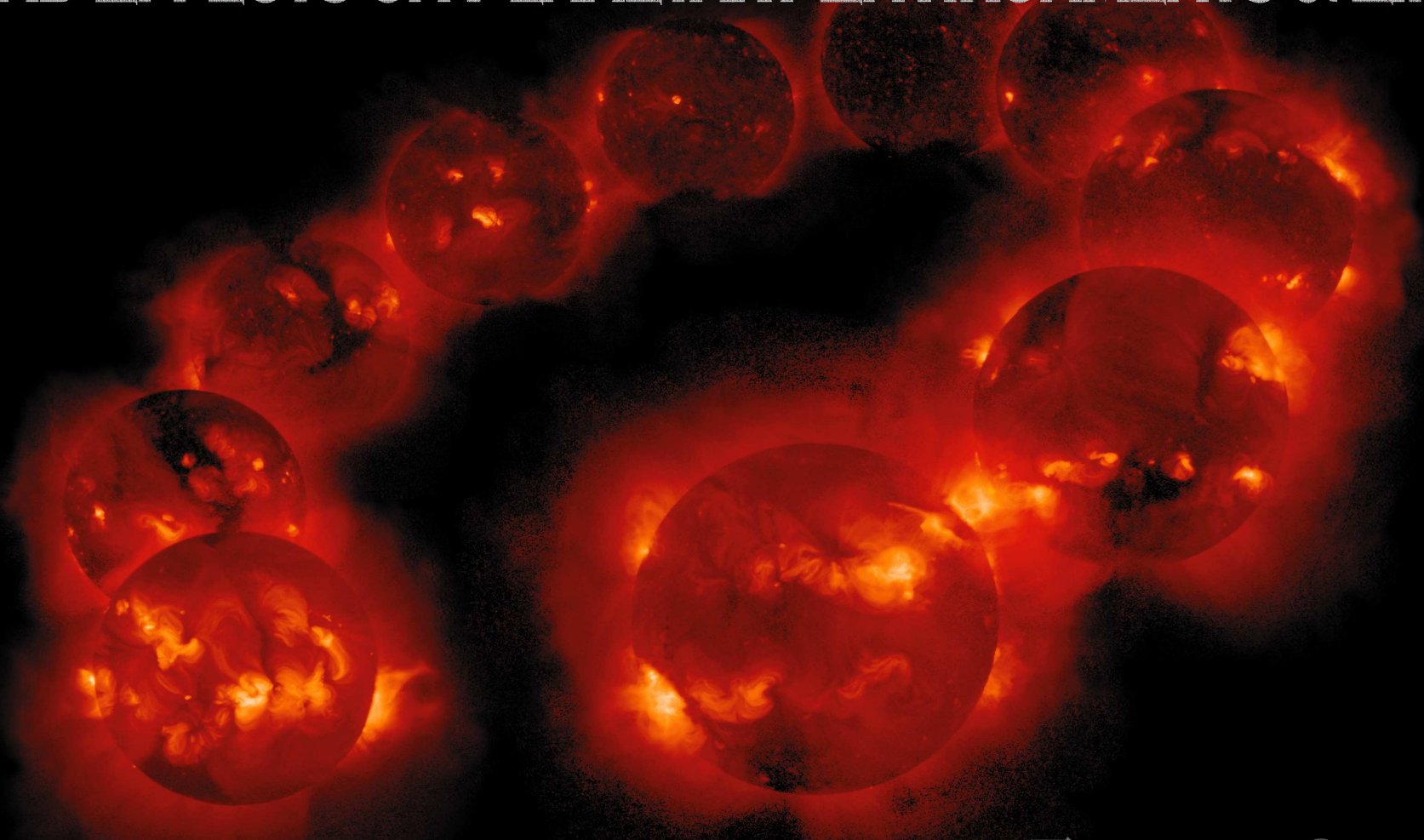


# HIGH ENERGY XUV EMISSION OF THE PALEO-SUN AND EFFECTS ON PLANETARY ENVIRONMENTS & LIFE



**EDWARD GUINAN**

**VILLANOVA UNIVERSITY**

# **OUTLINE**

- I. The Sun in Time Program:  
Background & Science Rational**
- II. Rotation-Age-Activity Relations and  
Irradiances for Solar-like Stars**
- III. Effects of the Young Sun's High XUV  
Emissions and Wind Fluxes on  
Paleo-Planetary Environments**
- IV. Summary and some conclusions**

# **COLLABORATORS**

## **“Sun in Time” Program**

### **Solar/Stellar Magnetic Activity and Dynamics**

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**Laurence DeWarf**

**Scott Engle**

**Manuel Güdel**

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**Catania, Italy**

**Univ. of Colorado, CASA**

**Univ. of Colorado, CASA**

**Villanova University**

### **Planets, Paleoplanets, and Exoplanets**

**Helmut Lammer**

**Manfred Cuntz**

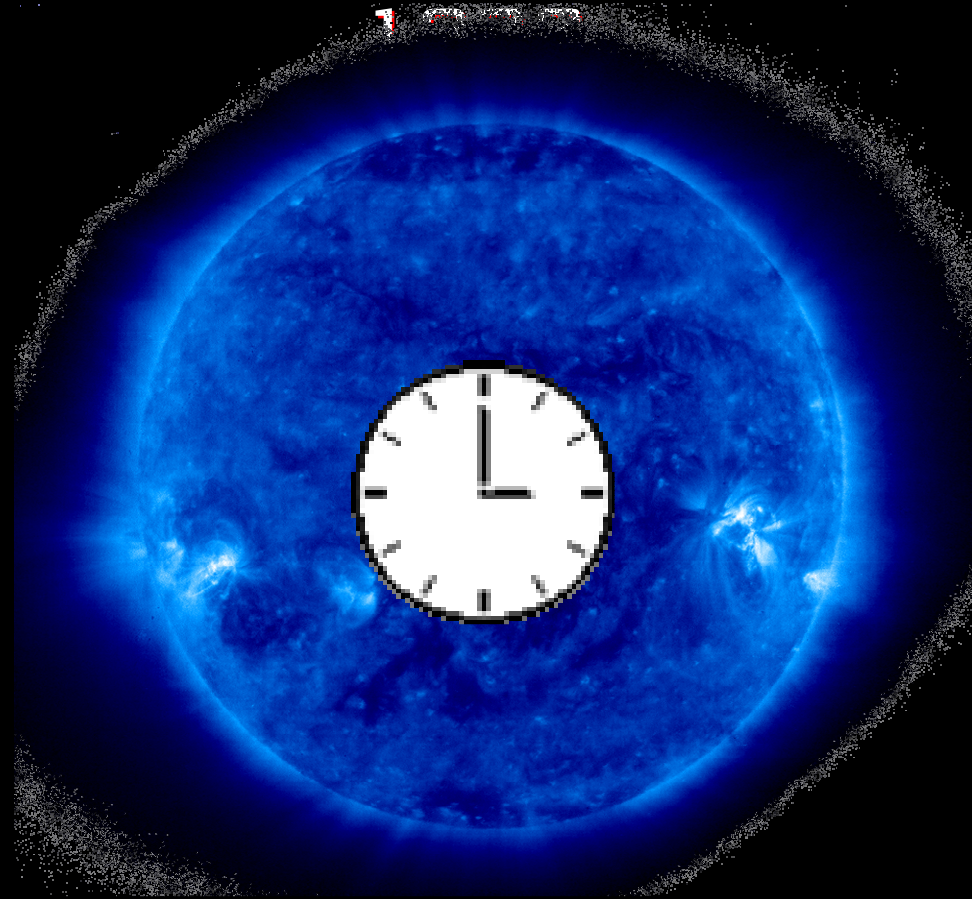
**Dirk Schulze-Makuch**

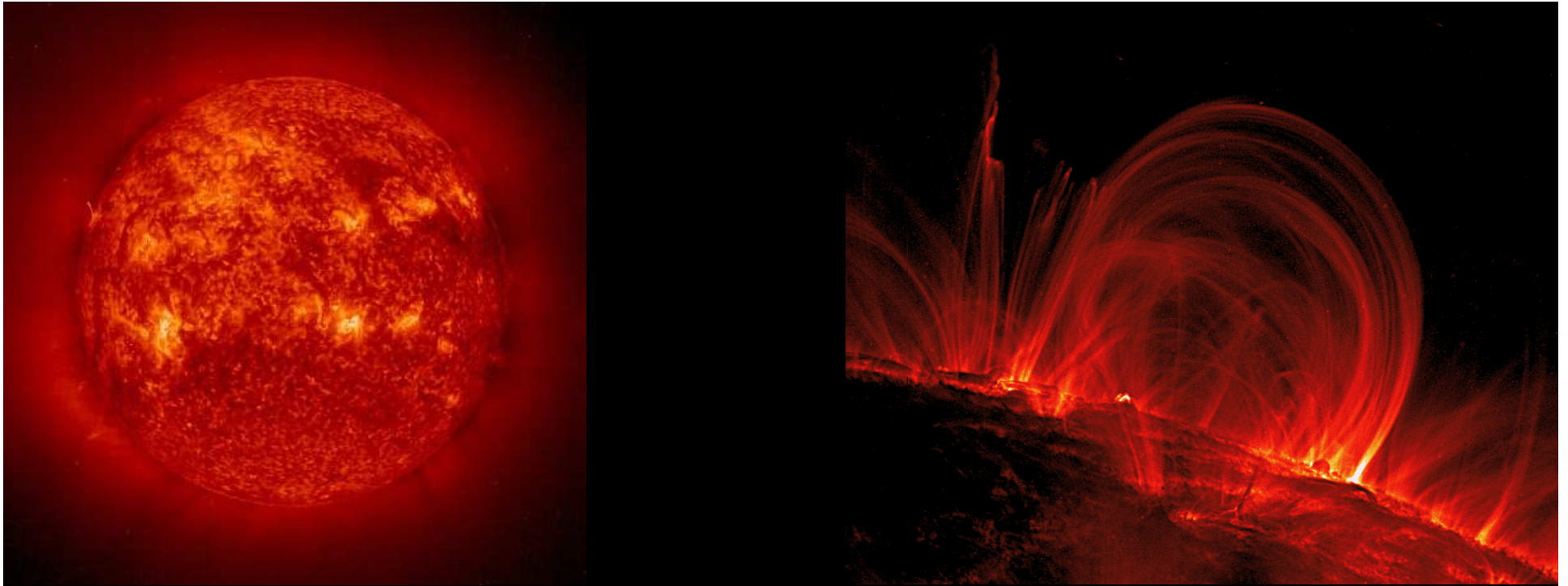
**Graz, Austria**

**Univ. of Texas, Arlington**

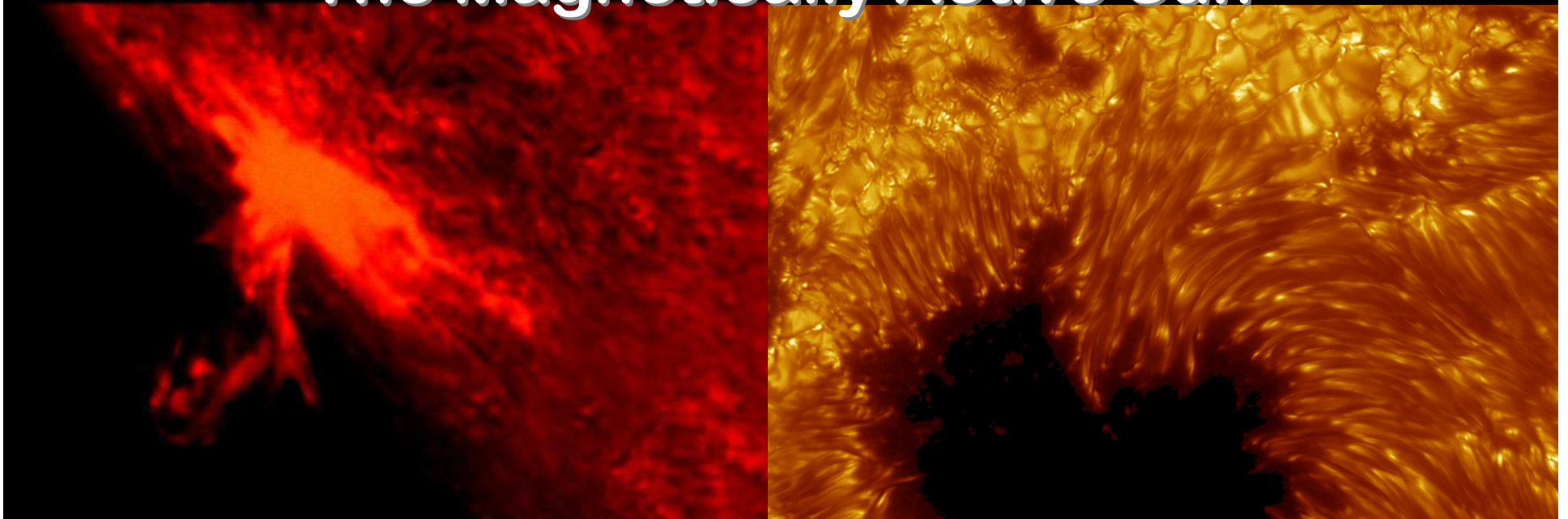
**Washington State University**

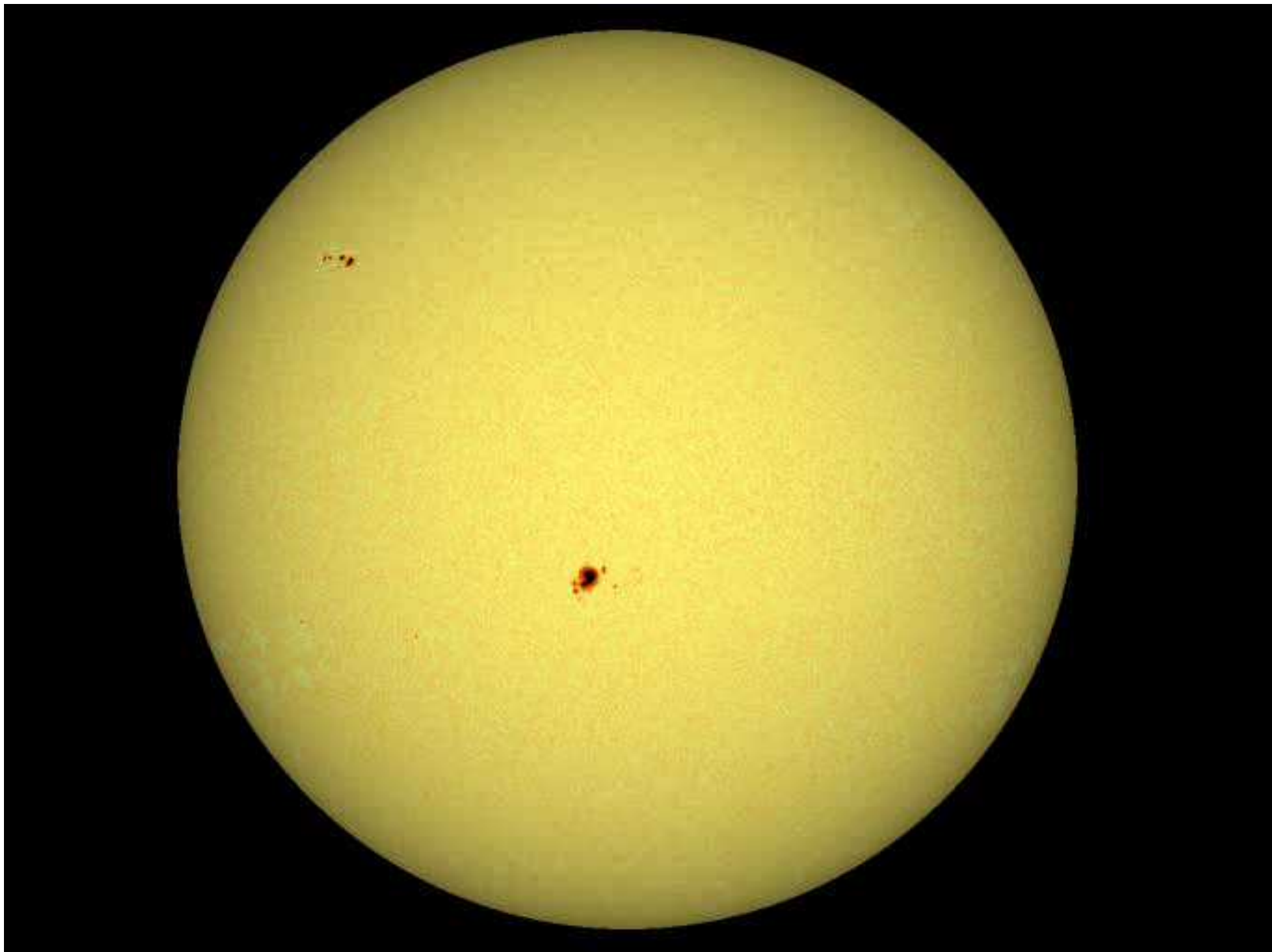
**THE “SUN IN TIME” IS A COMPREHENSIVE  
MULTI-FREQUENCY PROGRAM TO STUDY  
THE MAGNETIC EVOLUTION OF THE SUN  
THROUGH SOLAR PROXIES STARTED IN**





