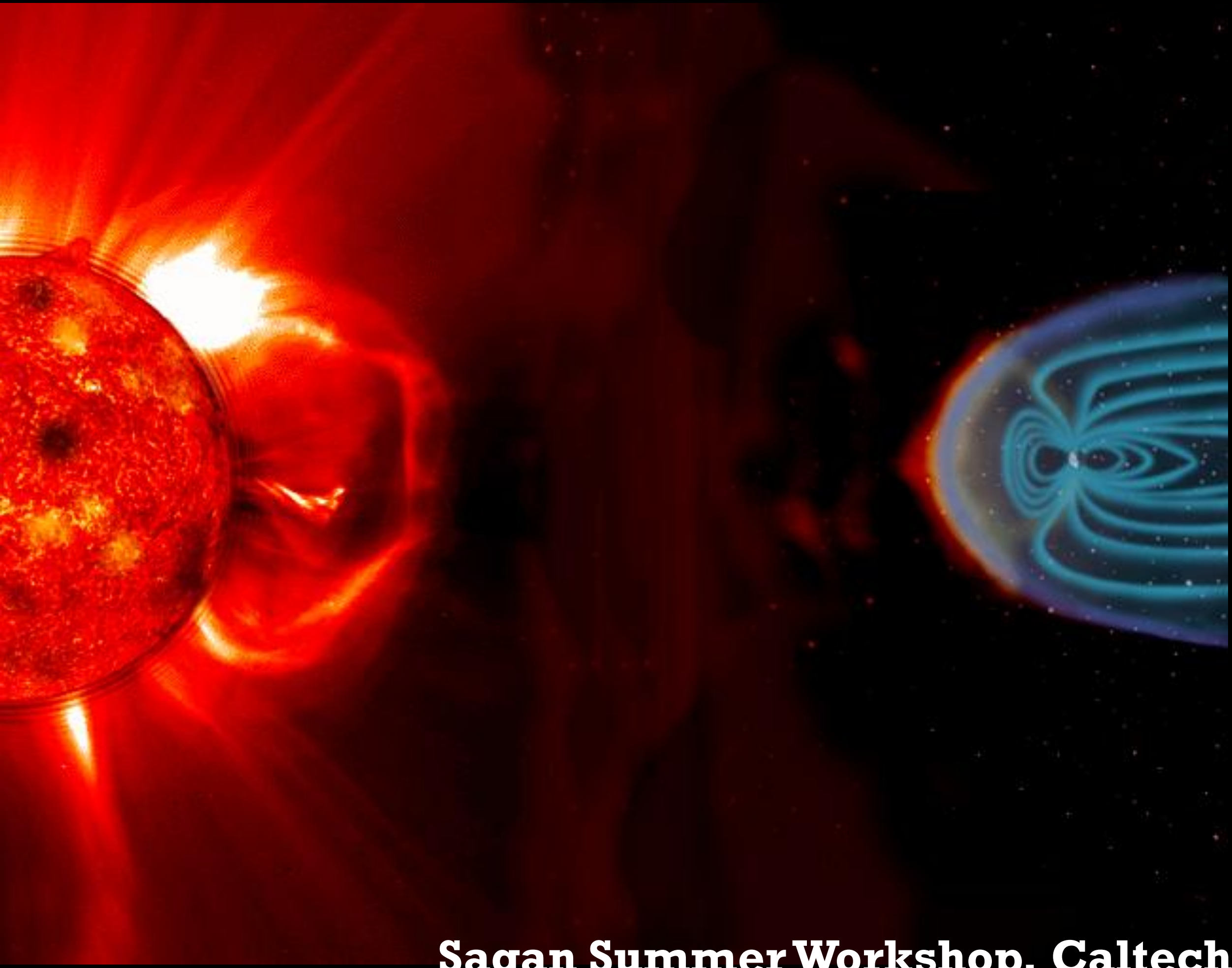
STAR - PLANET INTERACTIONS:

IMPACT OF HOST STAR ON PLANET HABITABILITY: EMPHASIS ON RED DWARFS



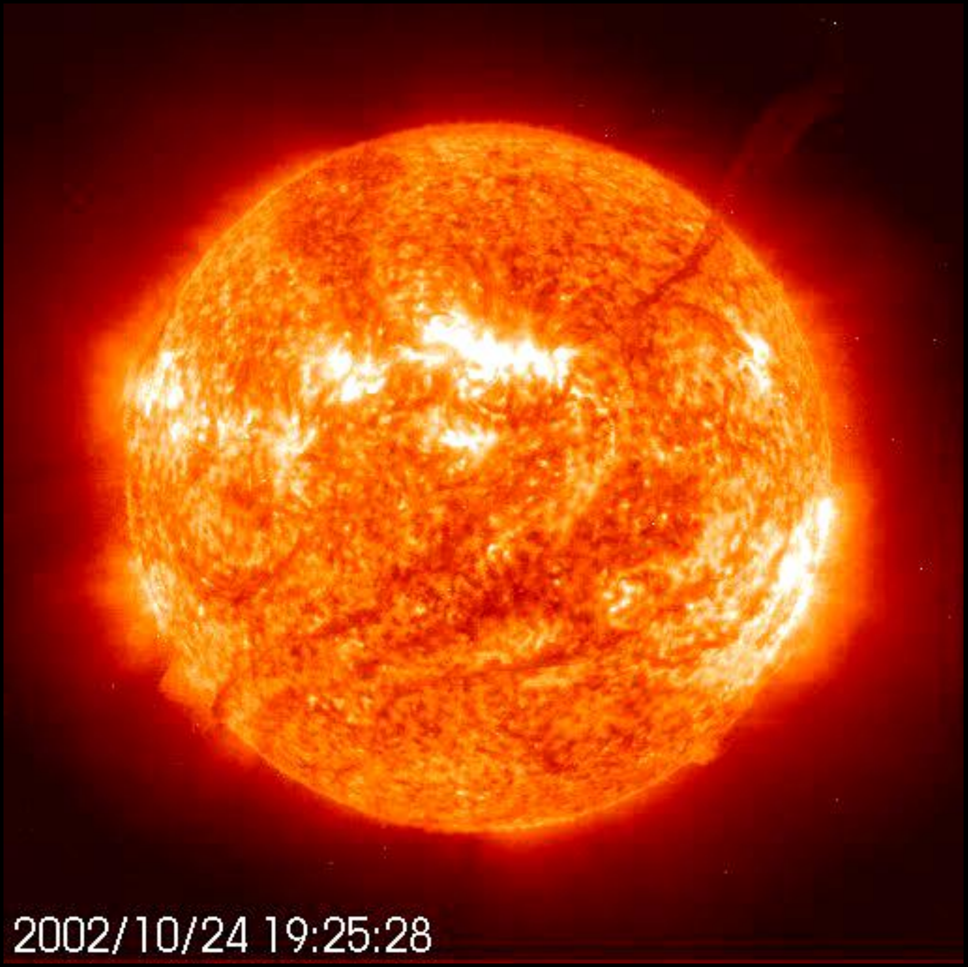
Ed Guinan

Villanova University

Sagan Summer Workshop, Caltech July 2010

Talking Points

- Local Examples of Solar/Stellar X-UV Radiation & Wind Impacts on Planetary Atmospheres
- “Sun in Time” program – solar-type stars with different ages & X-UV Irradiance of the early Sun
- “Living with a Red Dwarf” Program
- Nuclear / Magnetic Evolution of dK & dM-stars
- Magnetic Dynamo-Driven X-UV Radiation & Flares of red dwarf stars
- Some Astrobiological Consequences
- Highlight: The dM star + planet systems - GJ 581 Planetary System- large Earth-size planets in the Habitable Zone? And transiting planet in GJ 436
- Conclusions



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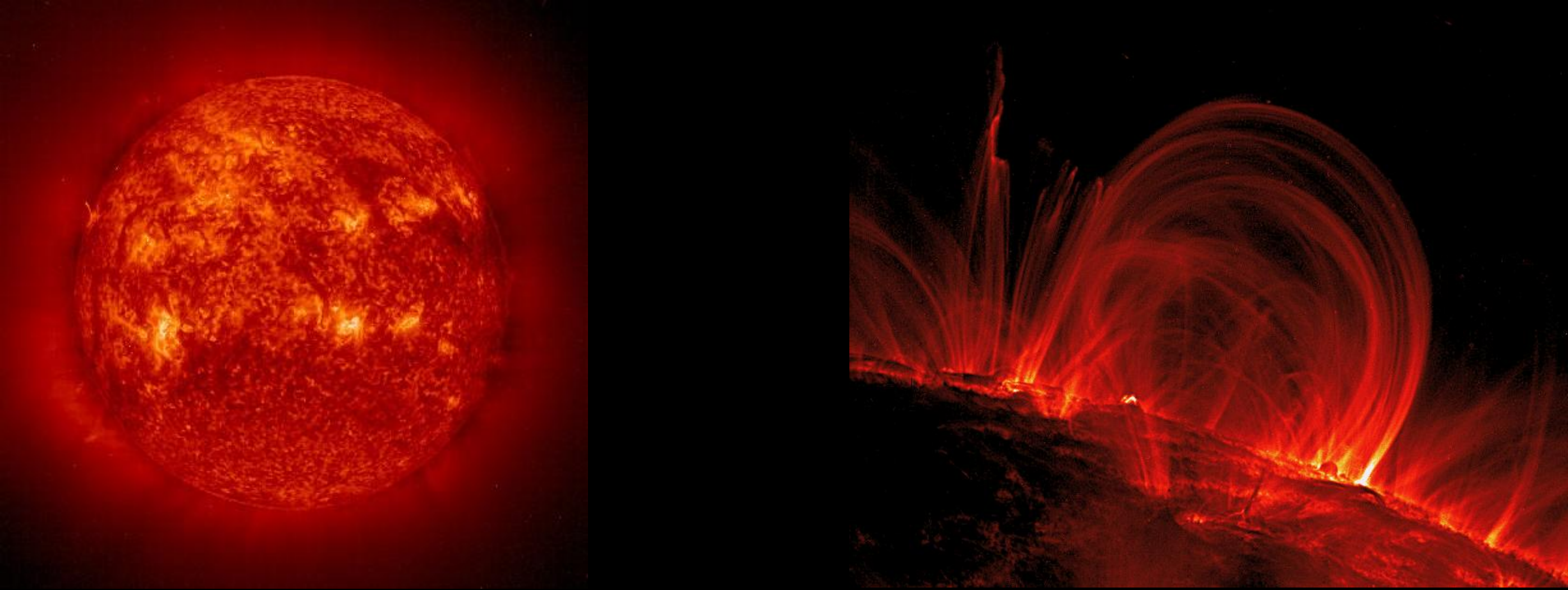
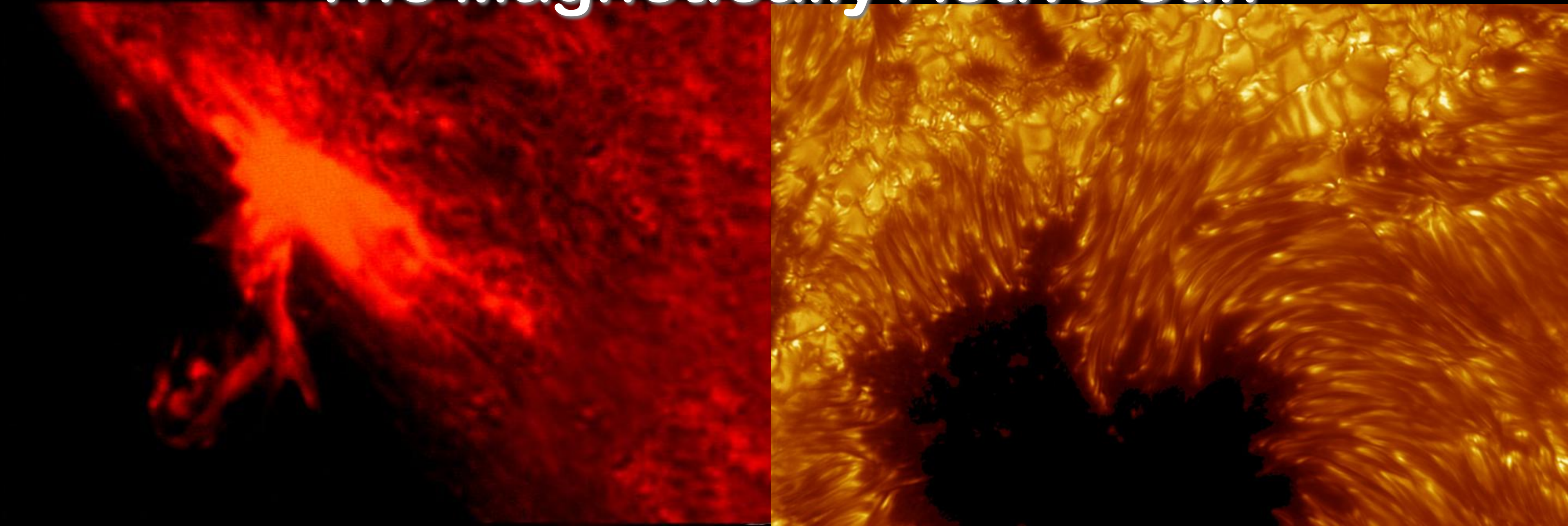
I. Local Examples of Stellar XUV Radiation & Wind Impacts on Planetary Atmospheres



The Magnetically Active Sun



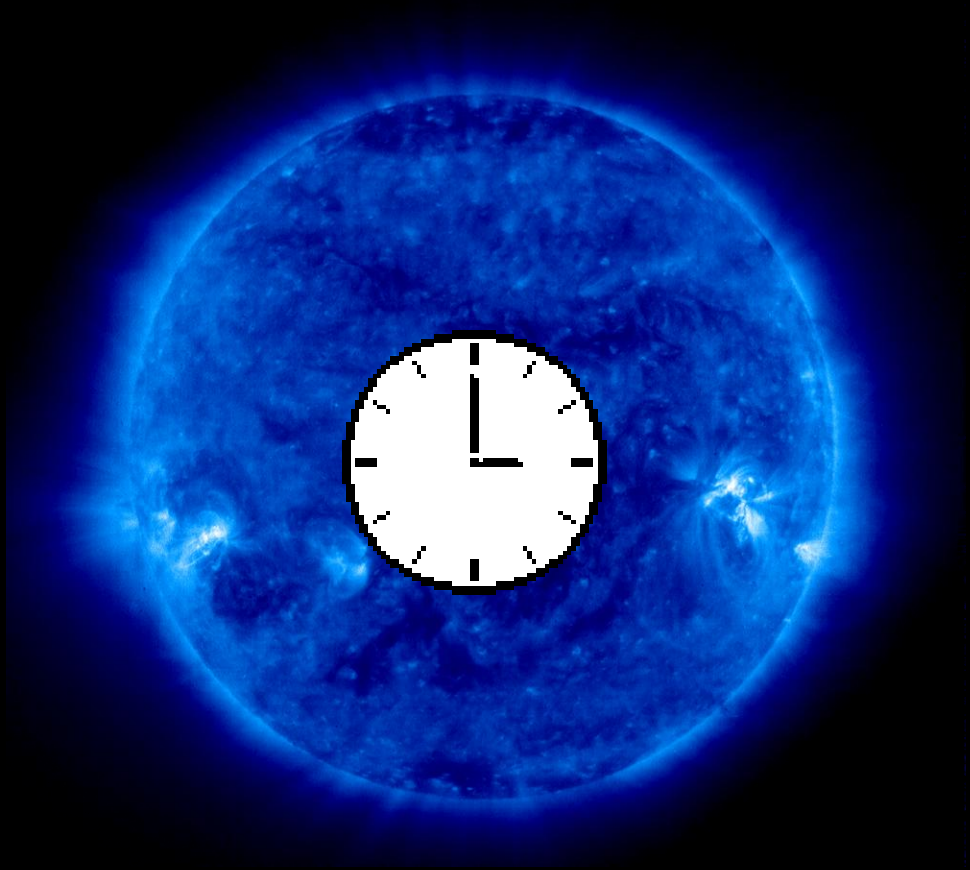

SOHO

(C) Daryl Pederson

Steele Hill/NASA

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

(Start: 1988)



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 main sequence G0-5 stars
- Known rotation periods
- Well-determined temperatures, luminosities and metallicities & distances
- Age estimates from membership in clusters, moving groups, period-rotation relation and/or evolutionary model fits
- Recently extended to include more common dK – dM stars with deep outer convection zones (Focus of this talk)

→ 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.

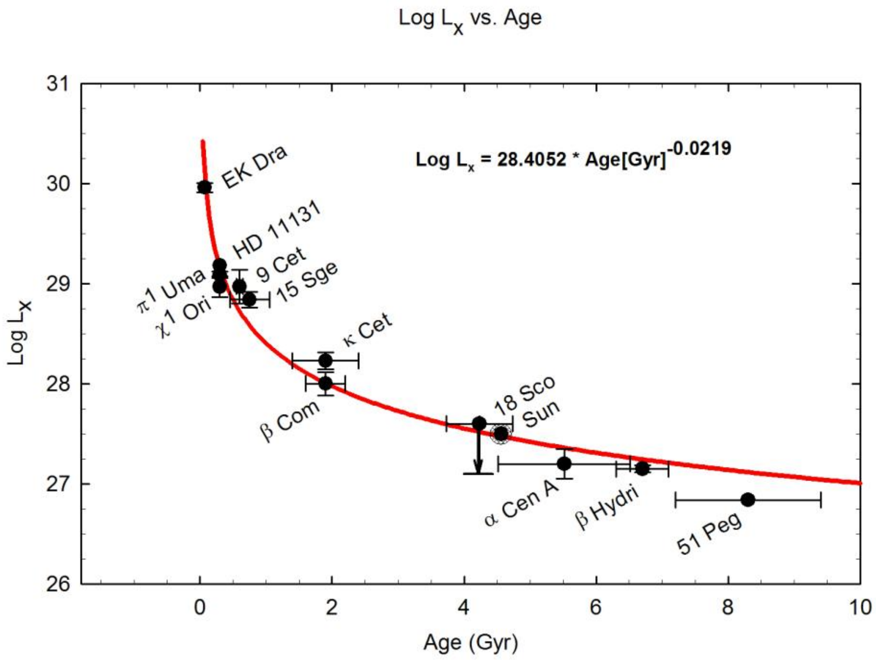
Focused on the high-energy irradiance study (X-ray and UV). Most of the observations have been acquired from space satellites to overcome atmospheric absorption over last 20 years.

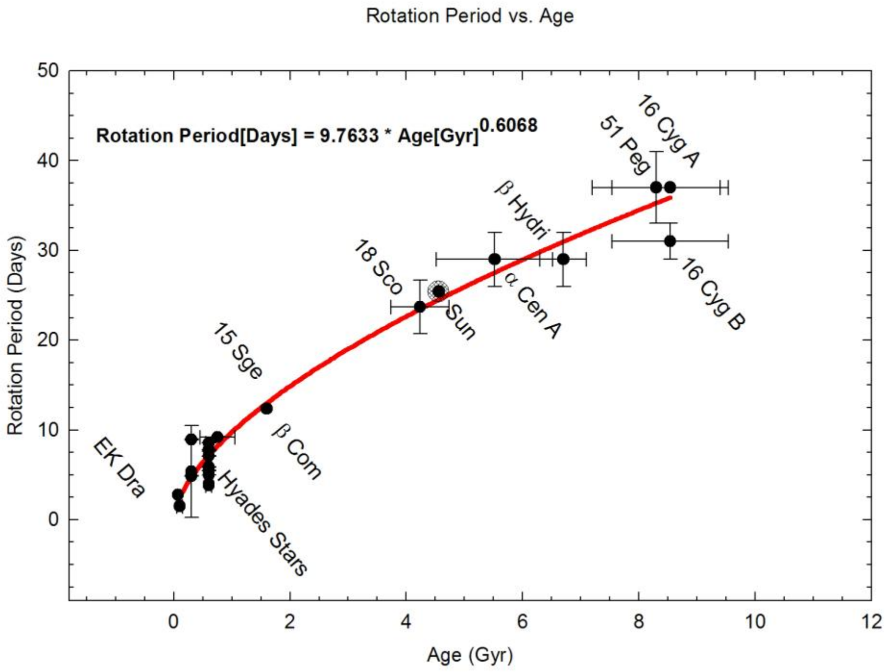
Why high energy?

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)

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





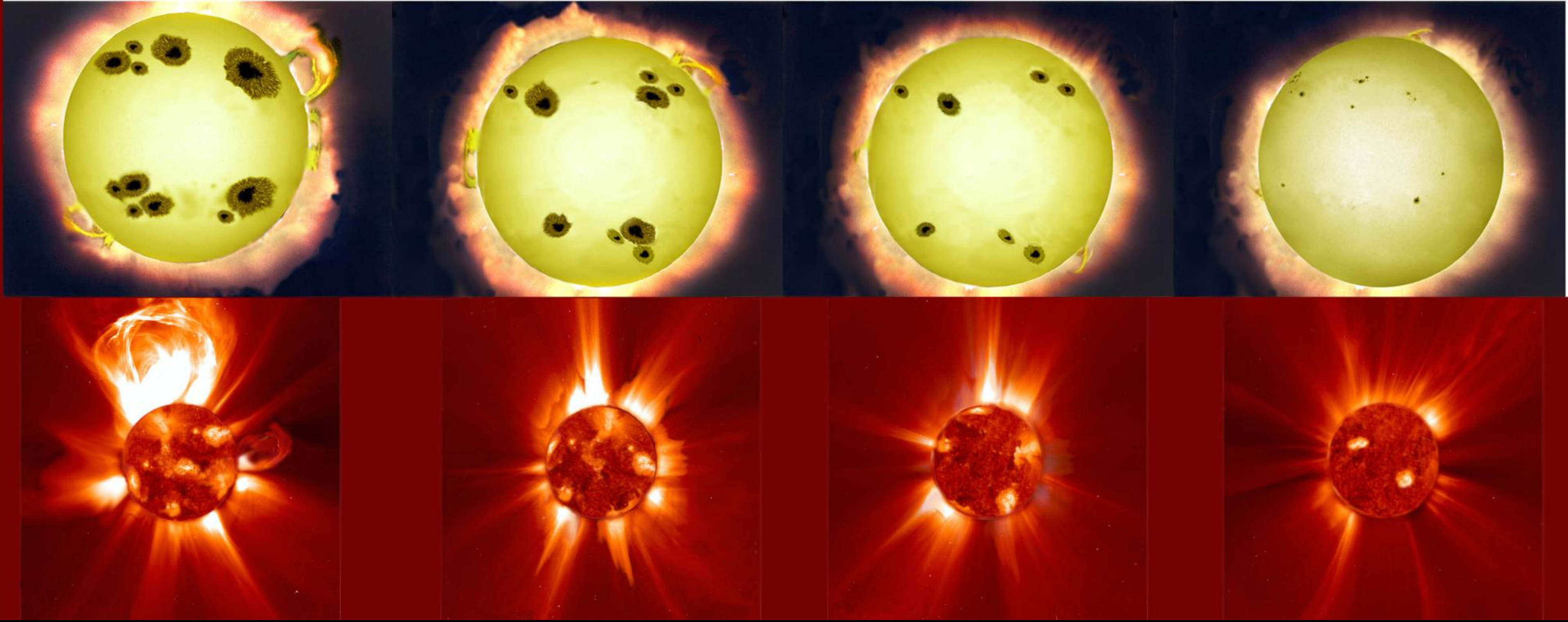
Age vs. X-ray Luminosity (log L_x)

Age vs. Rotational Period

Loss of Angular momentum over time takes place via magnetic winds for stars with convective zones and dynamos (i.e. spectral types G,K,M stars)

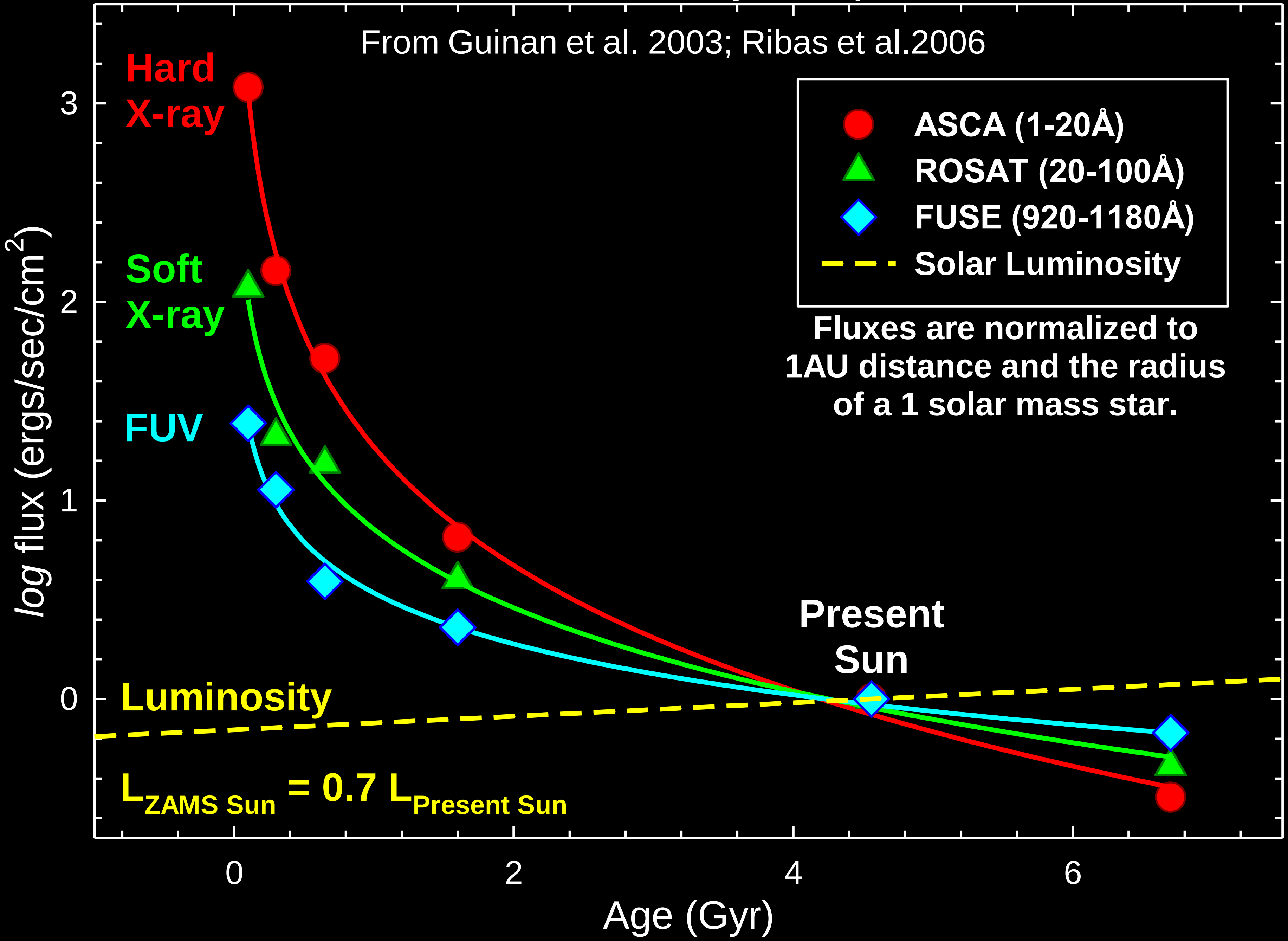
OUR SUN THROUGHOUT THE AGES

Age, Rotation, Spot coverage and Coronal X-ray Emission



< 300 Myr	~ 650 Myr	~ 2 Gyr	4 - 5 Gyr
Lx ~ 5-10 E+29 erg/s	~ 5-10 E+28	~ 1E+28	~ 1E+27
P(rot) 2 -4 d; 10% spots	~8 d; 2- 5% spots	~14d; ~1% spots	~25d ; 0.2% spots

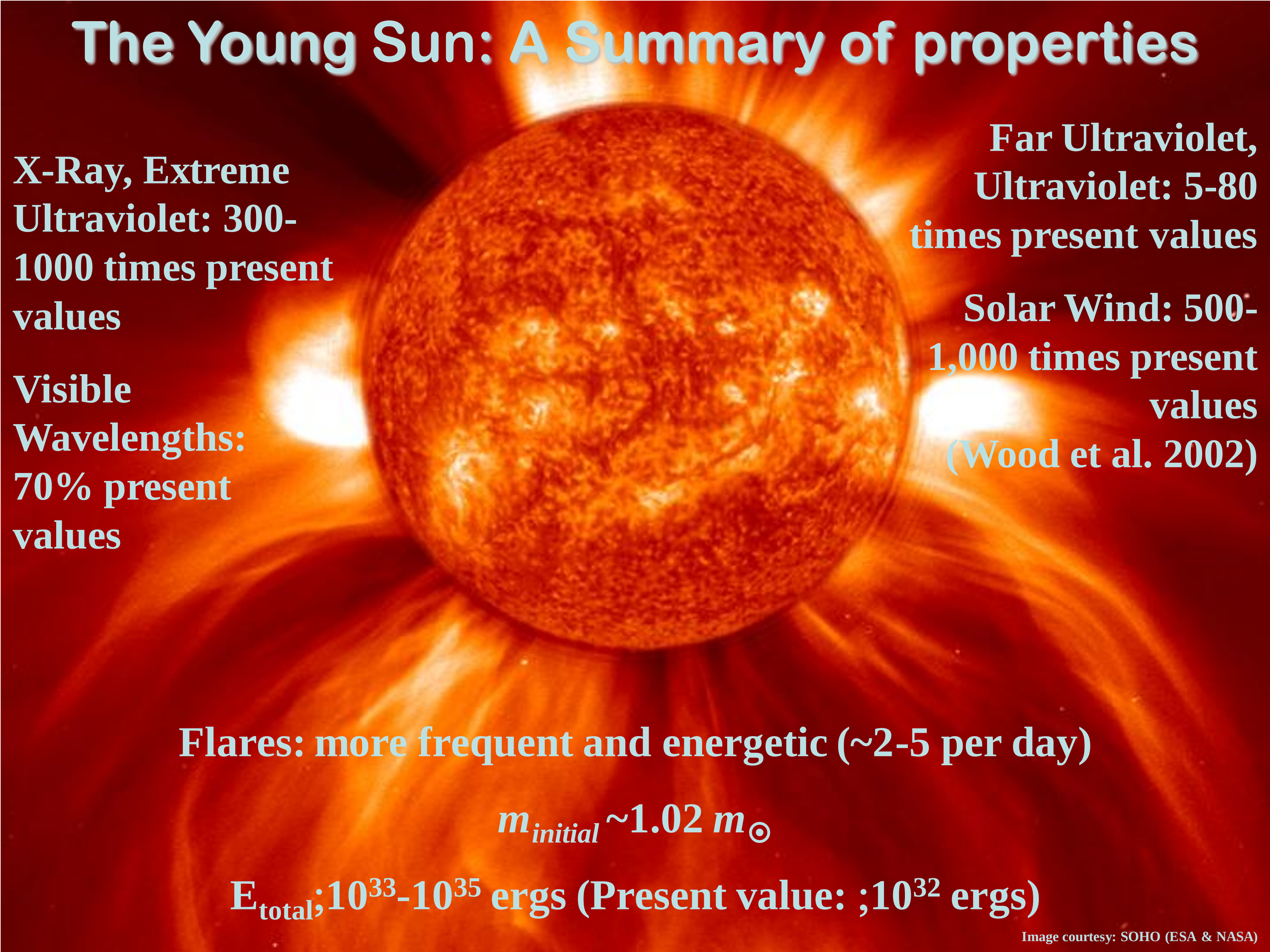
"Sun in Time" Relative X-ray to Optical Irradiances



From Guinan et al. 2003; Ribas et al.2006

Fluxes are normalized to 1AU distance and the radius of a 1 solar mass star.

