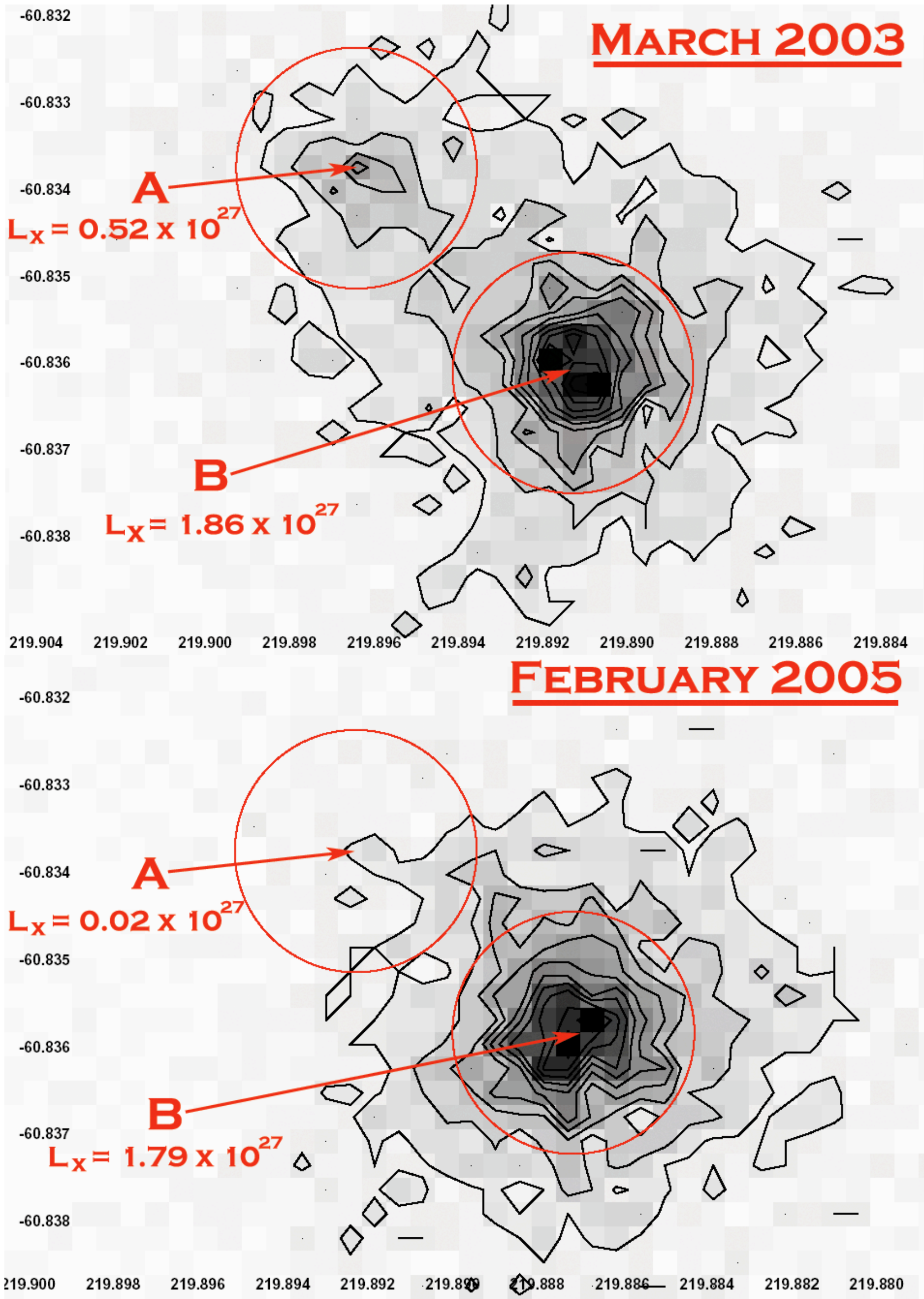

Long-Term X-ray / Coronal & Optical Variations of the young "*Sun in Time*" star EK Dra (~100 Myr) displaying ~10 year cycle

**3. Long-term Monitoring of Young Solar-type Stars to study flares and possibly observe Coronal Mass Ejection (CME) events.**

- only FUSE has the spectral resolution to get velocities

**4. FUSE Observations of Surprises:**

- For example --- Huge Coronal X-ray dimming of the bright nearby G2V solar twin - $\alpha$ Cen A (Robrade, Schmitt & Favata (2005), A&A, 442)