# The Magnetically Active Sun

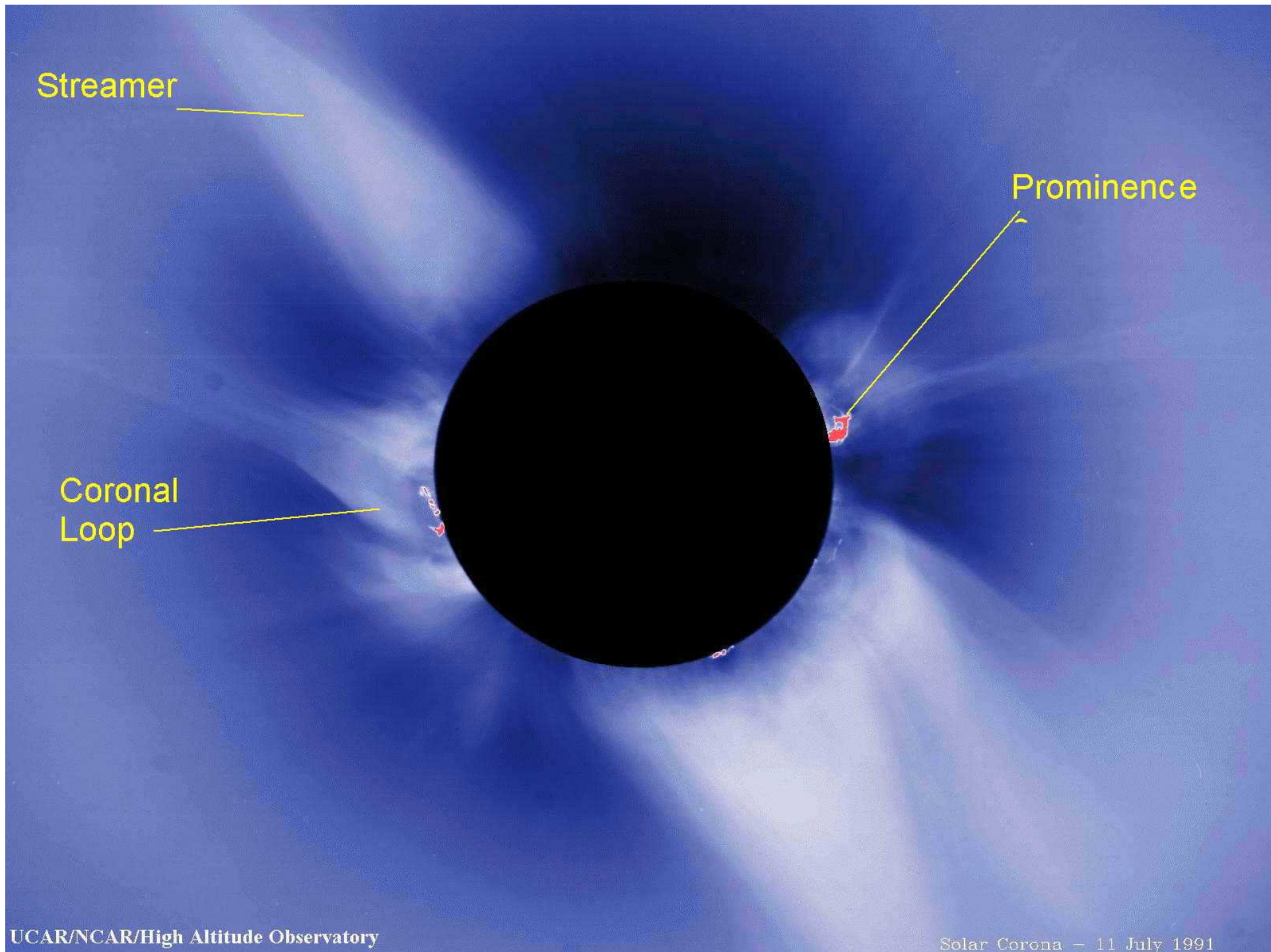


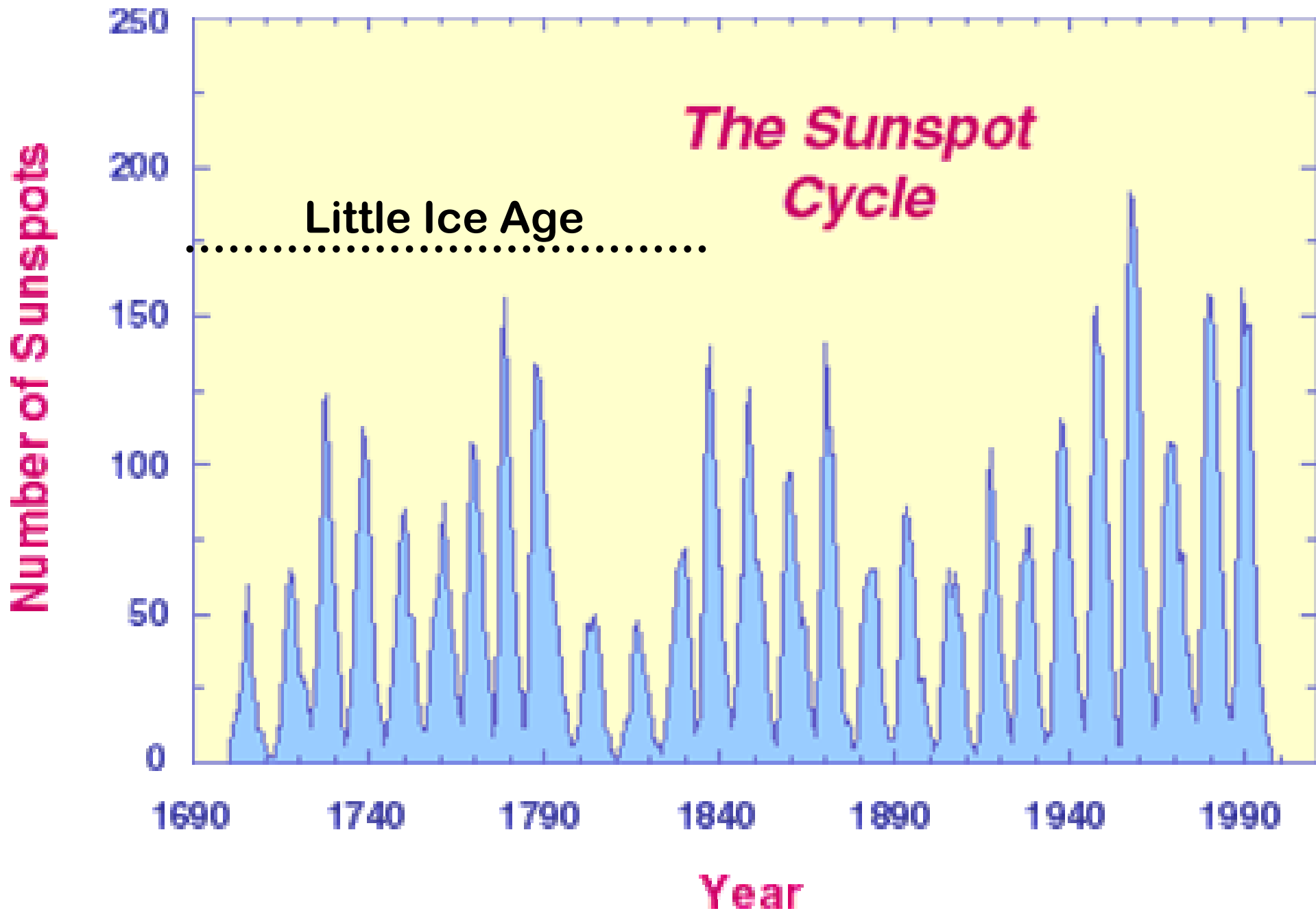


Streamer

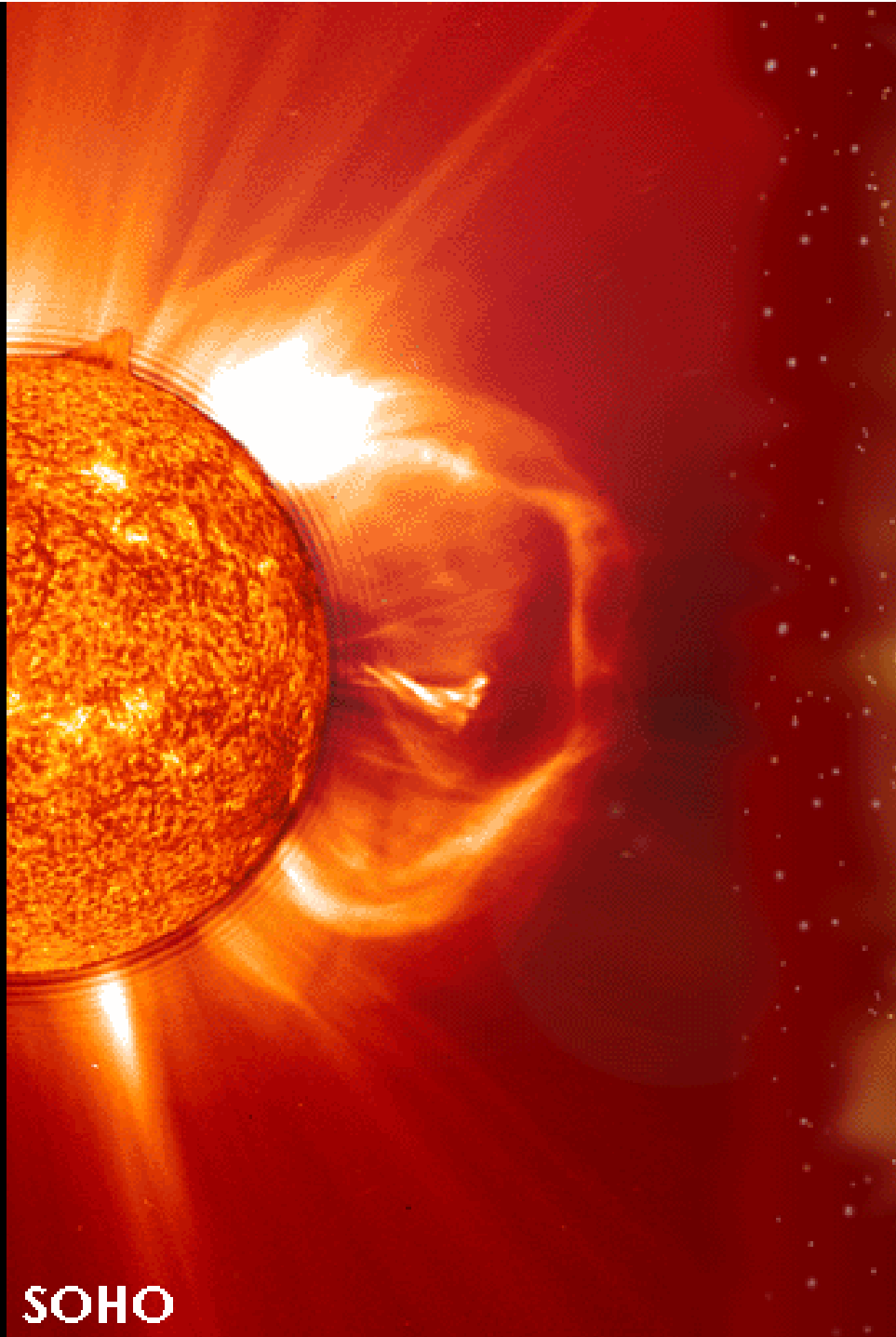
Prominence

Coronal  
Loop









SOHO




*(C) Daryl Pederson*

Steele Hill/NASA

The **“Sun in Time” Program** is a ~20 yr comprehensive, multi-frequency program to study the magnetic evolution of the Sun through stellar proxies with different ages.

The main features of the stellar sample are:

- Single nearby main sequence G0-5 stars (~25 primary stars)
- Known rotation periods (young dG stars rotate fast / active)
- Well-determined temperatures, luminosities and metallicities & distances
- Age estimates through membership in star clusters, moving groups, period-rot. relationships or evolutionary model fits
- **Recently extended to include dK – dM stars (~120 stars)-  
Living with a Red Dwarf Program**

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

# **OBSERVATIONAL DATA**

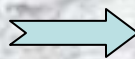
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**Multi-frequency program with observations in the X-ray, EUV, FUV, NUV, optical, IR and radio domains.**

**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; Guinan et al. 2003) 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  photo-  
ionization and photochemical reactions**

**(O<sub>2</sub>, O<sub>3</sub>, CO<sub>2</sub>, H<sub>2</sub>O, CH<sub>4</sub> ...)**

# X-RAY

*ROSAT*



*ASCA*



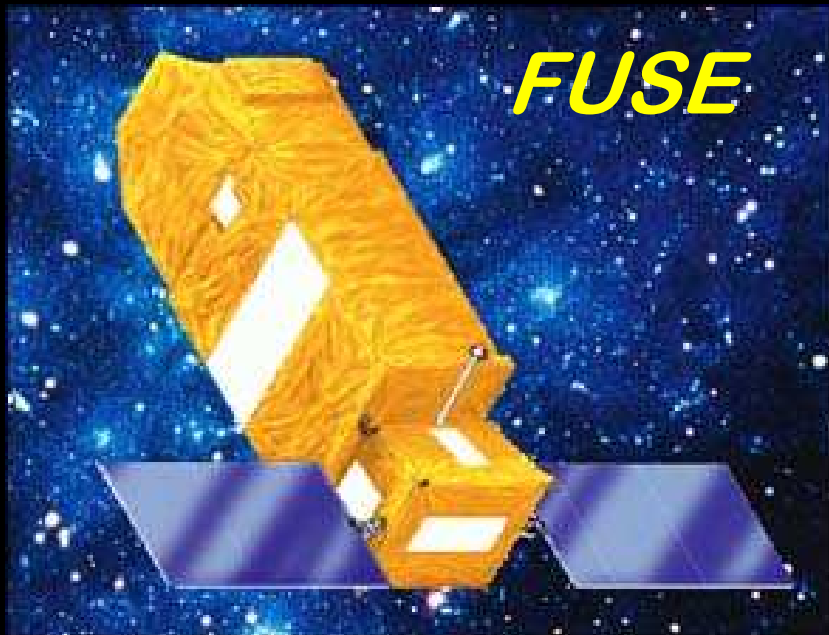
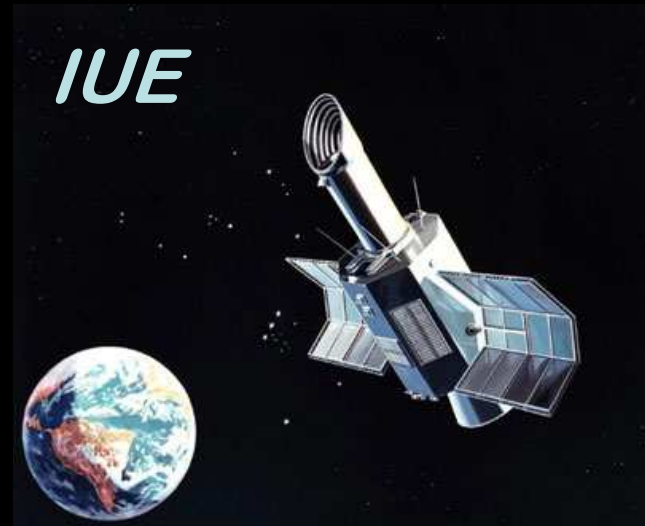
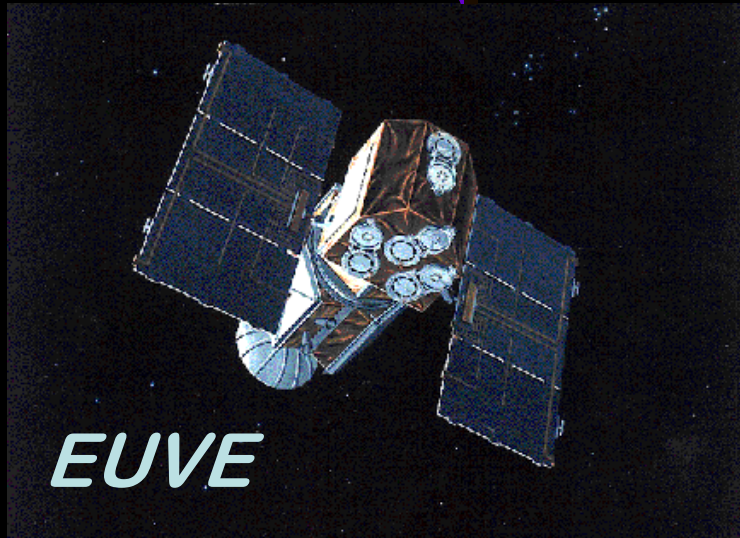
*XMM*



*Chandra*



# EUV/UV

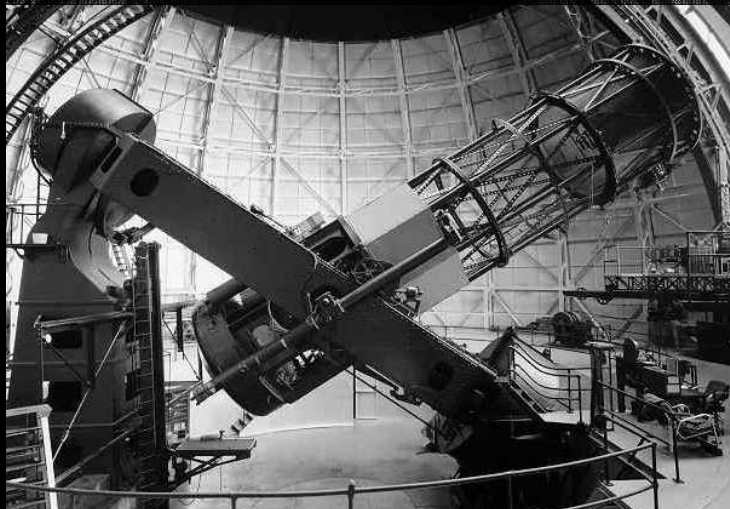


# OPTICAL

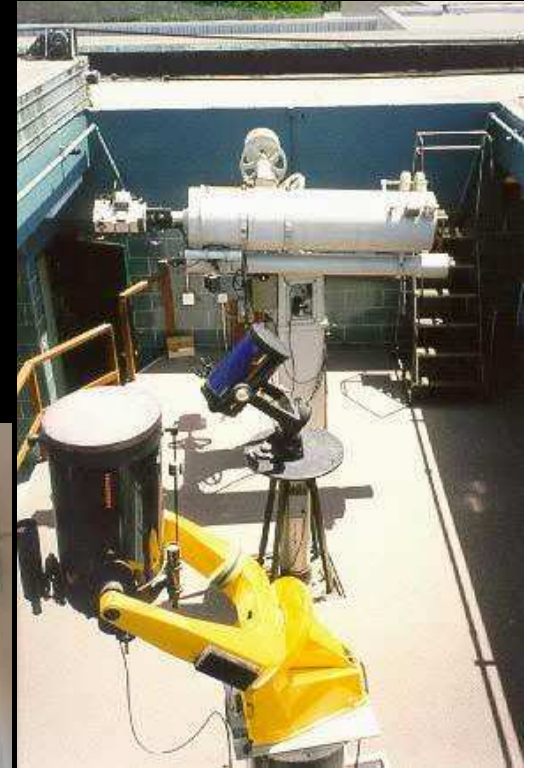
*FCAPT*



Mt. Wilson 100"