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

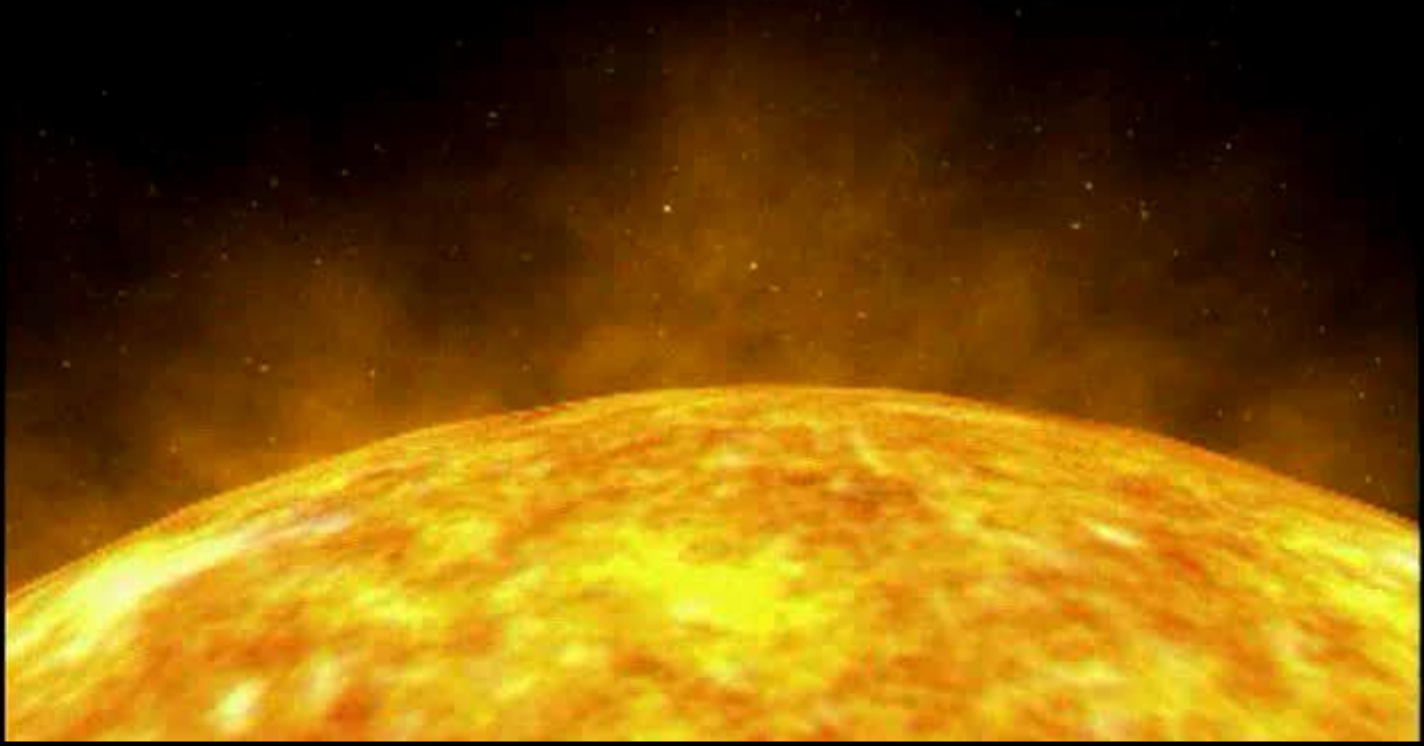
Solar Wind: 500-1,000 times present values (Wood et al. 2002)

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

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

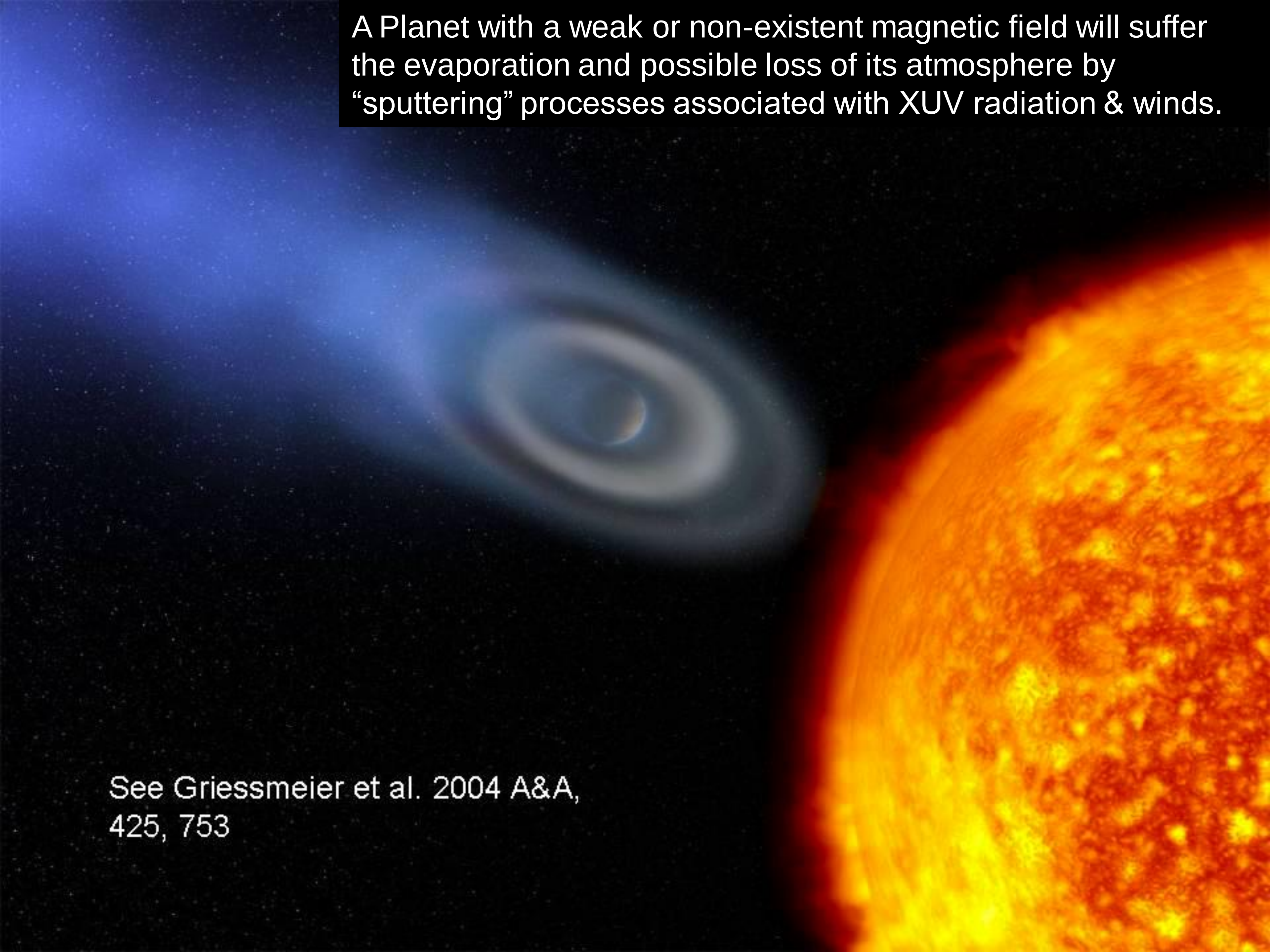
E_{total};10^{33}-10^{35} ergs (Present value: ;10^{32} ergs)

Image courtesy: SOHO (ESA & NASA)



THE EFFECTS OF THE ACTIVE YOUNG SUN ON PLANETS

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

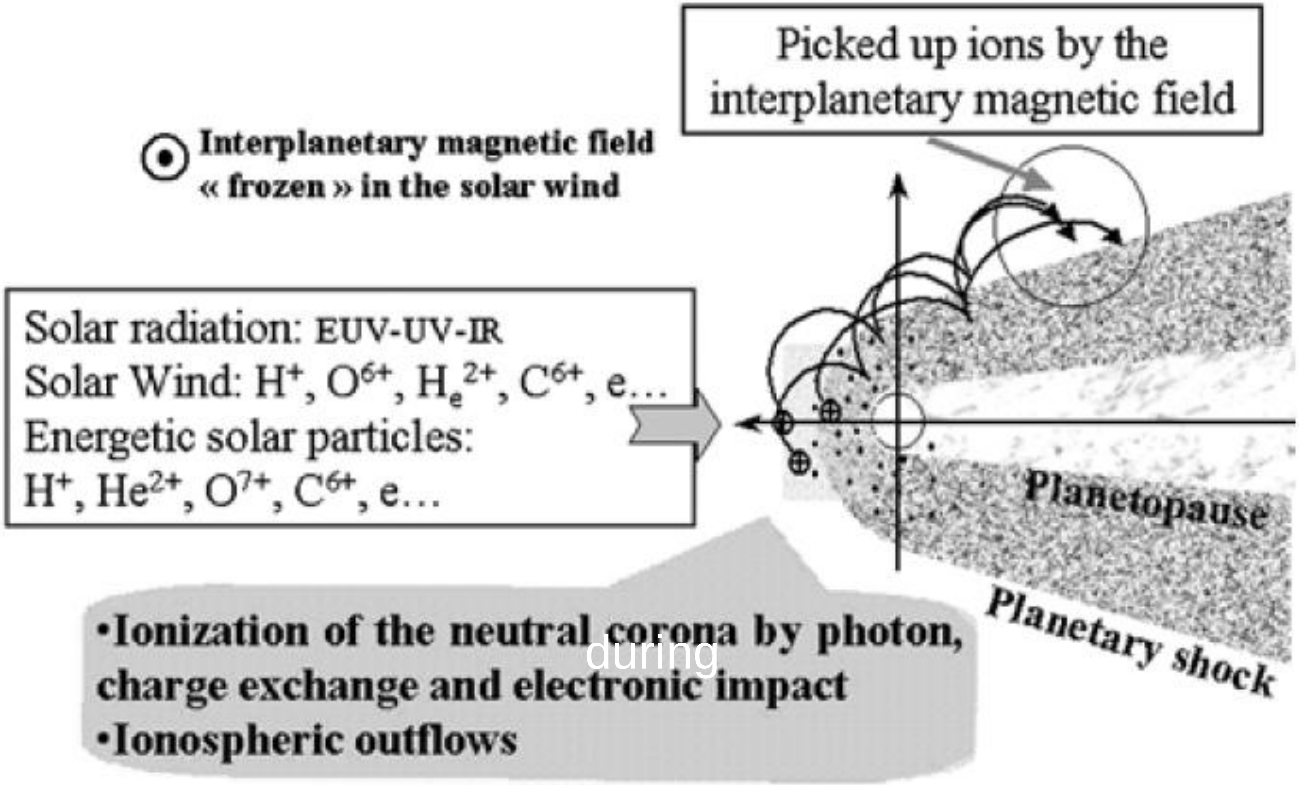
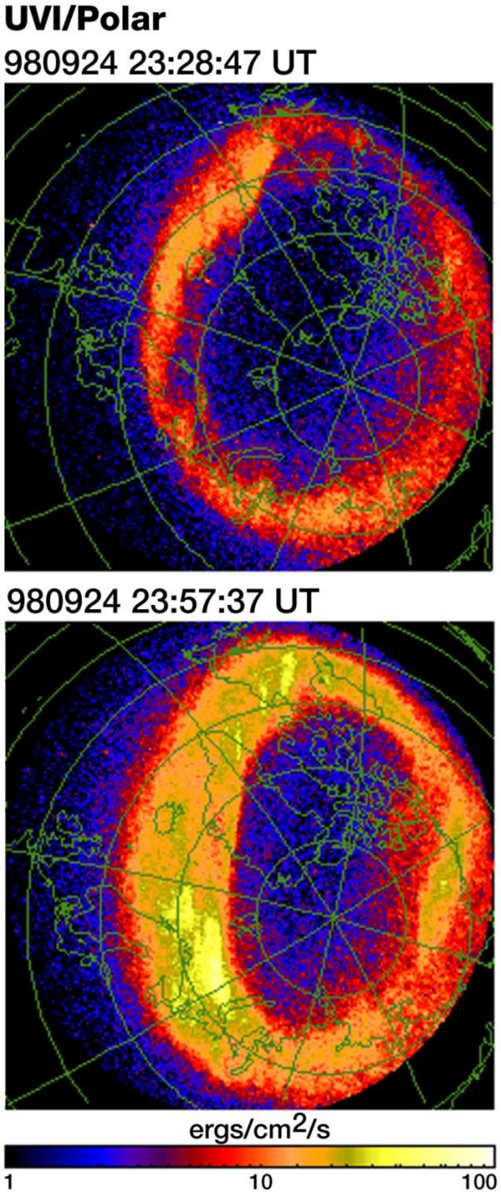


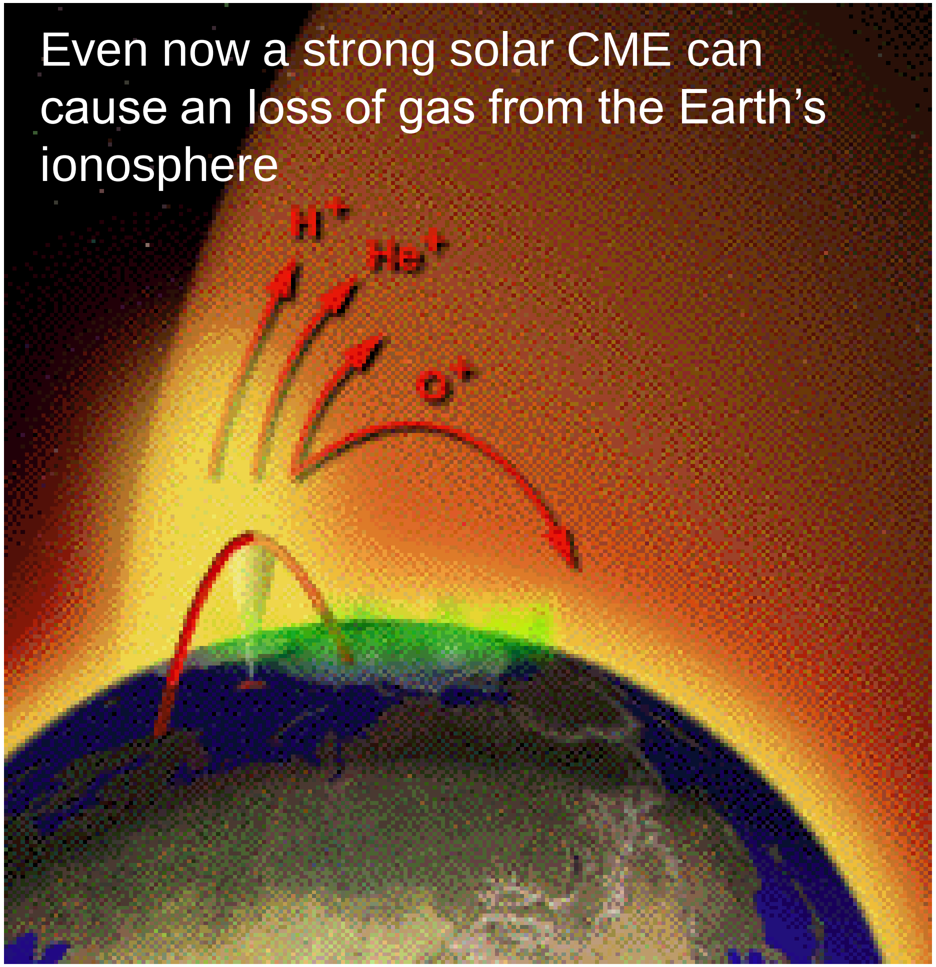
Fig. 3 Illustration of picked up planetary ions, directed backwards to a planetary atmosphere, which is not protected by a strong magnetic field. These ions can act together with solar wind particles as sputter agents (courtesy of F. Leblanc)

From Lammer et al. 2008 , Space Sci. Rev –Atmospheric Escape and Evolution of Terrestrial Planets and Satellites

Auroral Displays on Earth viewed by the NASA UVI Polar Mission before and during a large CME event



Even now a strong solar CME can cause an loss of gas from the Earth's ionosphere



The polar aurora fountain sprays ions - oxygen, helium, and hydrogen - from Earth's upper ionosphere into deep space. The loss is tiny compared to the immense volume of air in our atmosphere, but is significant in terms of what drives space weather around our world. (NASA)

MESSENGER AT MERCURY

Evidence of Sputtered Sodium gas blown off Mercury by Solar winds and X-UV radiation from the present Sun

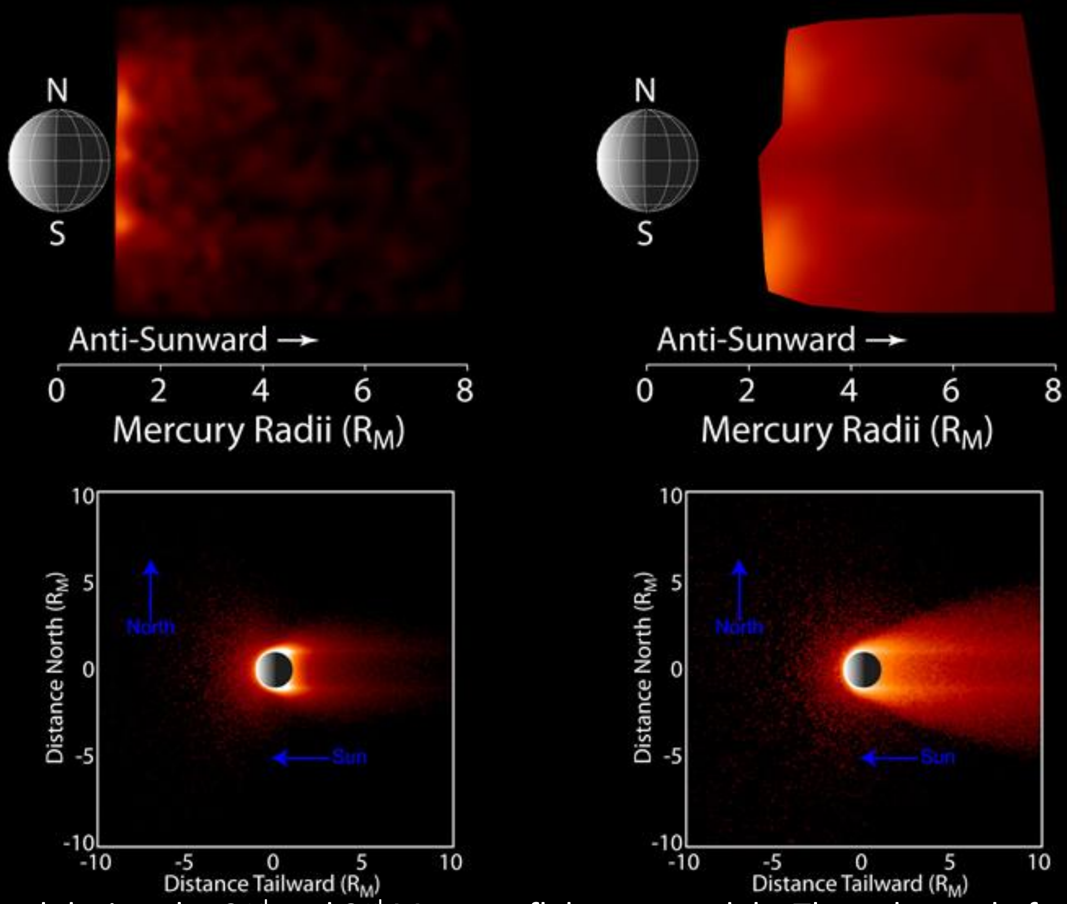
Sodium Emission in Mercury's Tail

Third Flyby

Second Flyby

Third flyby scale stretched 5X

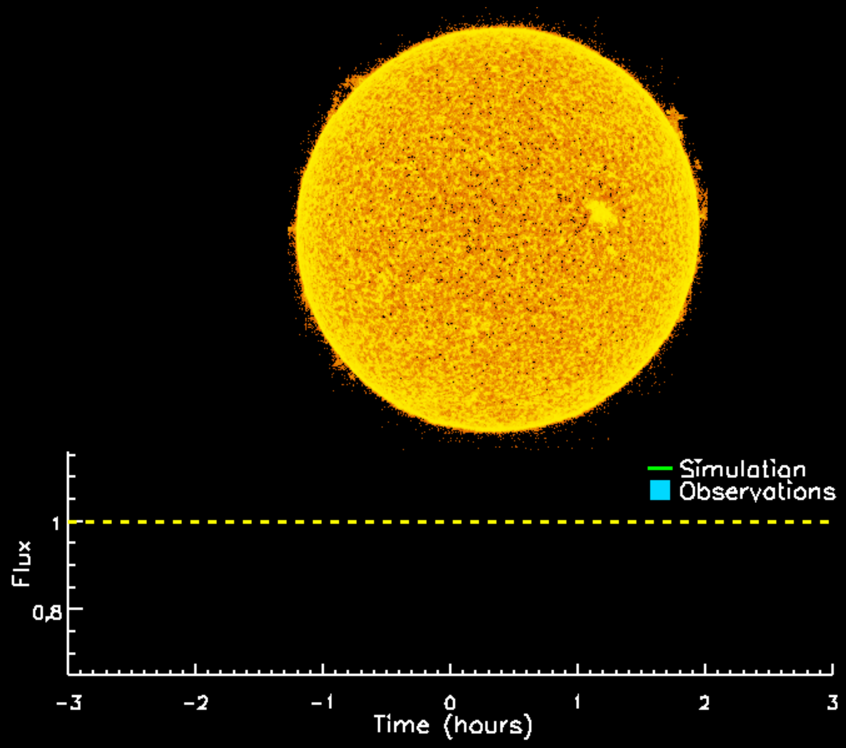
Models at flyby conditions

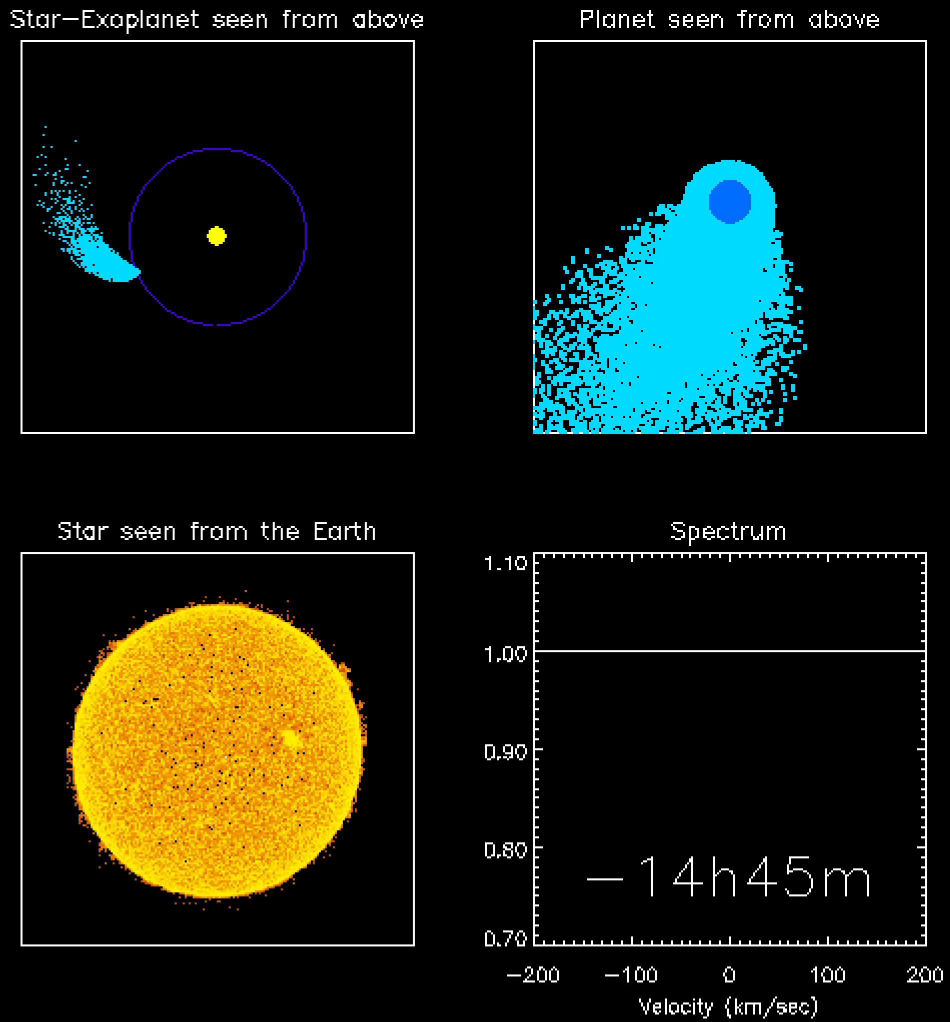


Comparison of the neutral sodium observed during the 2nd and 3rd Mercury flybys to models. The color scale for the 3rd flyby has been stretched to show the distribution of sodium more clearly. As in previous flybys, the distinct north and south enhancements in the emission that result from material being sputtered from the surface at high latitudes on the dayside are seen.

A computer simulation of the evaporating extra-solar planet HD 209458b

Vidal-Madjar et al. 2003





The graphic shows the 9 measurements of lyman alpha flux during the transit of the planet (blue squares).
The green line is the simulation.

The right-bottom panel shows the absorption spectrum due to the evaporating hydrogen when the planet is passing in front of its star.

EFFECTS OF YOUNG SUN'S ACTIVITY ON MERCURY & VENUS

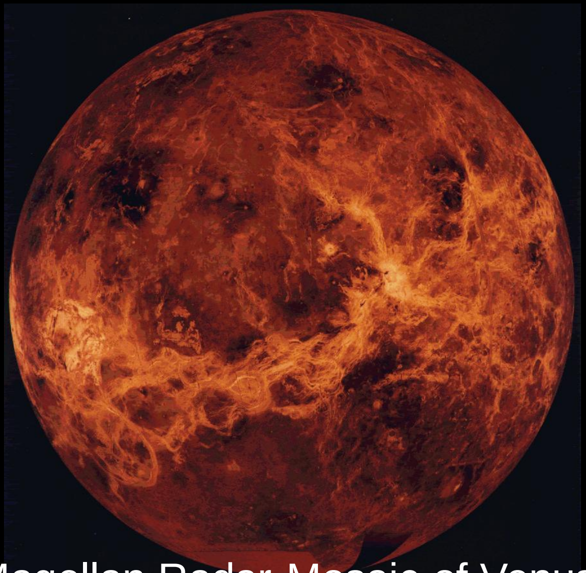
Mercury: Given the closeness of Mercury to the Sun (0.39 AU), the radiation and winds of the young, active Sun ravaged the planet, completely eliminating its atmosphere and possibly even eroding away a significant fraction of its mantle. This resulted in a planet with a disproportionately large iron core, relative to its overall size.

Mariner 10 images the barren Mercury

Venus: Investigate evolution of the Venus' atmosphere -D/H abundance indicates past oceans- but all lost from Sun. Maybe the young Sun's enhanced activity played a major role?

It did! : $H_20 \rightarrow H + H + O$ (all lost quickly).

Result - Within the first ~½ Gyr, Venus lost all of its water inventory



Magellan Radar Mosaic of Venus

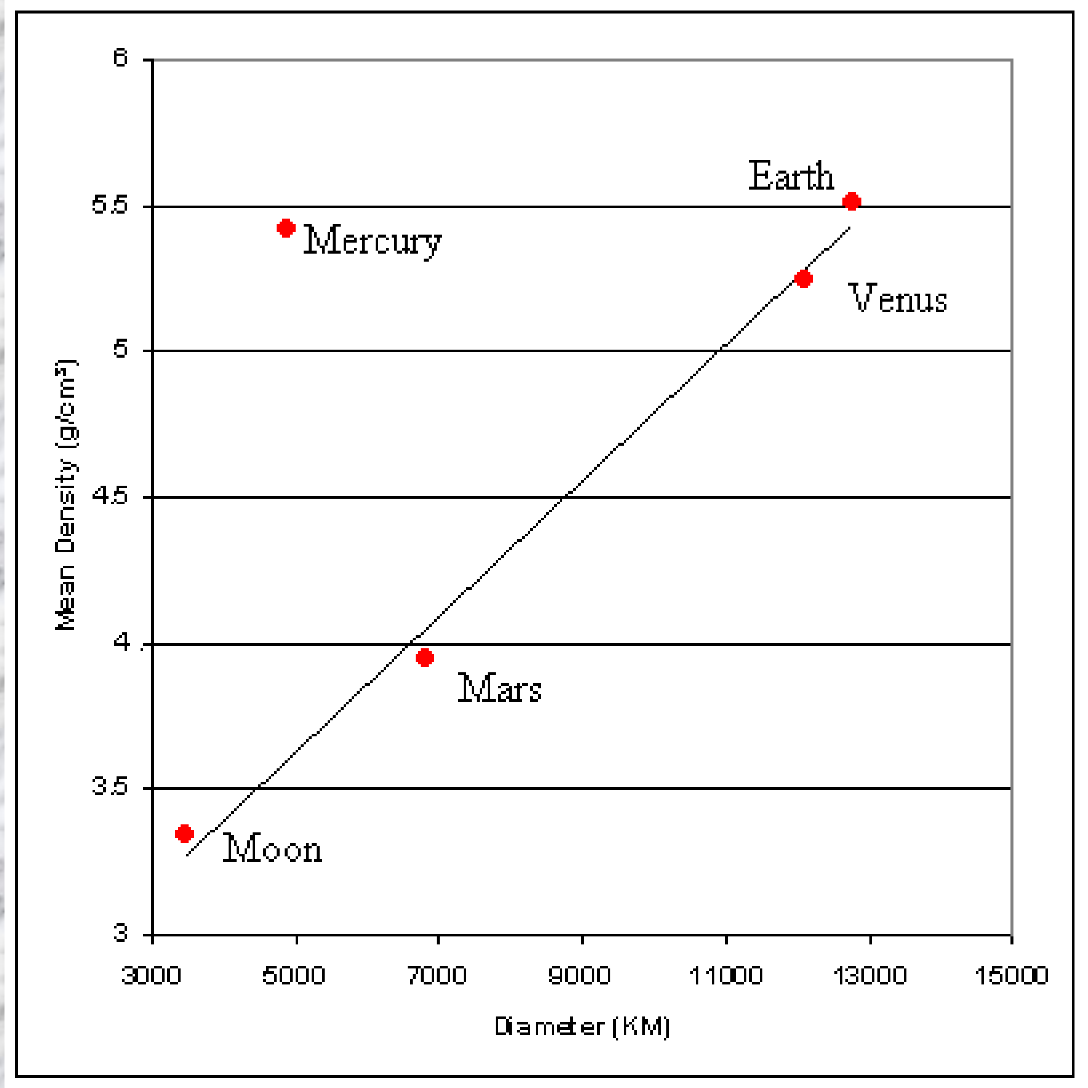
THE YOUNG SUN WAS NOT KIND TO ITS NEAREST PLANET- MERCURY:

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

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

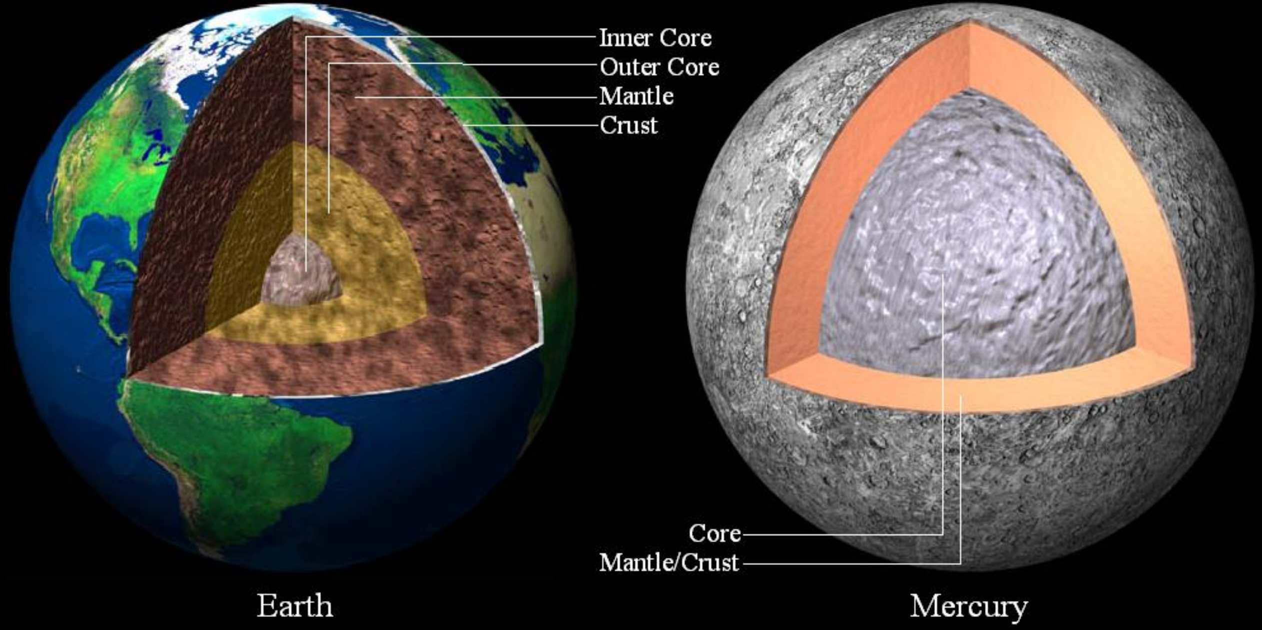


Image credits: Walter Myers (top); Calvin J. Hamilton (bottom)

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

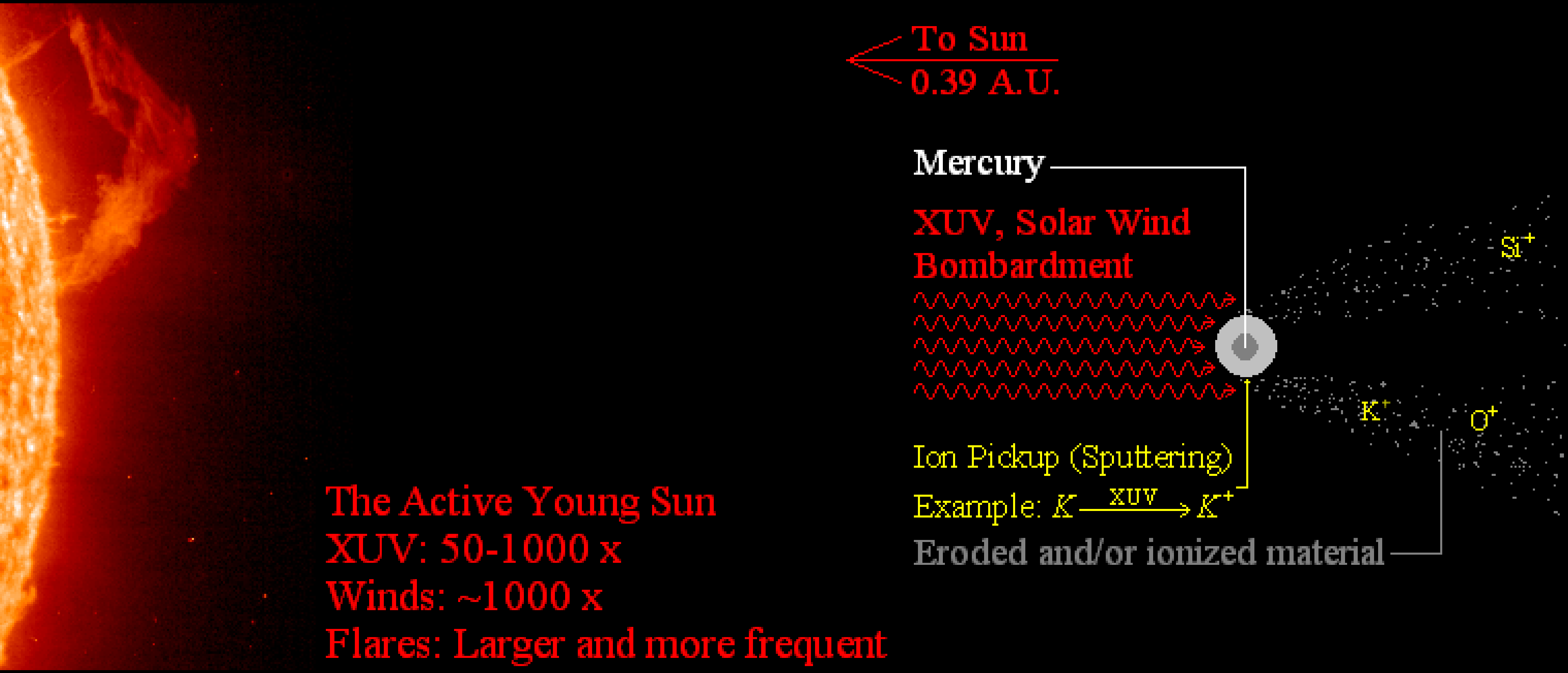


Image credit: SOHO (ESA & NASA)