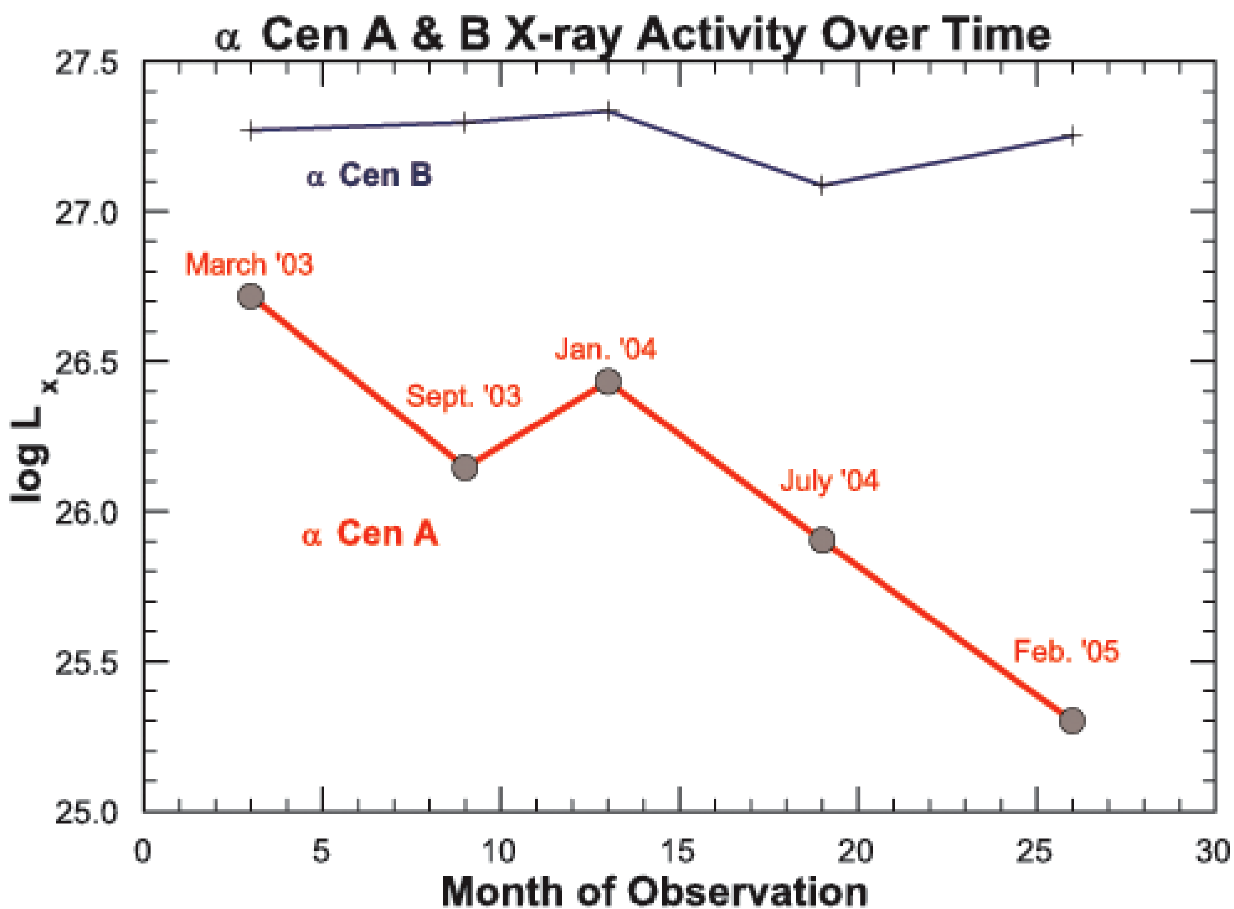

# Studying the Remarkable Decrease in X-ray Activity Recently Observed in $\alpha$ Cen A

**A decrease of 26x in 2 years!**

(Robrade, Schmitt & Favata (2005), A&A, 442)

# The Sun and other solar-type stars are full of surprises. Complementary FUSE Observations are planned (Proposal #: 05-FUSE7-0075) for $\alpha$ Cen A & B during 2006.

- O VI and C III will probe the behavior of plasmas in the 50,000 – 500,000 K range.
- Study changes in FUV irradiance during deep activity minimum.
- Infer Sun's FUV emission during its Maunder Minimum (1700's)



Our Whole-hearted thanks

goes to the FUSE Science

and Engineering Teams