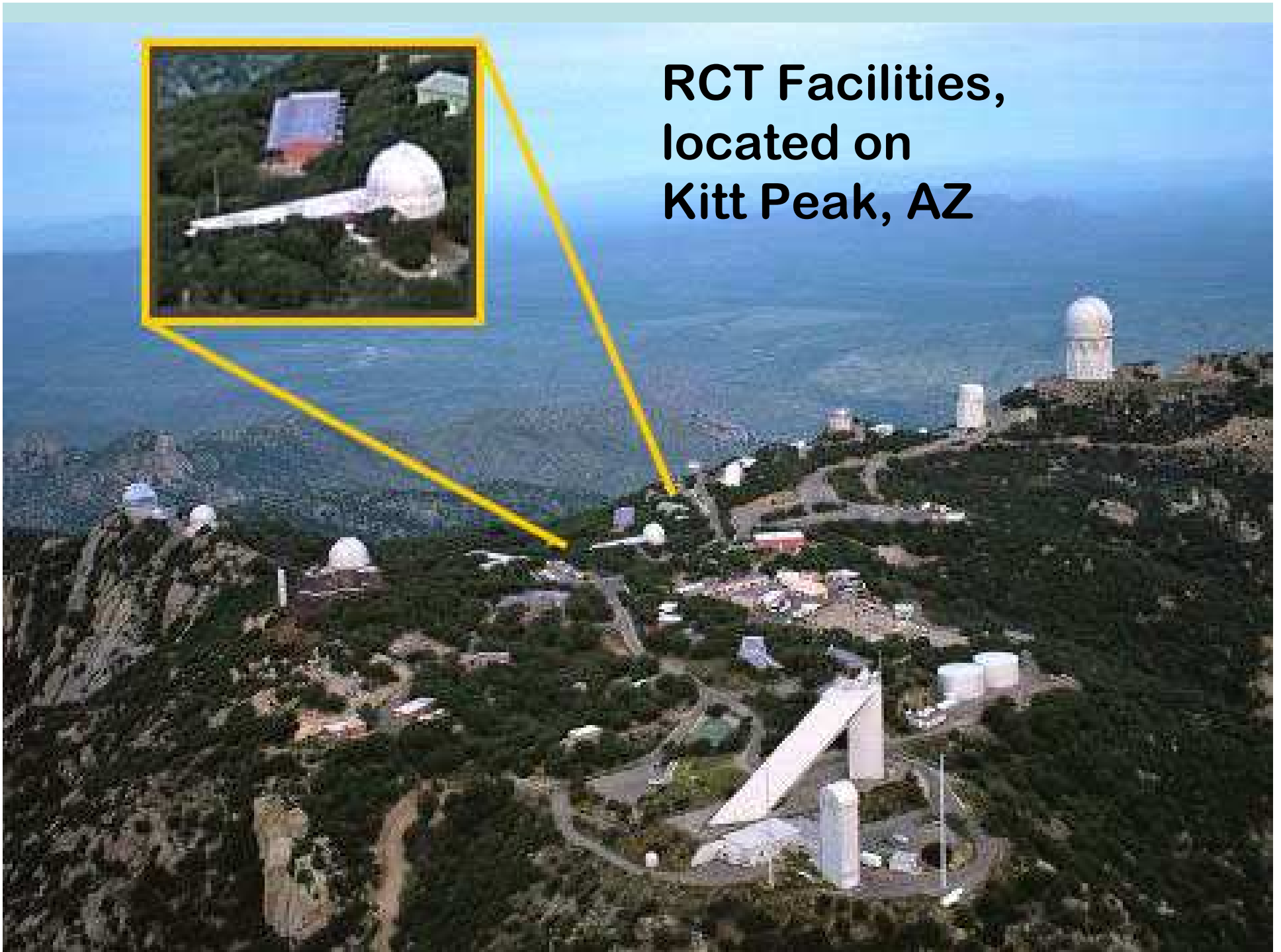


*VU 15"*



**RCT**

**RCT Facilities,  
located on  
Kitt Peak, AZ**

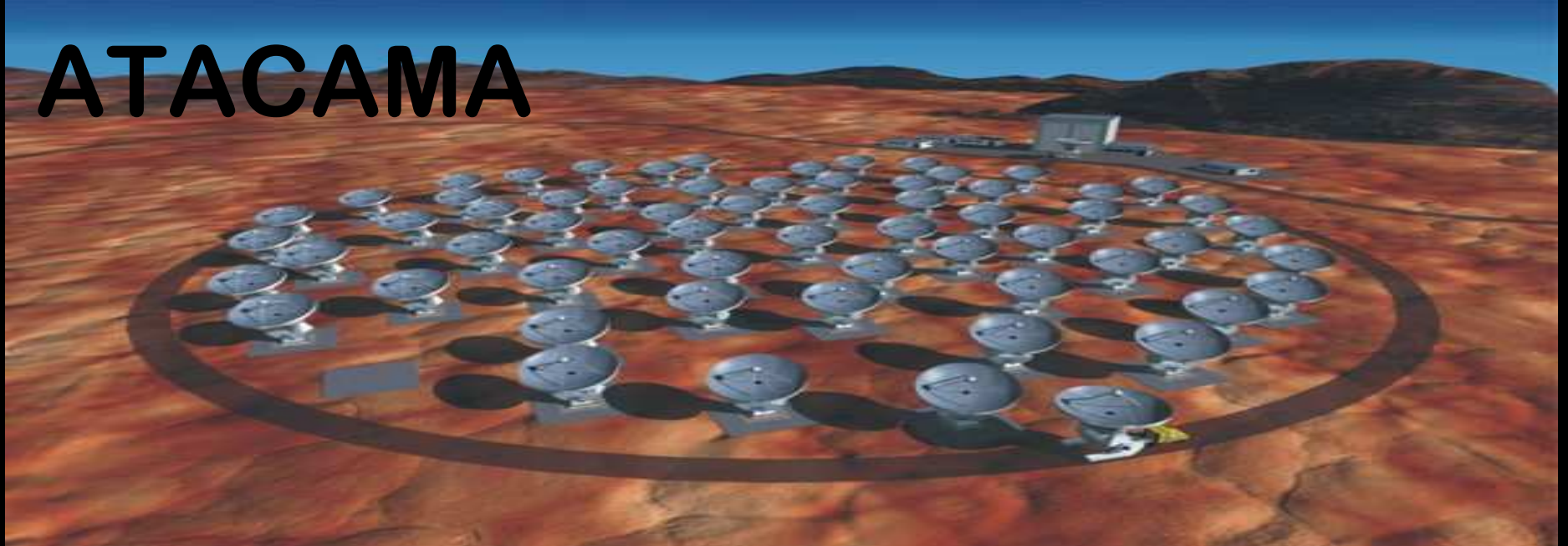


# RADIO



VLA

**ATACAMA**

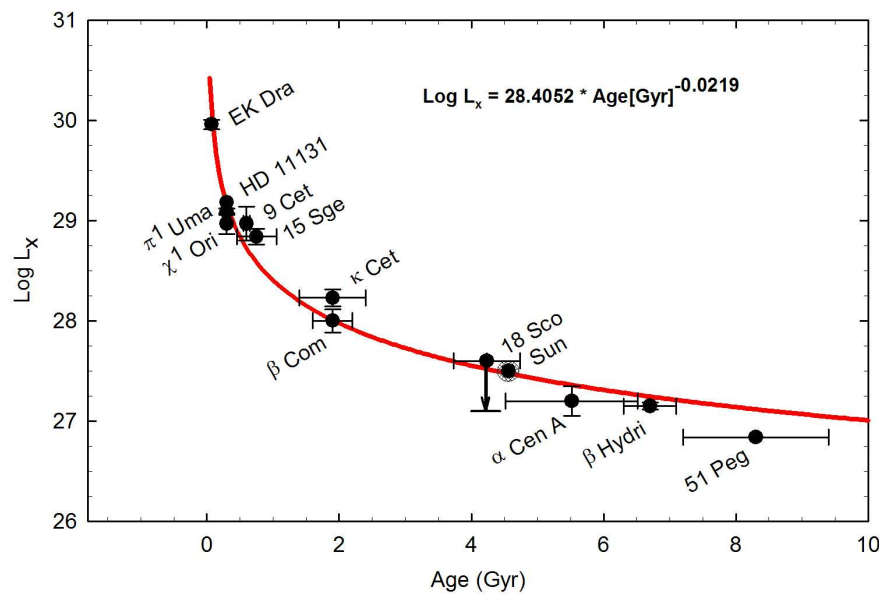




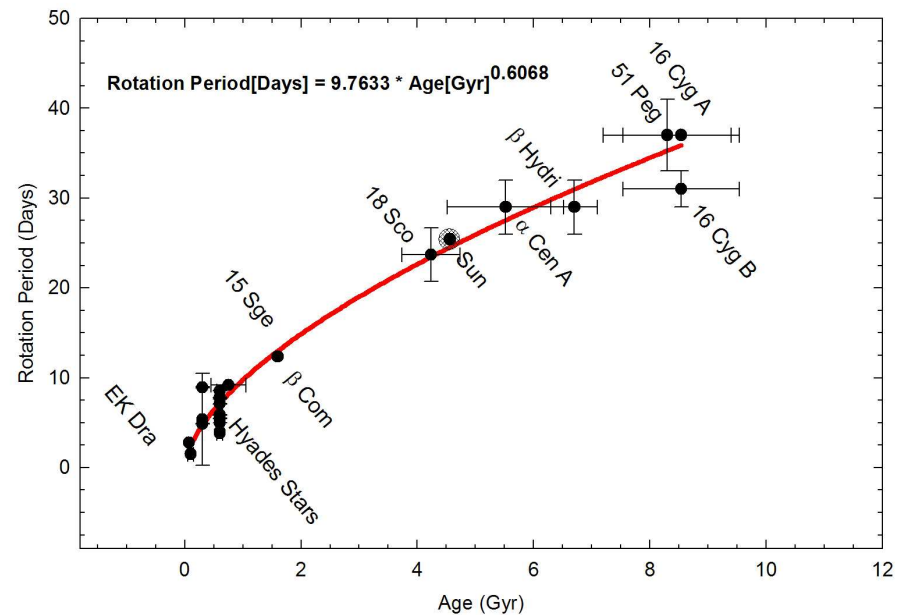
# Results

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

Log  $L_x$  vs. Age



Rotation Period vs. Age



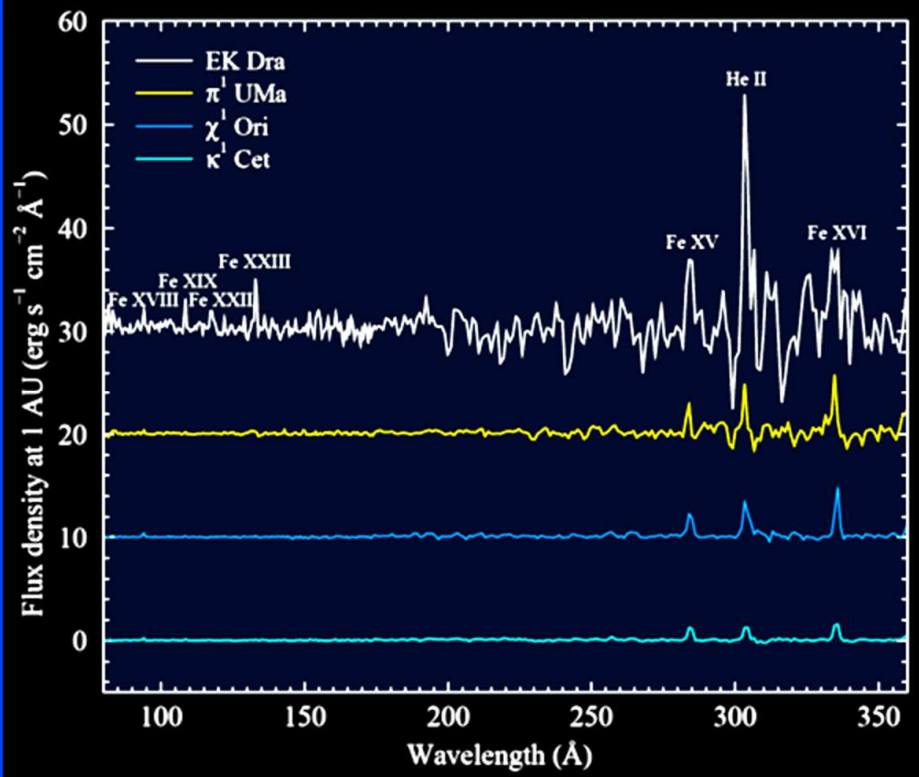
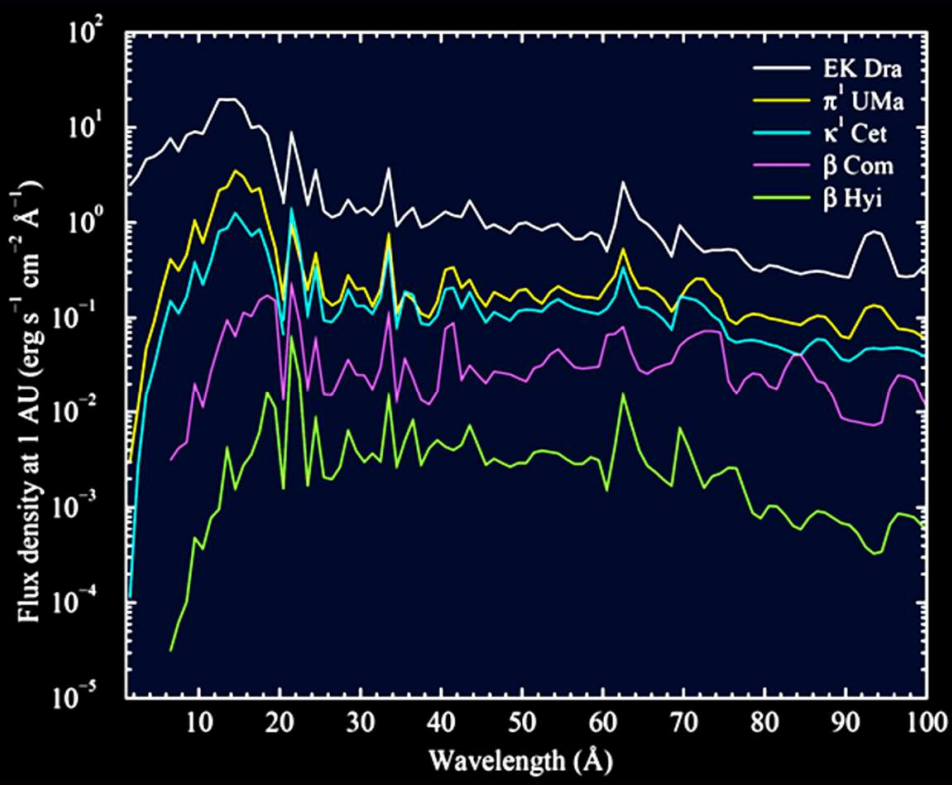
Age vs. X-ray Luminosity ( $\log L_x$ )

Age vs. Rotational Period

CORONAL

← X-RAY

(ROSAT)



EUV

(EUVE) →

CORONAL

EMISSION

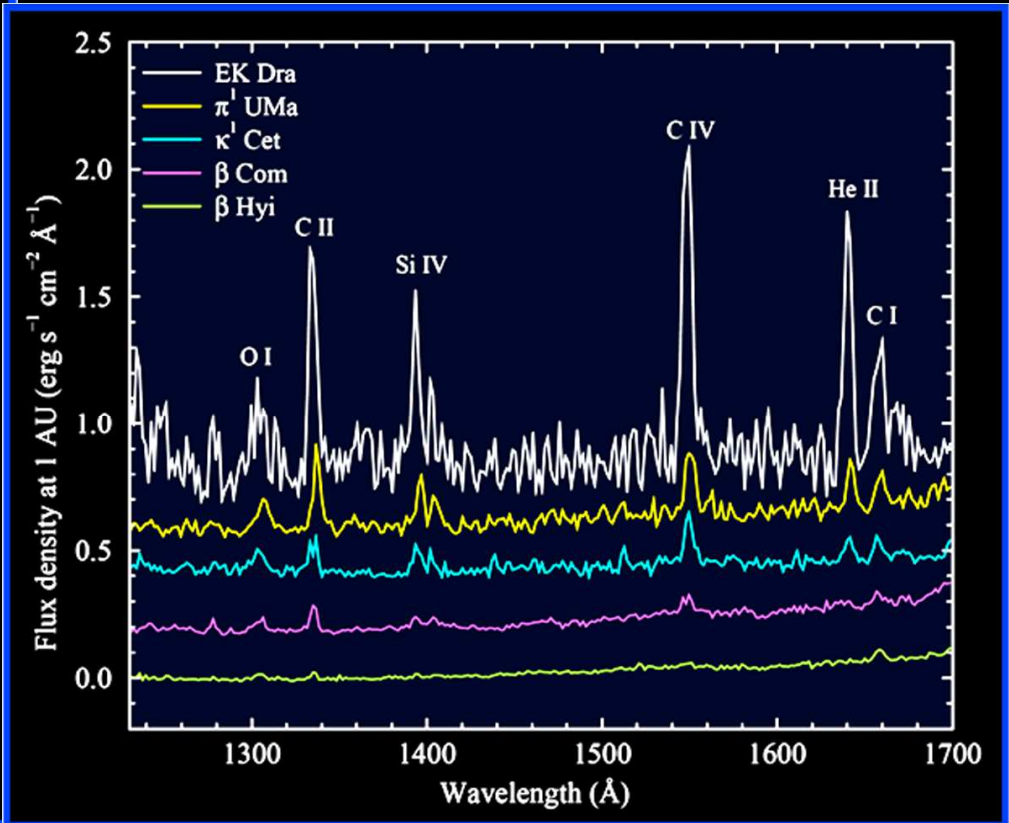
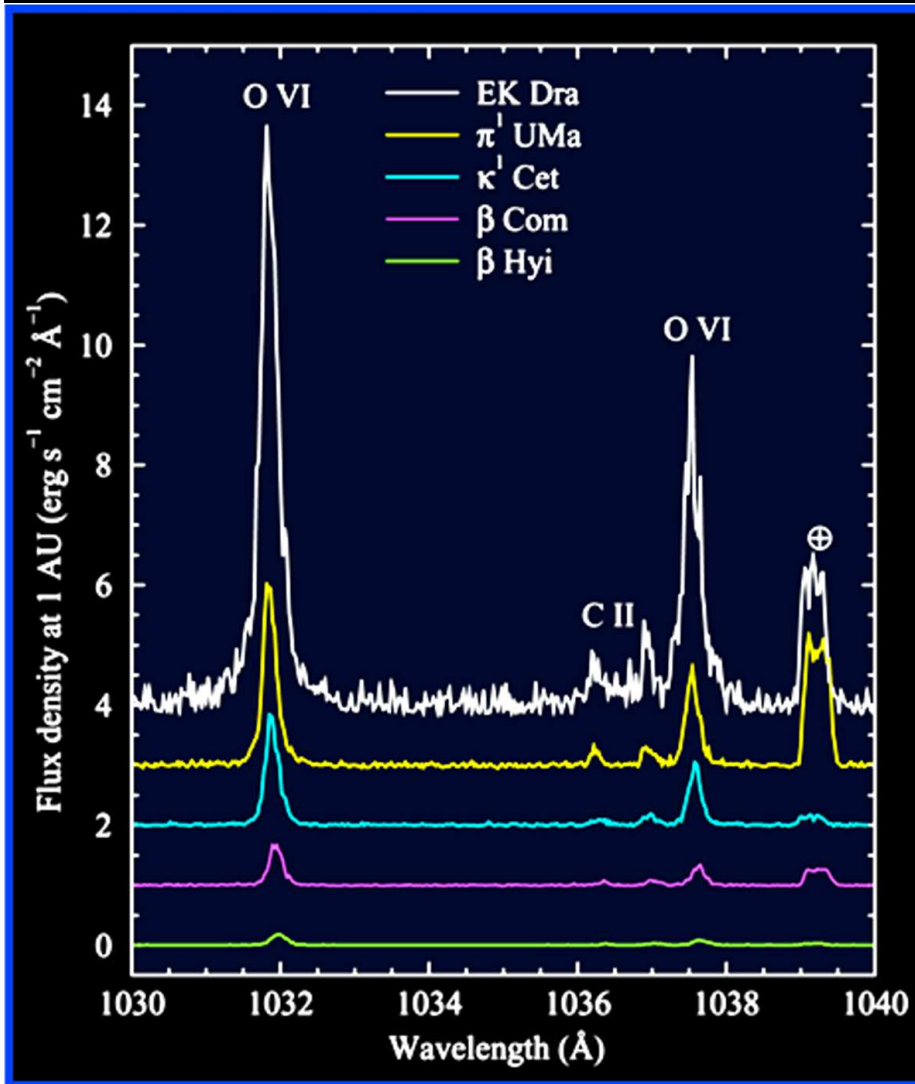
# FUV (FUSE)