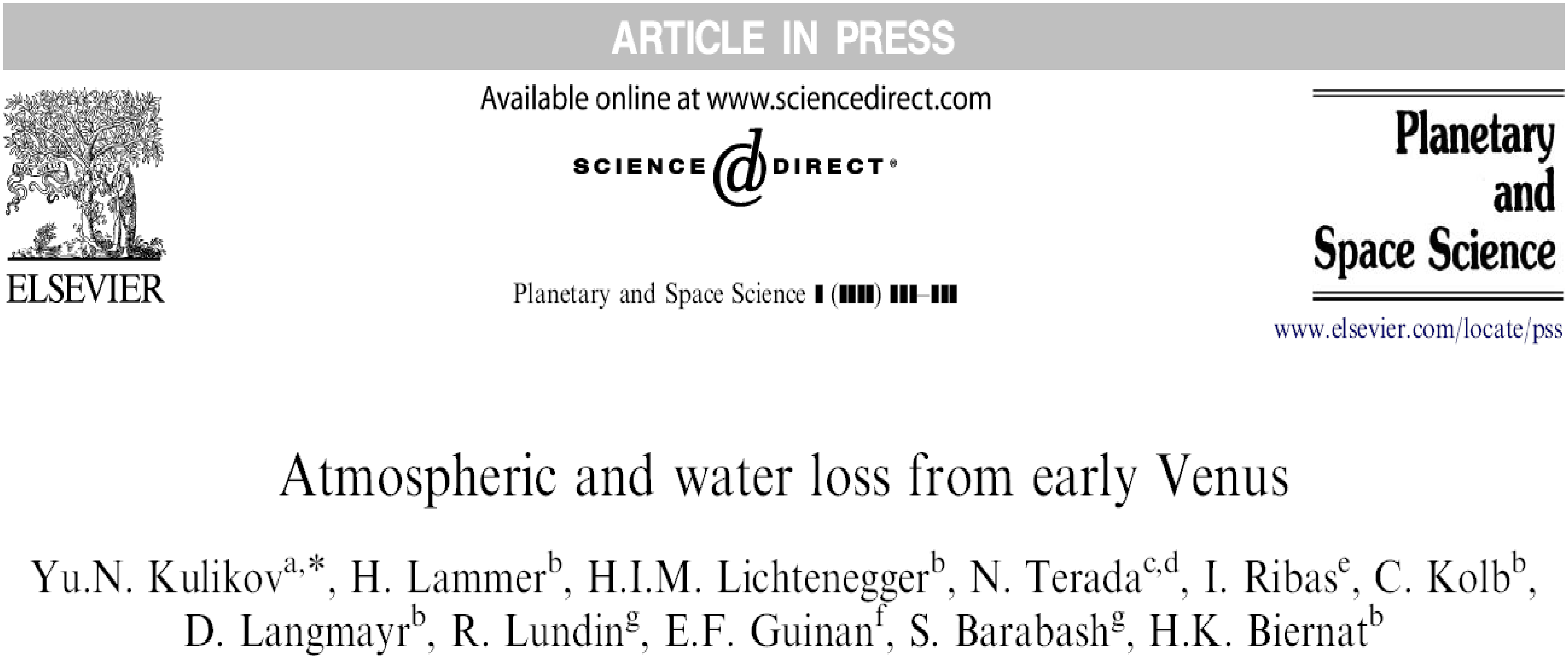
Some Consequences of the Young Sun's Enhanced Activity and XUV Flares II: Venus

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 (D/H indicates that oceans once were present on early Venus)
  - Maybe the young Sun's enhanced activity played a major role?

    e.g. $H_2O \xrightarrow[FUV]{} OH+H$



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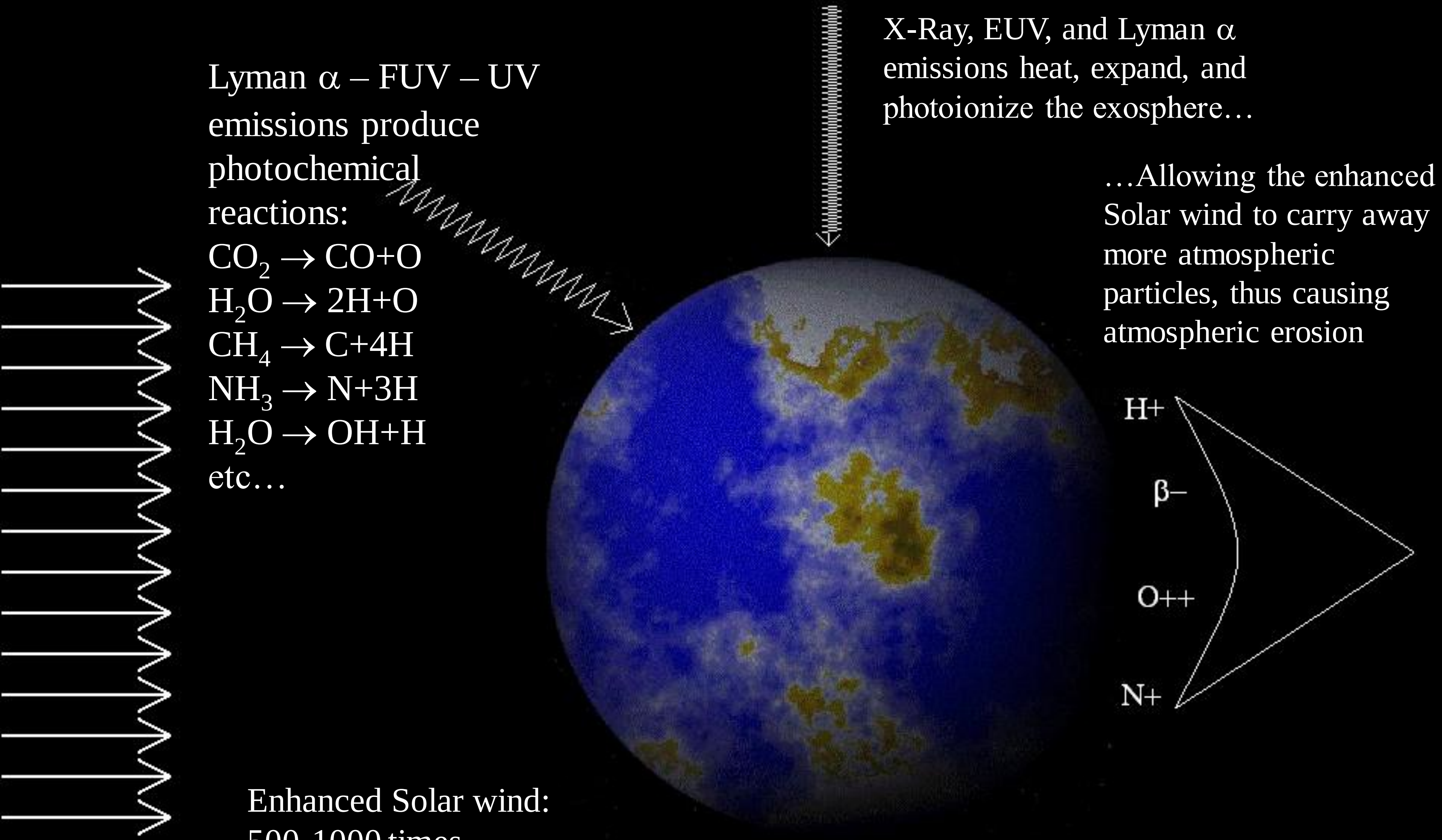
Atmospheric and water loss from early Venus

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

EARTH

Effects of the young Sun on the Earth



Lyman α – FUV – UV emissions produce photochemical reactions:

$CO_2 \rightarrow CO+O$
$H_2O \rightarrow 2H+O$
$CH_4 \rightarrow C+4H$
$NH_3 \rightarrow N+3H$
$H_2O \rightarrow OH+H$
etc…

X-Ray, EUV, and Lyman α emissions heat, expand, and photoionize the exosphere…

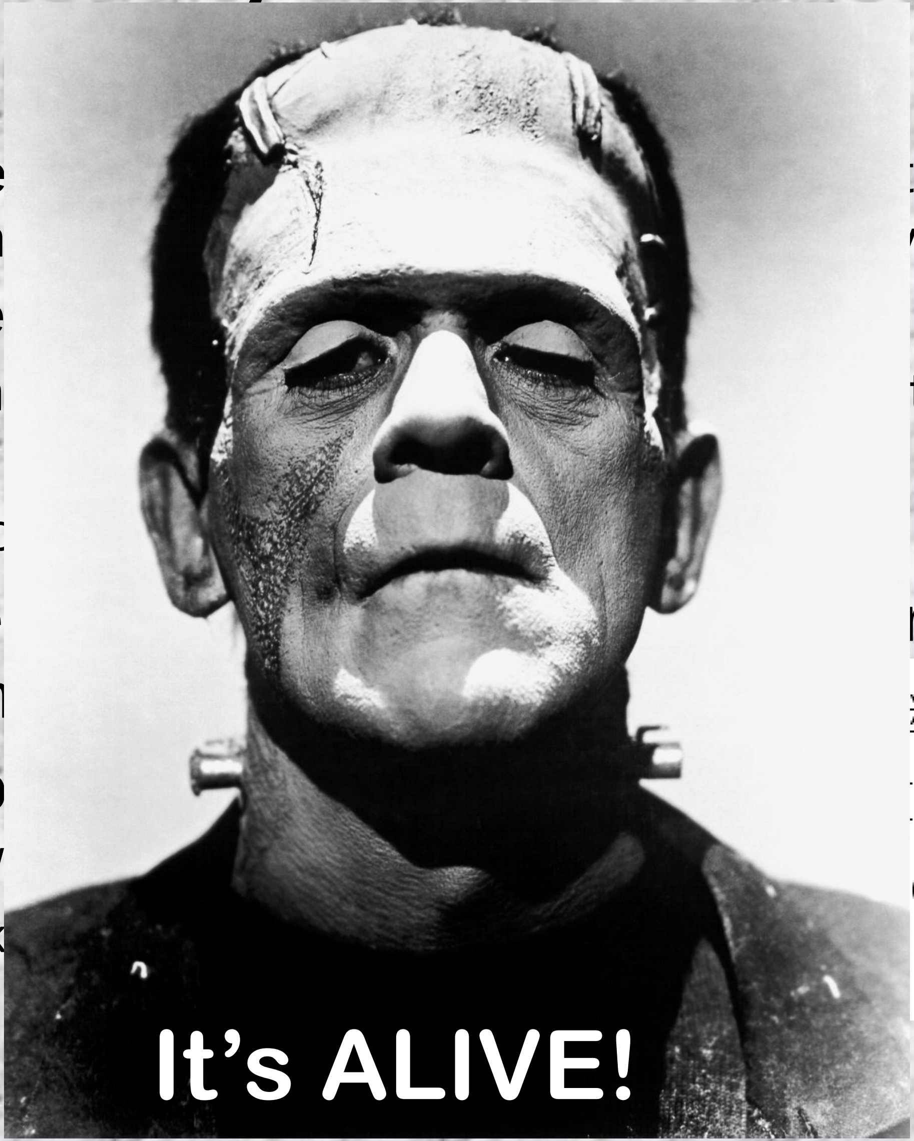
…Allowing the enhanced Solar wind to carry away more atmospheric particles, thus causing atmospheric erosion

Enhanced Solar wind: 500-1000 times present values

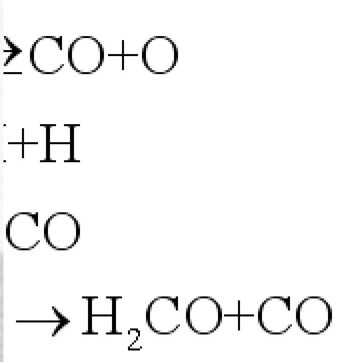
Some Consequences of the Young Sun's Enhanced Activity and XUV Flares III: Earth

- A Young active
  the evolution of
  the Earth's atm
  volution of life.
- Problems unde
  - Destruction
    trong FUV
    radiation
  - Formation c
  - Photoche
    rmation of
    organic m
  - H_2CO (fo
    - Element/

    Ribose, a k
  - Many other

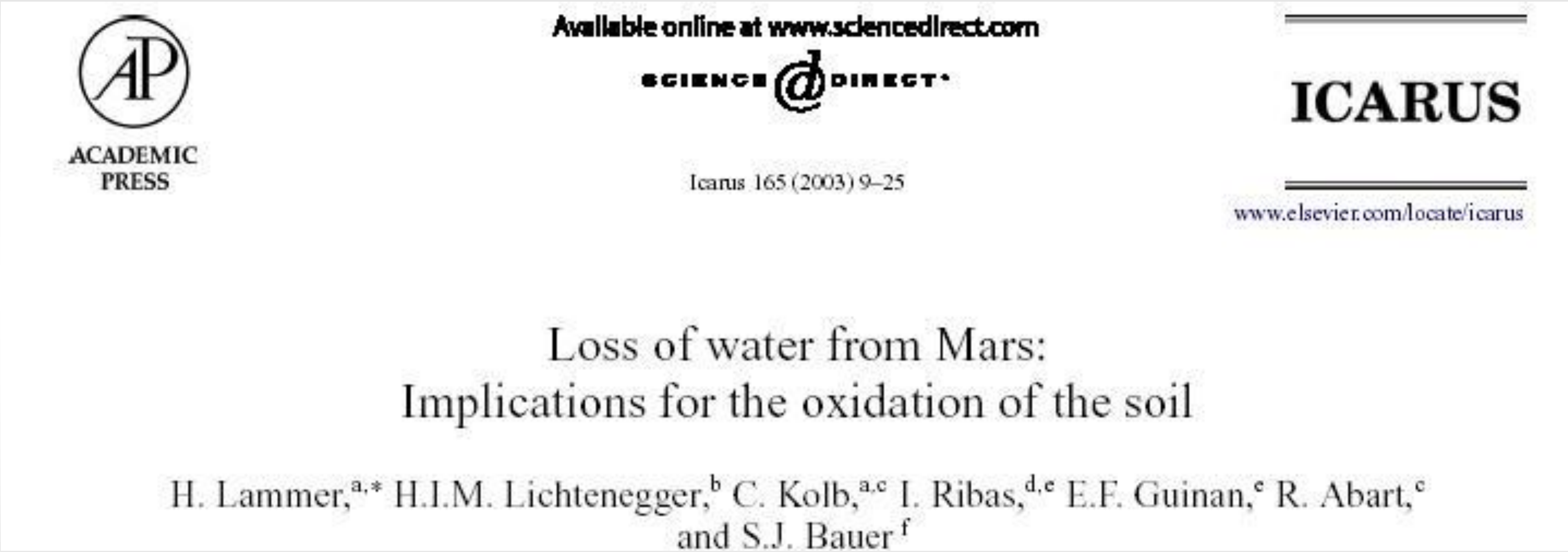


It's ALIVE!



The Secret to the success of life on Earth - A Strong Magnetic Field & Magnetosphere that shielded the early Earth from the young Active Sun's massive winds and strong flares, & CME Events

Loss of Water on Mars



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Icarus 165 (2003) 9–25

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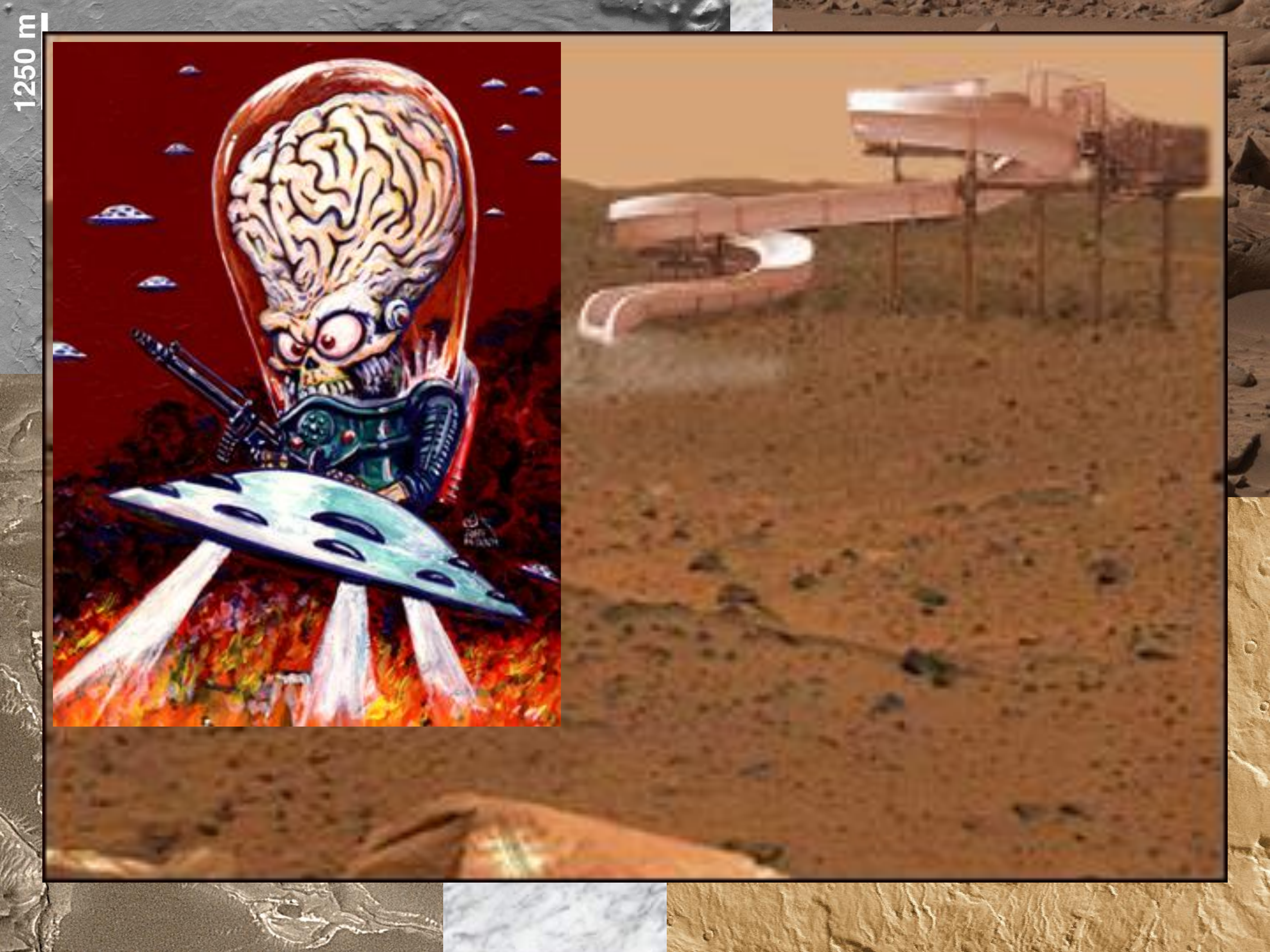
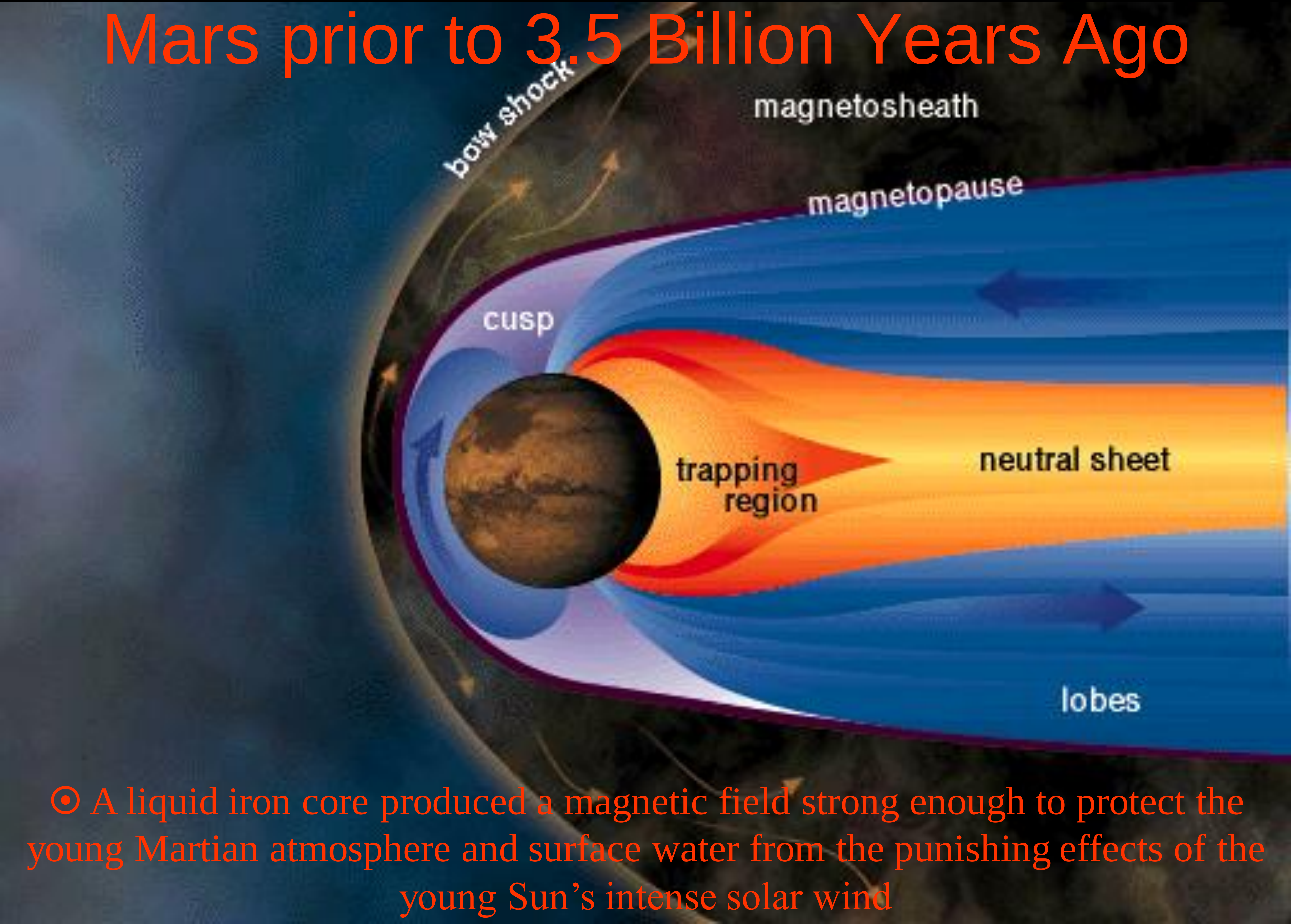
Loss of water from Mars: Implications for the oxidation of the soil

H. Lammer,[a,*] H.I.M. Lichtenegger,[b] C. Kolb,[a,c] I. Ribas,[d,e] E.F. Guinan,[e] R. Abart,[c] and S.J. Bauer[f]


1250 m

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

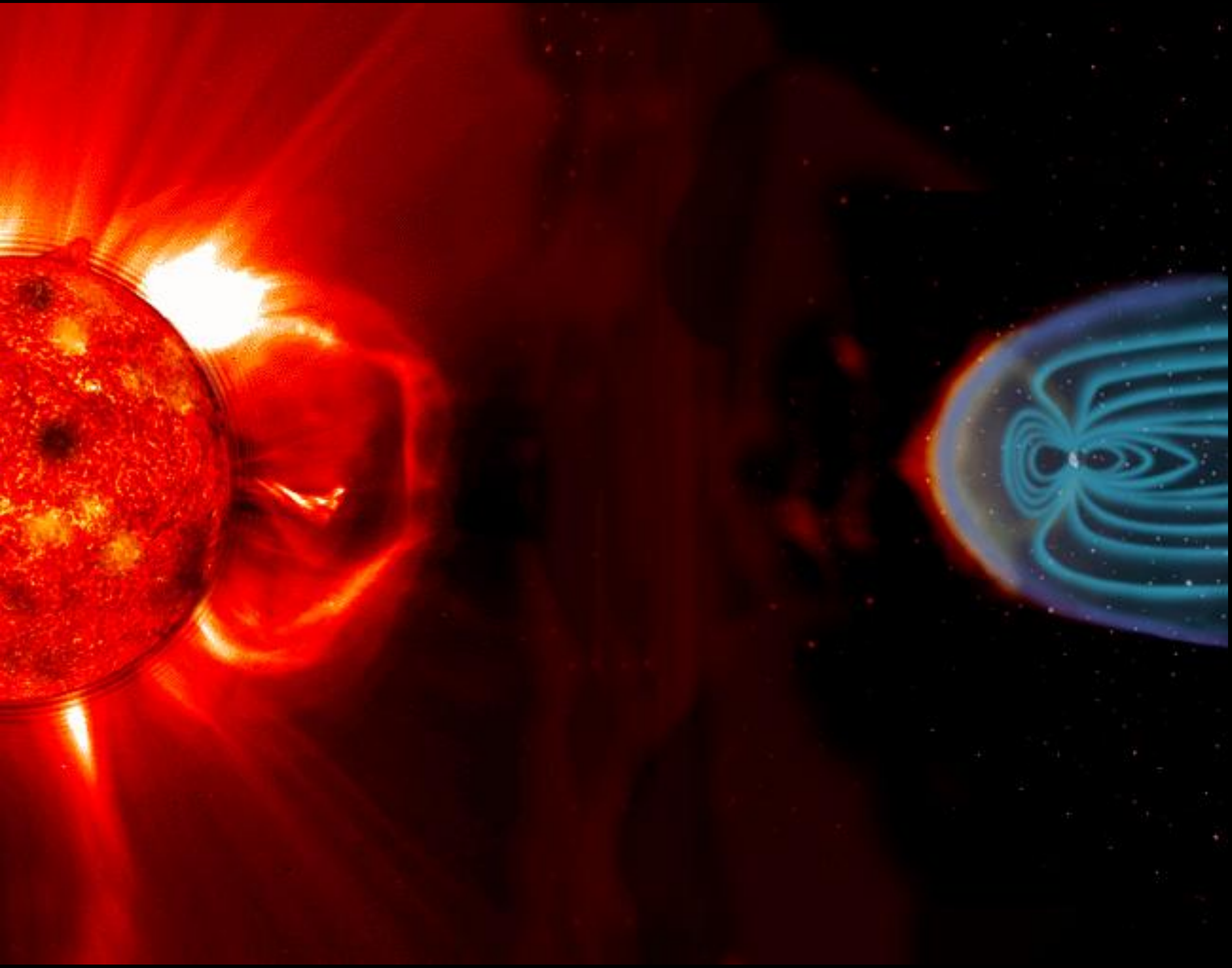
Mars after 3.5 Billion Years Ago

- years ago, Mars' core solidified, shutting down the Martian magnetic dynamo. Roughly 3.5 Billion
- Without a magnetic field, the outer Martian atmosphere was subjected to the ionizing effects and strong winds of the young 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

Michael J. Dulude

LIVING WITH A RED DWARF:

ON THE SUITABILITY OF RED DWARF STARS FOR SUPPORTING LIFE ON HOSTED PLANETS



With Scott Engle, John Bochanski, Stella Kafka & Villanova Undergrads

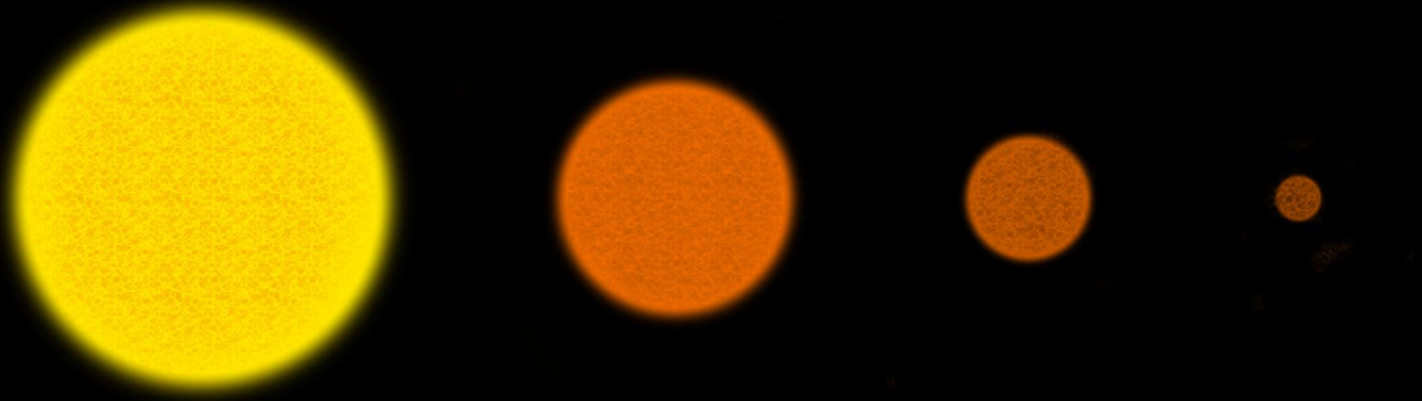
THE "LIVING WITH A RED DWARF" PROGRAM

www.astronomy.villanova.edu/livingwithareddwarf/opener.htm

The original “Living With a Red Dwarf” Program logo

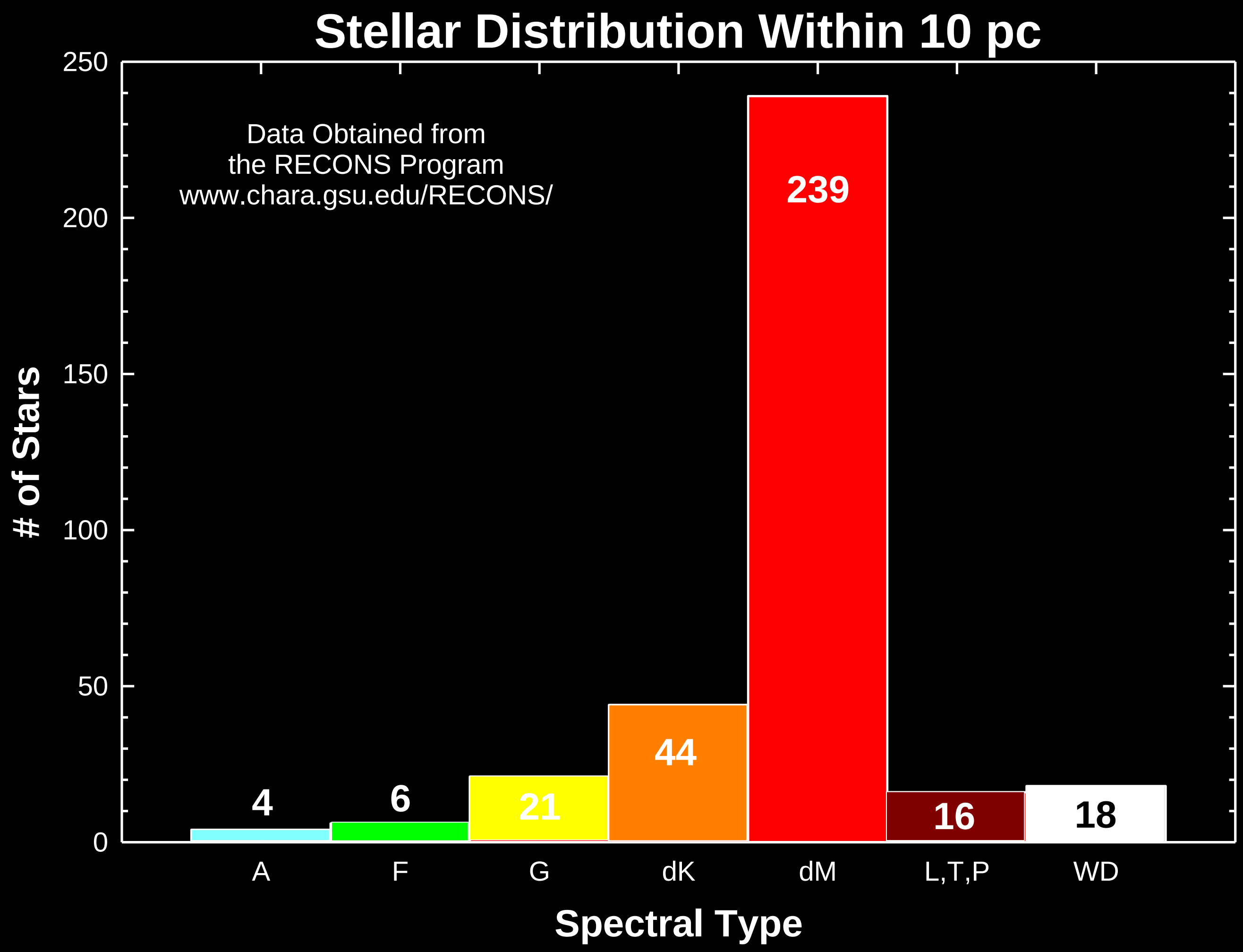
Some Basics of dM-stars

- Mass ~ (dM8) 0.07 > M < (dM0) 0.6 $M_\odot$
- Effective Temperatures < 3700 K
- Luminosity < 0.05 $L_\odot$
- Lifetimes > 10^{12} yr
- ~75 % of all stars in Galaxy
- Deep outer convection zones – fully convective for dM4 and later
- Starting to be studied for Planets (super-Earths)
- Results of the SDSS Latest Data Release (DR7.1)
  - 340 million photometric objects
    - Over 30 million M dwarfs observed with SDSS!
  - 1.4 million spectra (see Bochanski 2008)
    - 50,000 M dwarfs



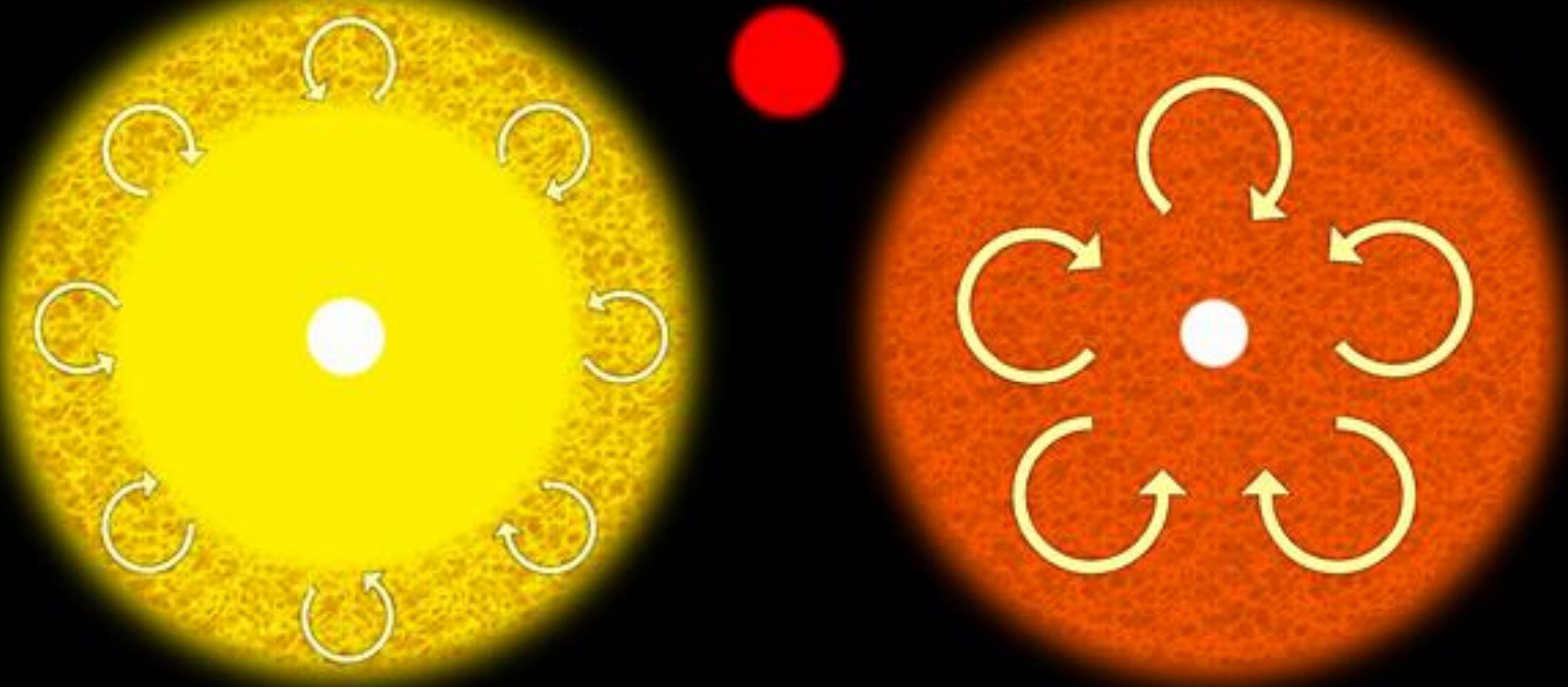
	Sun	dM0	dM5	dM8
T_{eff}	= 5780 K	= 3850 K	= 3240 K	= ~2640 K
Mass	= 1 $M_\odot$	= $0.47_\odot$	= $0.21_\odot$	= ~$0.10_\odot$
Radius	= 1 $R_\odot$	= $0.62_\odot$	= $0.32_\odot$	= ~$0.13_\odot$
Lumin.	= 1 $L_\odot$	= $0.063_\odot$	= $0.008_\odot$	= ~$0.0008_\odot$

Physical properties of dM0-dM8 stars compared to the Sun.