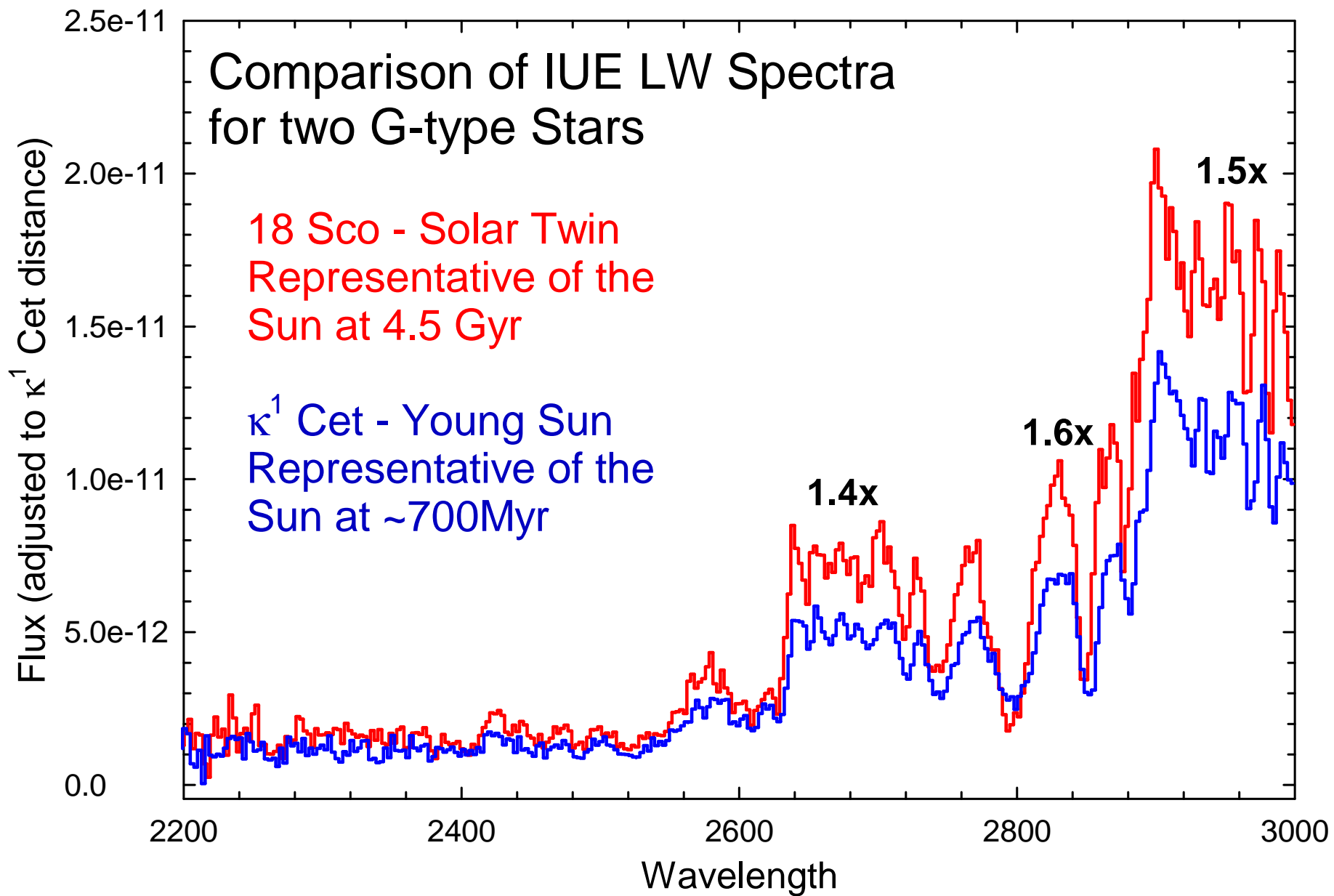
TRANSITION REGION  
CHROMOSPHERIC  
CORONAL

# FUV / UV

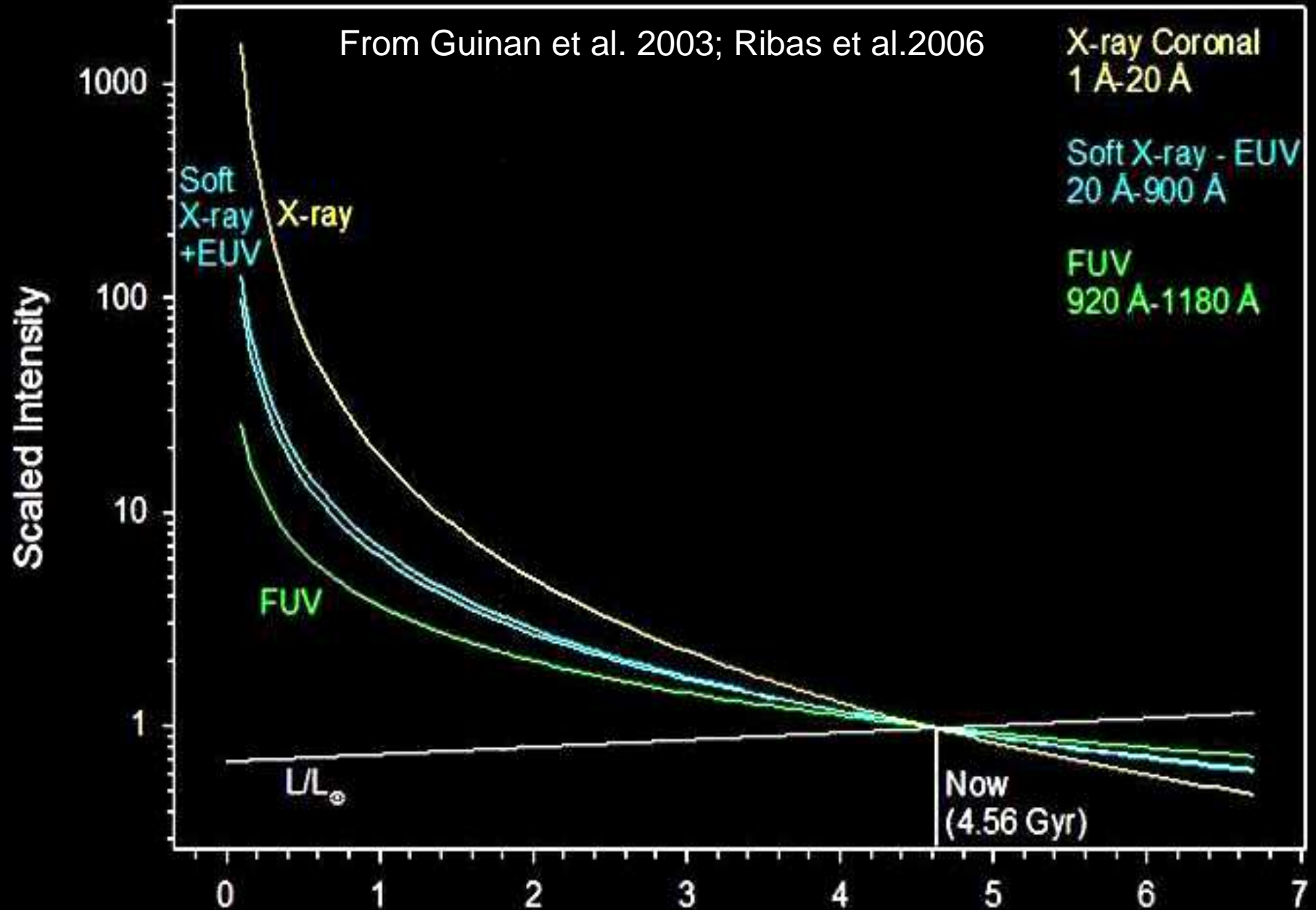
(FROM IUE)

TR / CHROMOSPHERIC  
EMISSIONS

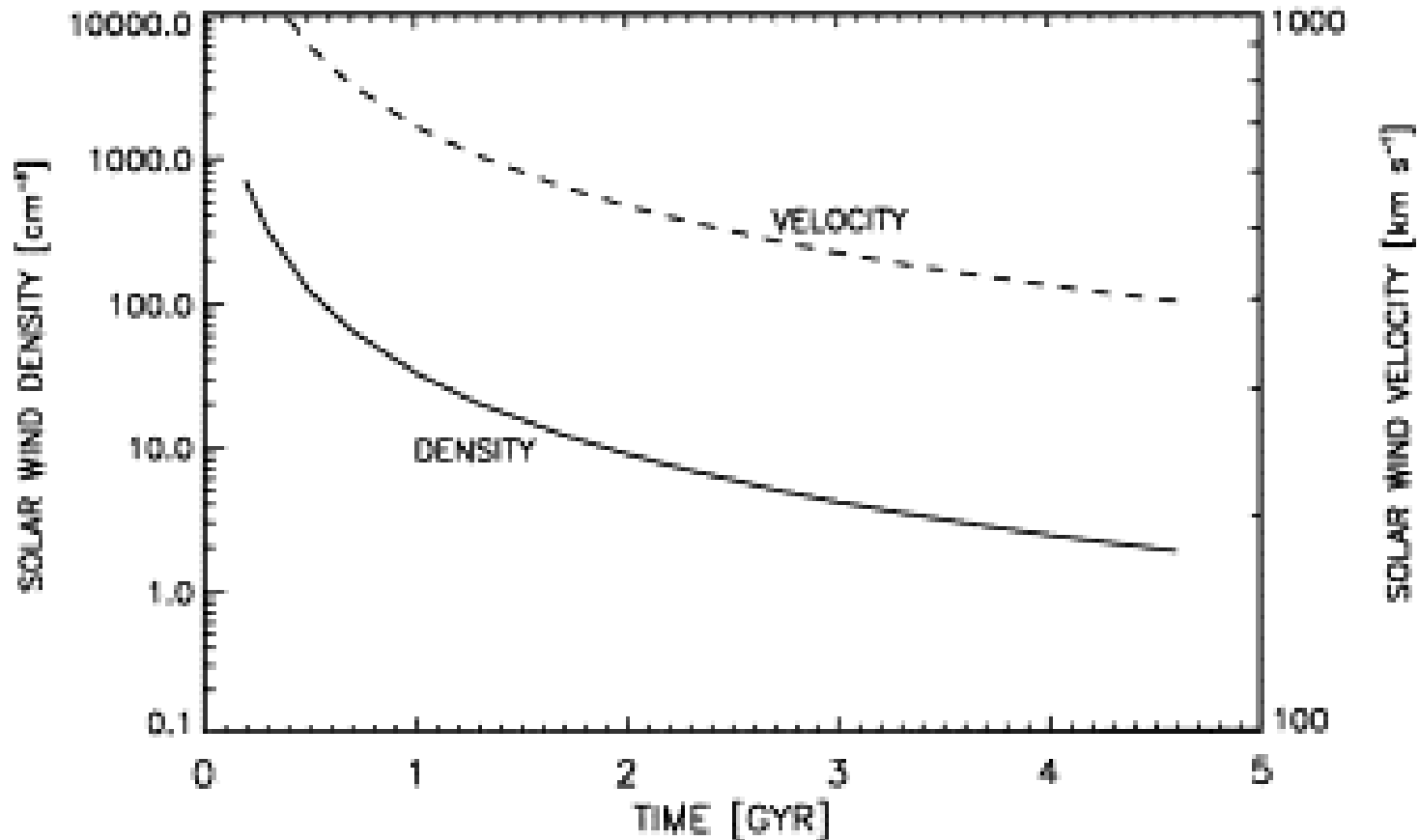


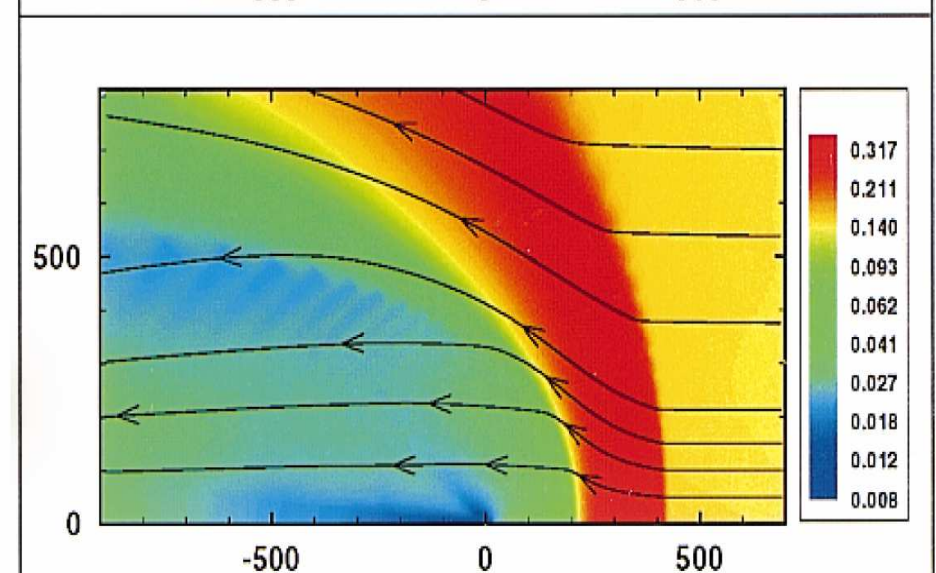
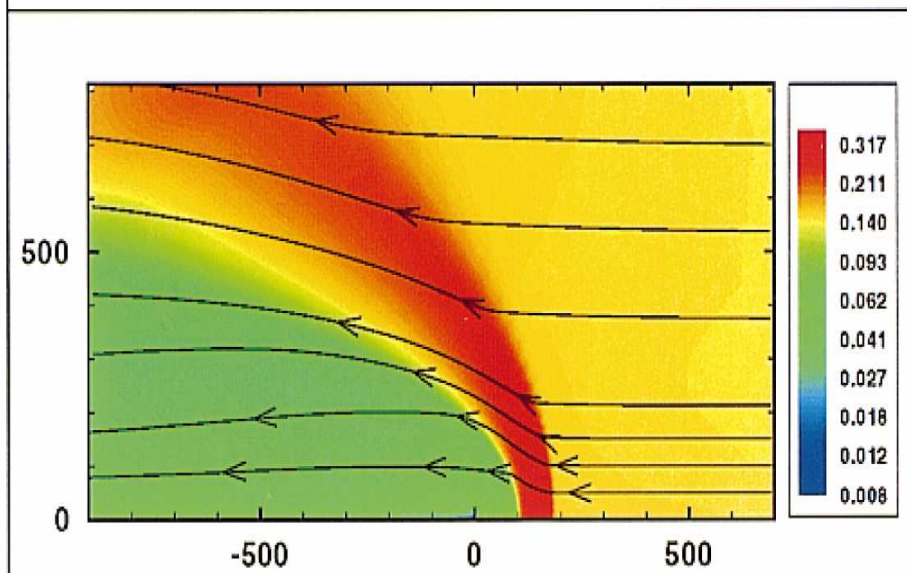
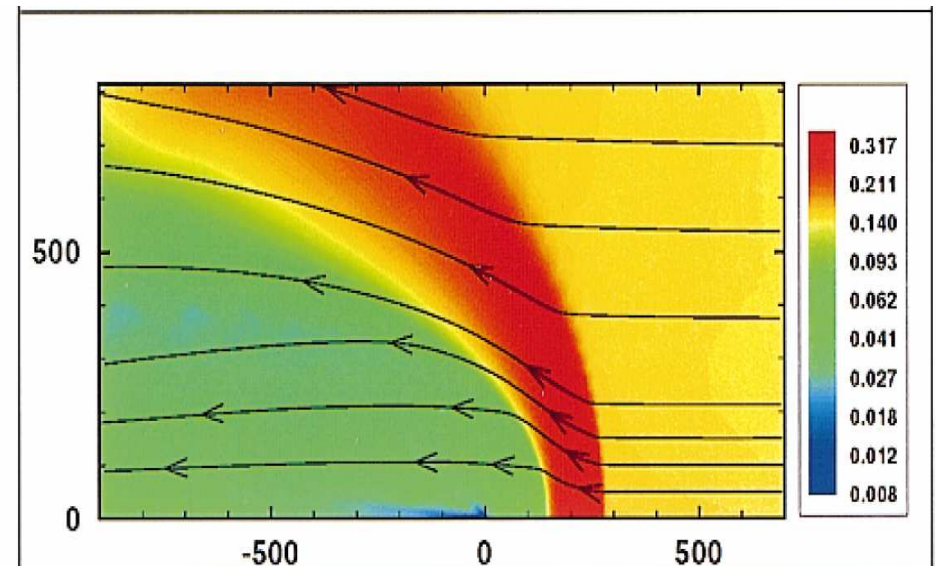
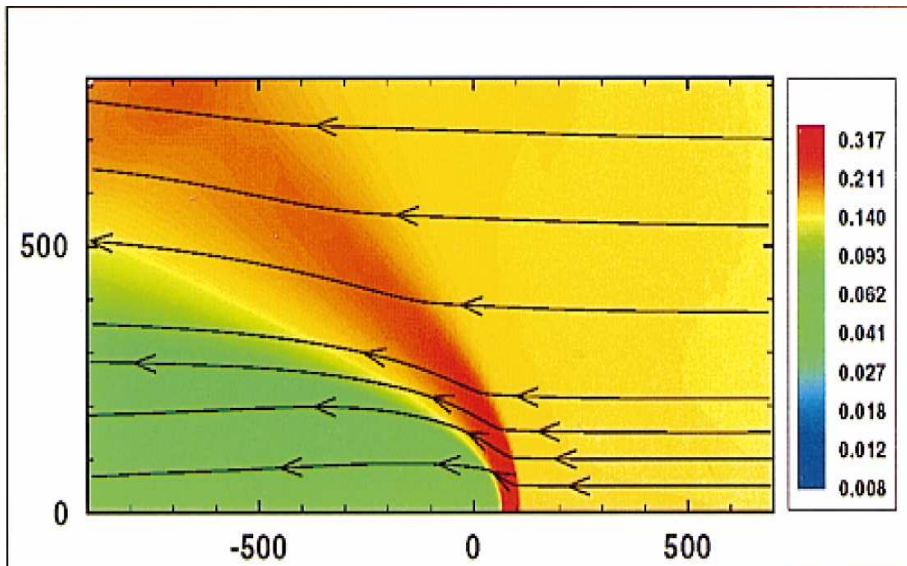


# For the Sun from Solar Proxies



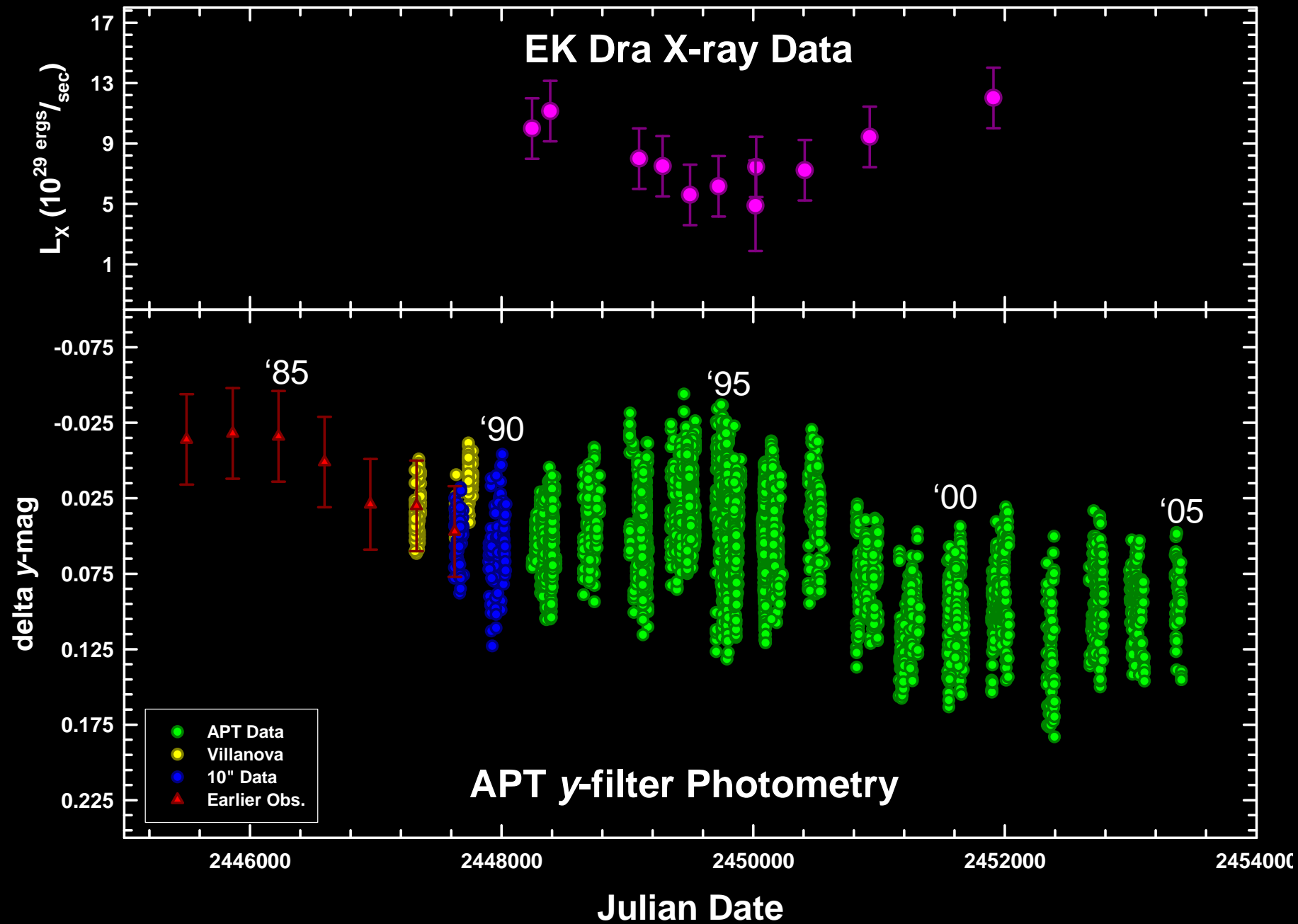
# Estimates of the Solar-wind over Time (based on Lyman-alpha /Astrosphere measures from Brian Wood (NRL))





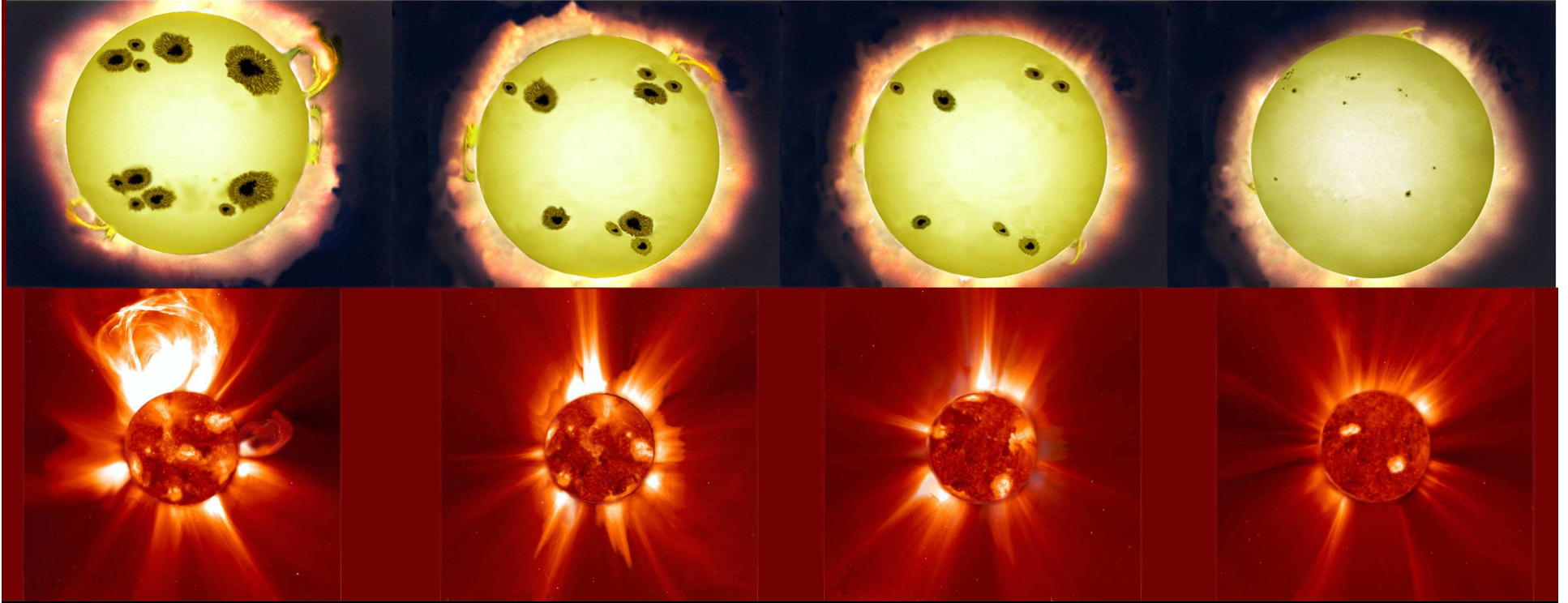
**Distribution of H I density predicted by hydrodynamic models of the  $\alpha$  Cen / Proxima Cen astrospheres, assuming stellar mass-loss rates of (from top to bottom) 0.2, 0.5, 1.0, and 2.0  $M_{\odot}$ . The distance scale is in astronomical units. Streamlines show the H I flow pattern.**

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





# OUR SUN THROUGHOUT THE AGES



Artwork by: Joseph DePasquale

# The Young Sun: A Summary of properties

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

Visible  
Wavelengths:  
70% present  
values

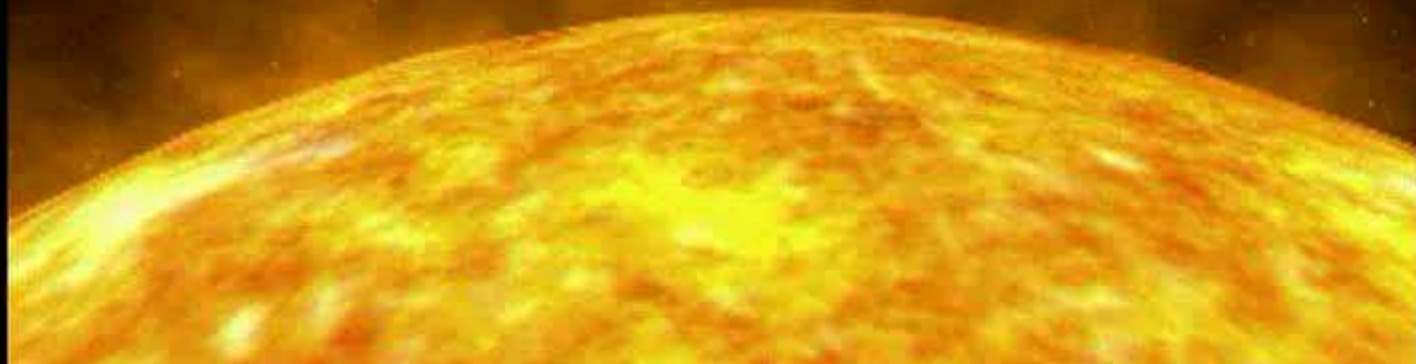
Far Ultraviolet,  
Ultraviolet: 5-80  
times present values

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

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

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

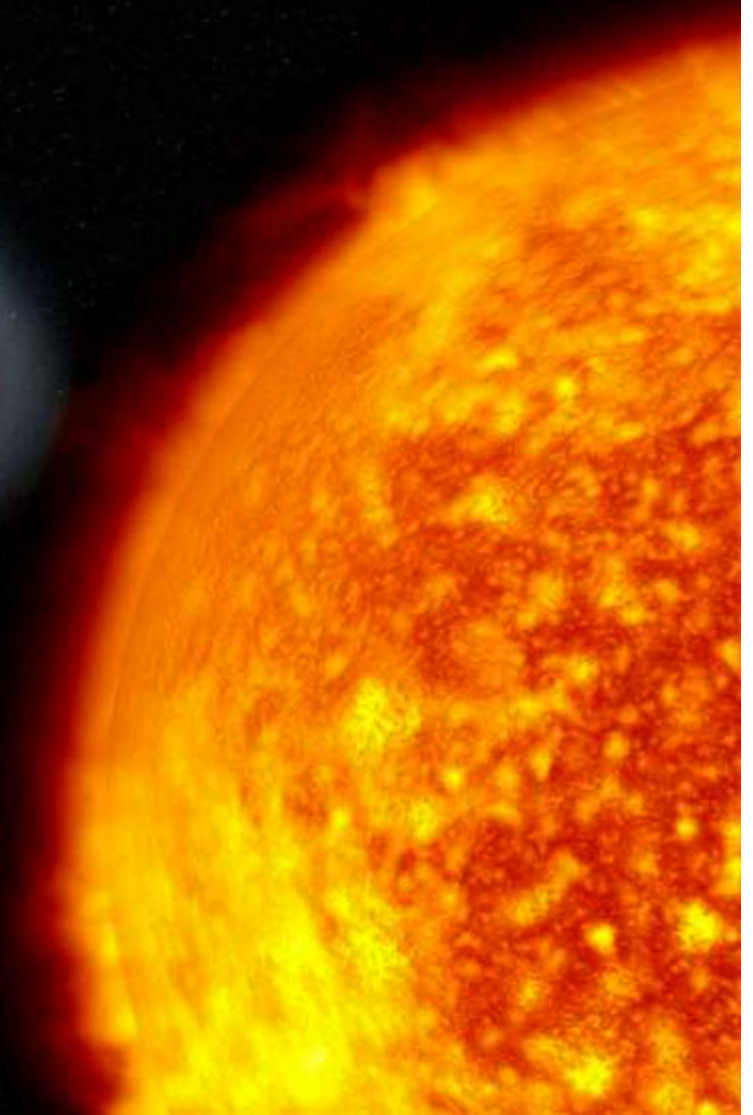
$$E_{total} \simeq 10^{33}-10^{35} \text{ ergs (Present value: } \simeq 10^{32} \text{ ergs)}$$



# THE EFFECTS OF THE ACTIVE YOUNG SUN ON PLANETS

A Planet with a weak or non-existent magnetic field will suffer the evaporation and possible loss of its atmosphere by “sputtering” processes associated with XUV radiation & winds.

See Griessmeier et al. 2004 A&A,  
425, 753



# **THE YOUNG SUN WAS NOT KIND TO ITS NEAREST PLANET MERCURY:**

## **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**

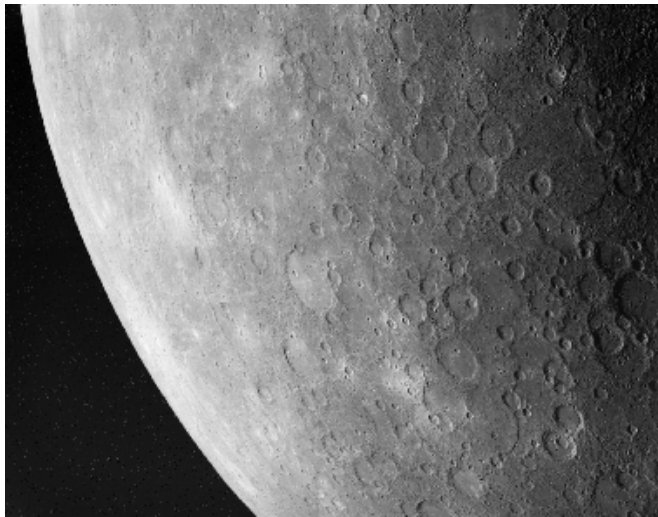
**Villanova University**

**U. de Barcelona**

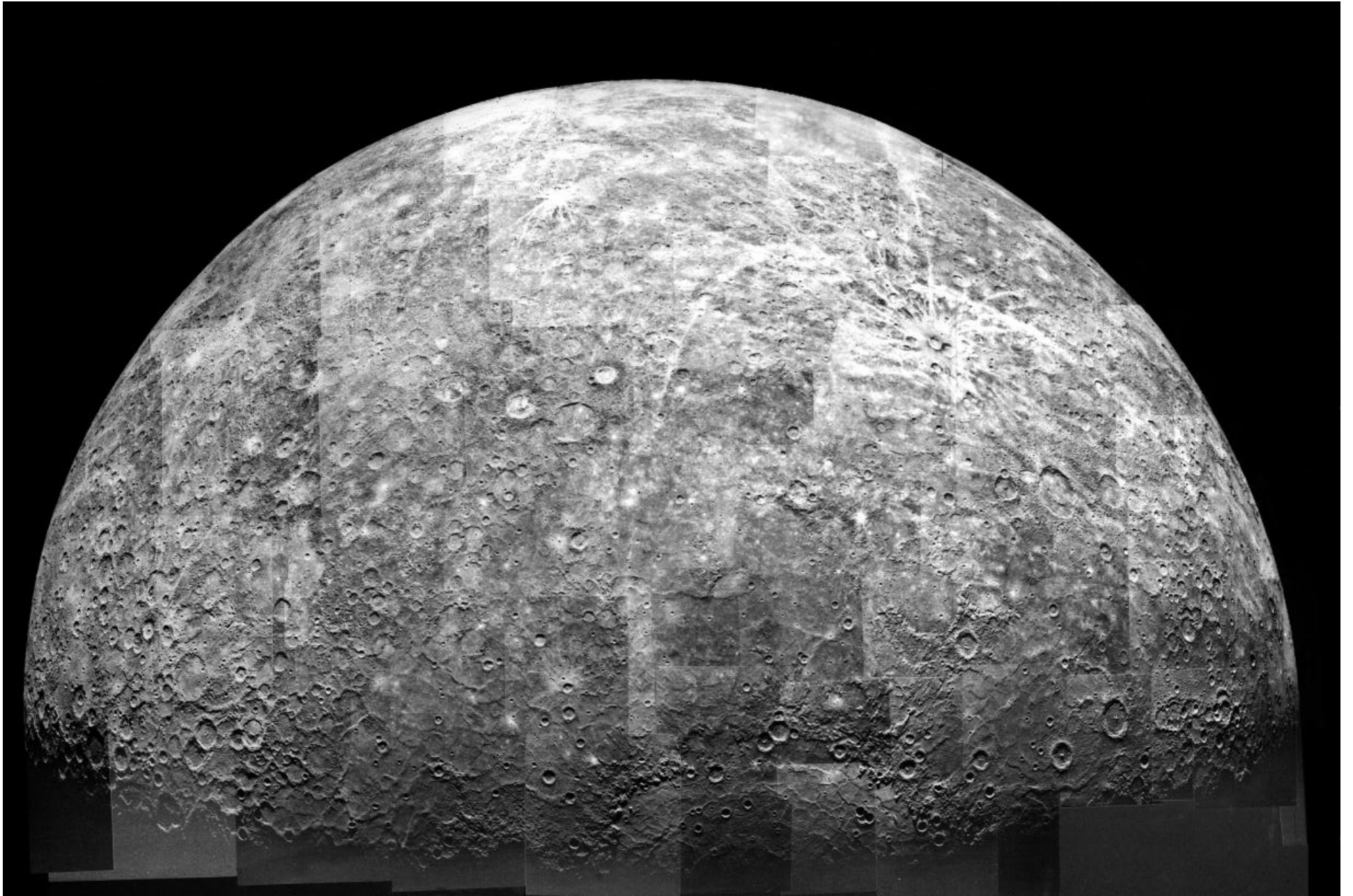
# Some Consequences of the Young Sun's Enhanced Activity and XUV Flares I: Mercury