M-stars comprise ~75% of nearby stars

Note: Proxima (dM5) scaled to solar radius
(actual size 0.1 solar)



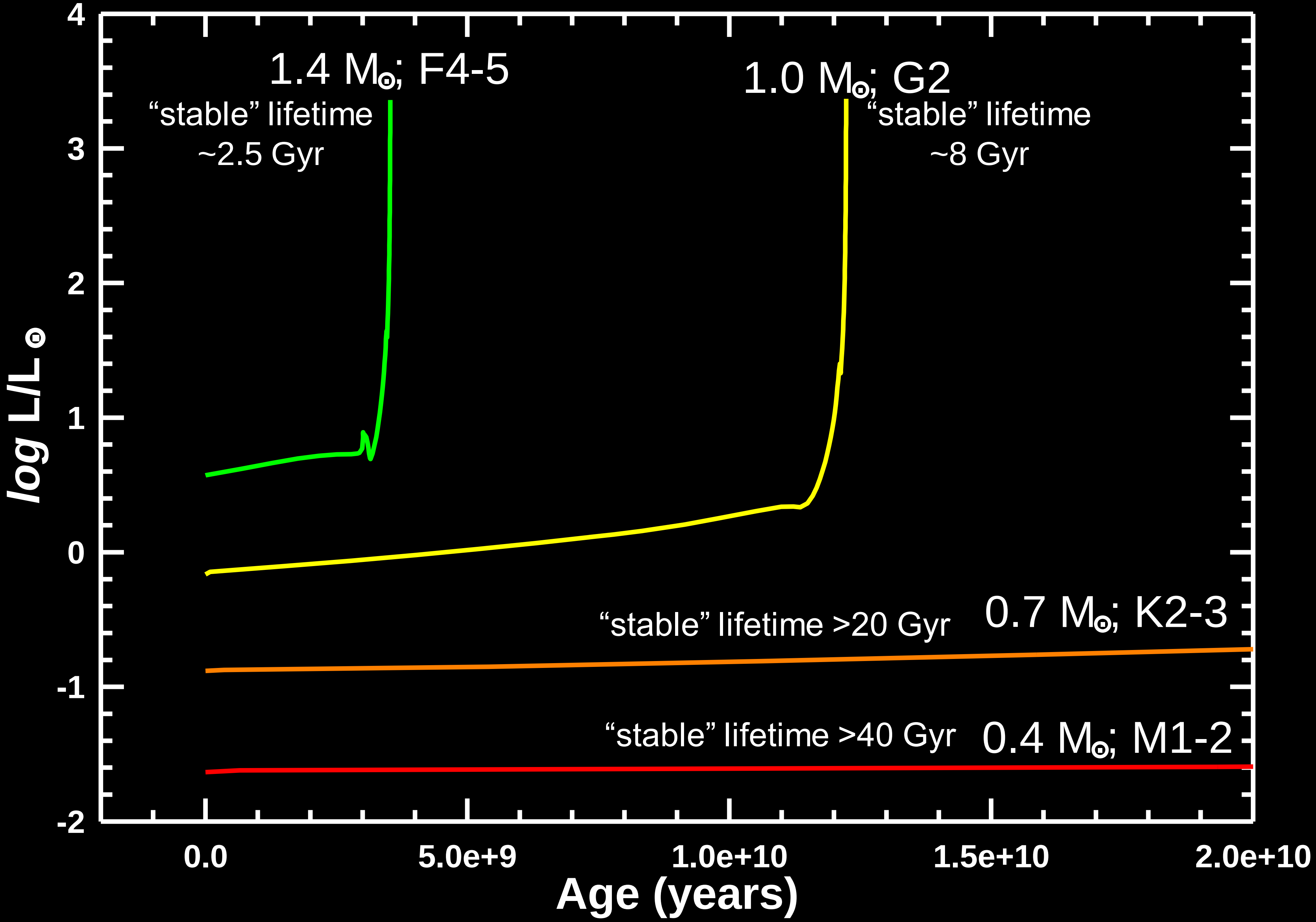
Sun (G2)

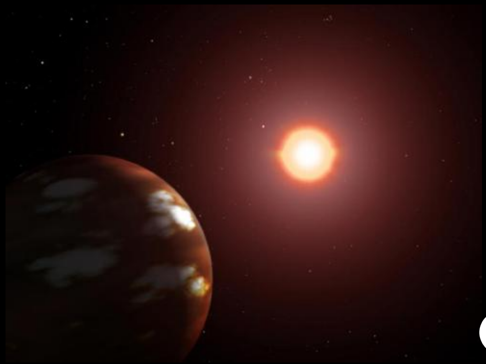
Convective Zone
located at 0.73 R.
log $L_X/L_{bol} = 10^{-6}$

dM5

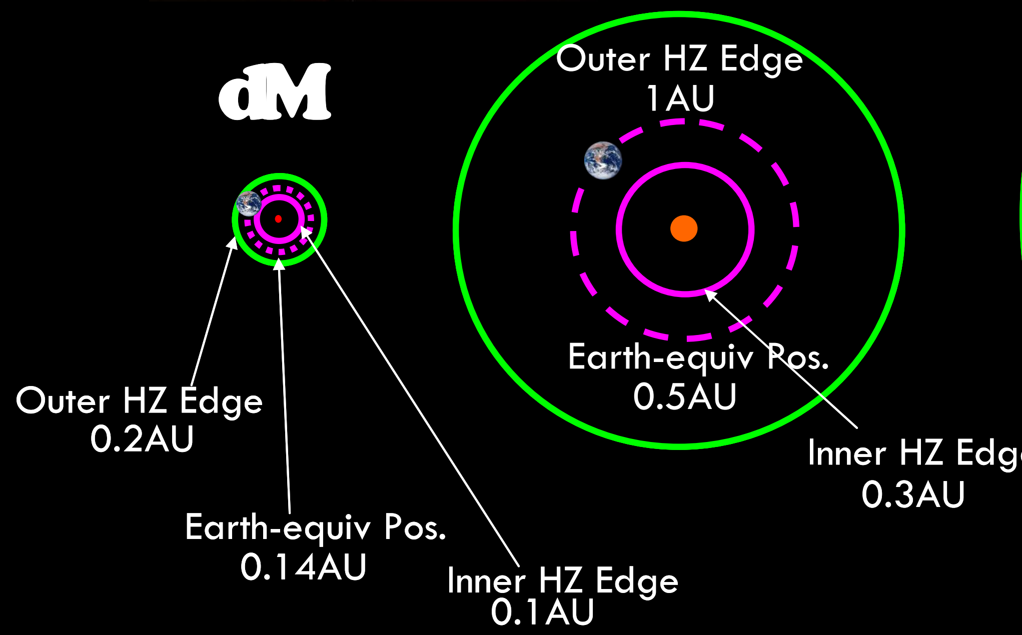
Fully Convective
Outer Envelope
log $L_X/L_{bol} = 10^{-3}$
(10^3x stronger)

Evolution of F-G-K-M Stars Over Time





dK



dM

Outer HZ Edge
0.2AU

Earth-equiv Pos.
0.14AU

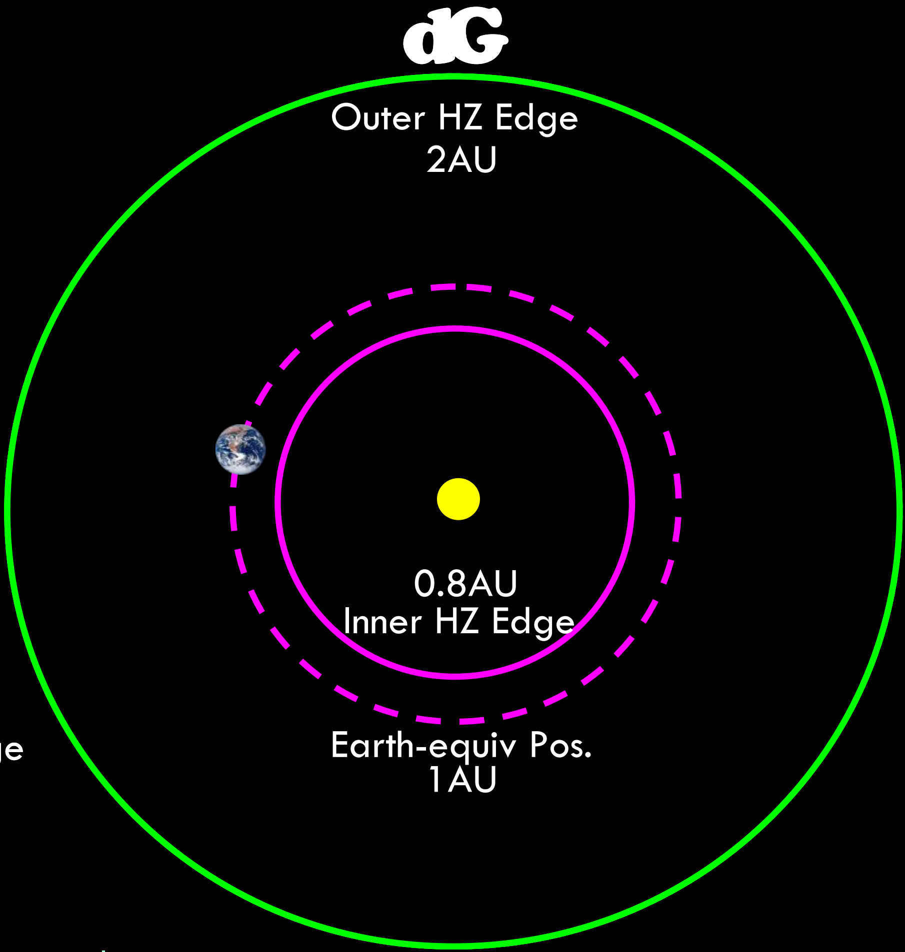
Inner HZ Edge
0.1AU

Outer HZ Edge
1AU

Earth-equiv Pos.
0.5AU

Inner HZ Edge
0.3AU

dG



Outer HZ Edge
2AU

0.8AU
Inner HZ Edge

Earth-equiv Pos.
1AU

* Earth not drawn to scale

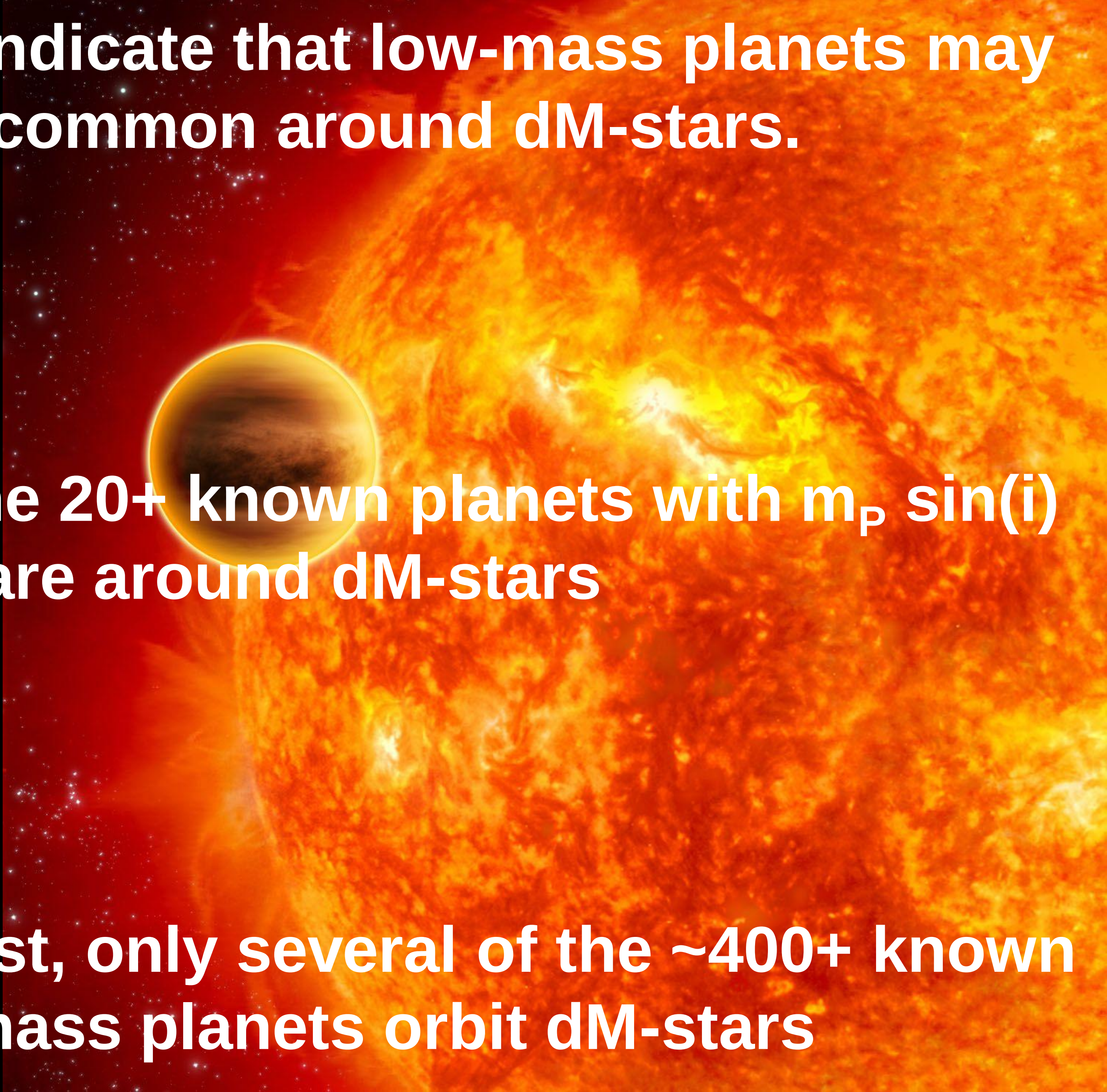
Liquid Water Habitable Zones for mid-dM, -dK and -dG stars. Note that the HZs of dM-stars are located <0.3 AU from host star.

Some Examples of dM Star - Planetary Systems

Name	Spec.	V-mag	Dist.	Planet	Period	Mass	Orb. Dist.
GJ 876	dM4	10.17	4.7 pc	b	1.938 d	7.5Me	0.02 AU
				c	30.46 d	0.8 MJ	0.13 AU
				d	60.83	2.5 MJ	0.21 AU
GJ 436	dM2.5	10.68	10.23	b	2.644-d	22.6 Me	0.029AU
				c:	5.185-d	~5.0 Me	0.045AU
GJ 581	dM3	10.56	6.27	b	5.368-d	15.7 Me	0.04 AU
				c	12.93-d	~5.0 Me	0.07 AU
				d	66.6-d	~7.7Me	0.22 AU
GJ 849	dM3.5	10.42	8.77	b	1849-d	0.8 MJ	2.35 AU
GJ 674	dM2.5	9.36	4.54	b	4.694-d	11.1Me	0.04 AU
GJ 317	dM3.5	13.00	9.01	b	692.9-d	1.2 MJ	0.95 AU
GJ 176	dM2.5	9.97	9.42	b	8.78-d	~8.4 Me	0.066AU

GJ 581 c & GJ 581 d are super Earths located near the inner hotter edge and outer cooler edge of the star's HZ, respectively

GJ 436b is a transiting system



- Studies indicate that low-mass planets may be more common around dM-stars.

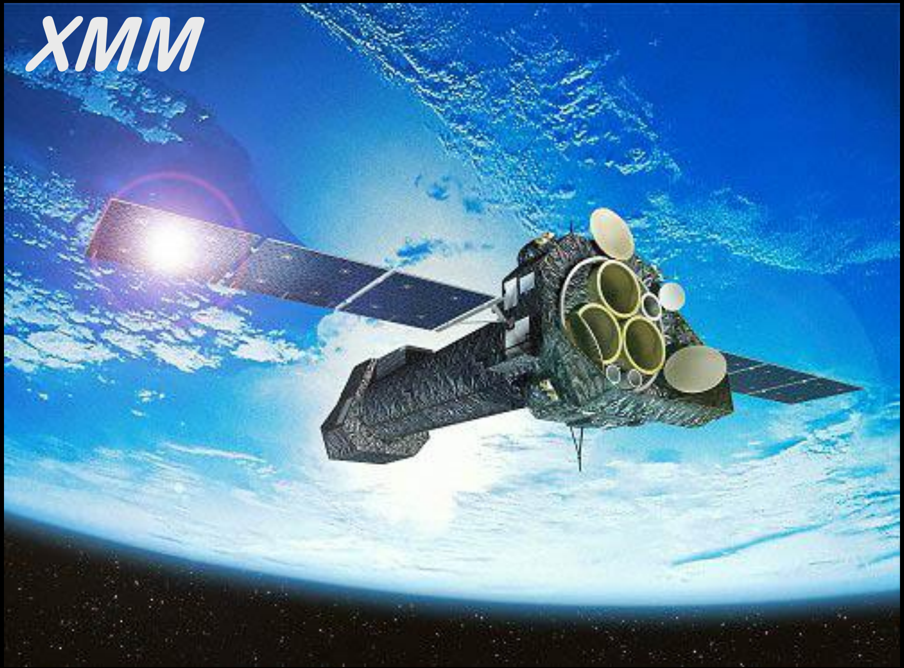
- ~1/3 of the 20+ known planets with m_P sin(i) < 0.1 M_J are around dM-stars

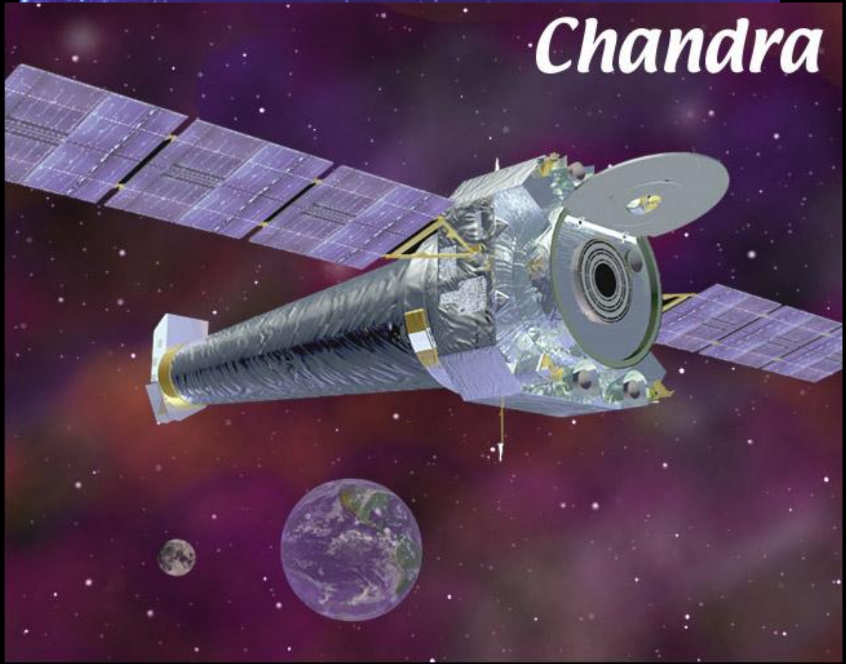
- In contrast, only several of the ~400+ known Jupiter-mass planets orbit dM-stars

X-RAY

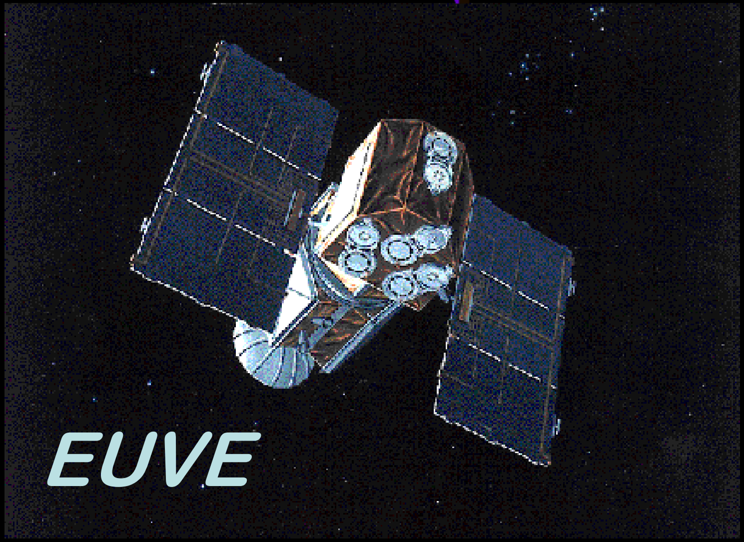

ROSAT

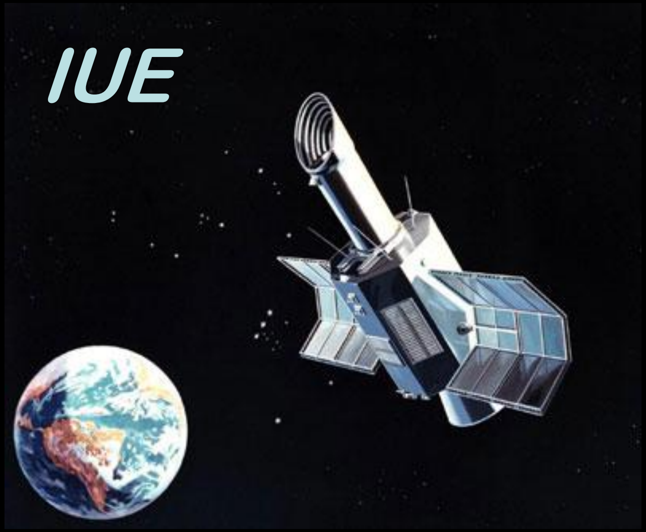

ASCA


XMM


Chandra

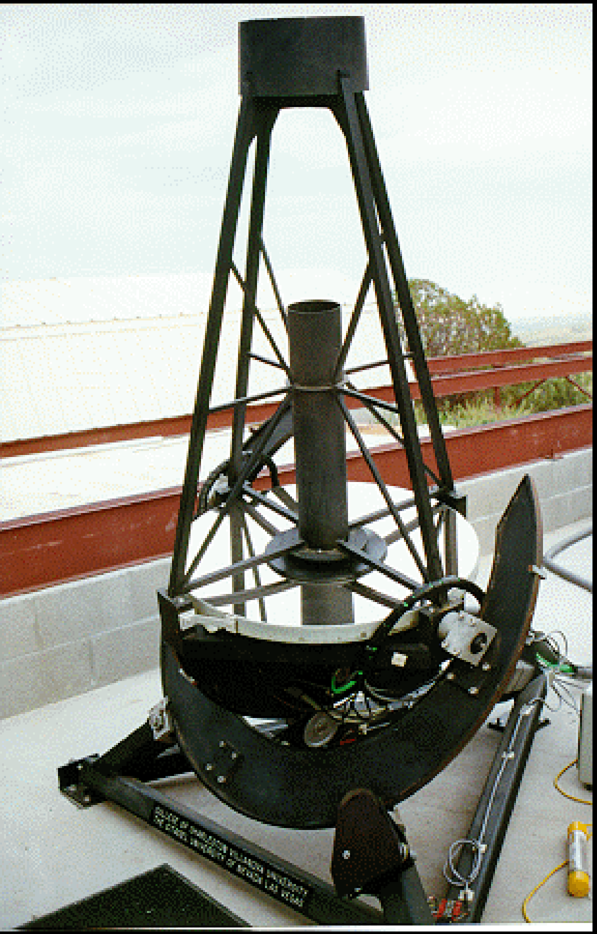
EUV/UV



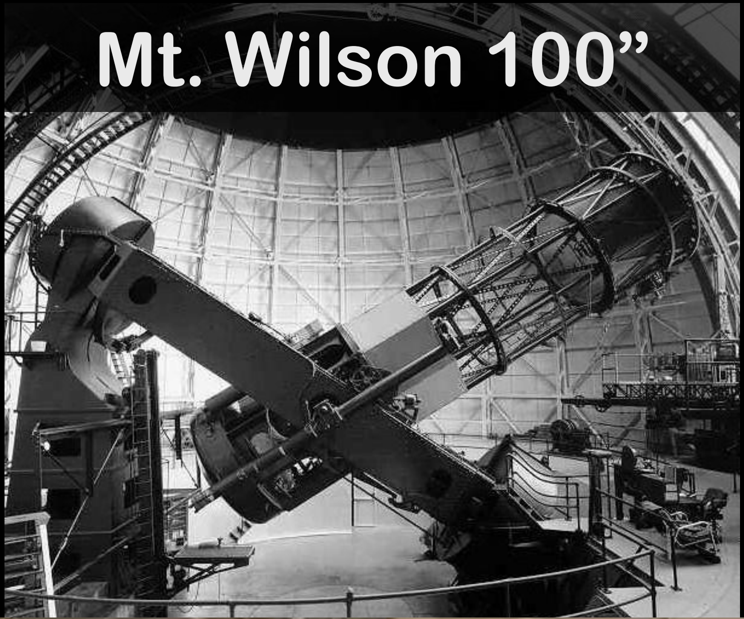


OPTICAL

0.8 m FCAPT



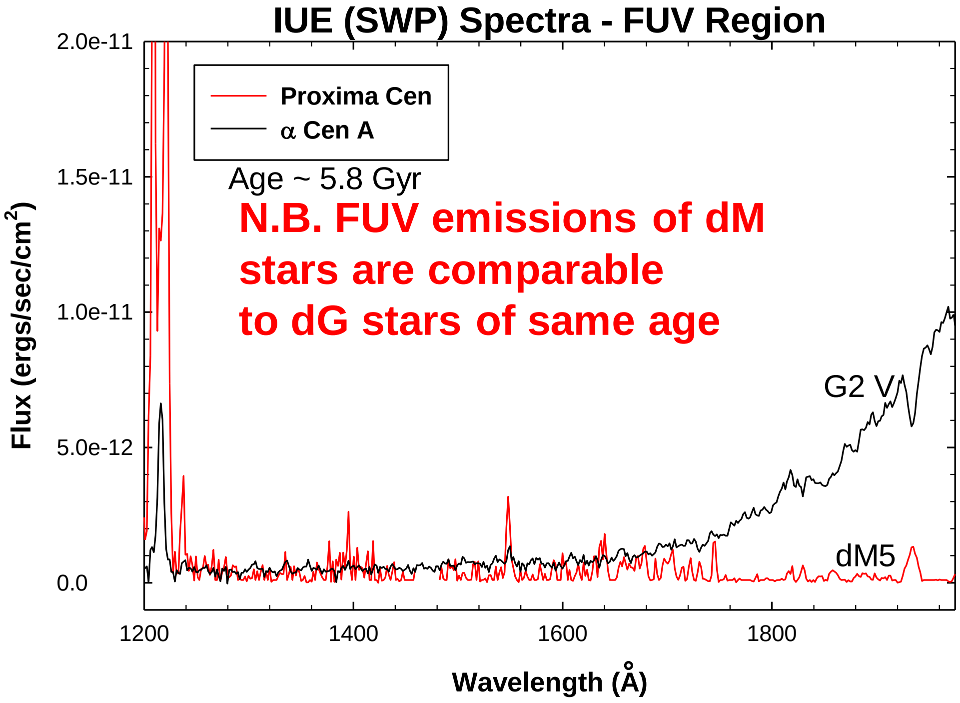
Mt. Wilson 100”



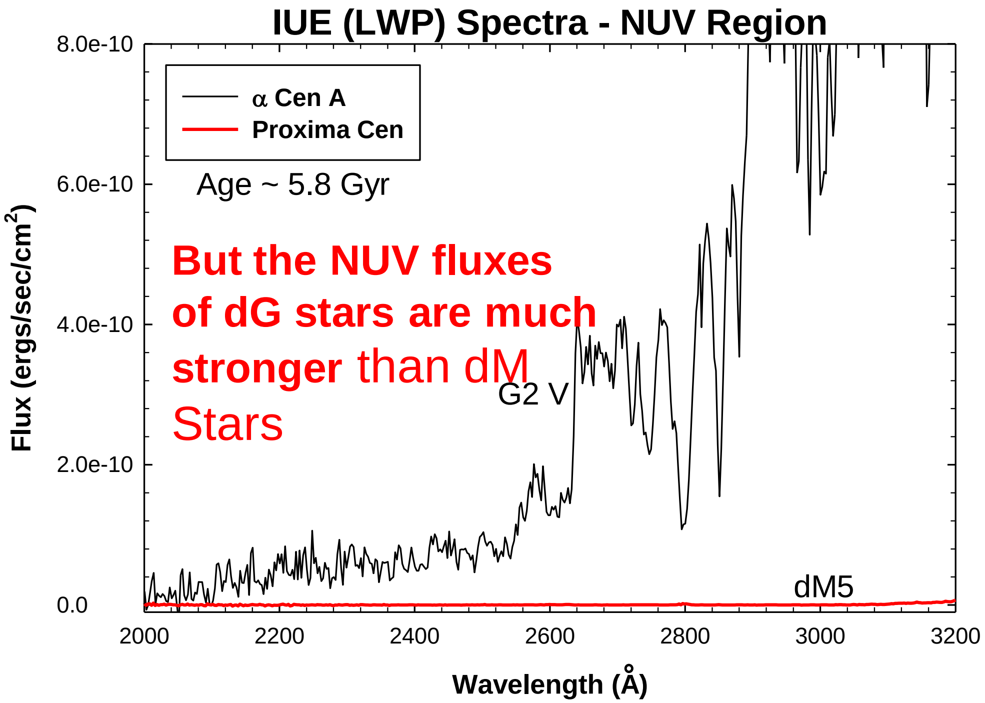
Villanova U.
38-cm
telescope

1.3 m RCT at Kitt Peak National Obs.

Comparison of UV Spectral Energy Distributions for a dM5 Star Relative to a G2 V Solar Analog

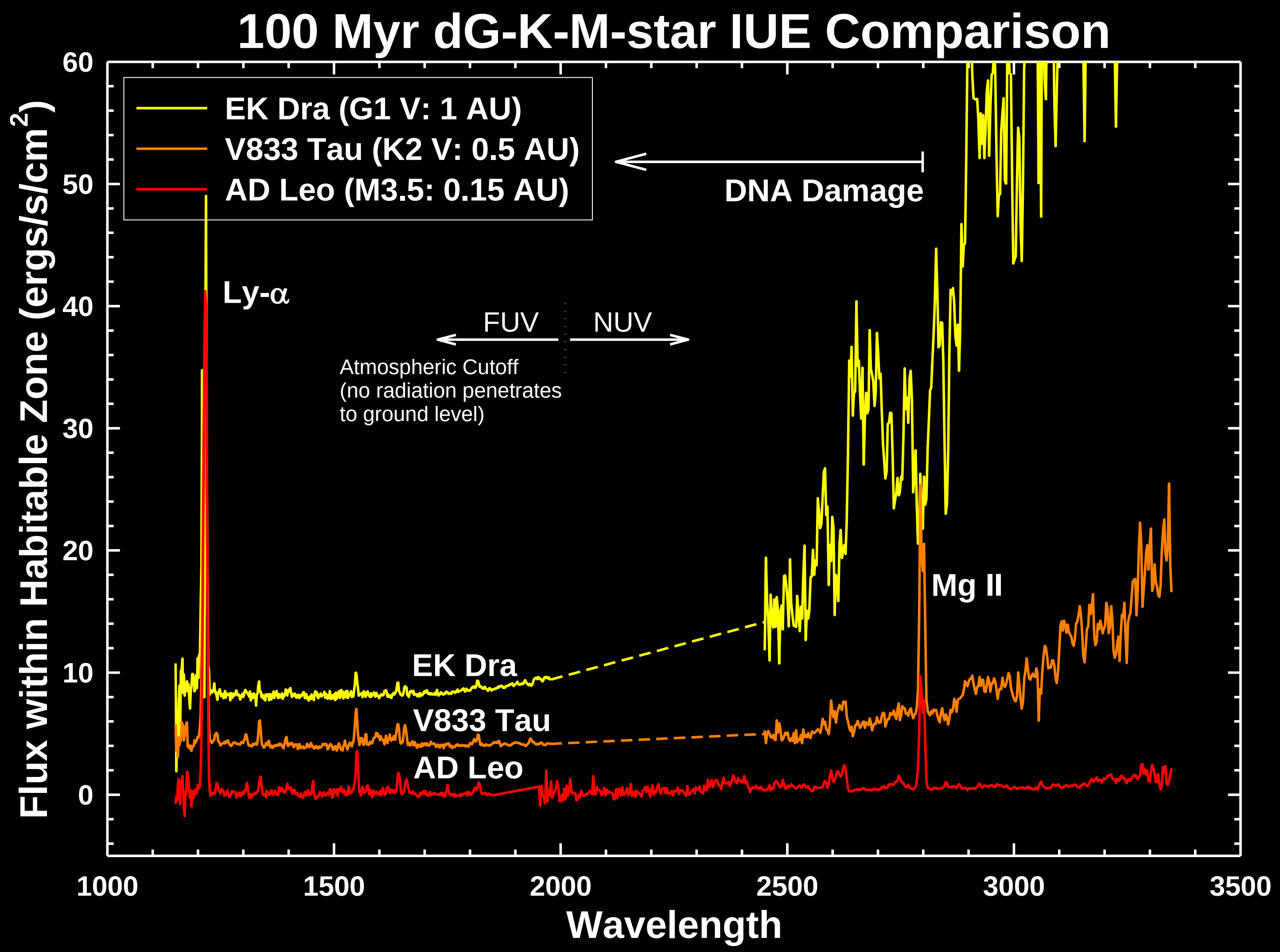


N.B. FUV emissions of dM stars are comparable to dG stars of same age

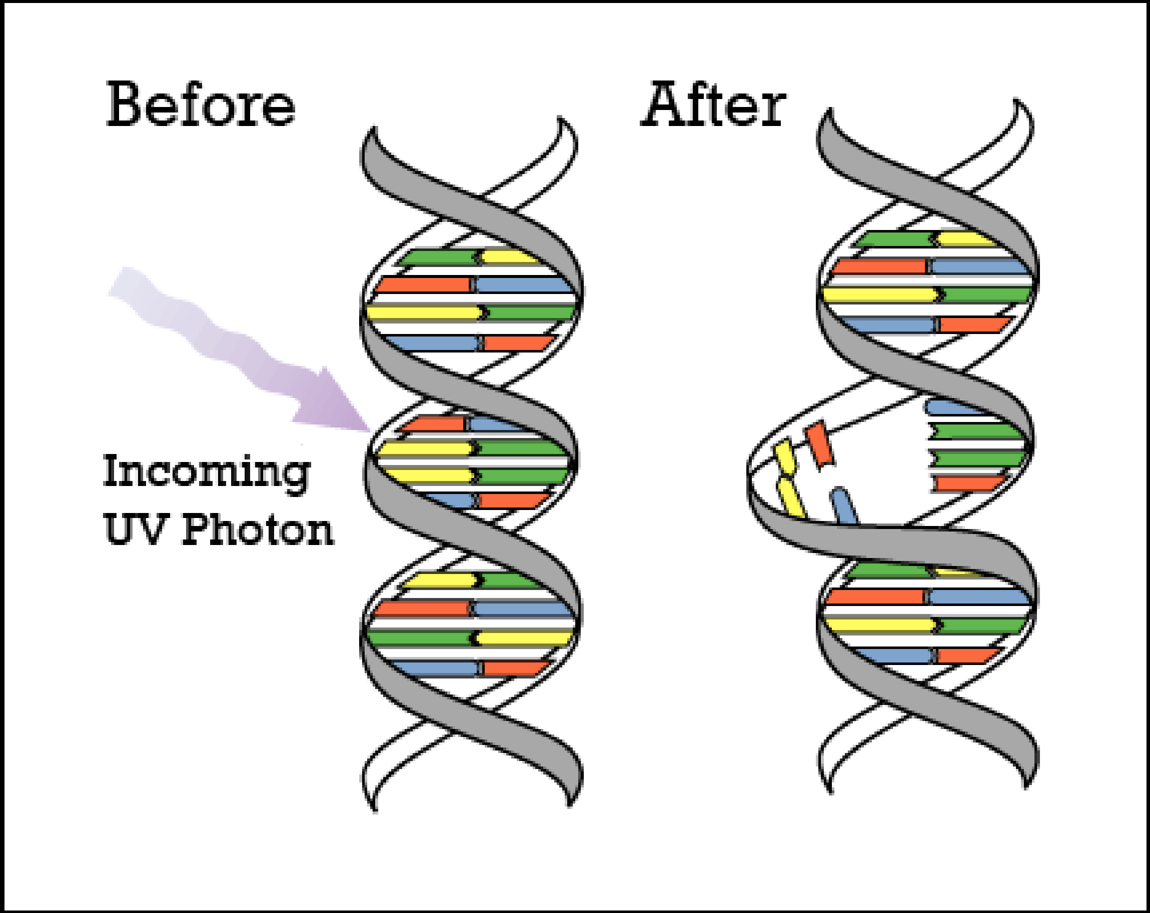


But the NUV fluxes of dG stars are much stronger than dM Stars

Note that in the FUV (wavelengths < than 1600Å), the chromospheric and TR line emissions of the dM star are comparable or greater than corresponding line emissions of the G2 V star. But at longer wavelengths in the NUV, the photospheric continuum of the G star dominates. For example, at NUV wavelengths the G star has fluxes 20 to over 1000 x higher. A planet with even a thin atmosphere will essentially block all incident FUV from reaching the planet's surface. While the NUV radiation (if present) can reach the surface and harm any unprotected life forms from DNA damage.



Comparison of FUV/NUV fluxes expected in the Habitable Zones of young G-M stars. Note the low NUV fluxes for dM stars.



Ultraviolet photons harm the DNA molecules of living organisms in different ways. In one common damage event, adjacent bases bond with each other, instead of across the "ladder". This makes a bulge, and the distorted DNA molecule does not function properly.

Determining Rotation Periods and Possible Activity Cycles of dM-Stars from time-series Photometry:

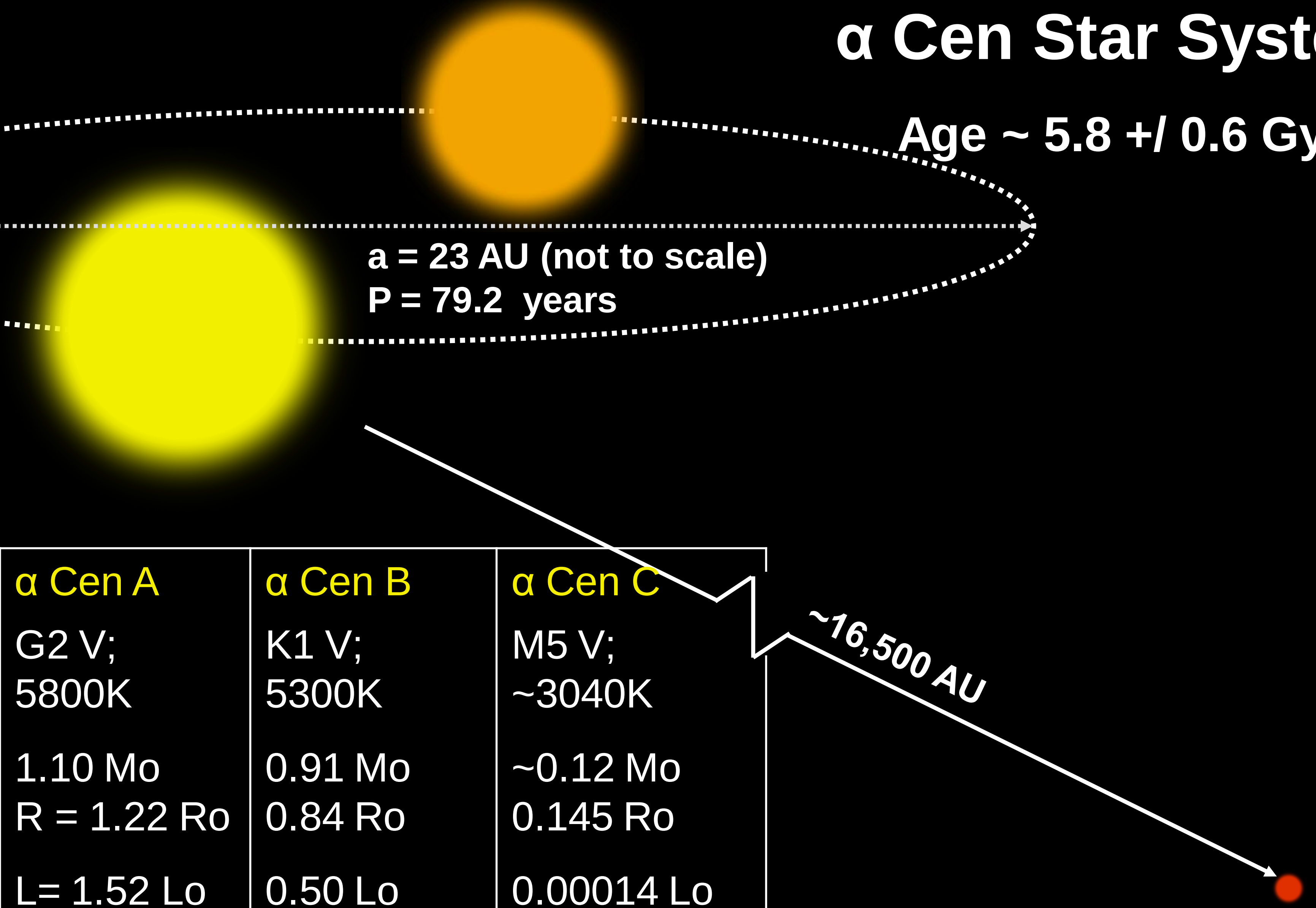
Calibration of

Age-Rotation-Activity

Engle and Guinan 90+ dK/M stars with rotation periods

α Cen Star System

Age ~ 5.8 +/ 0.6 Gyr



a = 23 AU (not to scale)
P = 79.2 years

~16,500 AU

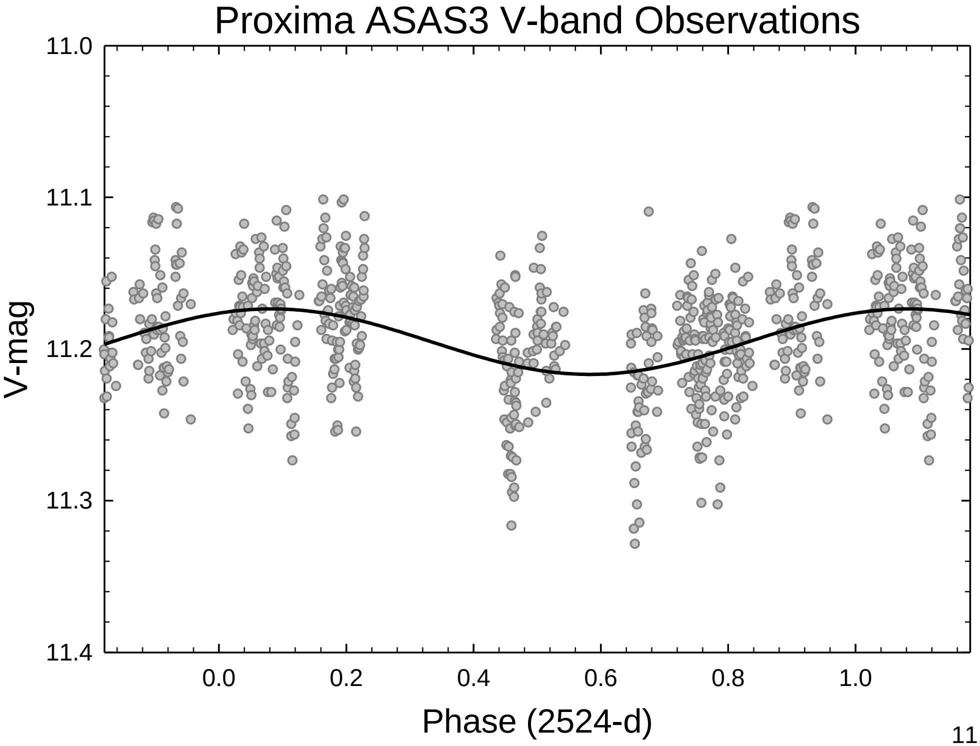
α Cen A	α Cen B	α Cen C
G2 V; 5800K	K1 V; 5300K	M5 V; ~3040K
1.10 Mo R = 1.22 Ro	0.91 Mo 0.84 Ro	~0.12 Mo 0.145 Ro
L= 1.52 Lo	0.50 Lo	0.00014 Lo
HZ:1.25 AU Rot: ~22 d	~0.74 AU 36.2 d	~0.07 AU 82.6 d

Proxima Cen

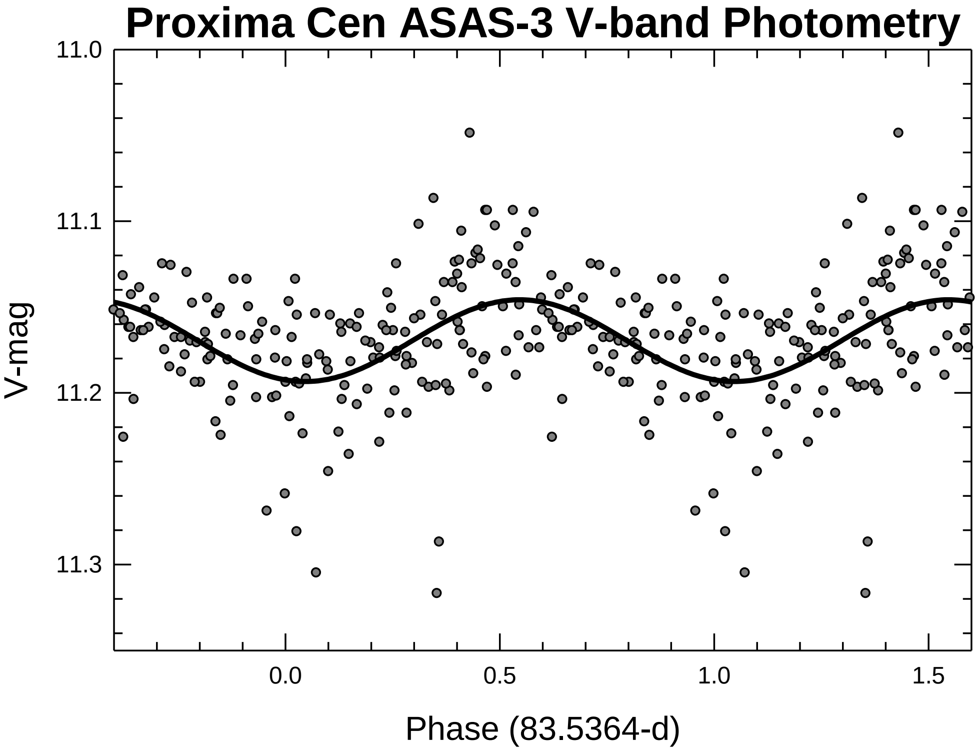
Porb ~ 0.5-1.5 Myr

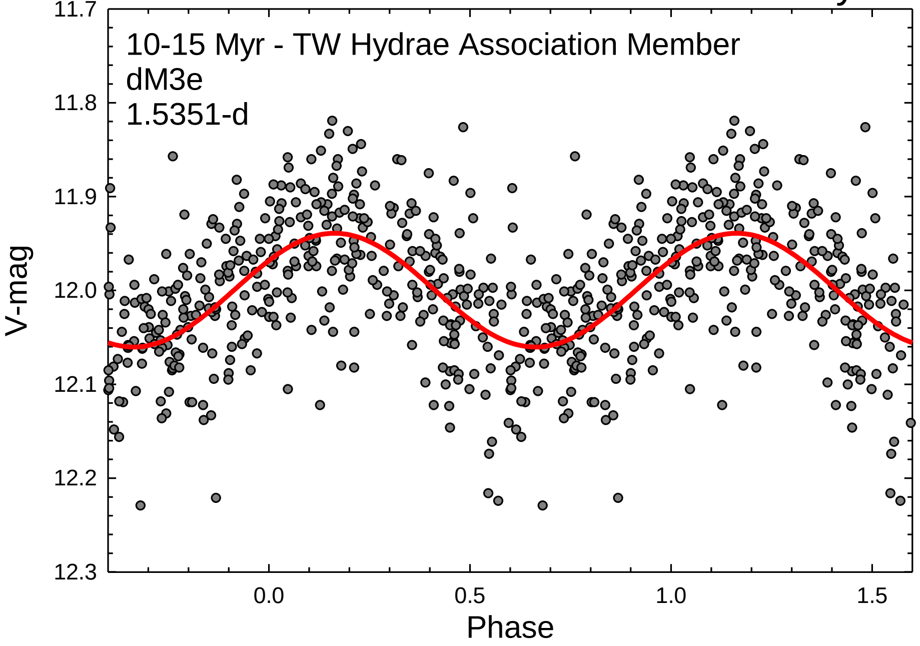
Proxima Cen

dM5.5e

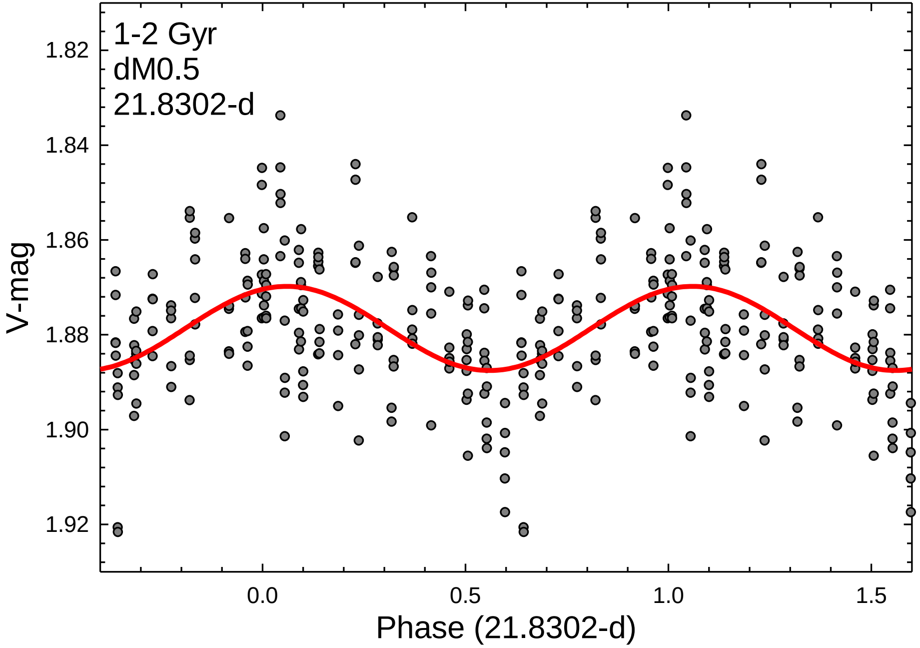

Proxima ASAS3 V-band Observations

Displays both long- (~6.9 yr) and short-term (~83.5-day) periodicities. The short-term period length matches up well to its age of ~5.8 Gyr.

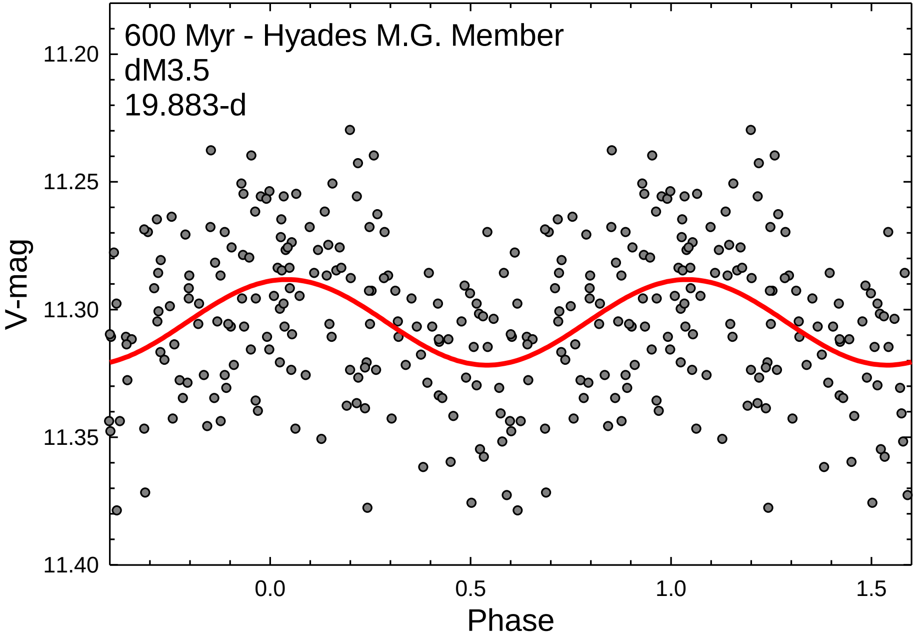

Proxima Cen ASAS-3 V-band Photometry



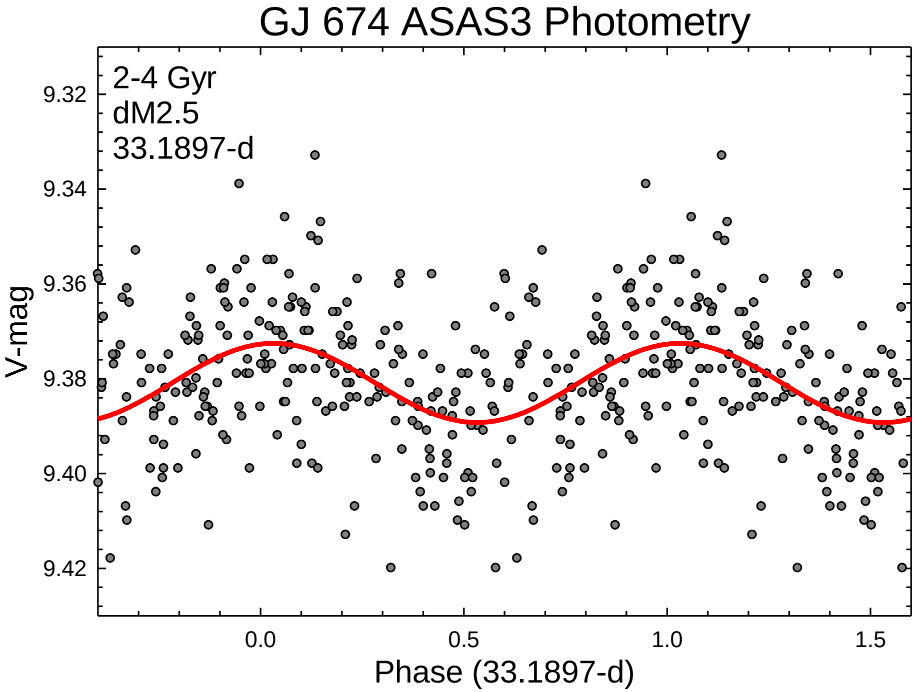
GSC 08056-00482 ASAS3 Photometry

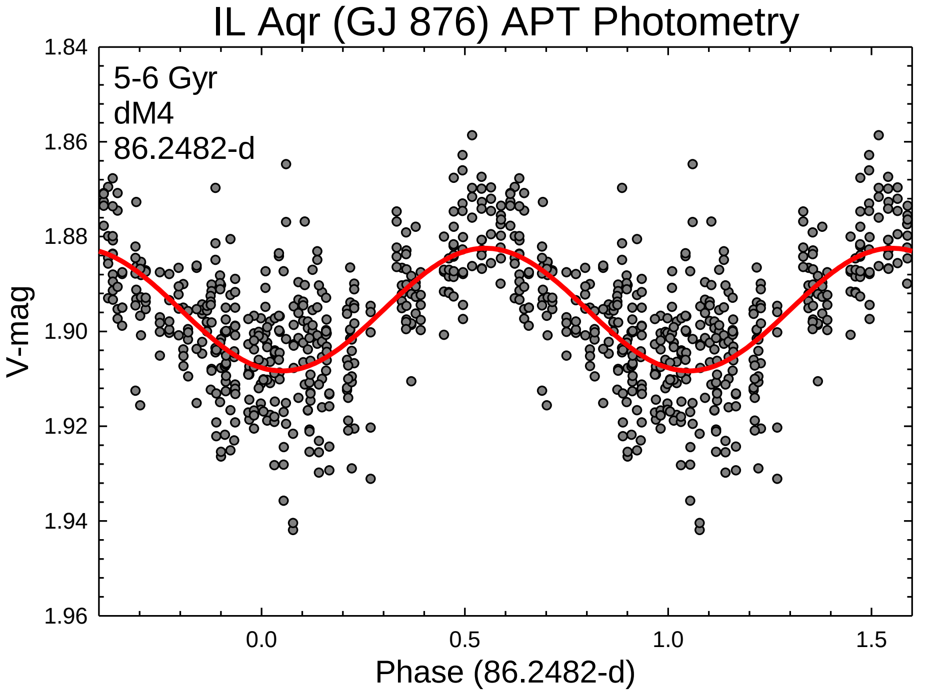


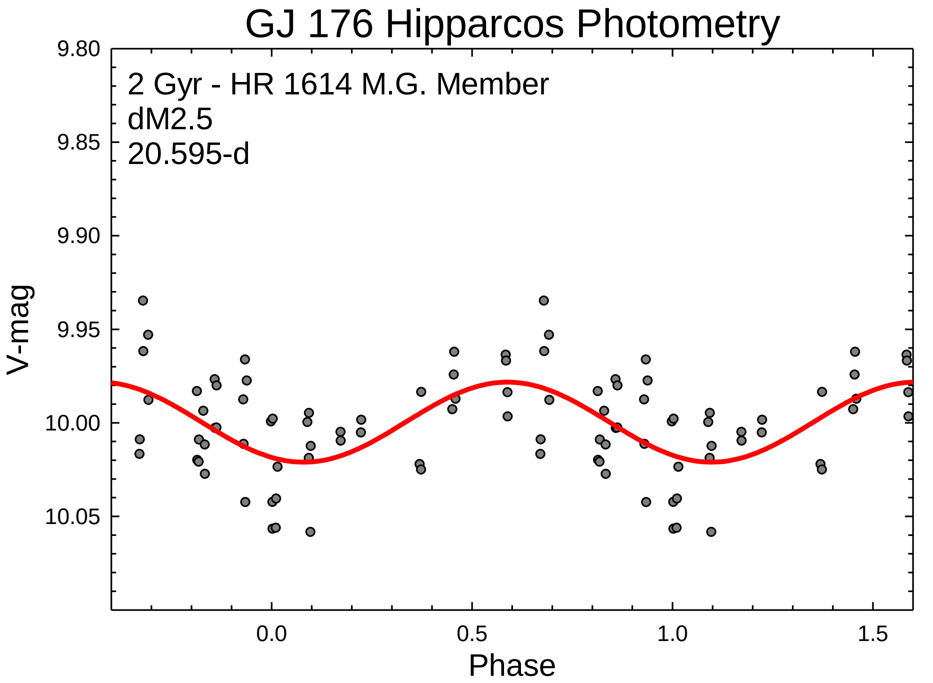
GJ 685 APT Photometry

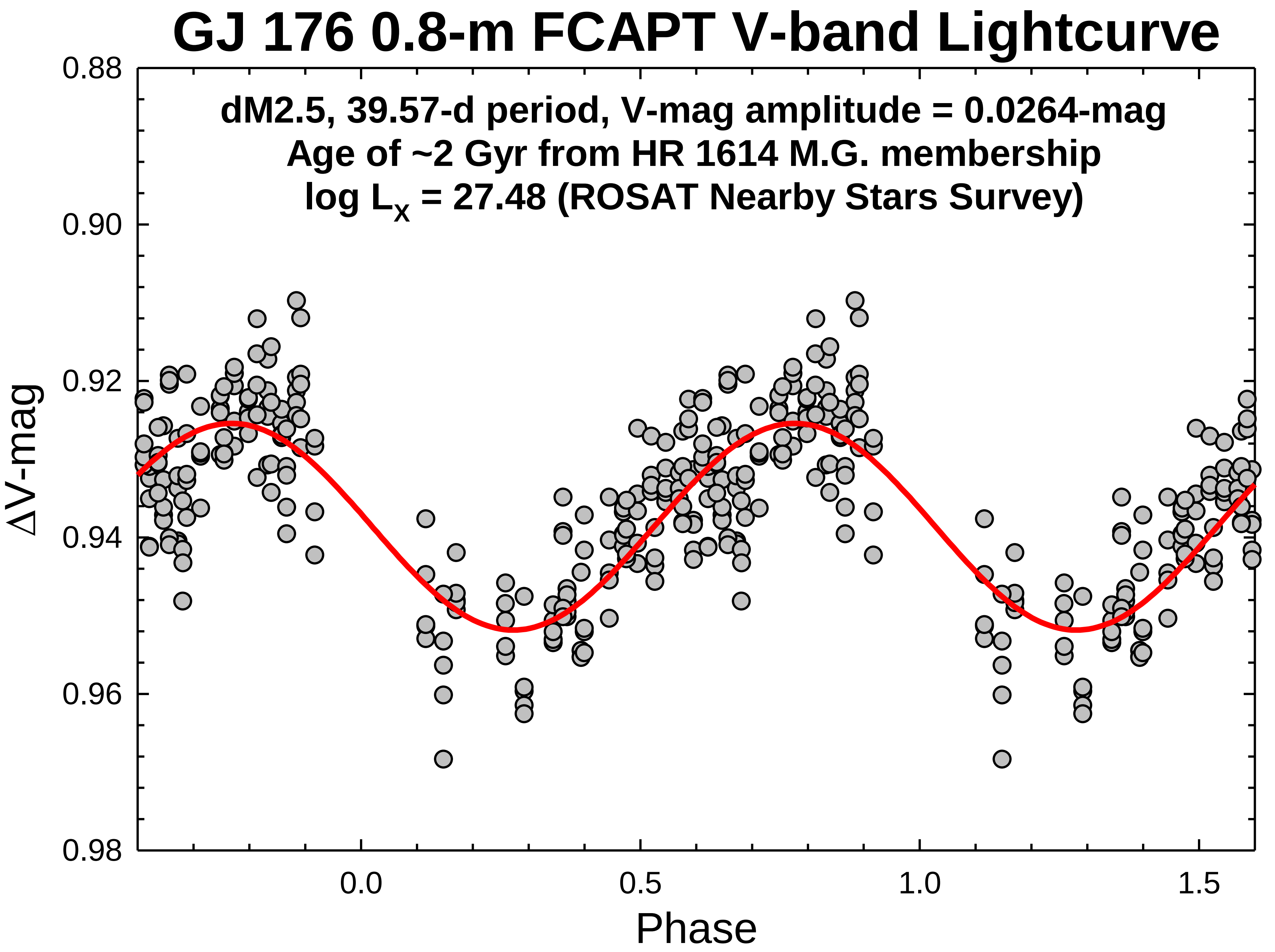


GJ 3379 ASAS3 Photometry


GJ 674 ASAS3 Photometry


IL Aqr (GJ 876) APT Photometry


GJ 176 Hipparcos Photometry

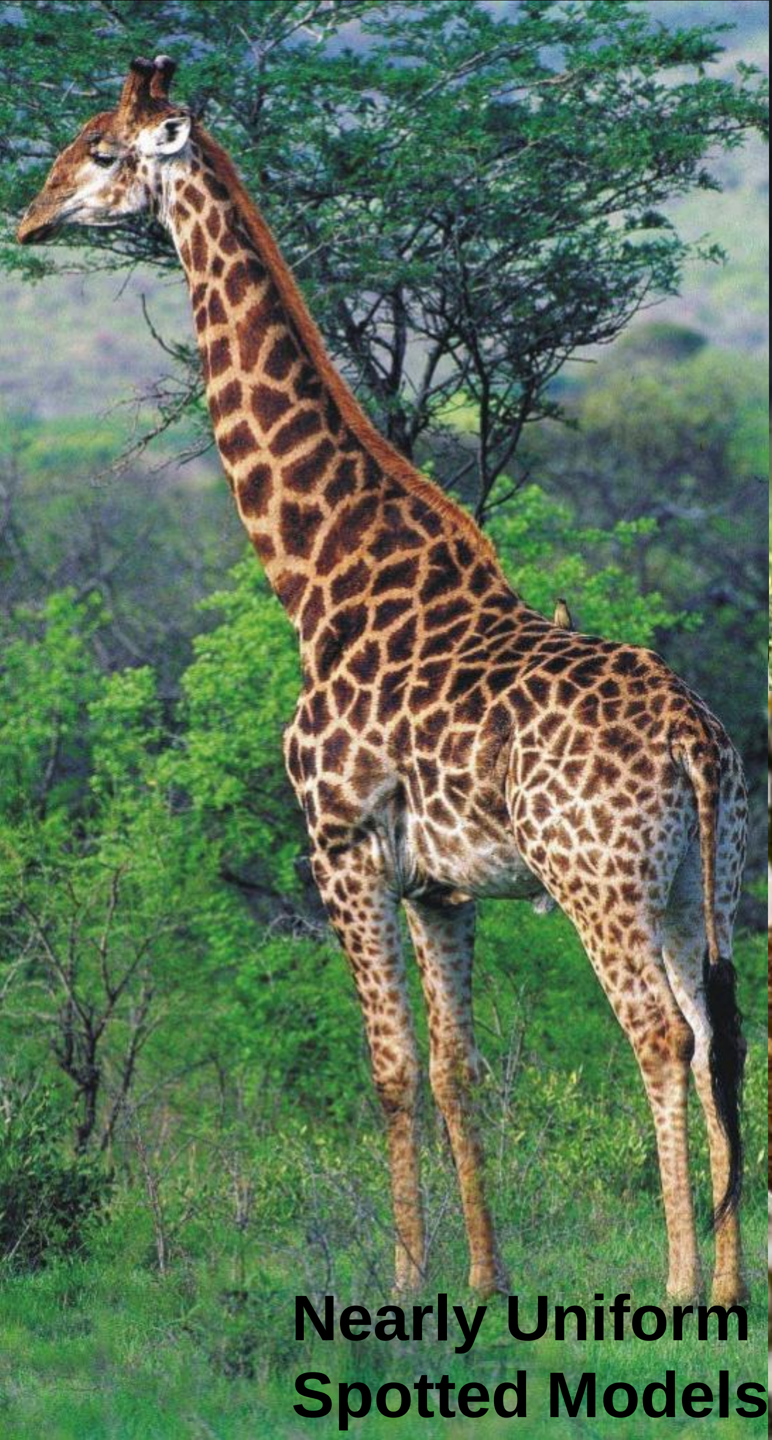


GJ 176 0.8-m FCAPT V-band Lightcurve

dM2.5, 39.57-d period, V-mag amplitude = 0.0264-mag
Age of ~2 Gyr from HR 1614 M.G. membership
log L_X = 27.48 (ROSAT Nearby Stars Survey)