## 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

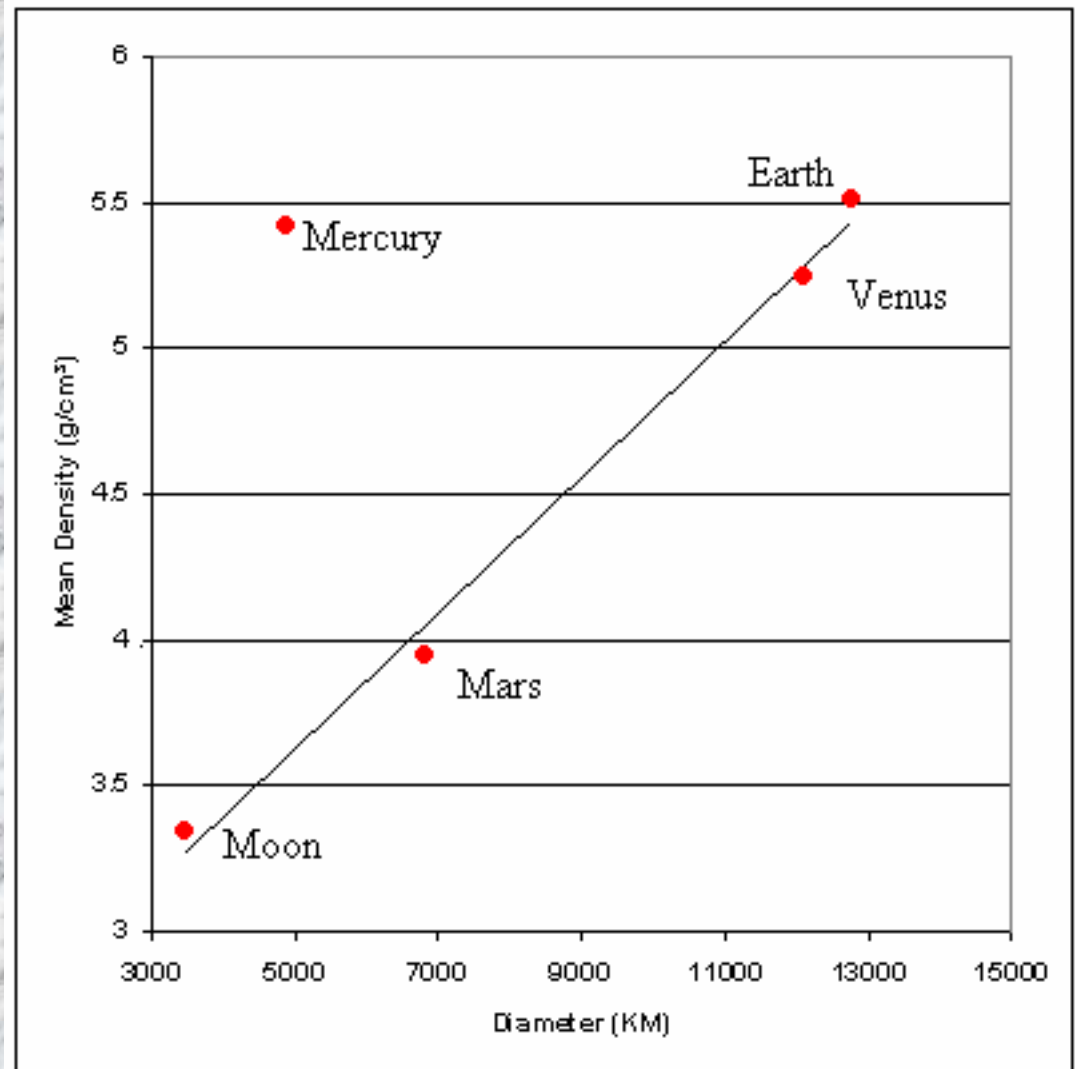


Mariner 10 Photomosaic of Mercury

Image Credit: Mariner 10, NASA

# 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.

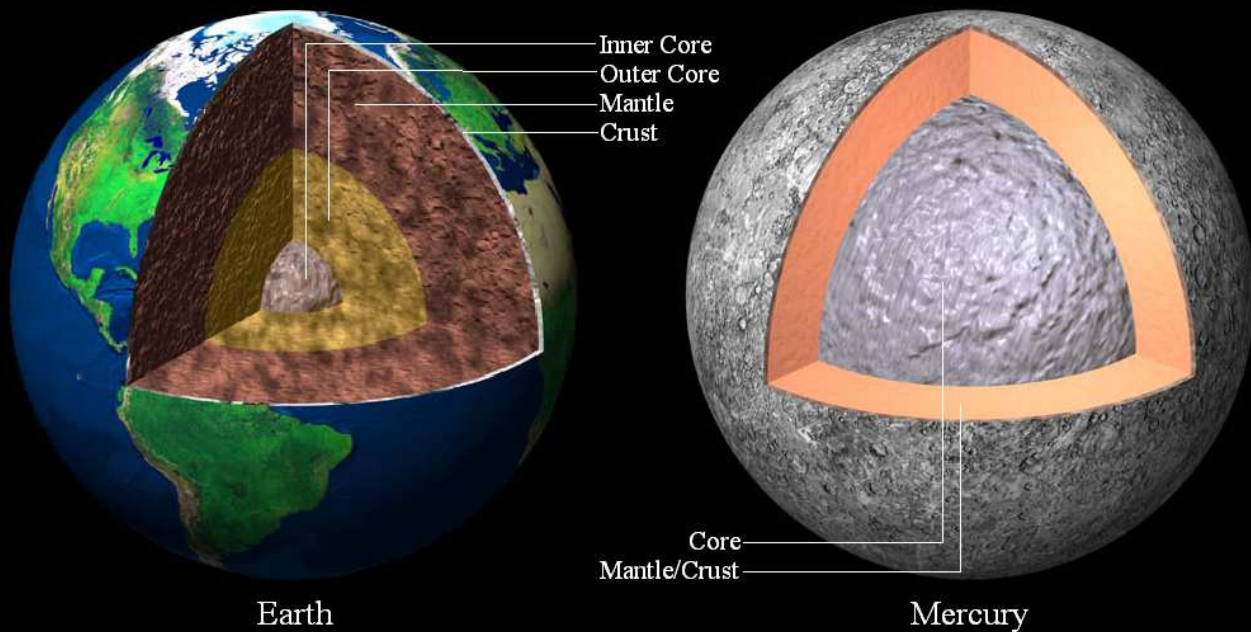




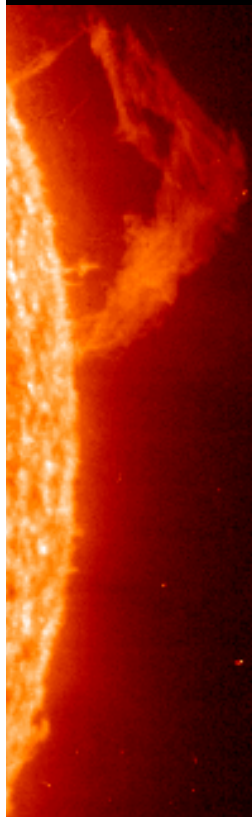
**Earth and Mercury drawn to actual scale- Illustrating the difference in size**



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



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

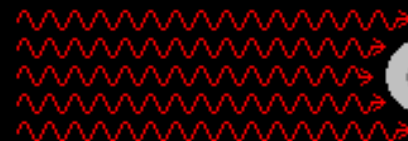


**The Active Young Sun**  
XUV: 50-1000 x  
Winds: ~1000 x  
Flares: Larger and more frequent

← **To Sun**  
**0.39 A.U.**

Mercury

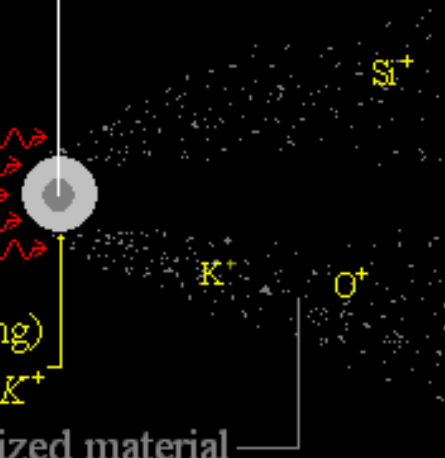
**XUV, Solar Wind Bombardment**



Ion Pickup (Sputtering)

Example:  $K \xrightarrow{\text{XUV}} K^+$

Eroded and/or ionized material



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## Atmospheric and water loss from early Venus

Yu.N. Kulikov<sup>a,\*</sup>, H. Lammer<sup>b</sup>, H.I.M. Lichtenegger<sup>b</sup>, N. Terada<sup>c,d</sup>, I. Ribas<sup>e</sup>, C. Kolb<sup>b</sup>,  
D. Langmayr<sup>b</sup>, R. Lundin<sup>g</sup>, E.F. Guinan<sup>f</sup>, S. Barabash<sup>g</sup>, H.K. Biernat<sup>b</sup>

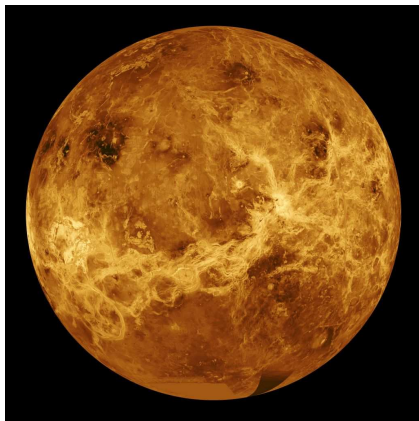
# Magellan synthetic aperture radar mosaic of Venus



# 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<sub>2</sub>
- $d = 0.71$  AU



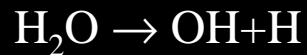
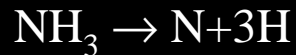
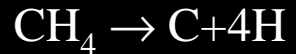
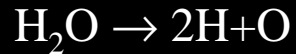
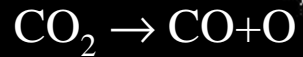
- Photochemistry/photoionization Effects
  - Venus has a slow rotation period ( $P_{\text{rot}} = 243$  days) and a very weak magnetic dynamo.
  - Venus is thus not protected from the Sun's plasma by planetary magnetic field.
- Investigate evolution of the Venus' atmosphere
  - Maybe the young Sun's enhanced activity played a major role?  
(e.g. )



# EARTH



Lyman  $\alpha$  – FUV – UV  
emissions produce  
photochemical  
reactions:



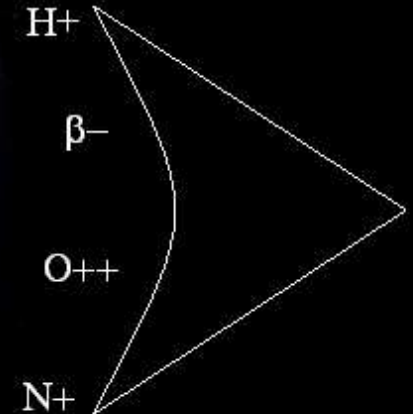
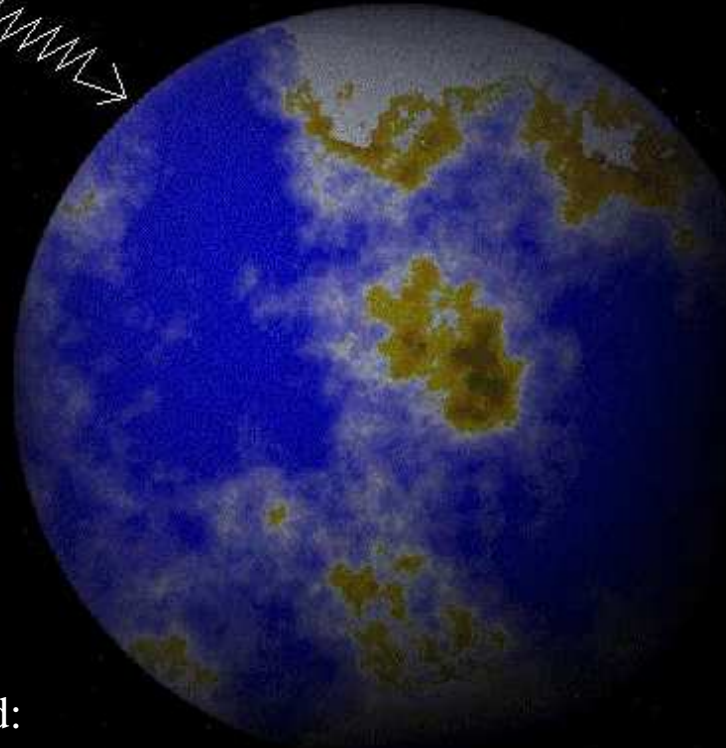
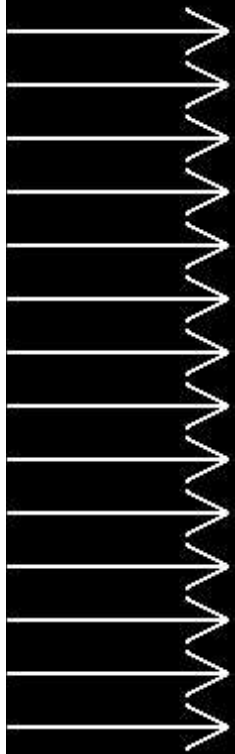
etc...

X-Ray, EUV, and Lyman  $\alpha$   
emissions heat, expand, and  
photoionize the exosphere...

...Allowing the enhanced  
Solar wind to carry away  
more atmospheric  
particles, thus causing  
atmospheric erosion

Enhanced Solar wind:  
500-1000 times  
present values

Effects of the young Sun on the Earth



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

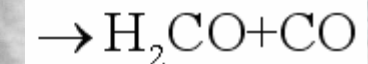
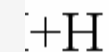
- A Young active Sun heated the Earth's atmosphere
- Problems under consideration
  - Destruction of organic molecules by radiation
  - Formation of prebiotic molecules
  - Photochemical synthesis of organic molecules
  - $\text{H}_2\text{CO}$  (formaldehyde) formation
    - Element/compound
    - Ribose, a key sugar
  - Many other consequences



the evolution of life.

strong FUV

formation of



**It's ALIVE!**



# 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<sub>2</sub>
- 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

- (280+)

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

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

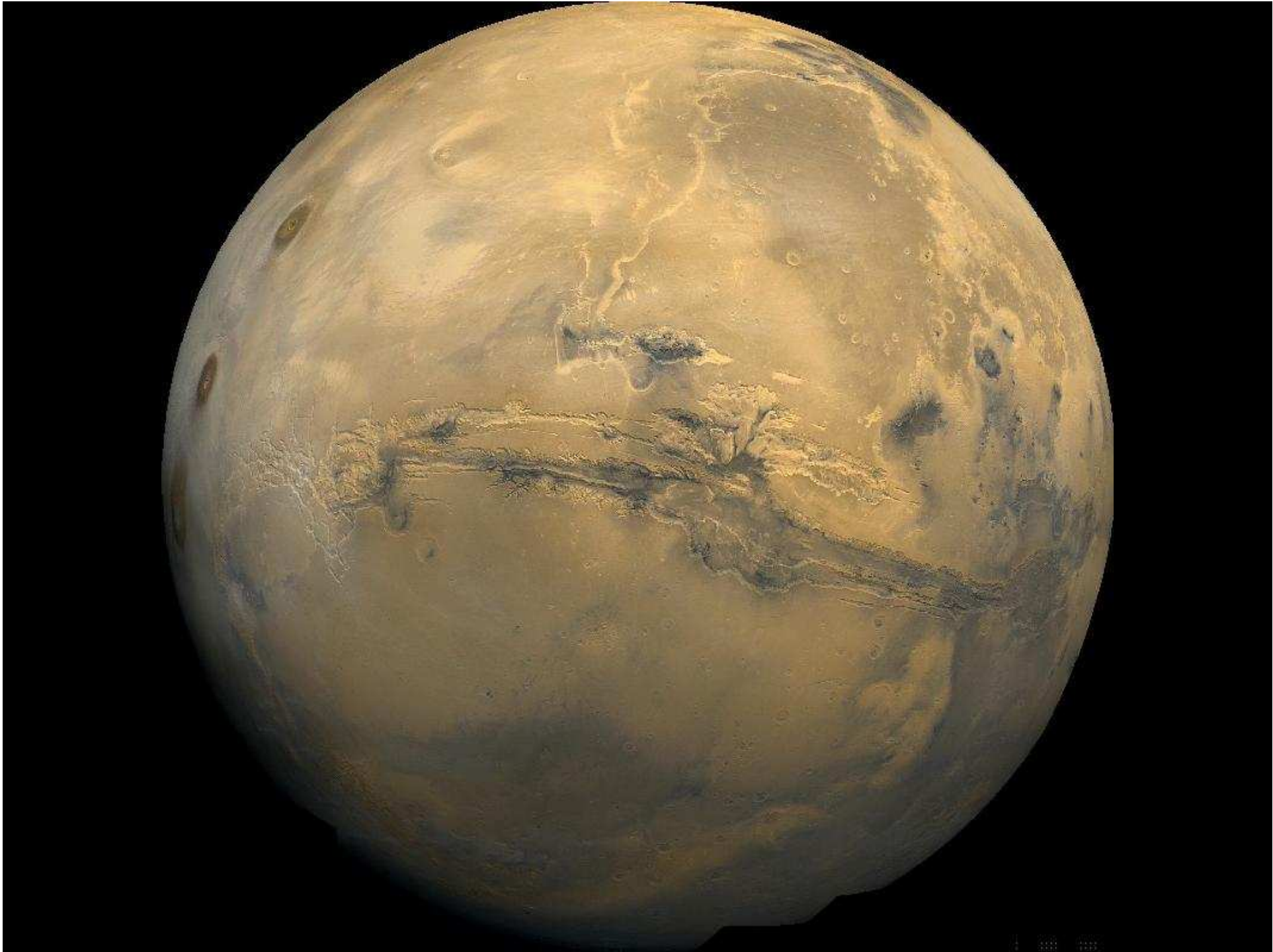
**Early Sun: Strong XUV Irradiances**  
**~50-1000x present**  
**Winds > 500x present**  
**Strong, frequent flares**