From the modeling of the light curves of dwarf M stars, It is likely that the star is heavily covered with star spots and active regions. The observed periodic ~1.5- 5.0 % light variations likely arise from a slightly uneven spot coverage on the rotating star

We now have light curves of ~ 90 K2 V- M6 V stars with ages from 10 Myr -12 Gyr (and rotations from 0.5 - 200 days



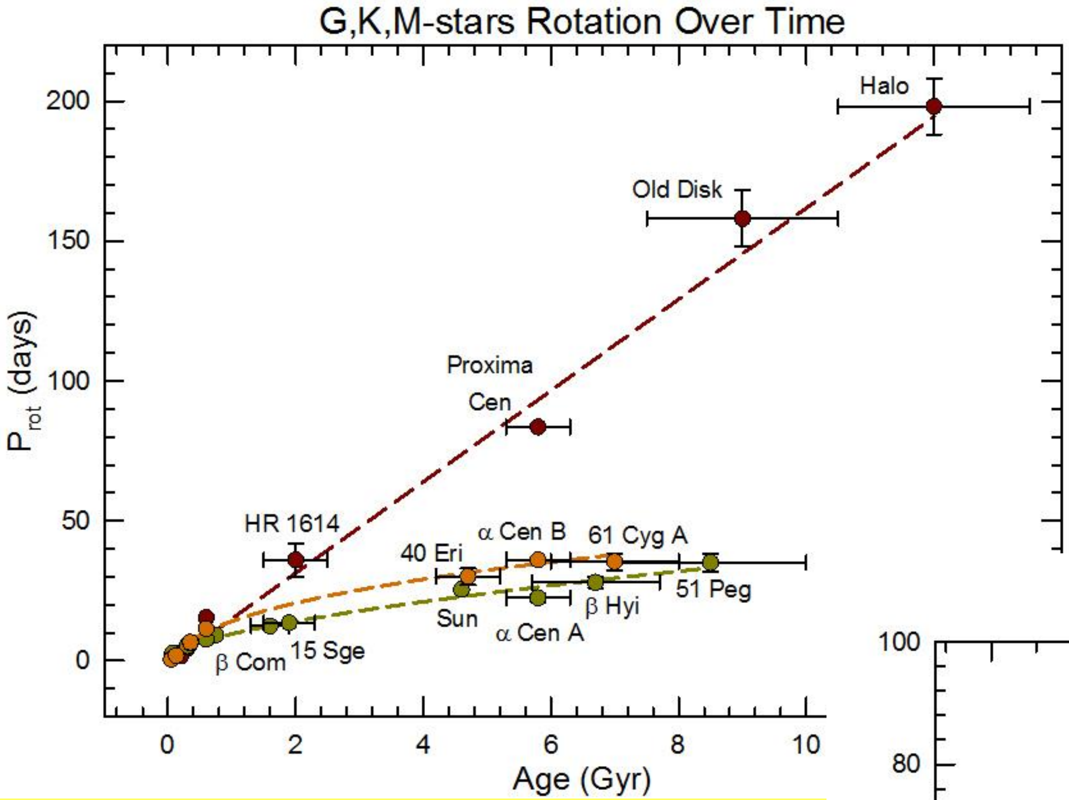
Nearly Uniform
Spotted Models

Uneven Spot Distribution Model

Period-Rotation Relations

For G0-5 V; K0-5 V, and M0-5V stars

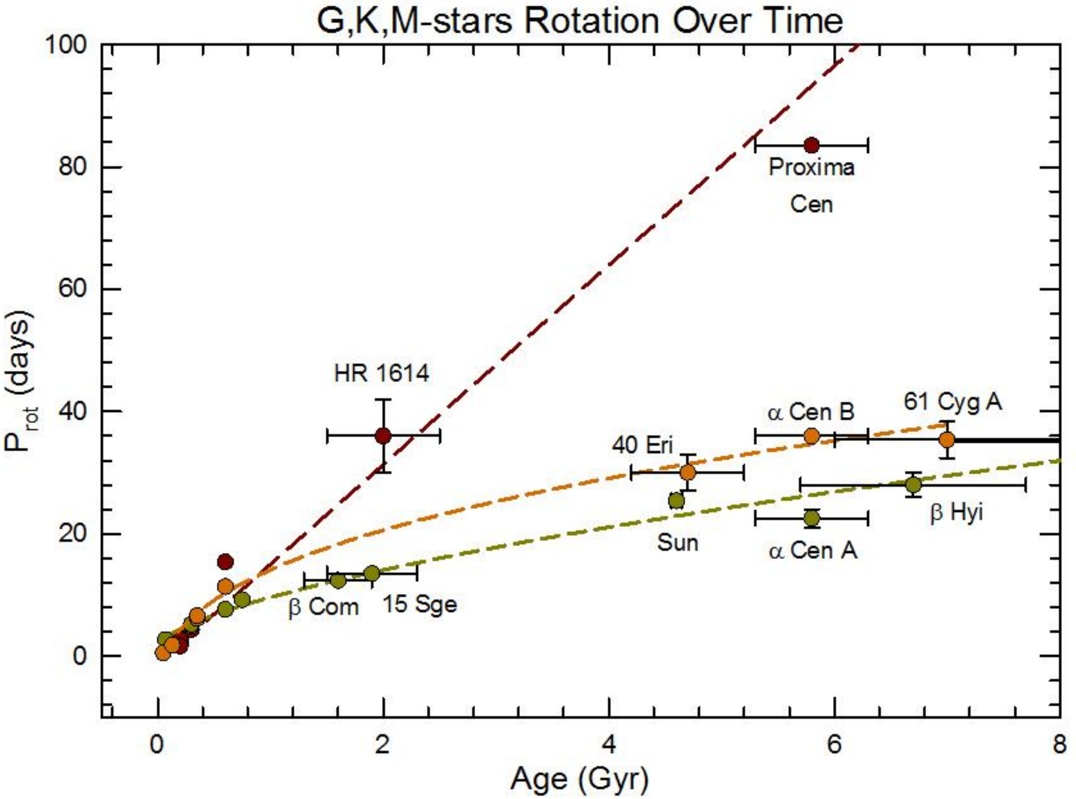
From Guinan & Engle (2010)



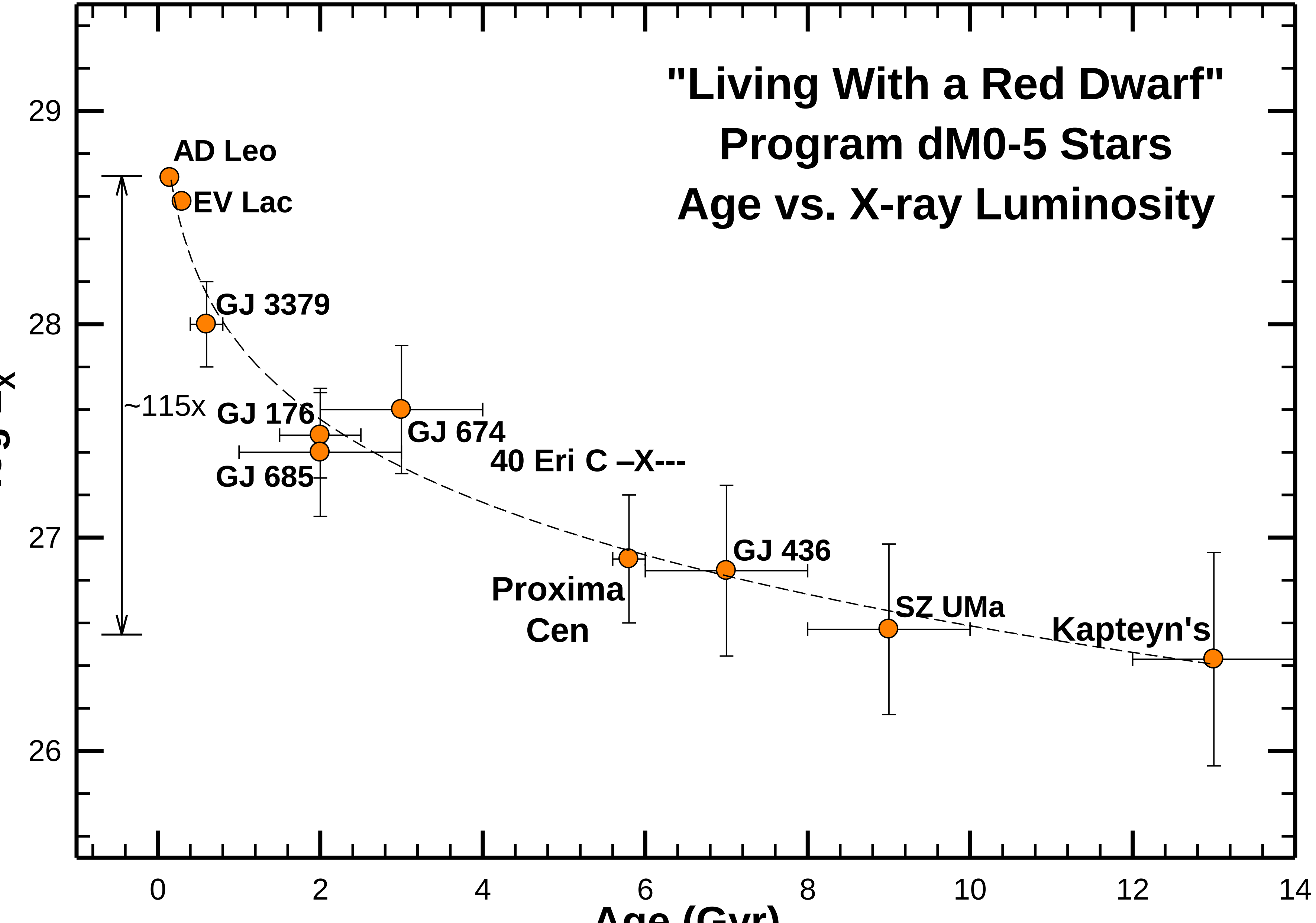
Parameter	Value	StdErr
y0	1.587e+0	2.145e+0
a	8.016e+0	2.462e+0
b	6.410e-1	1.243e-1

Parameter	Value	StdErr
y0	-7.022e+0	4.530e+0
a	2.113e+1	5.432e+0
b	3.867e-1	8.558e-2

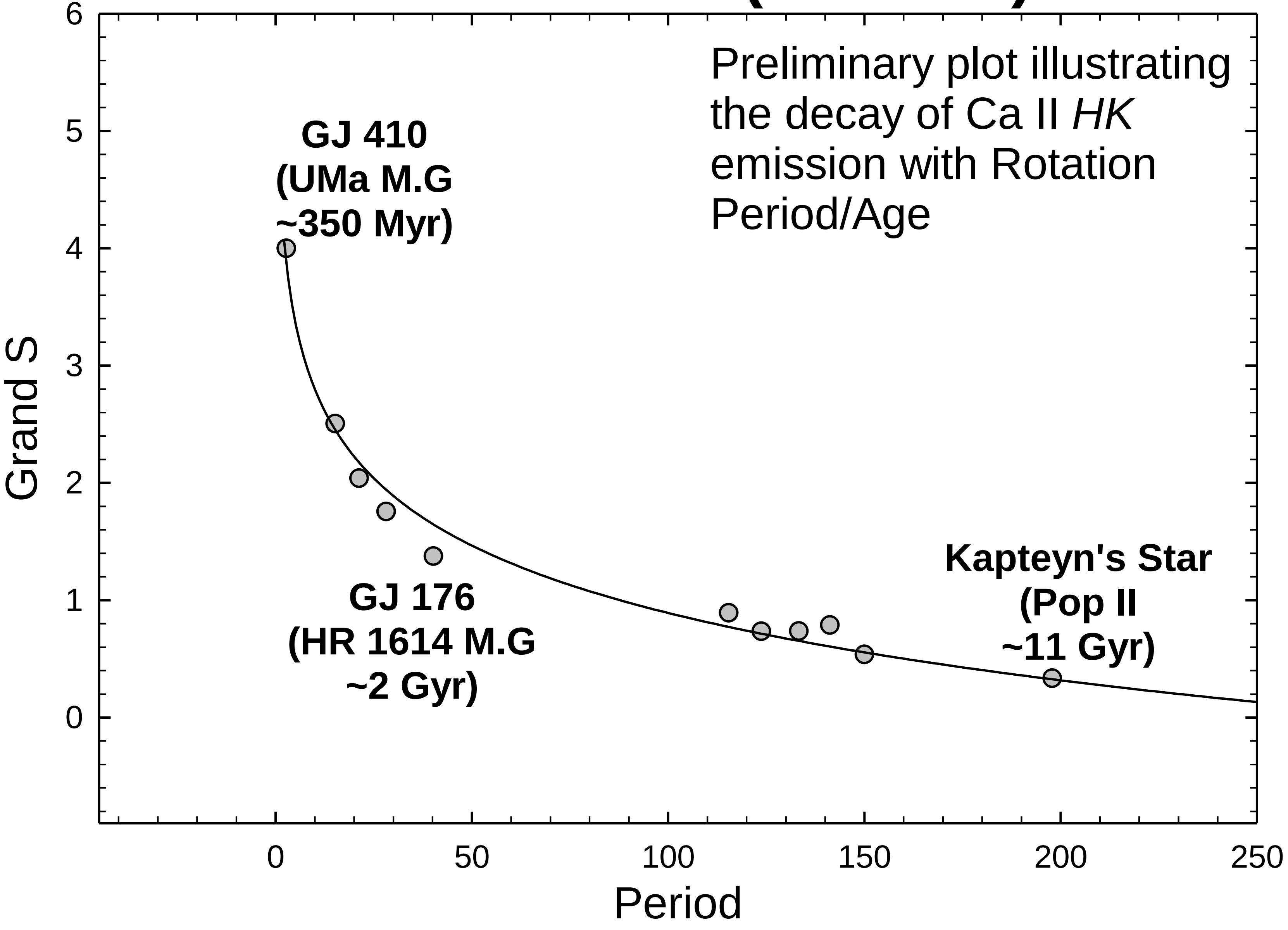
Parameter	Value	StdErr
y0	-1.297e+0	3.217e+0
a	1.631e+1	5.870e-1



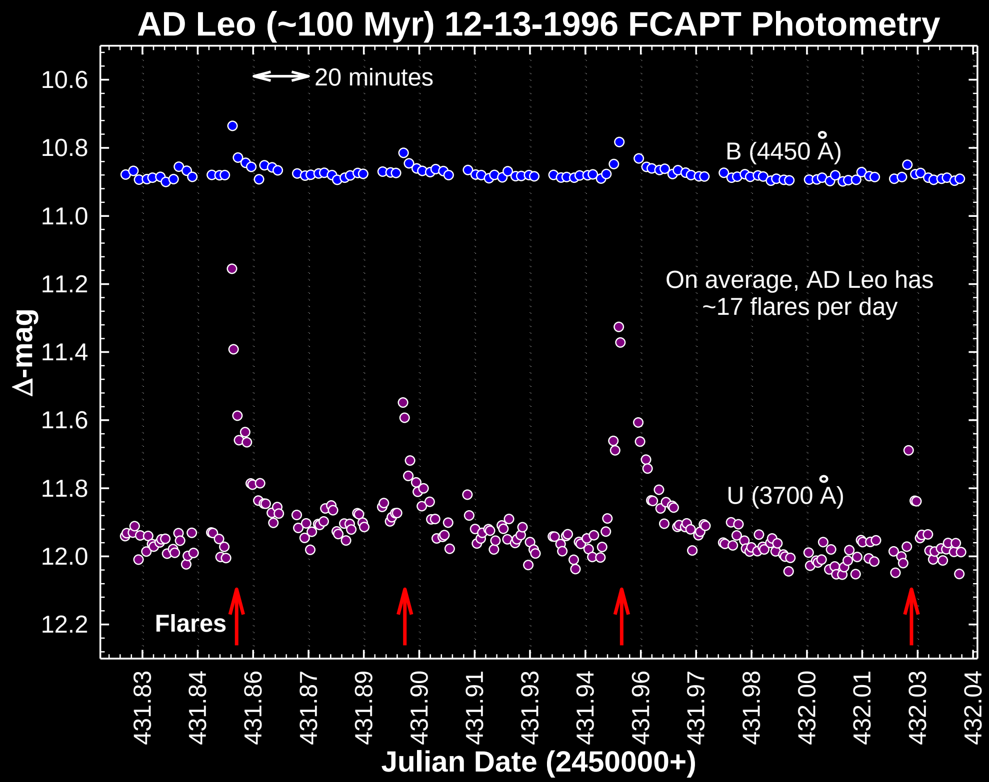
Coronal X-ray emission of dM0-5 stars plotted against age



LWARD 'Grand S' (Ca II *HK*) Plot

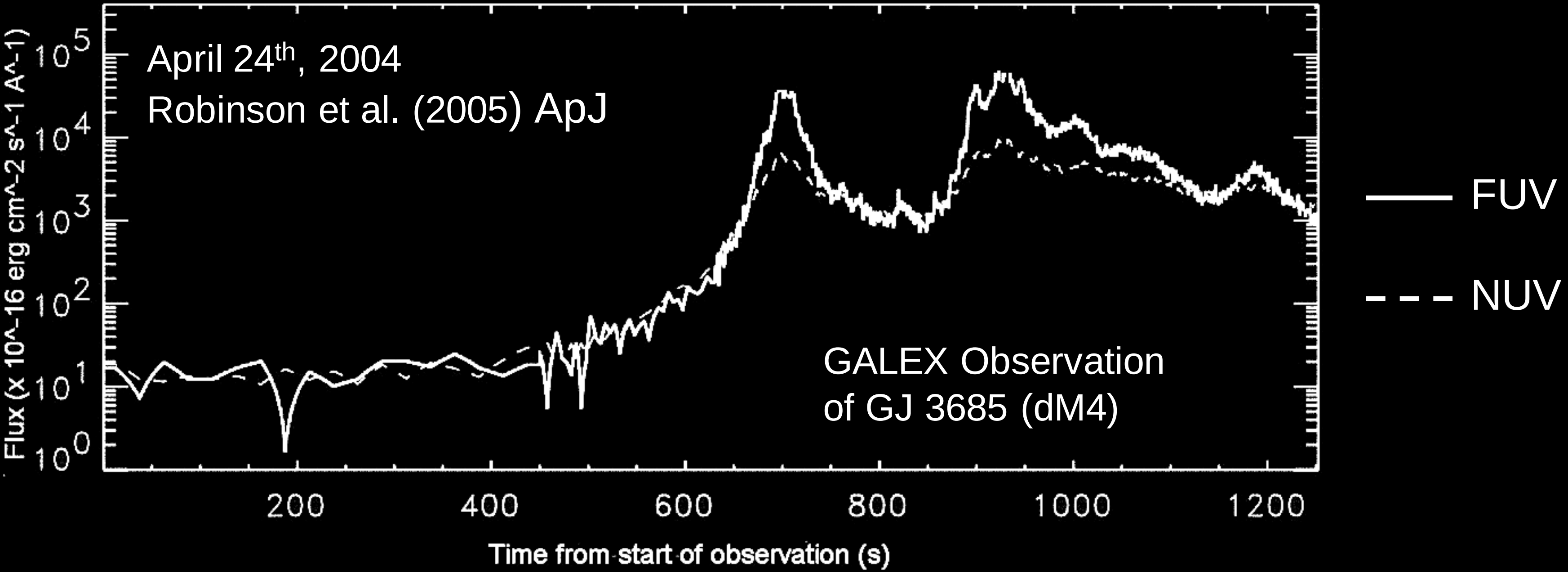

Preliminary plot illustrating the decay of Ca II *HK* emission with Rotation Period/Age

Flares on Red Dwarf Stars


AD Leo (~100 Myr) 12-13-1996 FCAPT Photometry

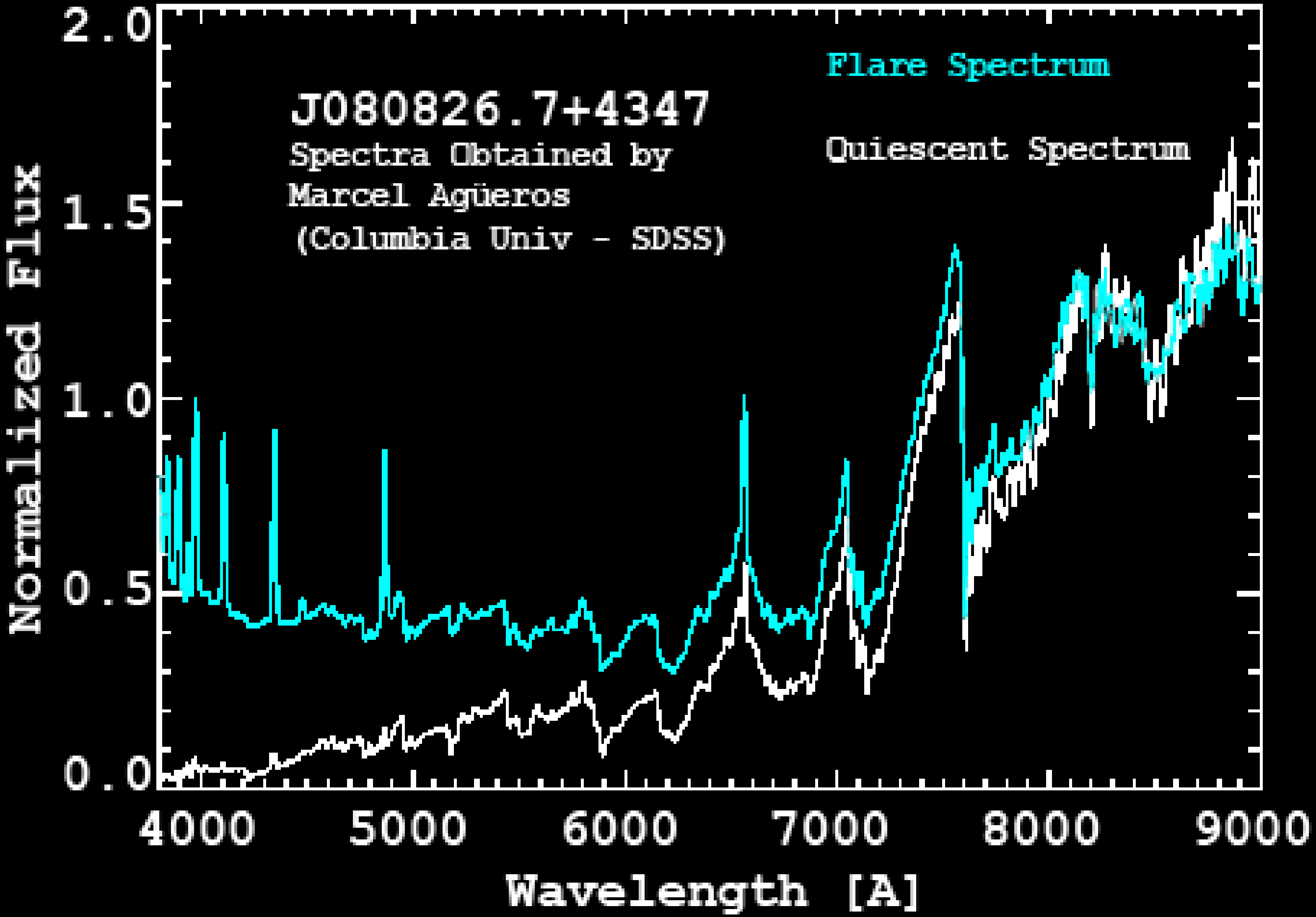
On average, AD Leo has ~17 flares per day

Given their efficient dynamos, flares are frequent on young dM stars. Flares are more prominent at UV wavelengths, with energies 100's to 1000's X those of typical solar flares. Flares are very frequent on young, active red dwarfs such as AD Leo (left), which has ~17 flares/day. Shown below is an example of a large UV flare observed by GALEX on the dM4 star GJ 3685. As shown, there was a 1000x enhancement over ~300 seconds, with a total energy ~10^6 that of a solar flare.

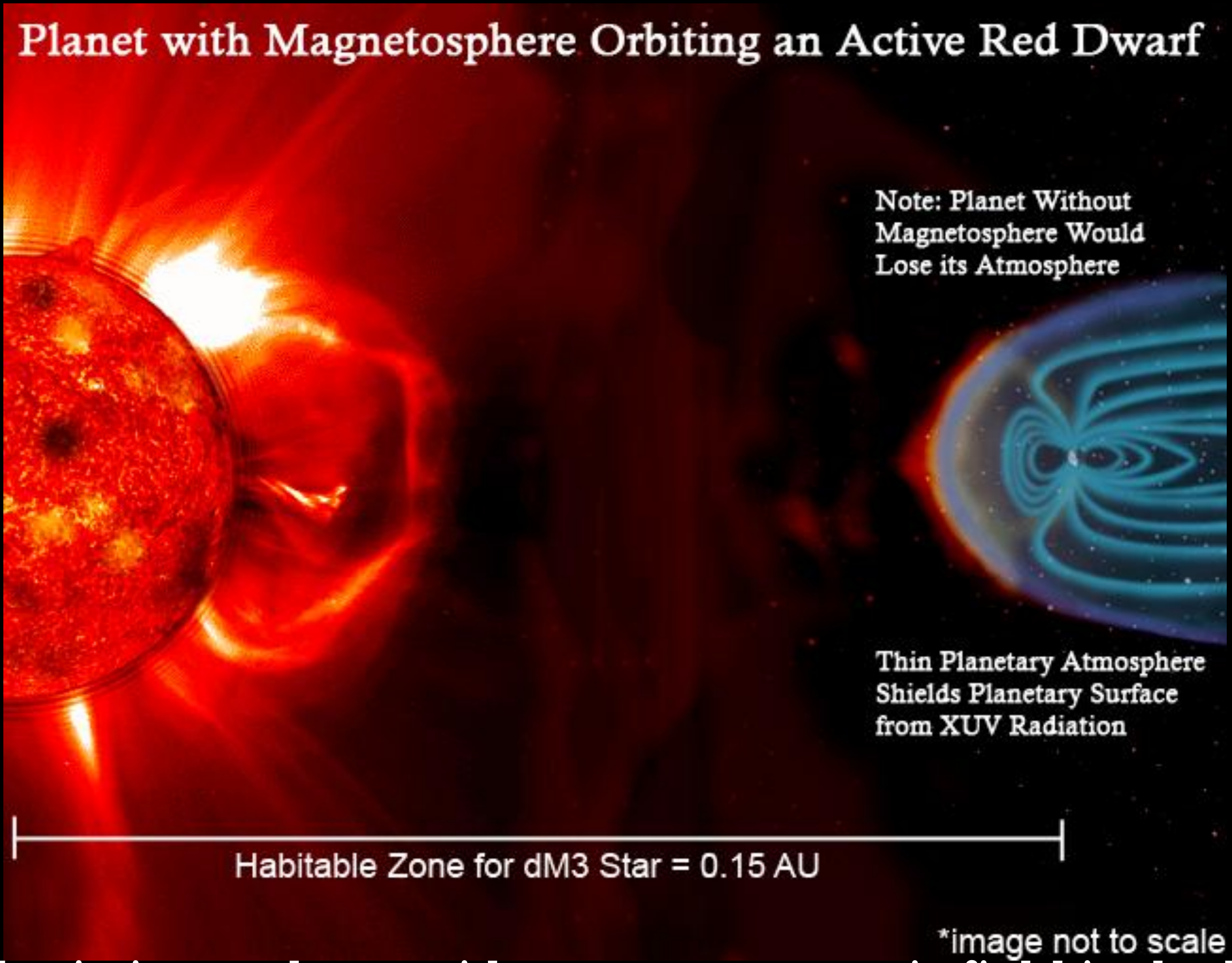

April 24th, 2004
Robinson et al. (2005) ApJ

GALEX Observation
of GJ 3685 (dM4)

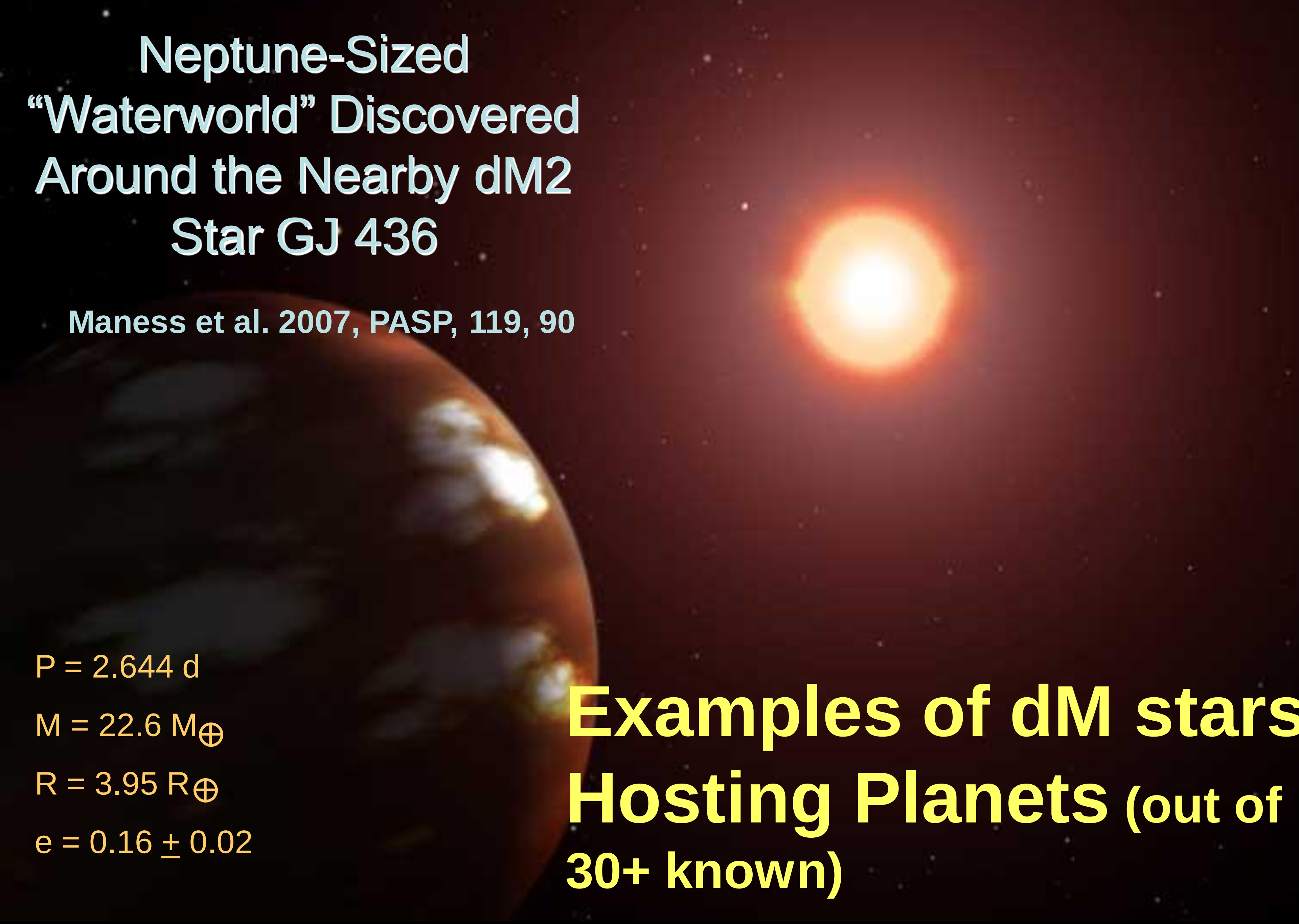
UV – Near IR Spectra of a dM-star Flare



Note the marked increase towards UV wavelengths caused by the flare. These increased levels of UV radiation can penetrate a hosted planet’s atmosphere and pose a threat to living organisms.



Cartoon depicting a planet with a strong magnetic field in the Habitable Zone of a dM3 star. A planet located in the HZ at ~0.15 AU would require a strong magnetosphere to prevent the erosion of its atmosphere from the strong XUV radiation and winds (plus flares) expected from a young dM star. Even a thin atmosphere will shield the surface of the planet from harmful XUV radiation.



Neptune-Sized “Waterworld” Discovered Around the Nearby dM2 Star GJ 436

Maness et al. 2007, PASP, 119, 90

$P = 2.644$ d

$M = 22.6\ M_\oplus$

$R = 3.95\ R_\oplus$

$e = 0.16 \pm 0.02$

Examples of dM stars Hosting Planets (out of 30+ known)

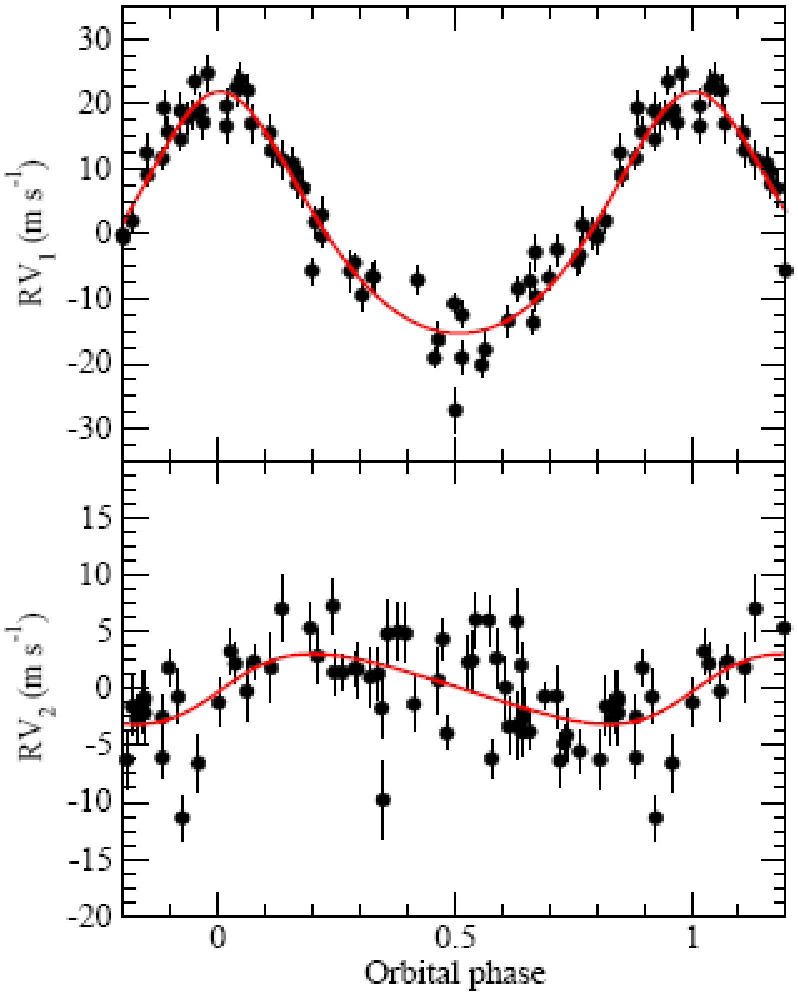


FIG. 2.— Two-planet radial velocity fit to GJ 436. Time series observations of radial velocities of GJ 436 (Maness et al. 2007) were fitted with a model considering the orbital motions of two planets combined plus a long term radial velocity drift (see Table 1). The panels show the radial velocities (with 1σ error bars) associated to each respective planet where the contribution from the other planet has been removed, together with the best orbital fit.

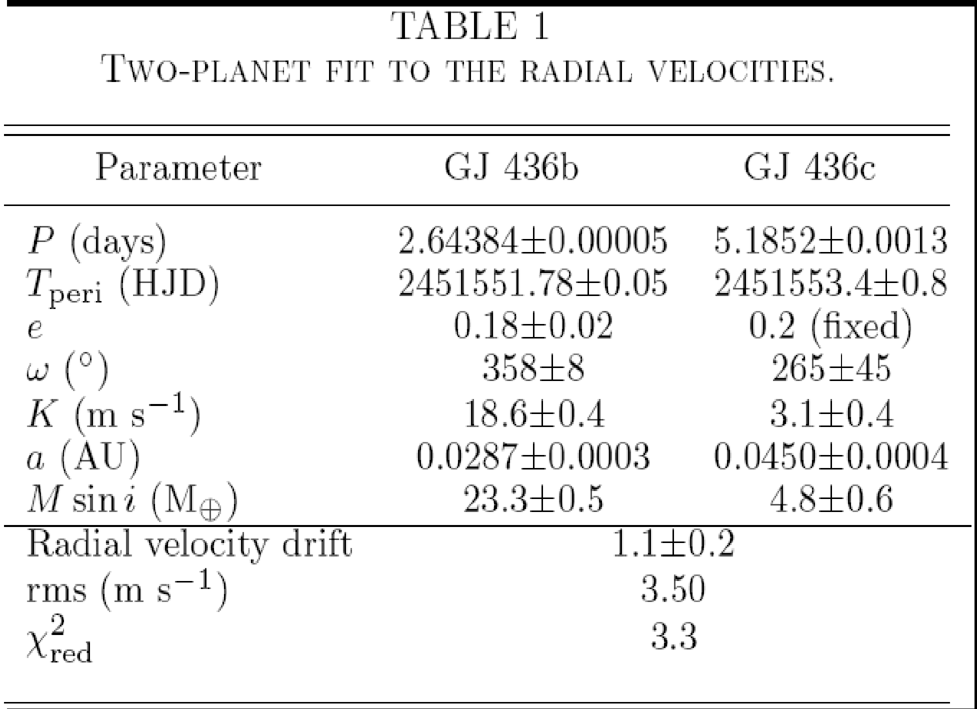


TABLE 1

TWO-PLANET FIT TO THE RADIAL VELOCITIES.

Parameter	GJ 436b	GJ 436c
P (days)	2.64384±0.00005	5.1852±0.0013
T_{peri} (HJD)	2451551.78±0.05	2451553.4±0.8
e	0.18±0.02	0.2 (fixed)
ω (°)	358±8	265±45
K (m s^{-1})	18.6±0.4	3.1±0.4
a (AU)	0.0287±0.0003	0.0450±0.0004
$M \sin i$ ($M_\oplus$)	23.3±0.5	4.8±0.6
Radial velocity drift	1.1±0.2	
rms (m s^{-1})	3.50	
χ^2_{red}	3.3	

Methane reported on GJ 436 b
Beaulieu et al. (2010)
No CO/CO2 seen.

Case Study -Gliese 581 Star – Planet System

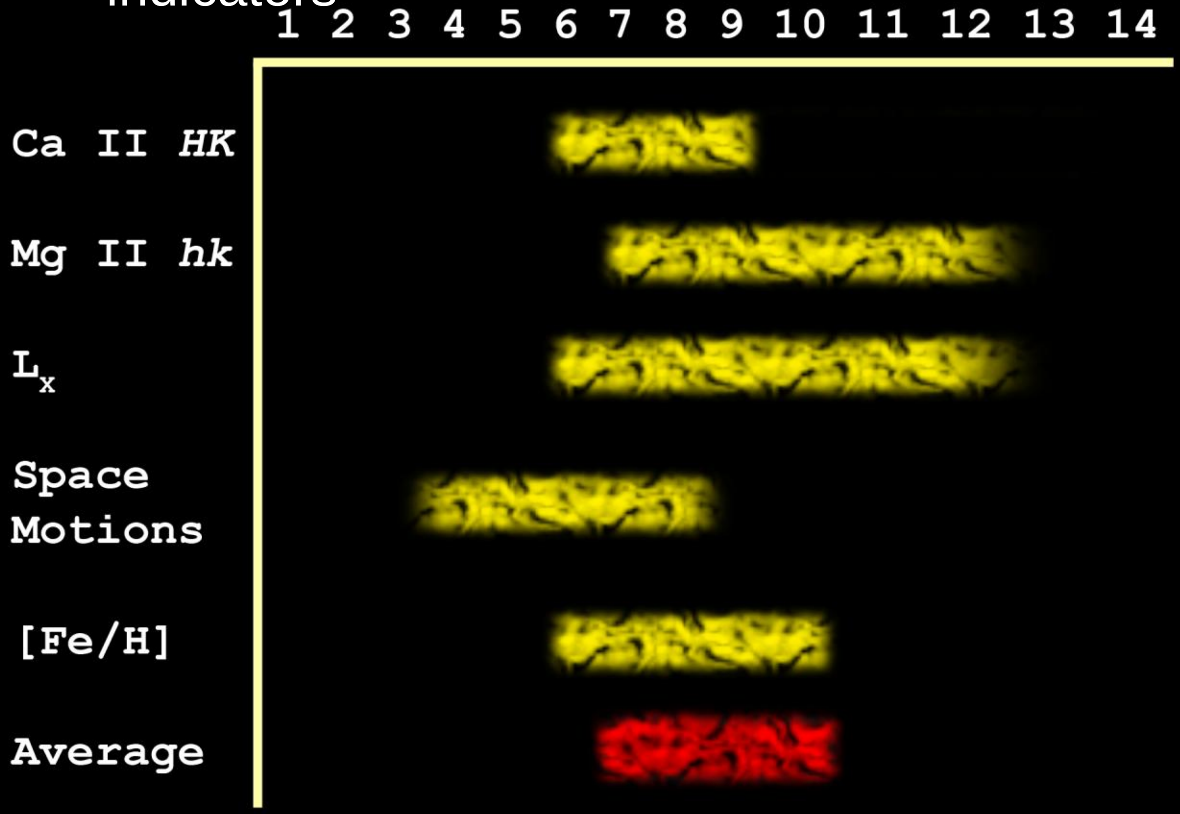
The Planetary System in Gliese 581

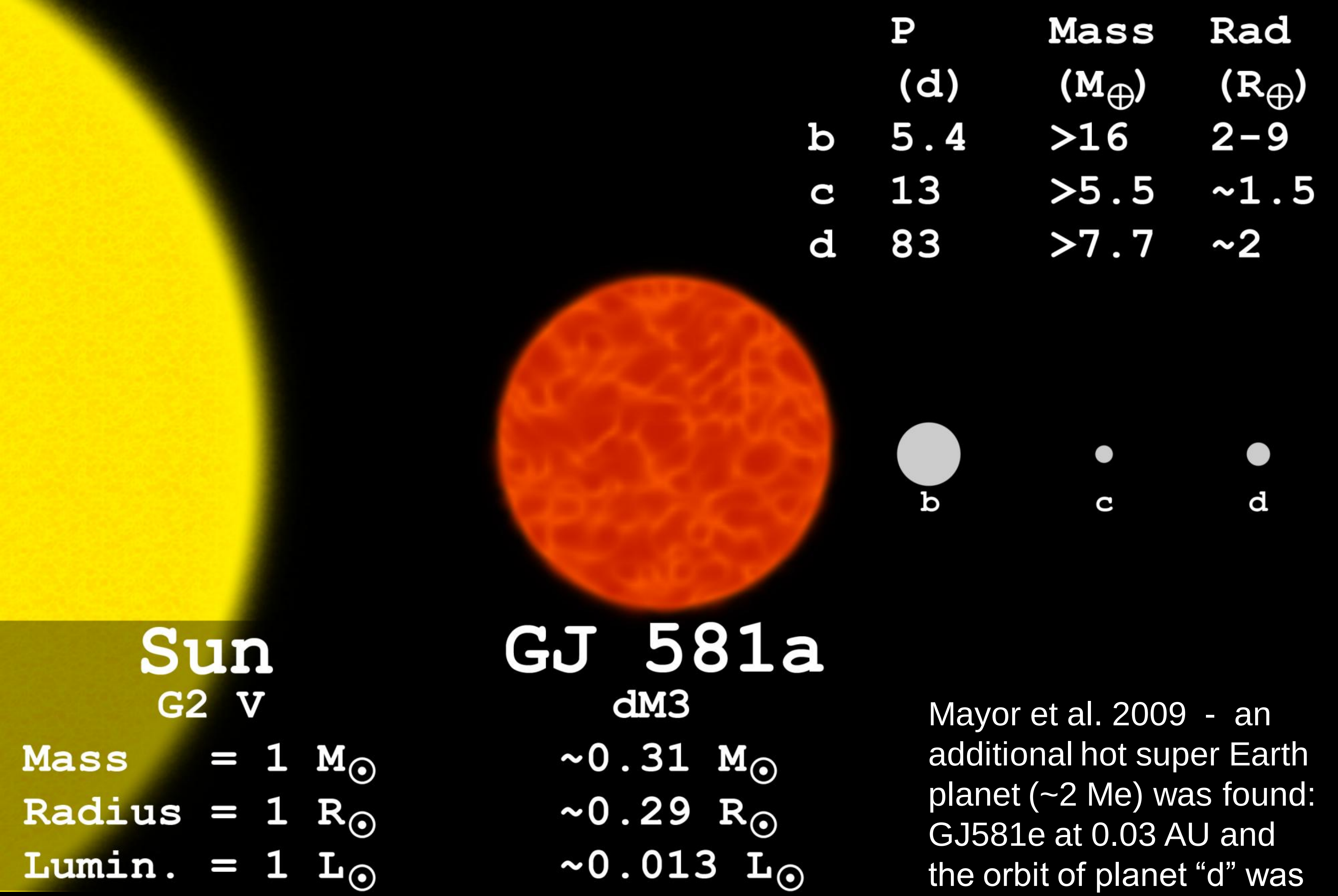
(Artist's Impression)

GJ 581 is an old star

Age Estimations for the GJ 581 System

New Result: Our Recent Photometry reveals a Rotation Period = 116 +/- 2 days. Using our Rotation-Age Relation (for dM stars) yields an age of **7.2 +/- 0.8 Gyr** for the star and planets. Agrees with other age indicators





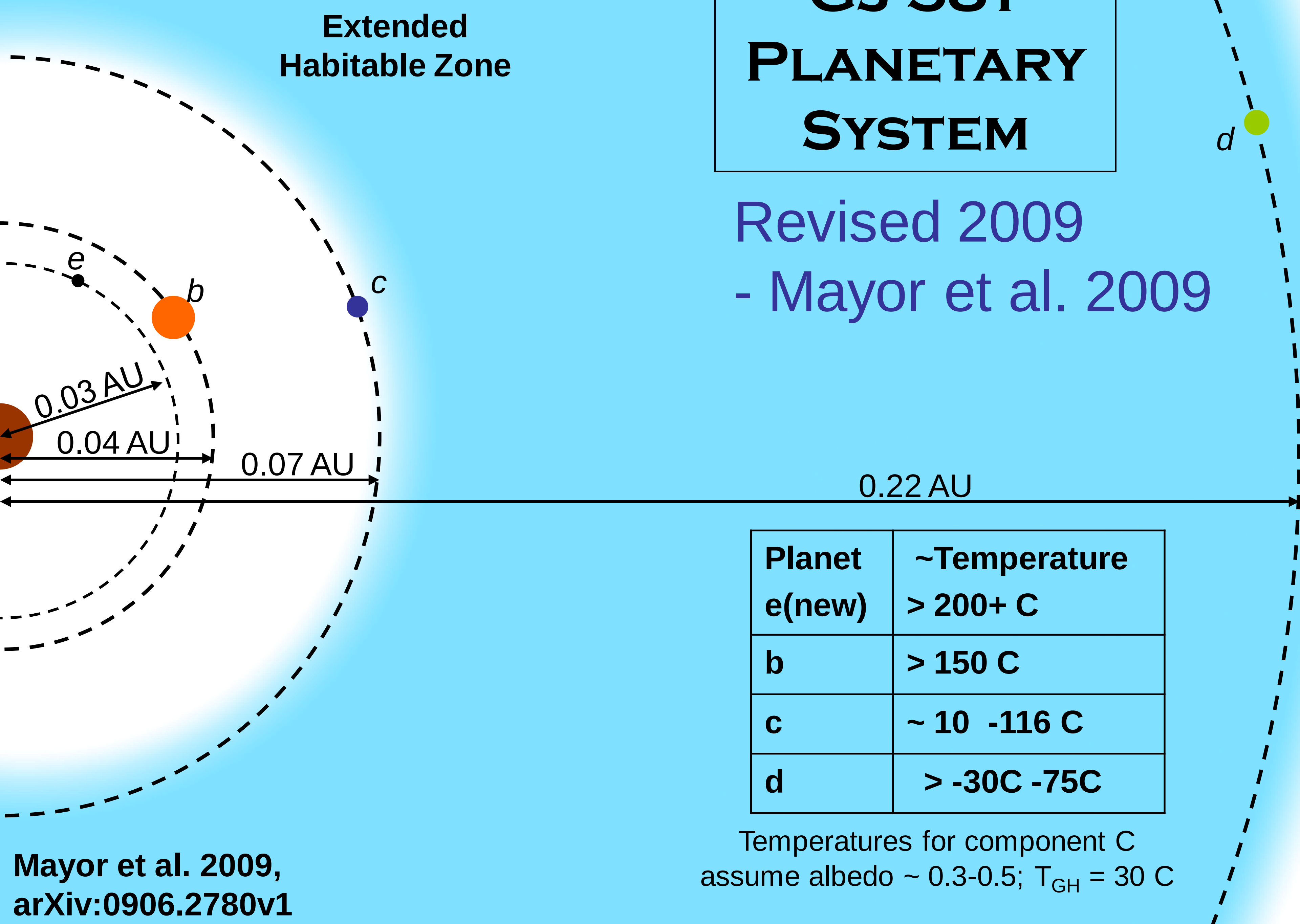
	P (d)	Mass ($M_\oplus$)	Rad ($R_\oplus$)
b	5.4	>16	2-9
c	13	>5.5	~1.5
d	83	>7.7	~2

	Sun	GJ 581a
	G2 V	dM3
Mass	= 1 $M_\odot$	~0.31 $M_\odot$
Radius	= 1 $R_\odot$	~0.29 $R_\odot$
Lumin.	= 1 $L_\odot$	~0.013 $L_\odot$

Mayor et al. 2009 - an additional hot super Earth planet (~2 Me) was found: GJ581e at 0.03 AU and the orbit of planet “d” was revised to 0.22 AU ; P= 67 days

GJ 581 Planetary System

Revised 2009
- Mayor et al. 2009

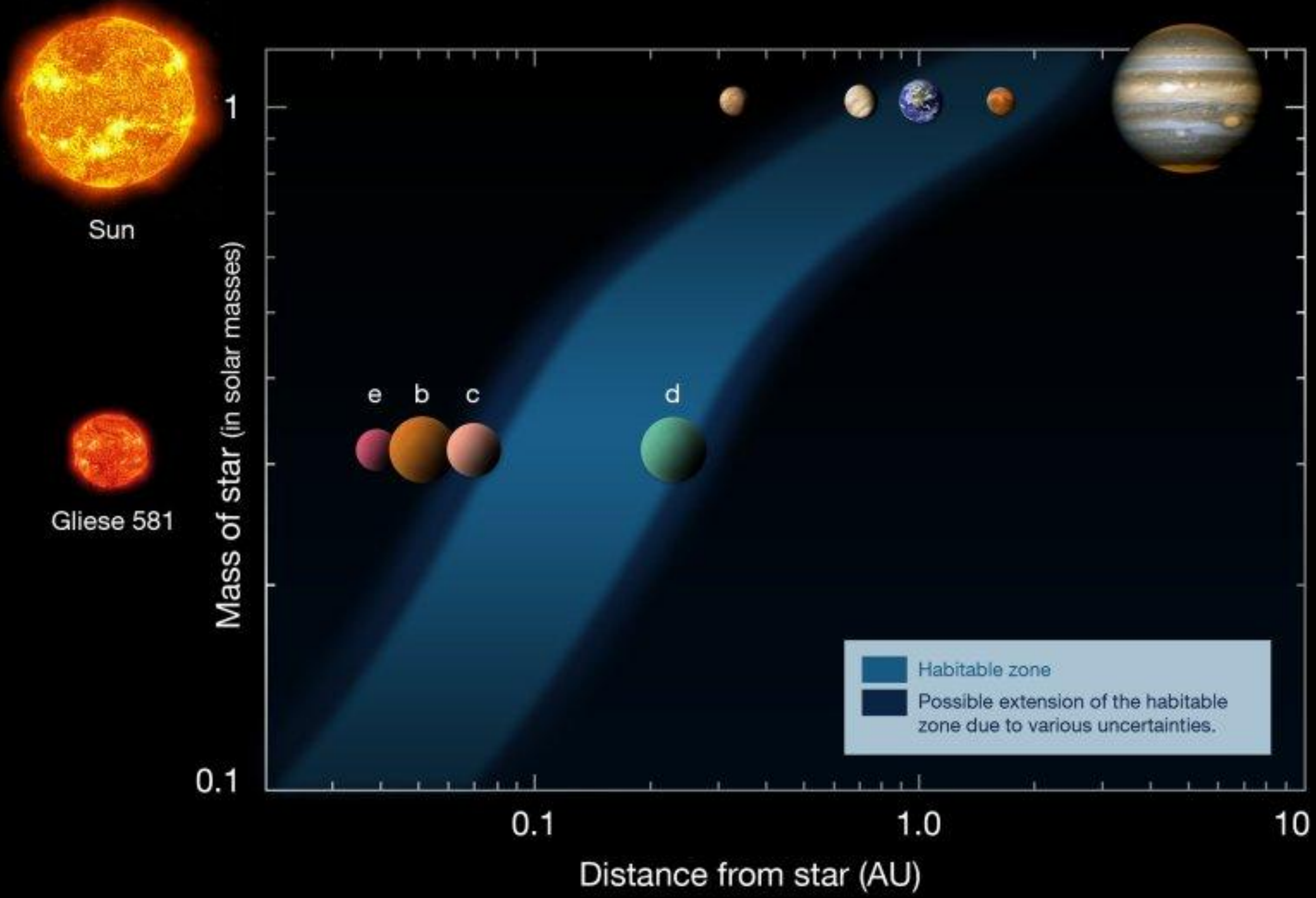


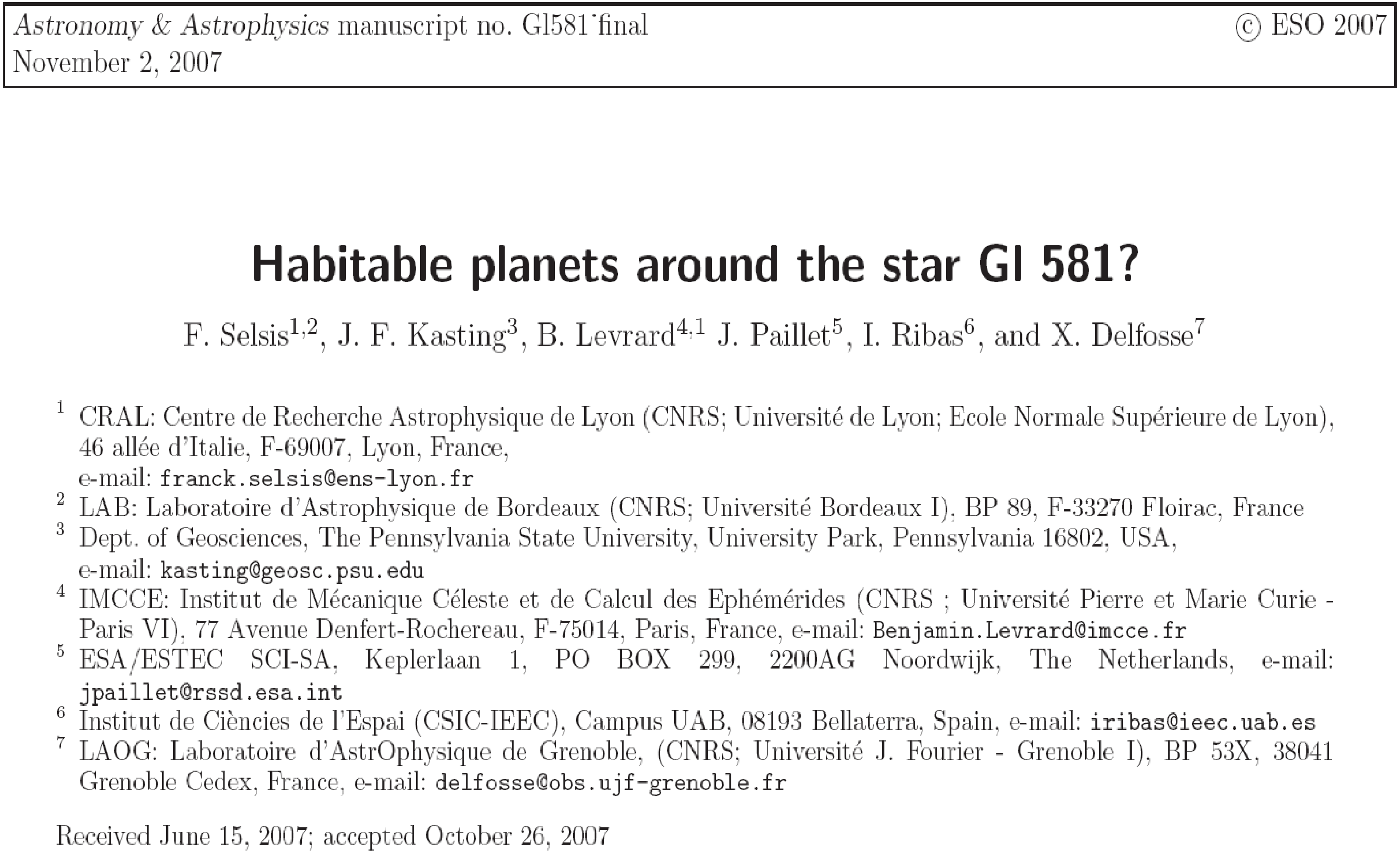
Planet	**~Temperature**
e(new)	**> 200+ C**
b	**> 150 C**
c	**~ 10 -116 C**
d	**> -30C -75C**

Temperatures for component C
assume albedo ~ 0.3-0.5; T_{GH} = 30 C

Mayor et al. 2009,
arXiv:0906.2780v1

Gliese 581 Planetary system – locations of planets relative to the Habitable Zone. HZ of Sun and planets also shown.





Astronomy & Astrophysics manuscript no. Gl581˙final
November 2, 2007

Habitable planets around the star Gl 581?

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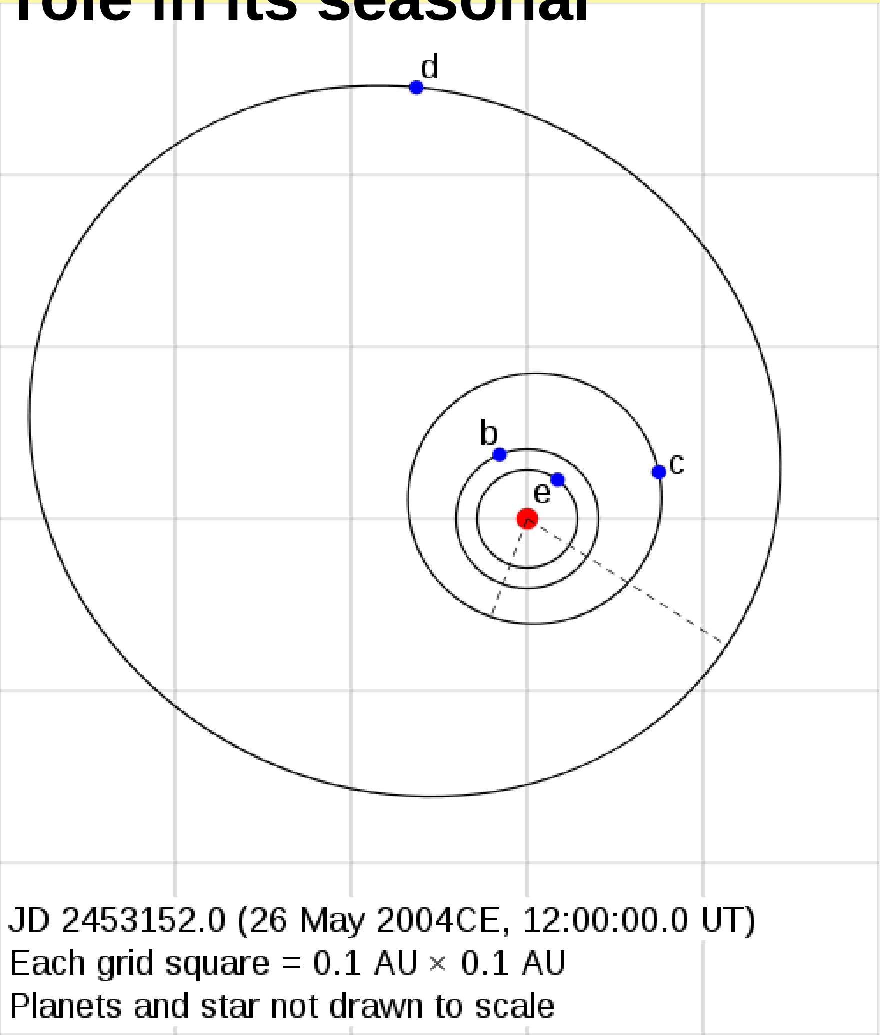
Bottom line: Gl 581c – probably too hot but maybe not? / Gl 581 d – cold but with a moderate greenhouse effect (+80C) could be habitable. (for comparison Earth GH ~30C+)

Planet Orbits of the GJ 581 System

GJ 581d (M ~ 8Me; P = 66.8-d; a = 0.22 AU; e ~0.37);
Could be habitable with a moderately strong greenhouse effect of ~110 C yields <T> ~ +5C.
But eccentricity plays a major role in its seasonal Climate. T(ap-0.3AU) ~18C
T(peri=0.14AU) ~+49 C
(Adopting Albedo =0.5)
Best Case for Life (so far).
See Selsis et al. 2007

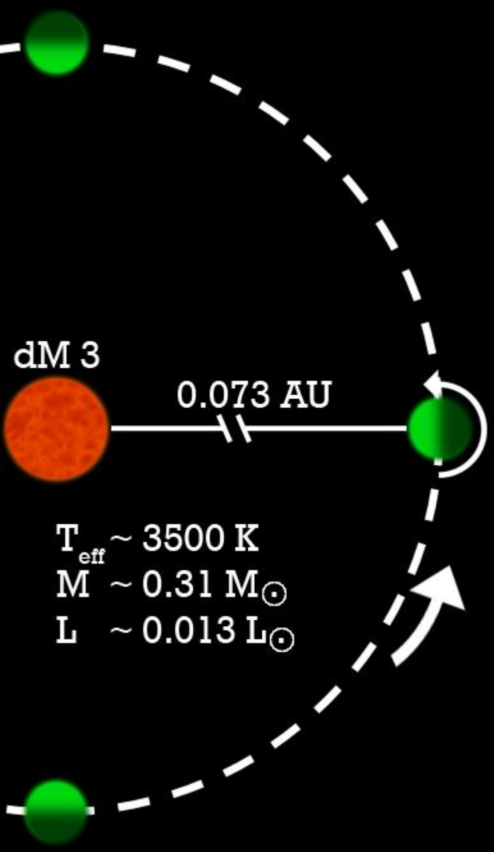


JD 2453152.0 (26 May 2004CE, 12:00:00.0 UT)
Each grid square = 0.1 AU × 0.1 AU
Planets and star not drawn to scale

GJ 581 c

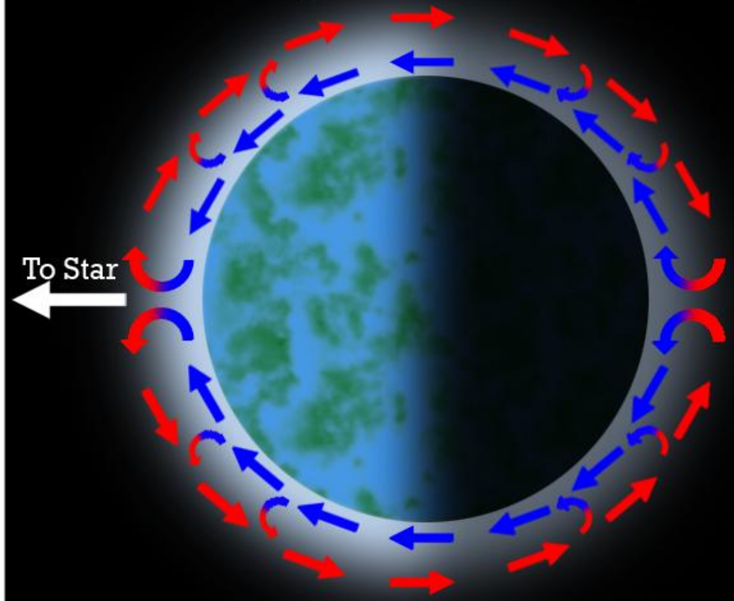
Synchronously Rotating Planet in inner Habitable Zone of GJ 581 (dM3) at 0.073 AU

$P_{orbit} \sim 13$ days
$P_{rotation} \sim 13$ days



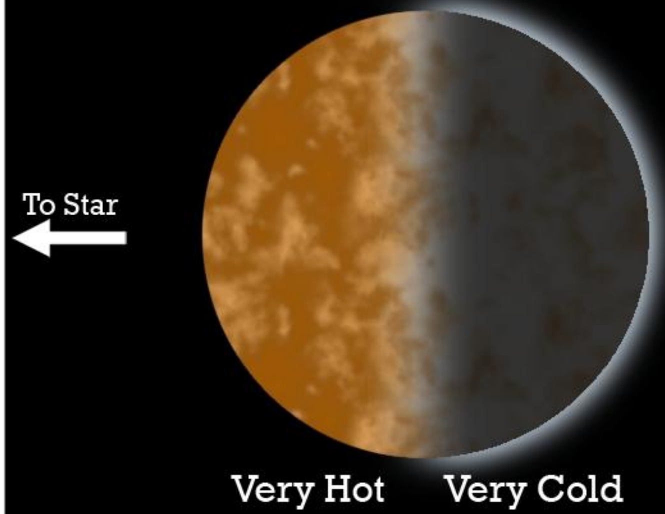
$T_{eff} \sim 3500$ K
$M \sim 0.31\ M_{\odot}$
$L \sim 0.013\ L_{\odot}$

*Based in part on the work of Joshi et al. (Icarus, 420, 450 (1997))



Thick Atmosphere
(~1 bar +)

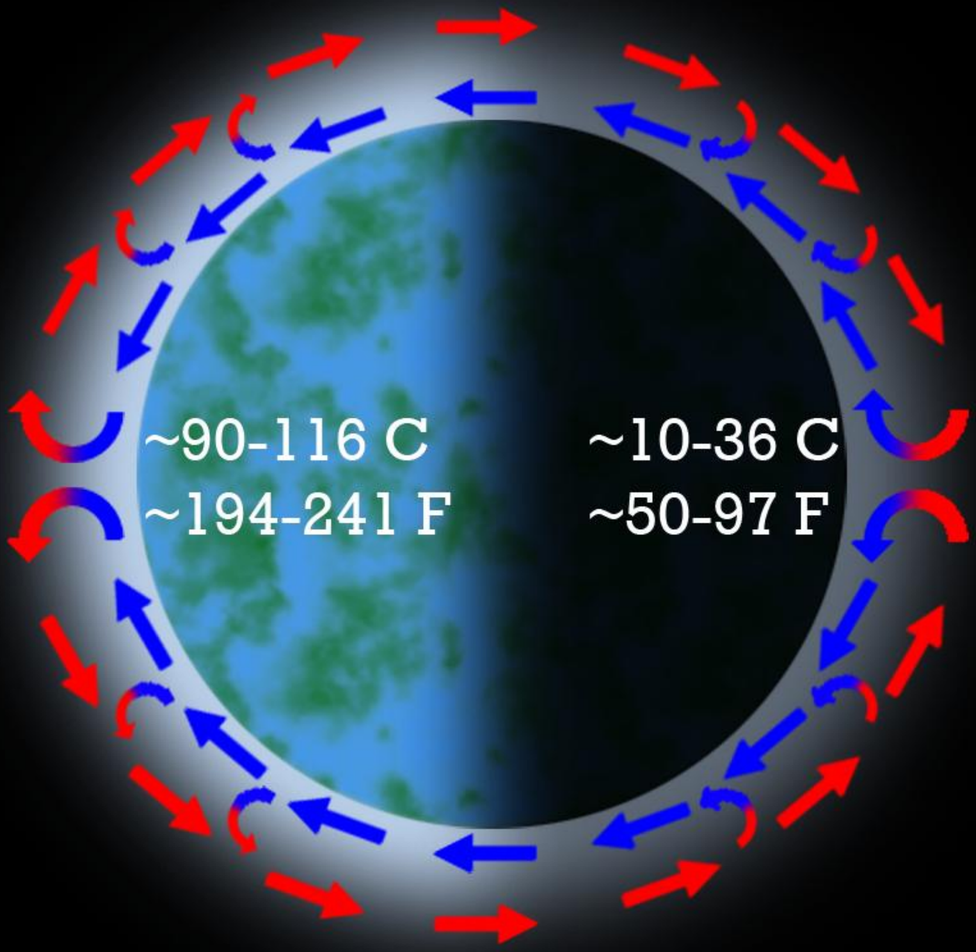
Atmosphere mixed by convection & conduction. Only small temperature differences between illuminated & dark hemispheres.