## Mars in the Past

- >3.0 Gyr ago
- ~1 Bar Atmosphere
- Warm, moist atmosphere
- Liquid water oceans
- CO<sub>2</sub>, N<sub>2</sub>, O<sub>2</sub>, H<sub>2</sub>O
- (hot) liquid Fe-Ni Core & rapid rotation
- Implied strong magnetic field
- Magnetosphere

## Mars in the Present

- ~1/90 Bar Atmosphere
- Cold, dry, frozen CO<sub>2</sub> polar caps
- 95% CO<sub>2</sub>, N<sub>2</sub>, A Iron oxide soil
- Tectonically dead solid Fe core
- No significant magnetic field



1250 m





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Icarus 165 (2003) 9–25

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ICARUS

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[www.elsevier.com/locate/icarus](http://www.elsevier.com/locate/icarus)

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

H. Lammer,<sup>a,\*</sup> H.I.M. Lichtenegger,<sup>b</sup> C. Kolb,<sup>a,c</sup> I. Ribas,<sup>d,e</sup> E.F. Guinan,<sup>e</sup> R. Abart,<sup>e</sup>  
and S.J. Bauer<sup>f</sup>

<sup>a</sup> Space Research Institute, Department of Extraterrestrial Physics, Austrian Academy of Sciences, Schriedlstrasse 6, A-8042 Graz, Austria

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<sup>d</sup> Departament d'Astronomia i Meteorologia, Universitat de Barcelona, Av. Diagonal 647, 08028 Barcelona, Spain

<sup>e</sup> Department of Astronomy and Astrophysics, Villanova University, Villanova, PA 19085, USA

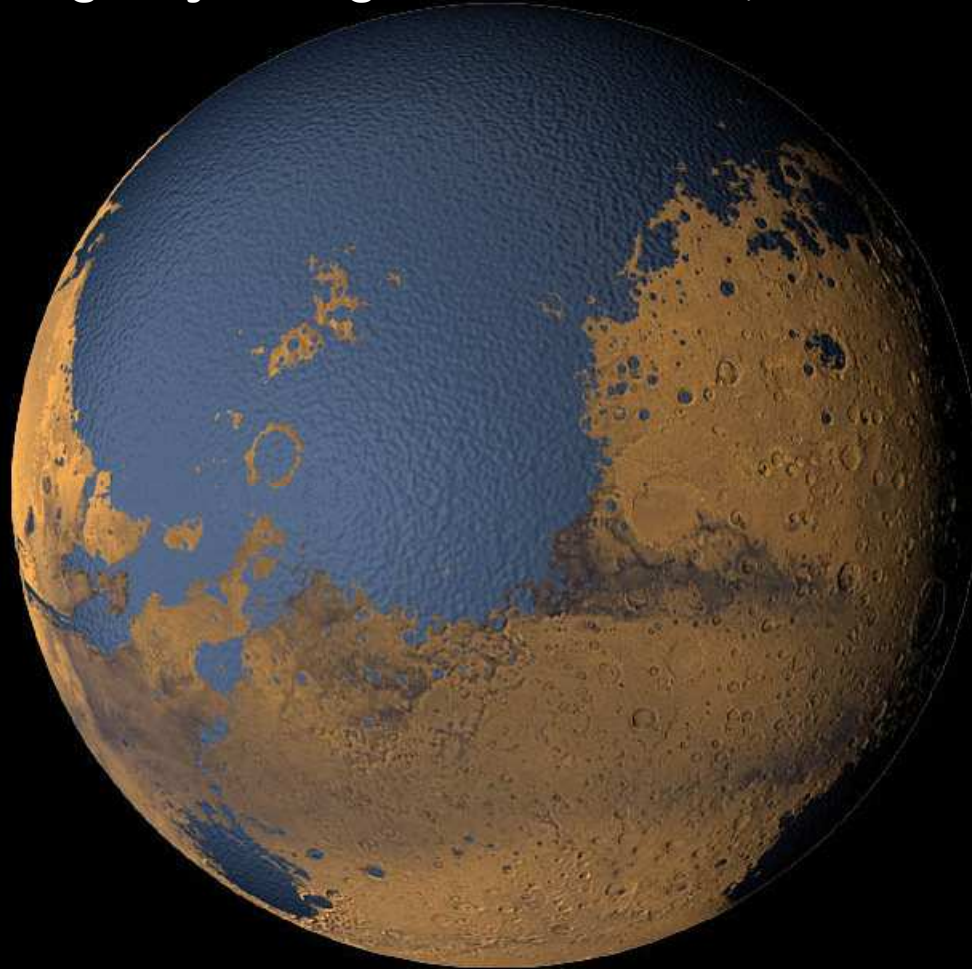
<sup>f</sup> Institute for Geophysics, Astrophysics and Meteorology, University of Graz, Universitätsplatz 5, A-8010 Graz, Austria

Received 12 October 2002; revised 13 March 2003

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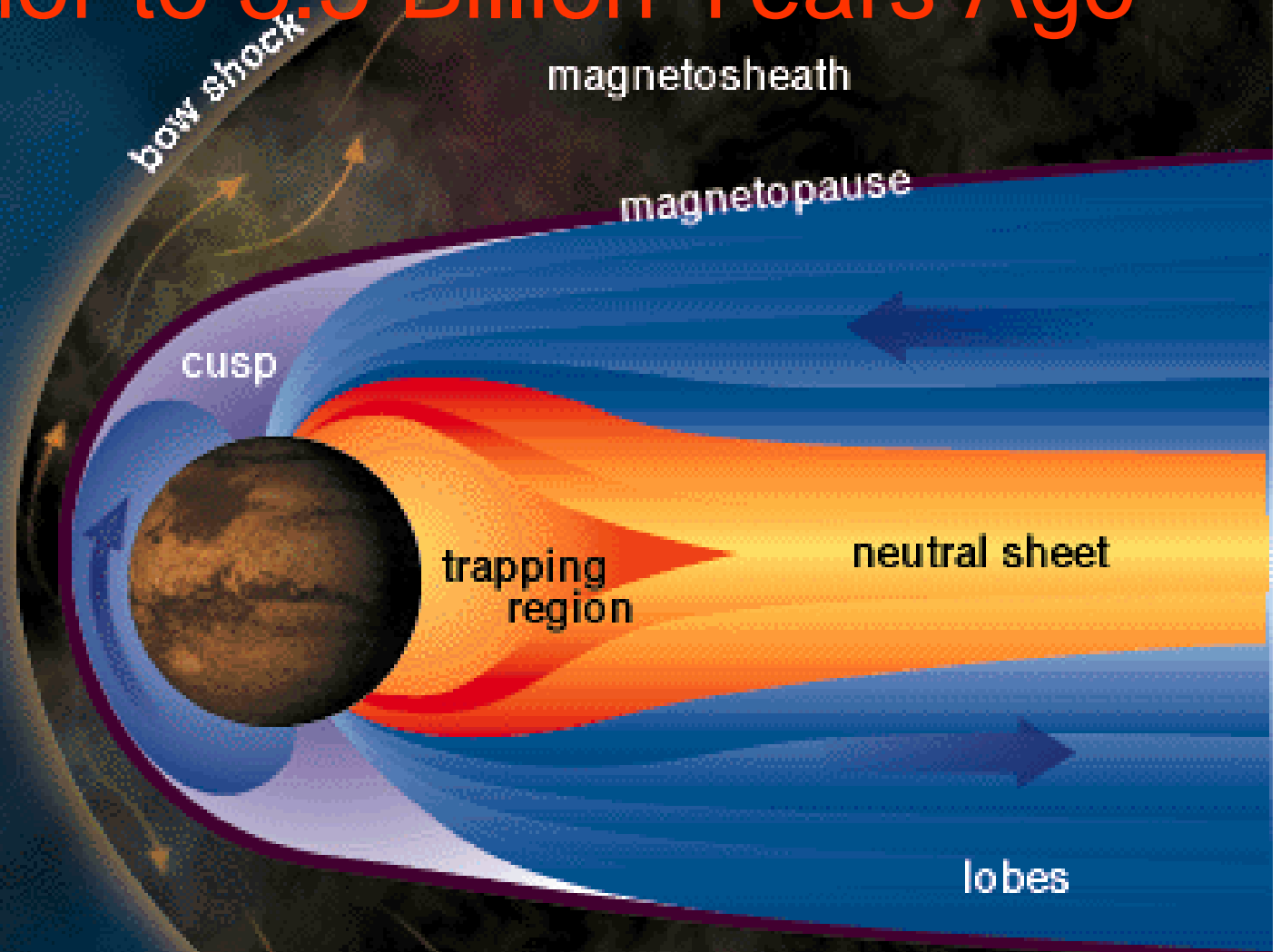
# Modeling the Early Environment of Mars

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.

# 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  $2\text{H}+\text{O}$ , where the lighter Hydrogen is lost to the space while the heavier Oxygen combines with iron on its surface





# Summary: How the Earth Survived the early onslaught of the young, active Sun

- The early Earth (as well as all close-in planets) were subjected to the strong activity of the early Sun. If not protected by a strong magnetosphere, the combination of strong XUV radiation, winds & frequent flares would have caused the loss of the water and atmosphere via ion pick-up mechanisms. Mercury, Venus and Mars all were strongly affected because of weak magnetic fields.
- The Strong X-UV radiation from the early Sun caused photo ionization and photochemical reactions in the Earth's atmosphere –some good and some bad for life. The X-FUV radiation affected the upper atm. But the NUV solar irradiation (>200nm) can penetrate the atm. (unless blocked by ozone). If the NUV radiation reaches the surface- say during a strong flare- it can sterilize or alter DNA of primitive life (and maybe it has?)
- Earth (and Mars during the first Gyr of its life when it had a magnetic field) were shielded from the Sun by magnetospheres and thus survived the ravages of the magnetically active young Sun. Mercury being so close to the Sun may have lost some of its mantle.

THE END



*Thank You...*

# 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)	$P_{\text{rot}}$ (d)	$\log L_X$ (erg/s)	Age (Gyr)	Age indicator, Membership
<u>47 Cas B</u>	G0-2 V	2.2	0.59	33.54	$\sim 1.0$	30.31	0.07	Pleiades Moving Group
<u>EK Dra</u>	G0 V	0.9	0.20	33.94	2.75	29.93	0.07	Pleiades Moving Group
<u><math>\pi^1</math> UMa</u>	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
<u><math>\chi^1</math> Ori</u>	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
<u><math>\kappa^1</math> Cet</u>	G5 V	1.08	0.11	9.16	9.2	28.79	0.75	Rotation-Age Relation
$\beta$ 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
<b>18 Sco</b>	<b>G2 V</b>	...	...	<b>14.03</b>	<b>23<math>\pm</math>3</b>	<b>&lt;28.0</b>	<b><math>\sim 4.4</math></b>	<b>Isochrones</b>
Sun	G2 V	...	...	1 AU	25.4	27.3	4.6	Isotopic Dating on Earth
<u><math>\alpha</math> Cen A</u>	G2 V	1.64	0.113	1.35	$\sim 24$	27.12	5-6	Isochrones, Rotation
<u><math>\beta</math> Hyi</u>	G2 IV	0.11	...	7.47	$\sim 28$	27.18	6.7	Isochrones

# EK Dra IUE SW Spectra

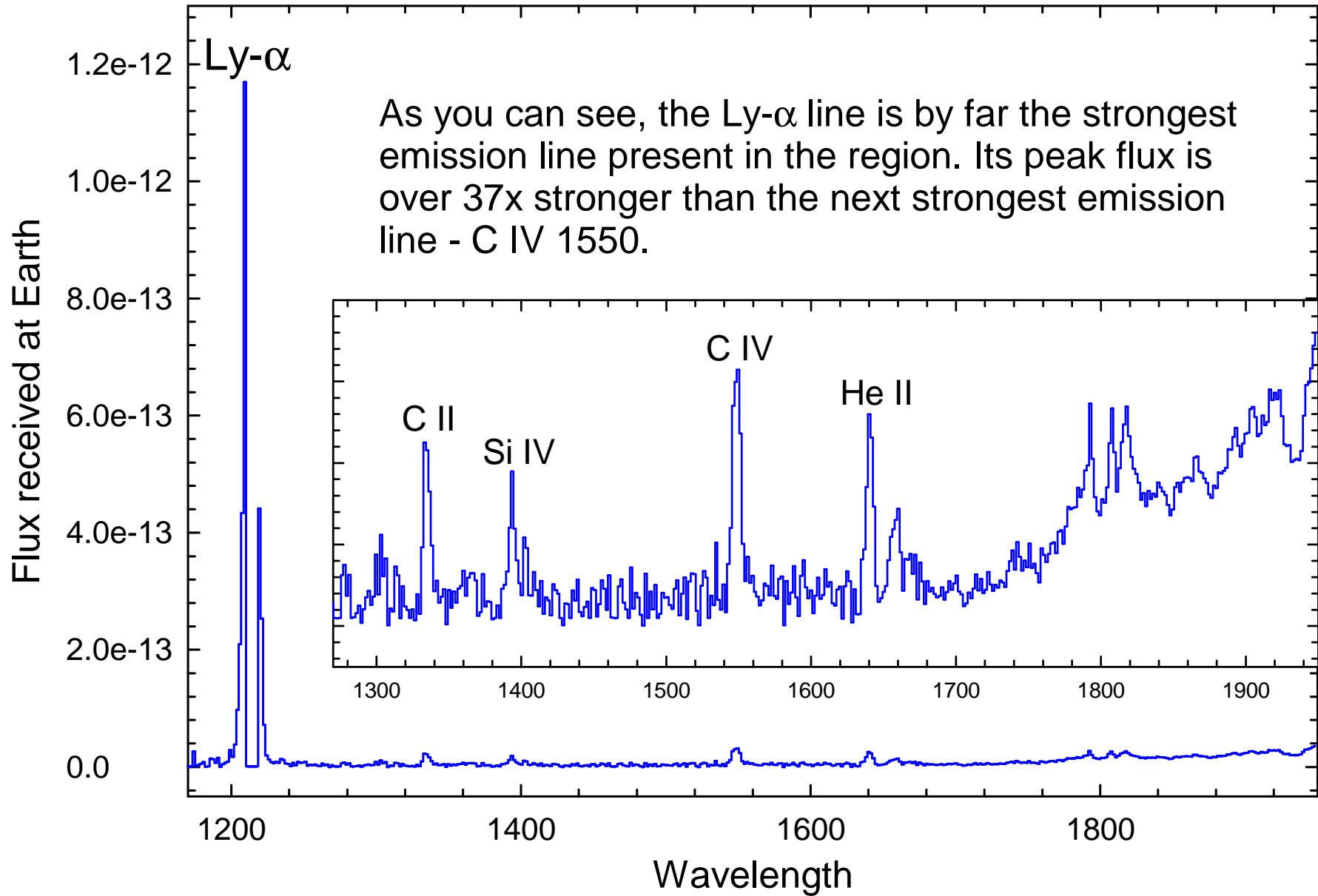
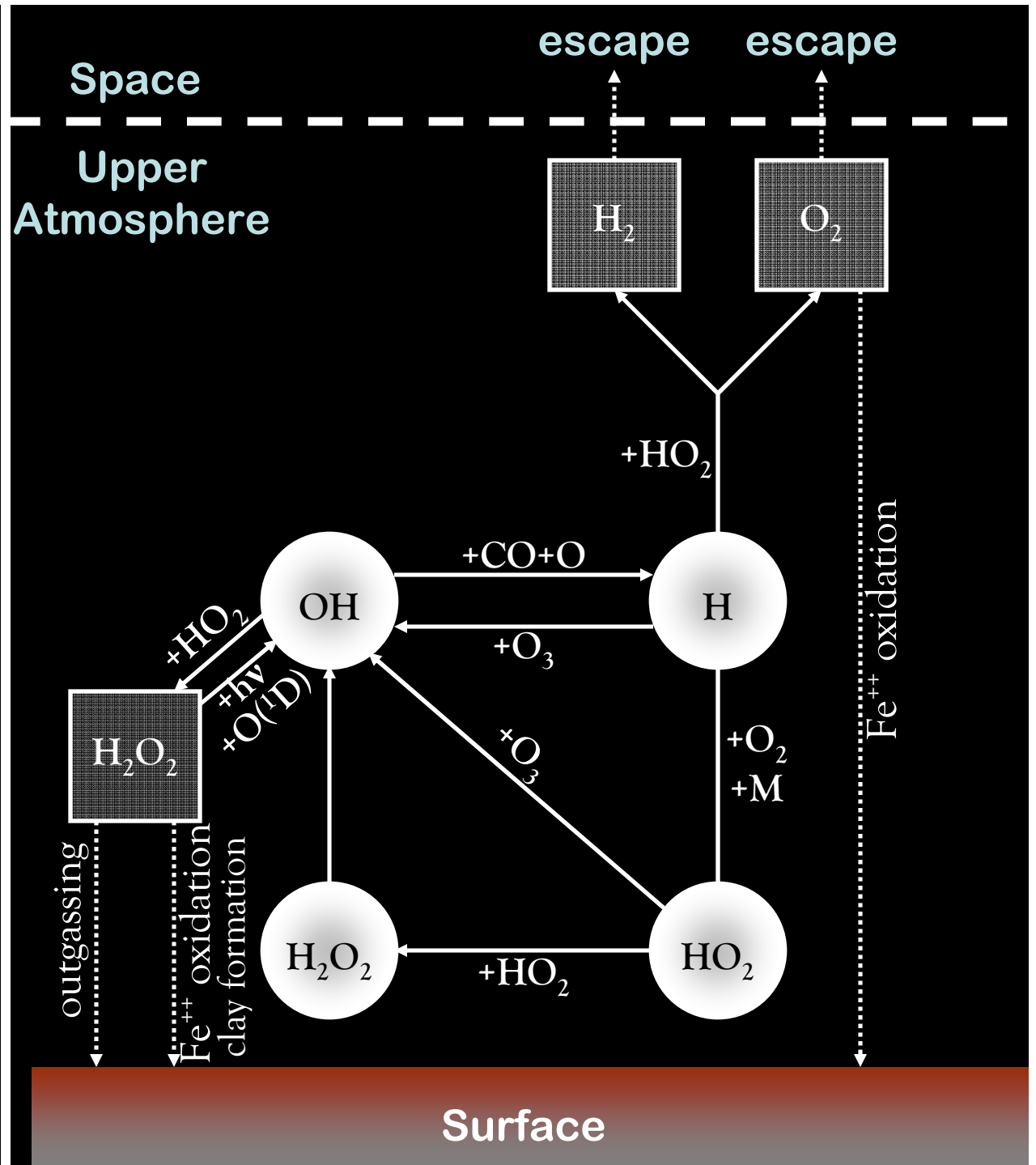
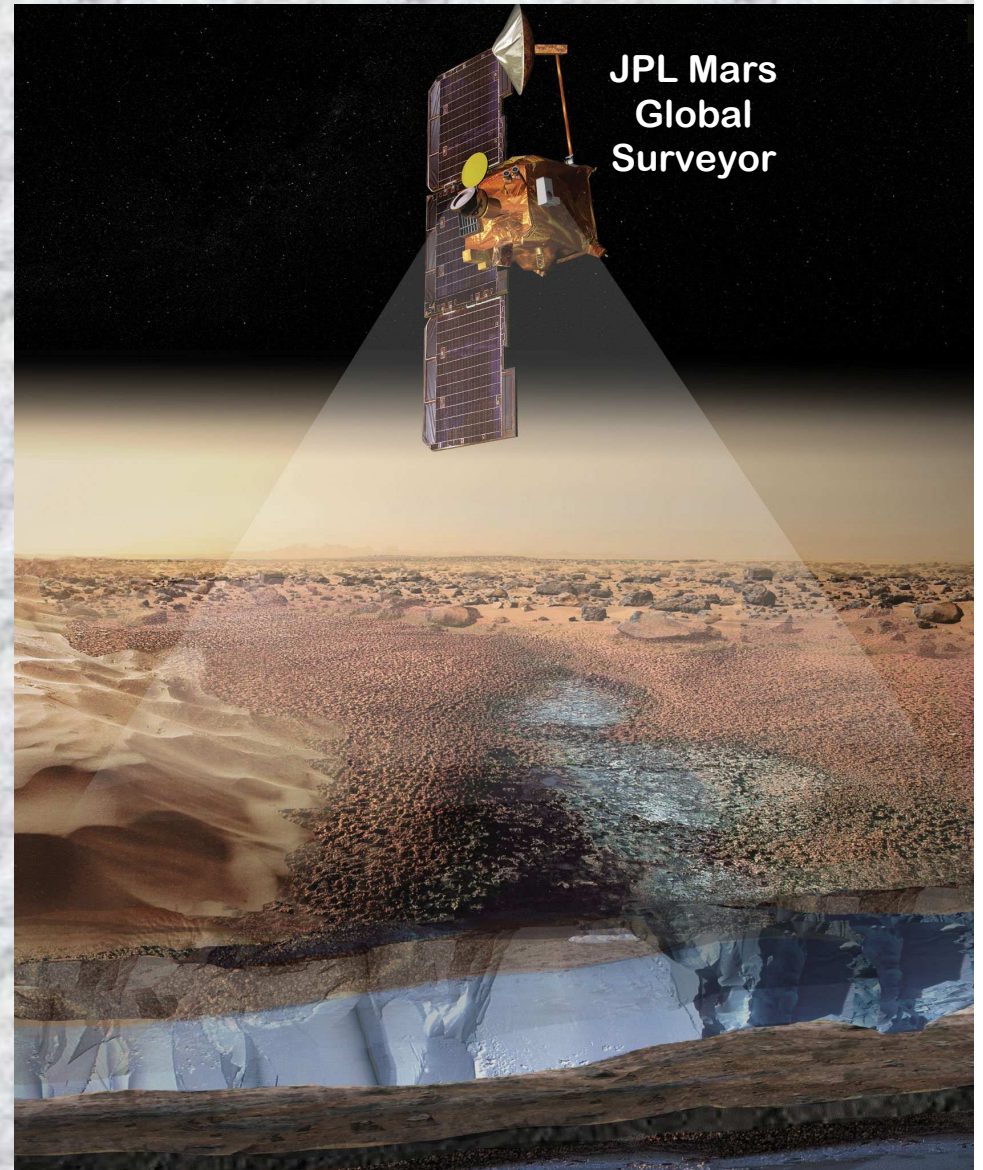