Thin Atmosphere
(~0.1 bar)

Atmosphere freezes out with sublimation on dark side. Minimal atmosphere remains on dark side. No atmosphere remains on hot side. H_2O & CO_2 ice cover dark side.

Estimation of Planetary Temperatures for the Super Earth GJ 581c



Input Parameters:
$L/L_{\odot} = 0.013$
dist. = 0.073 AU
albedo = 0.3 - 0.5
atm. ~ 1b
GH = 30 C

Modeling Results from Joshi et al. (Icarus, 420, 450 (1997))

For albedo 0.5:
$\langle T \rangle$ = 20 C + GH = 50 C
T_{illum} = 90 C; T_{dark} = 10 C

For albedo 0.3:
$\langle T \rangle$ = 46 C + GH = 76 C
T_{illum} = 116 C; T_{dark} = 36 C

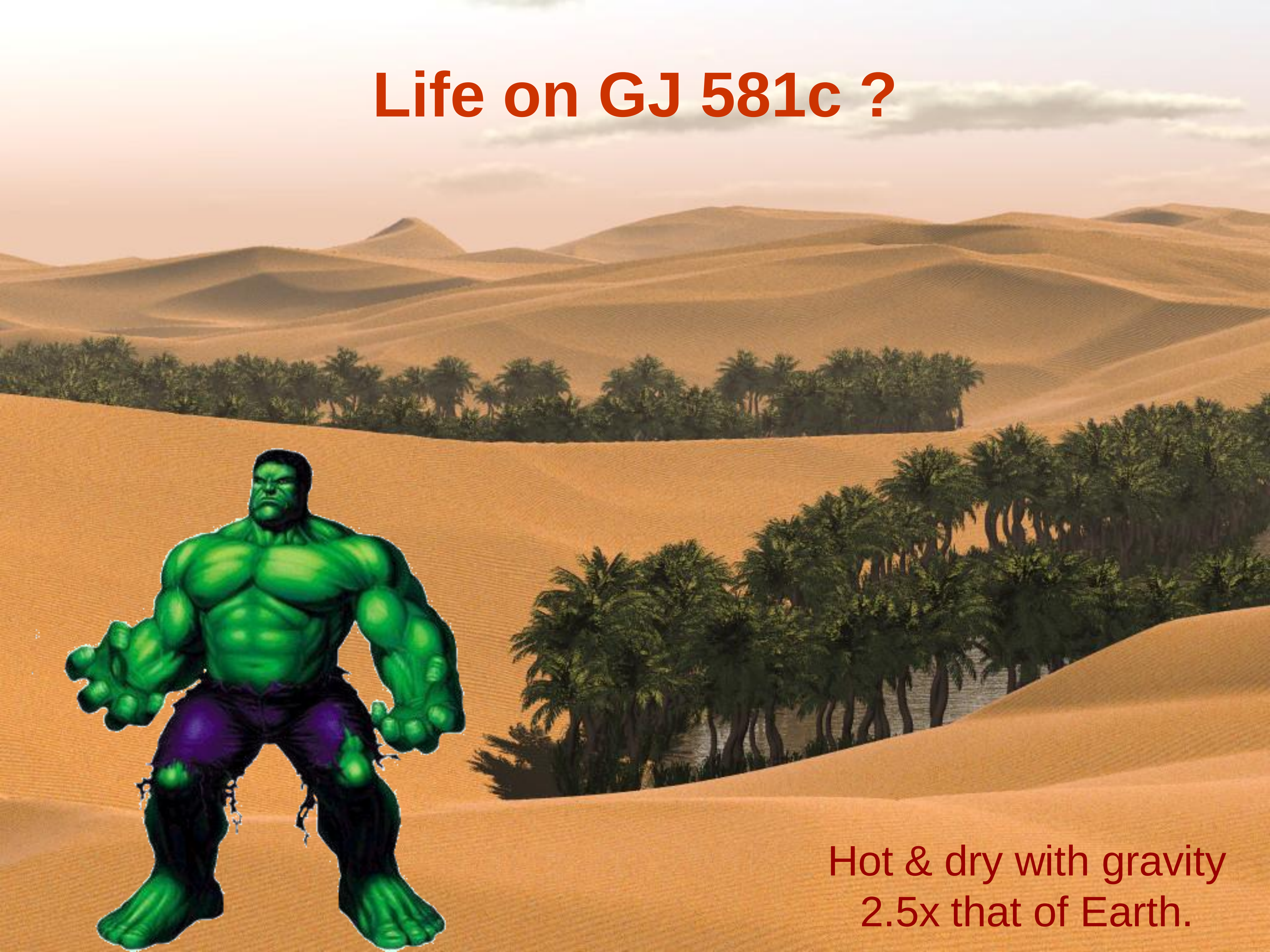
Advantages of Super Earths

e.g. GJ 581 c / d

ESO

Higher gravity –> retain atmosphere
Large liquid Iron core -> (with
rotation) -> Strong magnetic field
Large mass – high heat capacity
-> retain hot core/ plate tectonics

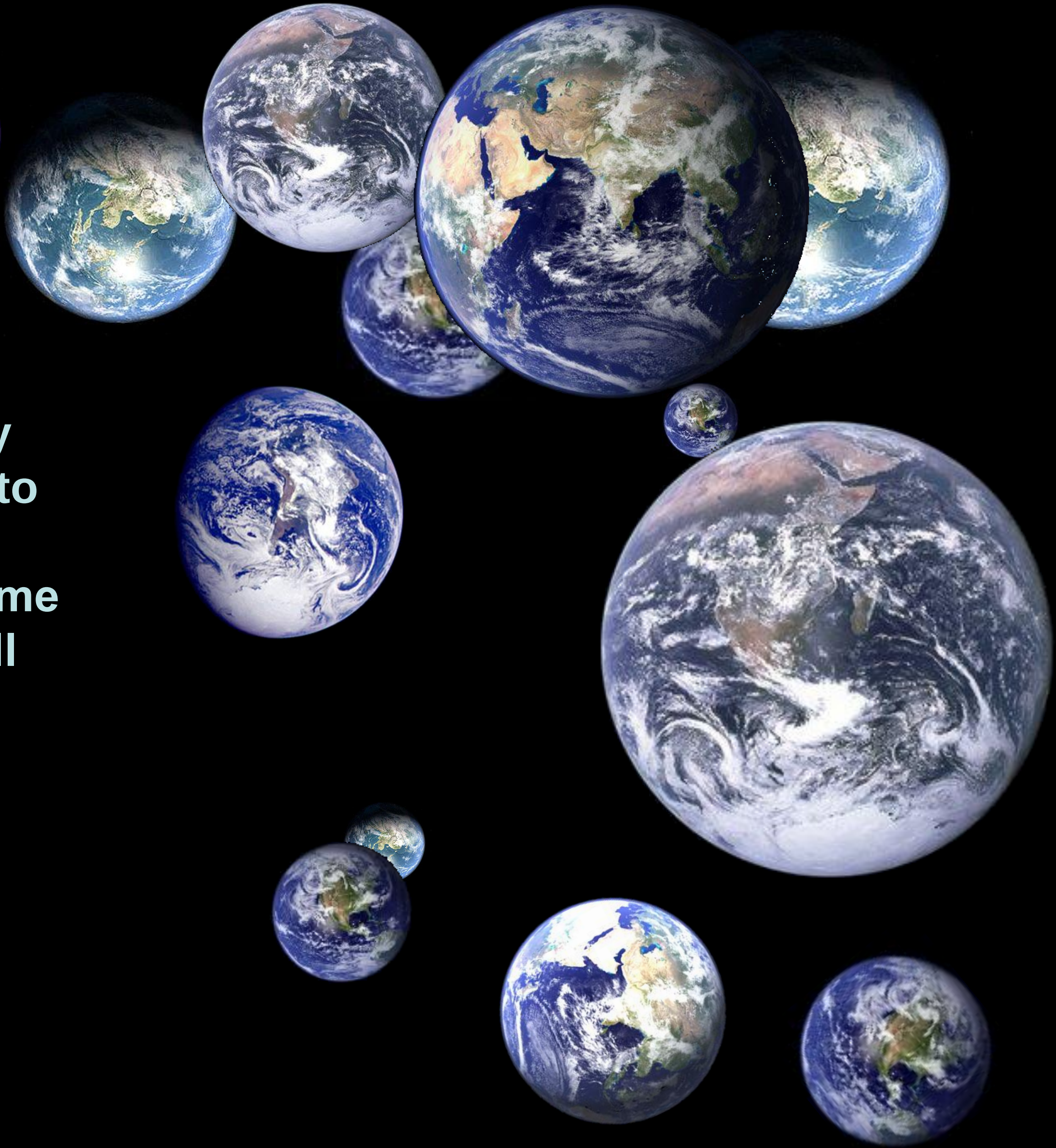
Life on GJ 581c ?



Hot & dry with gravity
2.5x that of Earth.

High Surface Gravity - could be challenging for some lifeforms

Image Credit:
http://wattsupwiththat.com/2009/03/10/heavy-global-warming-linked-to-gravity/



Perhaps there are many Earths out there for us to discover to around red dwarf stars…maybe some with life (maybe you will find some).

Some Conclusions

- Red Dwarf (dK/M) stars are the most numerous stars in the Galaxy (> 85% of all stars). They have very long lifetimes and nearly constant luminosities for 40+ Billion years. The shear numbers of dK/M stars greatly increase the chances for finding life in our Galaxy. (The focus of our study)
- Theoretically, dK/M stars should preferably form less massive planets than solar-type stars (see Boss 2005). Many dK/M stars discovered so far mostly host Neptune and "Super-Earth" type planets.
- The dM2 star GJ 581 is orbited by a large-Earth size planet -GJ 581c located in the warm edge & GJ 581d in the outer edge of the star's HZ. At present GJ 581d has the highest potential for habitability with a moderate GH effect (Selsis et al. A&A 476; 2007)

Habitable Zones of dM stars are located close to the host star (<0.3AU). Could present challenges for the planet retaining its atmosphere due (when young) due to intense X-UV radiation exposures and presumed strong winds/frequent flares.

- Also, tidal locking will occur within ~0.4 AU. A robust planetary magnetic field is needed for protection from the expected dense winds and strong ionizing radiation from the young active stars during the first billion years of their lives. However, dK stars maybe better suited since they have HZs ~ 0.5-1.2 AU. Also Super Earths with liquid iron cores (and thick atmospheres) and strong magnetic fields may be best choices for long-term habitability.

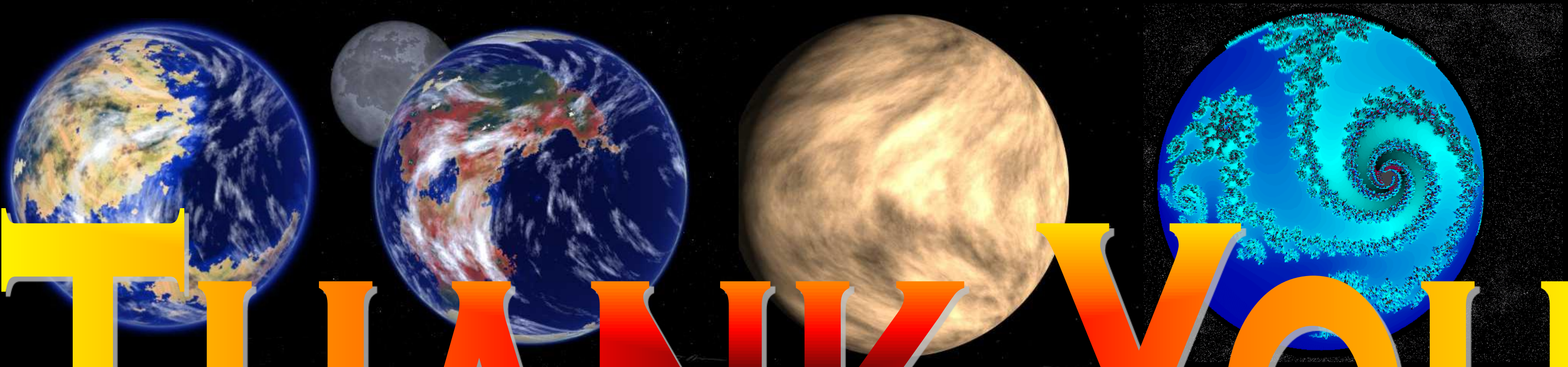
and finally ……

-Many dM & dK stars have ages much older than our Sun (e.g. GJ 581) so they could host very evolved (advanced?) forms of life - some >1-5 billion years older than the life on the Earth. Thus, older dK/M stars (which are not metal poor) make excellent targets for SETI programs.

-

GO FIND THEM!

Our study shows that dK/dM stars can be suitable hosts for planets capable of harboring life if these planets are early-on protected by thick atmospheres and strong magnetic fields



THANK YOU

Extra Slides

Impact of a Star on a Planet's Temperature

- Major Climate Factors (for a fast rot. Planet)
  - Irradiance – Flux received from Star
    - Most Important (Luminosity, $1/d^2$)
  - Albedo – reflectivity from ice/snow on surface and clouds of the host planet
  - Greenhouse Gases – H_2O, CH_4, & CO_2

$$T(K) = \frac{279[\,(1\text{-}A)\,L^*/L_{\odot}]^{1/4}}{r^{1/2}} + \Delta T_{GH}\,(K)$$

A = Albedo L^* = Luminosity of star (in solar units);

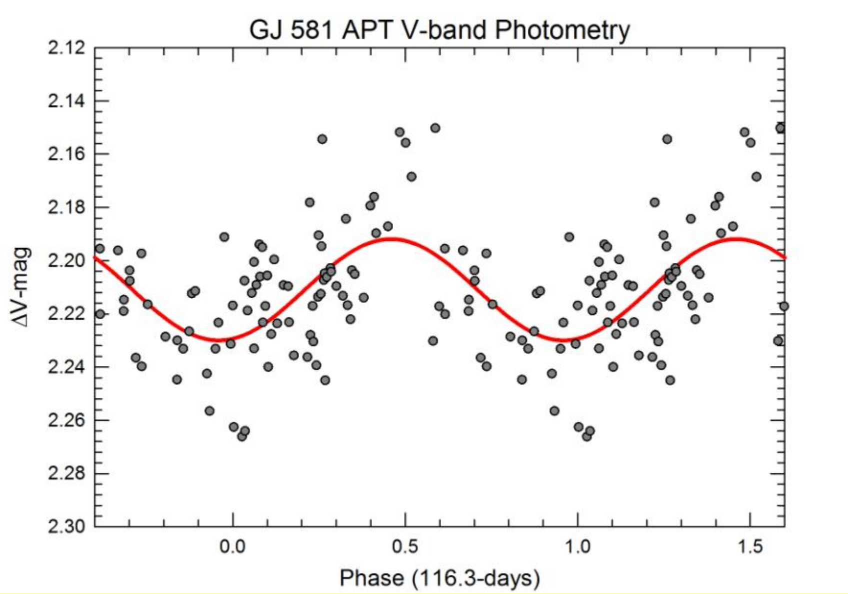
r = Distance in AU ΔT_{GH} = Greenhouse Enhancement

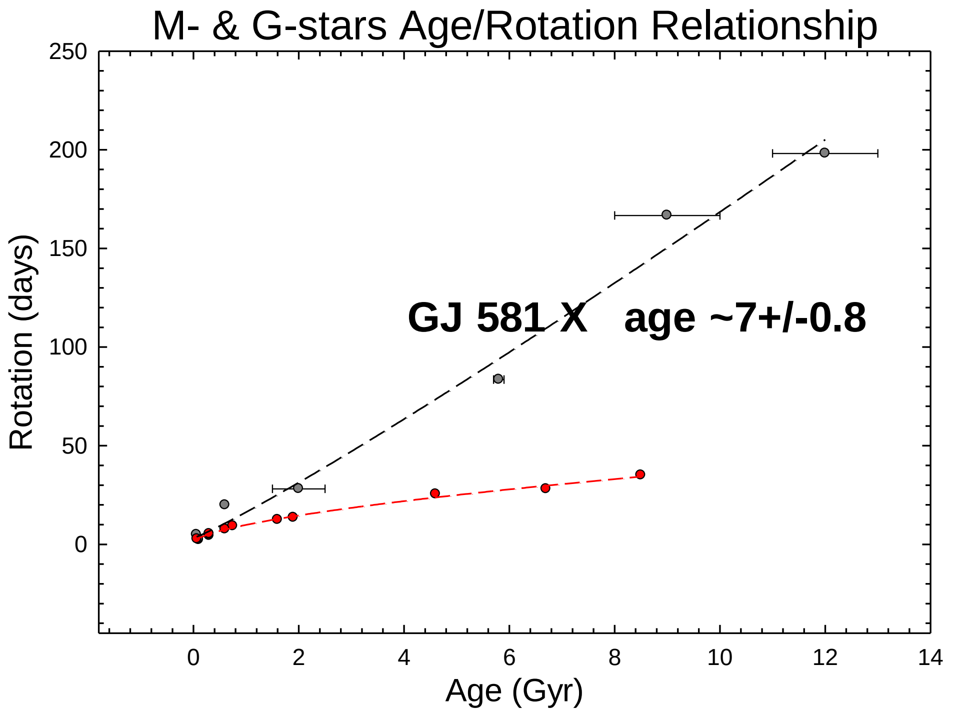
For Earth: r = 1 AU, A = 0.3, $\Delta T_{GH} \sim 31$ K → T = 286 K (~13 C)

Recent Estimation of the Age of GJ 581 system via its rotation period

Light curve plotted below
Showing 116 d period
Arising from star spots

Estimating age from
Prot – Age relation





Simulations of the Atmospheres of Synchronously Rotating Terrestrial Planets Orbiting M Dwarfs: Conditions for Atmospheric Collapse and the Implications for Habitability

Joshi et al. 1997, Icarus, 129, 450-465

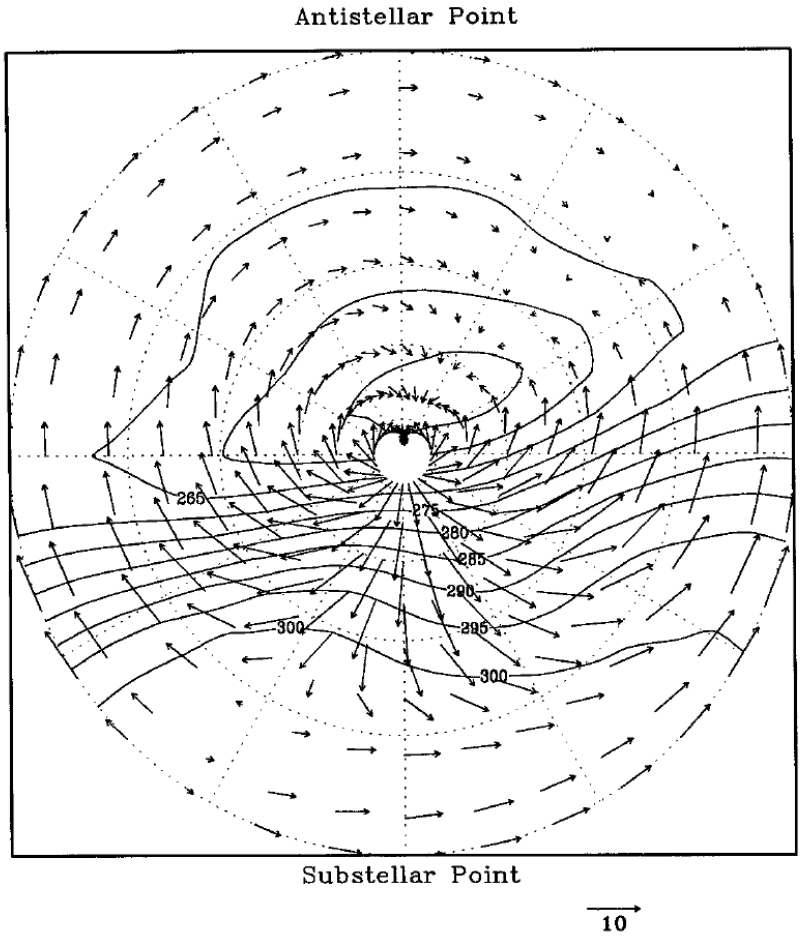


FIG. 10. Polar stereographic plot of temperatures (K) the horizontal wind vectors on the 950-mb surface (approximately 500 m above the ground).

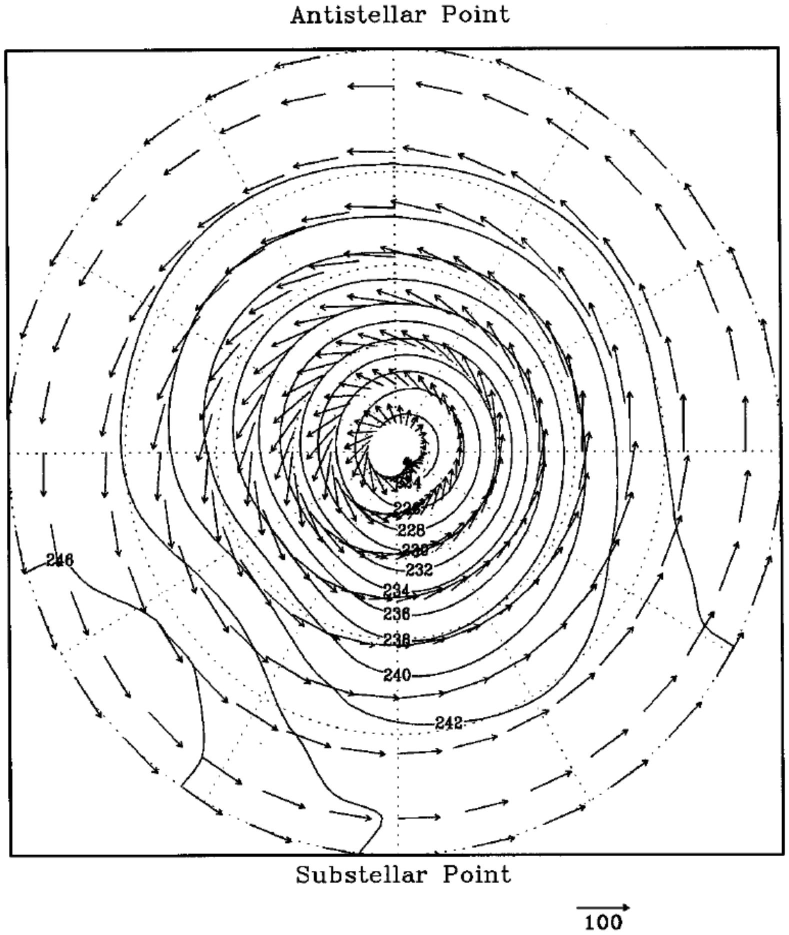


FIG. 11. Polar stereographic plot of temperatures (K) and horizontal wind vectors on the 150-mb surface (approximately 20 km above the ground).

Wide Red Dwarf / White Dwarf Binaries:

Utilizing WD Cooling Times to Determine Red Dwarf Ages

Silvestri, Hawley & Oswalt (2005), AJ, 129, 2428

SUMMARY

M star property	Astrobiology Assessment	Comments
dM stars are ubiquitous, comprising >75% of stars	Beneficial for life in general	High chance for at least some habitable planets
Extremely long, stable lifetimes with constant luminosities	Beneficial for life in general	This provides a stable environment for life to form and evolve on a possible dM star HZ planet. Especially beneficial for advanced/ intelligent life
There are many old dM stars (> 5 Gyr) in our galaxy.	Beneficial for life (statistically speaking), but there may be difficulties with the lack of metals on very old dM stars	Life could be much more evolved and more advanced than us at 4.6 Gyr. However, very old, metal poor, Pop II dM stars were likely not able to form rocky planets. A low metal environment would also be problematic for the development of life.
Theoretical studies by Boss (2006) indicate that "Super Earths" can easily form around dM stars	Beneficial for life in general	Planets hosted by dM stars should be at least as common as those hosted by solar-type stars. Even without much effort, several dM stars have been found to host planets.

Summary, cont…

HZs located very close to the host star at <0.1AU - 0.4AU	Possibly detrimental to Life	The planet can easily become tidally locked, thus global habitability would be difficult
Unlike solar-type stars, dM stars have essentially no photospheric continua in the UV (<2800 Å)	Beneficial for life once it is established	While UV irradiation is generally harmful to organisms, it is a powerful ingredient for evolutionary adaptations and might also have played a role in the origin of life
dM stars have very efficient magnetic dynamos, resulting strong XUV emissions but little NUV	Harmful for life in general	Harmful, but these types of radiation are easily filtered out by planetary atmospheres and may be beneficial for evolutionary adaptations
dM stars flare frequently and emit impulsive XUV energies	Both harmful and beneficial to life	Even a thin atmosphere (10 mb) does not allow any incoming XUV radiation with wavelengths <2000Å to reach the surface (Cockell et al., 2000, Cuntz et al., 2006). On the other hand, these impulsive bursts of radiation (with >2000Å) could aid evolutionary adaptation through mutations in the genetic material.

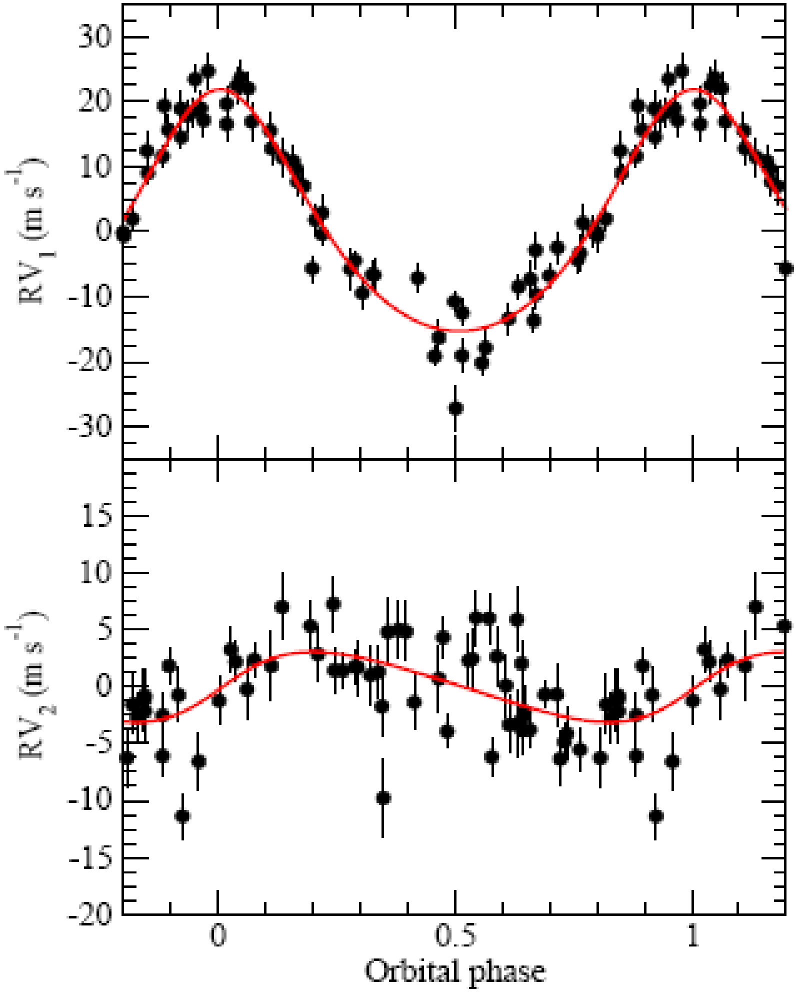


FIG. 2.— Two-planet radial velocity fit to GJ 436. Time series observations of radial velocities of GJ 436 (Maness et al. 2007) were fitted with a model considering the orbital motions of two planets combined plus a long term radial velocity drift (see Table 1). The panels show the radial velocities (with 1σ error bars) associated to each respective planet where the contribution from the other planet has been removed, together with the best orbital fit.

TABLE 1

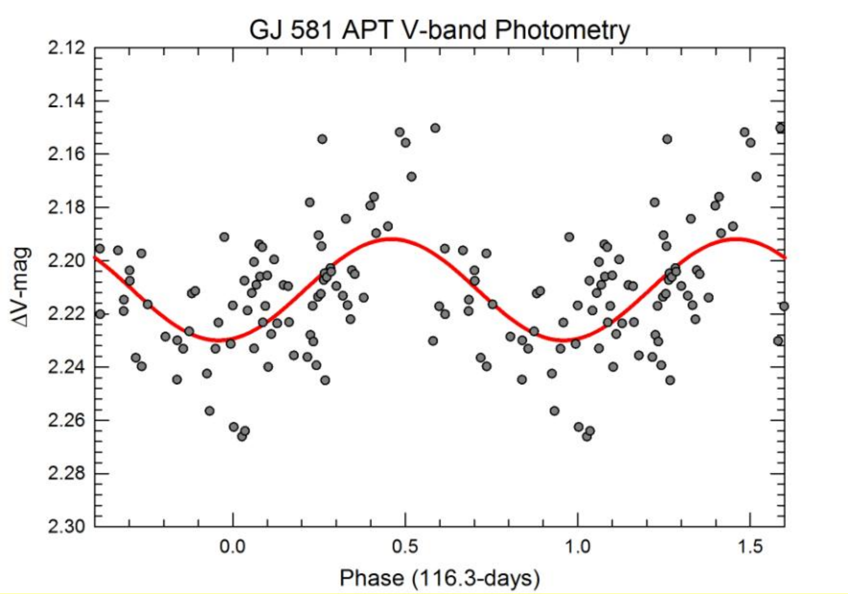
TWO-PLANET FIT TO THE RADIAL VELOCITIES.

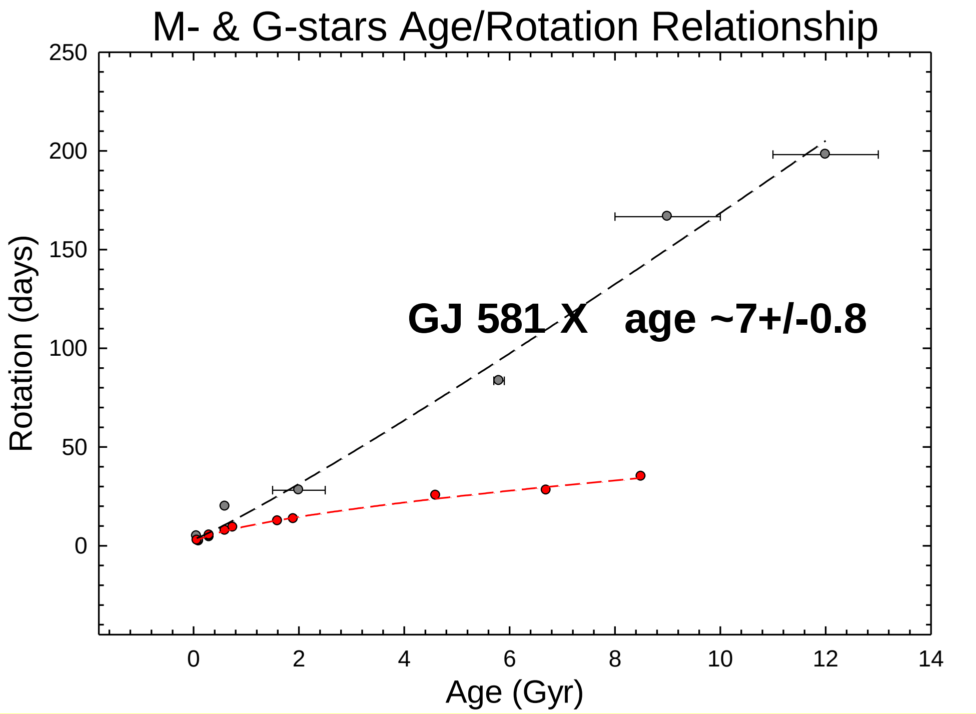
Parameter	GJ 436b	GJ 436c
P (days)	2.64384±0.00005	5.1852±0.0013
$T_{\rm peri}$ (HJD)	2451551.78±0.05	2451553.4±0.8
e	0.18±0.02	0.2 (fixed)
ω (°)	358±8	265±45
K (m s^{-1})	18.6±0.4	3.1±0.4
a (AU)	0.0287±0.0003	0.0450±0.0004
$M \sin i$ ($M_\oplus$)	23.3±0.5	4.8±0.6
Radial velocity drift	1.1±0.2	
rms (m s^{-1})	3.50	
$\chi^2_{\rm red}$	3.3	

Recent Estimation of the Age of GJ 581 system via its rotation period

Light curve plotted below
Showing 116 d period
Arising from star spots

Estimating age from
Prot – Age relation





GJ 581 X age ~7+/-0.8

Some Preliminary Conclusions

- Red Dwarf (dM) stars are the most numerous stars in the Galaxy (> 75% of all stars). They have very long lifetimes and nearly constant luminosities for 20+ Billion years. If found to harbor planets suitable for life, then the shear numbers of dM stars greatly increase the chances for finding life in our Galaxy.
- dM stars should preferably form less massive planets than solar-type stars (see Boss). In the seven nearby dM discovered so far to host planets - Neptune and "Super-Earth" type planets are the most common planets.
- The dM2 star GJ 581 is orbited by a large-Earth size planet (GJ 581c) located in the warm edge of the star's HZ.

Future Work

- Complete X-ray-UV irradiance tables for dM (and dK) stars with ages from ~10 Myr – 12 Gyr.
- Study X-ray coronal data from Chandra/XMM-Newton (X-ray-UV Archival data) to get ages for planet hosting dM stars (e.g. proposal submitted for GJ 581 to XMM-Newton in Oct-2007)
- Secure more reliable ages for older (2 Gyr+) dM stars to improve Lx-rotation-age relations (also for dK stars)
- Observe wide dM + WD binary systems - infer ages from white dwarf cooling time ages and from isochrone fits of main-sequence binary members (like Proxima Cen) -- see Silvestri et al. 2006.
- Determine rotations & star spot /activity cycles from photometry with our robotic telescopes and from archival ASAS photometry
- Improve flare UV data: Flare frequencies/ SEDs/ What about Coronal mass ejections?
- Stellar winds as a function of stellar age (from ALMA?). Need wind properties (densities/speed) as input (with XUV irradiances) to model atmospheres of hosted planets. Also can be done with Ly-alpha astrosphere studies with HST/STIS (see Brian Wood et al. 2005).

HD 209438b Transit eclipse