Illustration of the cycles and loss mechanisms for  $\text{H}_2\text{O}$  on Mars. Loss to space, surface oxidation via atmosphere-surface interaction processes, and hydration reactions are important.



- 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<sub>2</sub>O is lost, loss of greenhouse gases causes Mars to rapidly cool, and some frozen water is left behind (permafrost?).

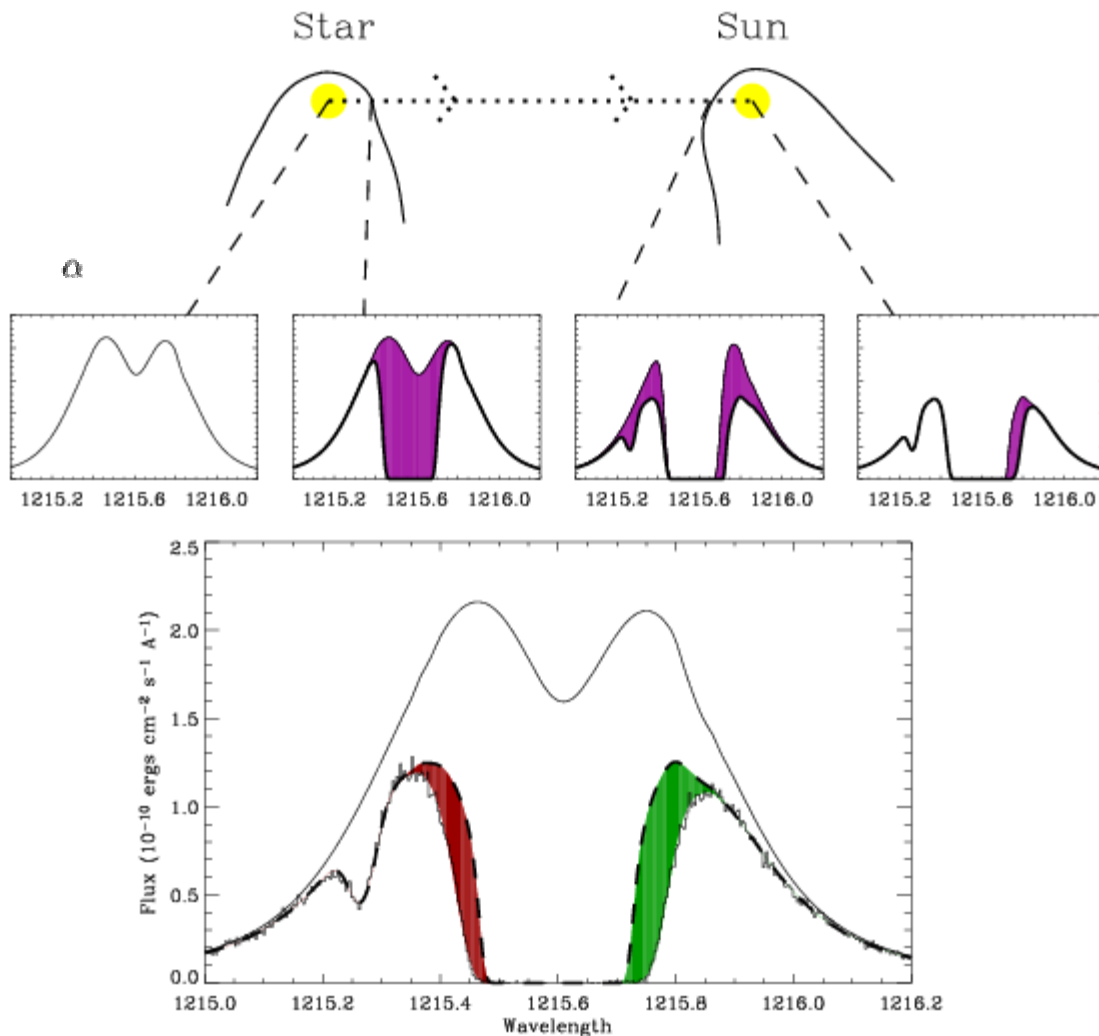
\* see Icarus, Volume 165, Issue 1, p. 9-25



# Astrospheres and Solar-like Stellar Winds

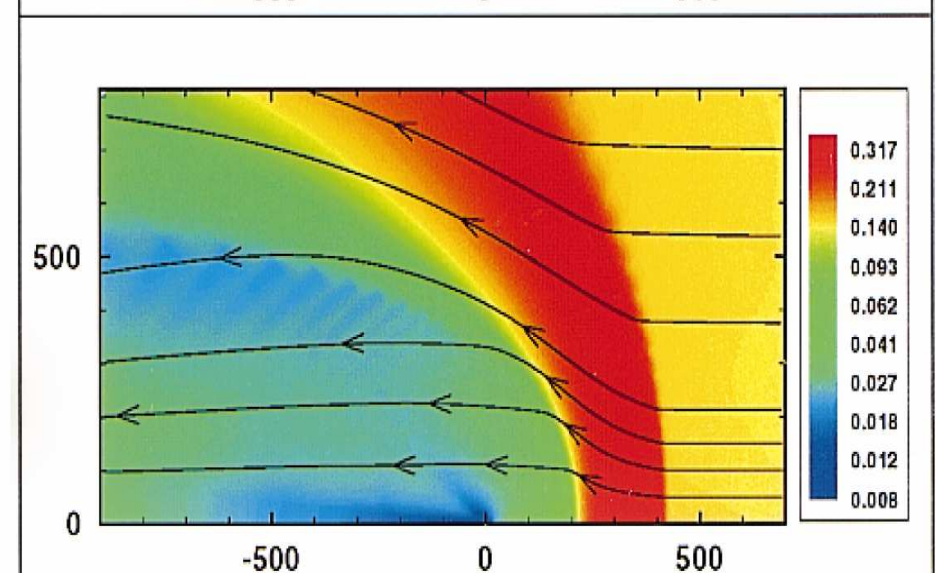
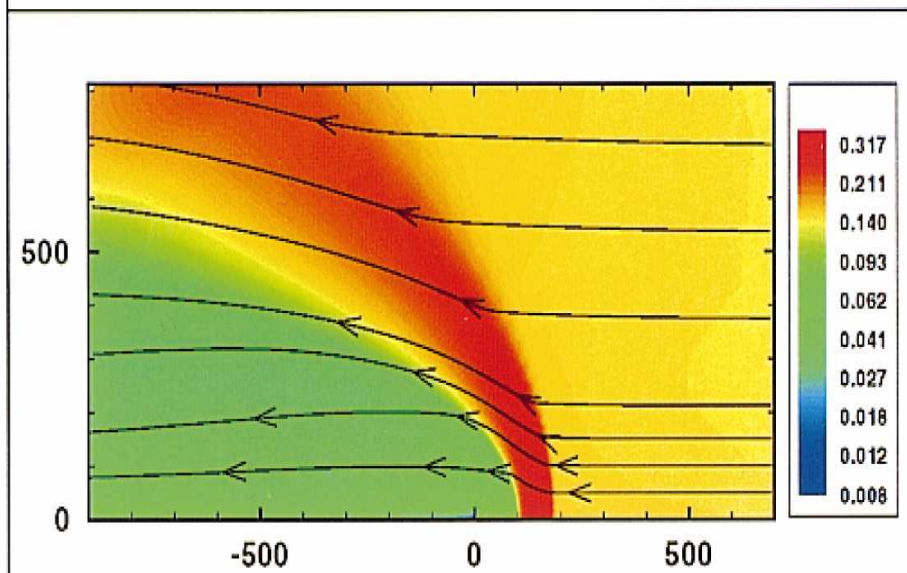
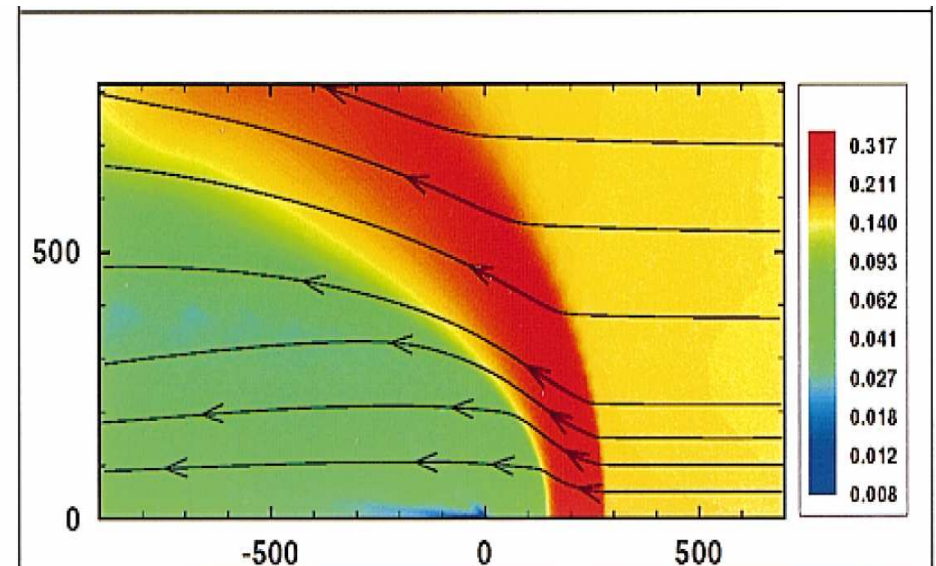
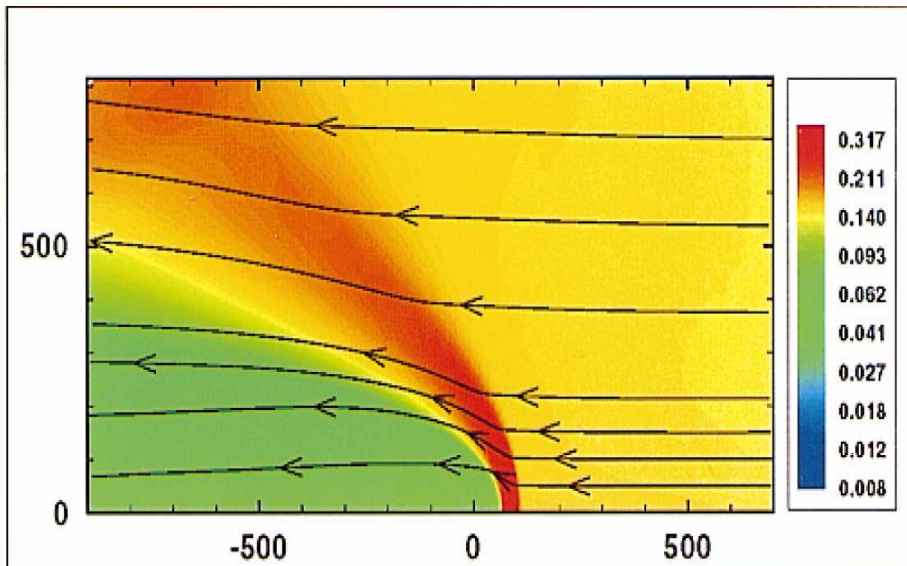
Brian E. Wood

*Living Reviews in Solar Physics*



Schematic diagram showing how a stellar Ly- $\alpha$  profile changes from its initial appearance at the star and then through various regions that absorb parts of the profile before it reaches an observer at Earth: the stellar astrosphere, the LISM, and finally the heliosphere. The lower panel shows the actual observed Ly- $\alpha$  profile of  $\alpha$  Cen B. The upper solid line is the assumed stellar emission profile and the dashed line is the ISM absorption alone. The excess absorption is due to heliospheric H I (green shading) and astrospheric H I (red shading).





**Distribution of H I density predicted by hydrodynamic models of the  $\alpha$  Cen / Proxima Cen astrospheres, assuming stellar mass-loss rates of (from top to bottom) 0.2, 0.5, 1.0, and 2.0  $M_{\odot}$ . The distance scale is in astronomical units. Streamlines show the H I flow pattern.**

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

- Ground based observations of heavy constituents like  $\text{Na}^+$ ,  $\text{K}^+$ , and  $\text{O}^+$  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.

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

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

# SOME FURTHER INVESTIGATIONS & FUTURE PLANS

- HST/STIS Spectroscopy of Ly- $\alpha$  for more program stars. (Ly- $\alpha$  emission is the strongest contributor to the FUV irradiance.)
- Direct measures of mass loss (winds) of solar program stars.
  - Ly- $\alpha$  – Astrospheres: Brian Wood (NRL)
  - Radio (mm/cm) Observations -  $F_{\nu} \leftrightarrow v^{2/3}$ : VLA/IRAM/100m. Greenbank; Future  $\rightarrow$  ALMA and GMT
- 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")
- Expanded the sample to dK & dM stars to study Activity -  $P_{\text{rot}}$ - Age Relations/XUV Spectral Irradiances/Winds(?) in support of exosolar planet missions such as COROT, Kepler, SIM & TPF-Darwin